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Bivalent Heat Pump Plant serving a Multi-Family Dwelling - Quantification of the Impact of Different Control Strategies and Parameterisations

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Abstract

This article shows the effects of different control strategies and controller parameterisations on the KPIs energy purchase costs and non-renewable primary energy consumption for a bivalent air-to-water heat pump plant. This demonstrates the importance of system automation and the commissioning phase for energy-efficient operation.

The study showed that KPIs were up to 39% exaggerated due to unfavourable parameterisation. If the optimum parameterisation cannot be determined on the basis of preliminary technical considerations, simulation-based variant studies are a suitable method for identifying a sound parameterisation. This is exemplified for some parameters in this article.

Motivation

In 2023, HVAC and BAS accounted for approximately 35% of the total energy consumption in Germany. In the context of climate change, it is necessary to reduce this energy consumption and avoid inefficiencies in this sector. In particular, the "performance gap" between planning and operation, which has been frequently mentioned in the literature, needs to be addressed. This gap is partly due to the use of simplistic models (factors) in the DIN V 18599 energy and DIN EN 12831 heating load calculation for the system. However, the actual system performance depends significantly on hydraulic and control boundary conditions. If these are not considered during the design phase, they cannot be specified in the tendering process and cannot be controlled during commissioning. As a result, the efficiencies achieved in operation sometimes deviate considerably from the predicted values. In order to sufficiently consider the aforementioned boundary conditions, it is necessary to apply a simulation instead of a stationary calculation method. Different operating states and time-step-dependent effects due to storage must be considered.

Case Study

System Components and Dimensioning

The system considered is serving a multi-family dwelling in Germany with a living area of 1250 m². It was built in 2014 with an equivalent insulation value of the building envelope of HT'=0.33 W/m²/K. Figure 1 shows the heat demand of the building including hot water supply.

An air-to-water heat pump with a rated thermal output of 14.8 kW and a COP=2.71 (A-7/W55) serves as the base load heat generator. The performance curve at two different supply temperatures $T_{HP,sup}$ (according to the data sheet) is also shown in Figure 1. As peak load generator a gas condensing boiler with a controllable output between 15 and 48 kW is used.

Hot water is heated decentralized in the building using home stations, which require a constant flow temperature of 55°C in the heating network all year round. Figure 1 shows that the bivalence point is at 5°C.

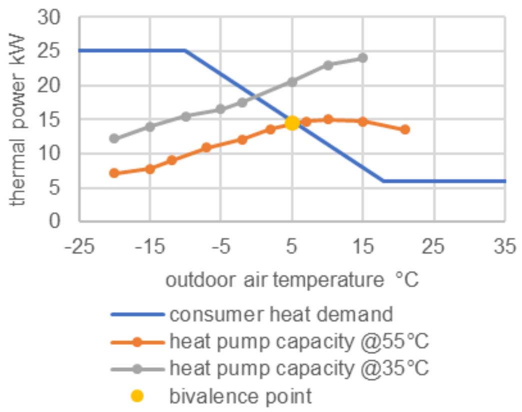

Figure 1 Comparison of load and power

In addition to the two heat generators, the system includes a 2000 litre heating water storage tank, which can be divided into an upper (warm) and a lower (cold) section. Assuming a spread of 20K (55/35°C) this storage has a thermal capacity of 47 kWh. The placement of the hydraulic connectors (A-F) plays an important role in correct operation - these are shown in Figure 2.

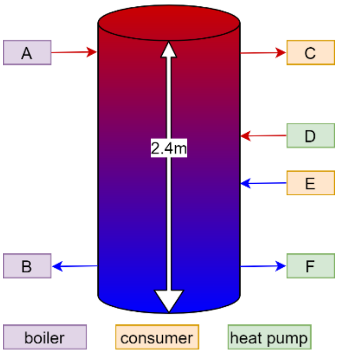

Figure 2 Geometry of the storage tank (to scale)

The calculation is based on the TRY04 data applicable to the location. In combination with the consumption characteristics shown in Figure 1, the required heating energy is shown in Figure 3.

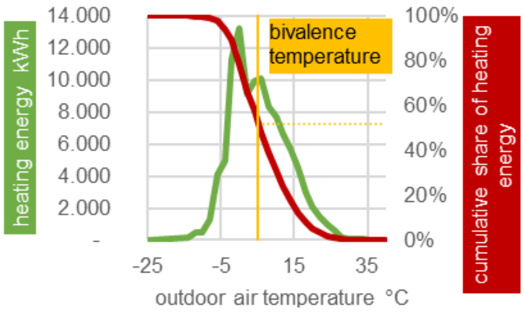

Figure 3 Heating energy depending on the outside temperature

Key Performance Indicators (KPIs)

Various key performance indicators (KPIs) can be used to evaluate the system: While minimizing operating costs (K) is desirable from the operator's perspective, minimizing non-renewable primary energy (PEV) is desirable from a macroeconomic perspective. This implies minimized CO2 emissions. One year is chosen as the period under consideration. Eq. 1 gives a general formulation of these KPIs.

$$KPI = \int_0^{8760h} (P_{el} * k_{el} + \dot{Q}_{gas} * k_{gas})\, dt \qquad 1$$

P_{el} hourly electricity consumption in kWh/h
$\dot{Q}_{gas}$ hourly gas consumption in kWh/h
k_{el}, k_{gas} expense factors with respect to the chosen KPI

The expense factors k from Eq. 1 differ according to the chosen KPI and are summarised in Table 1.

Table 1 KPI Expense factors k_i,j

energy carrier (j) / KPI (i)	**Electricity** k_i,el	**Gas** k_i,gas
Specific Cost k_K,j €/kWh	0,30	0,11
Primary energy factor k_PE,j kWh_PE,nr/kWh_EE	1,8	1,1

The energy balance must be fulfilled for the period under consideration. This period usually equals one year and is NOT included in the following equations as an index for reasons of readability. The buffer storage can compensate for certain short-term imbalances between consumption and generation (3).

$$Q_{prod} = Q_{HP} + Q_{Boiler} = Q_{load} \qquad 2$$

$$\dot{Q}_{prod} \sim \dot{Q}_{load},\ Q_{prod} = Q_{load}, \qquad 3$$

Q_{prod}, Q_{load} produced and consumed thermal energy of the system in kWh
Q_{HP}, Q_{Boiler} produced thermal energy by heat pump (HP) and boiler in kWh
$\dot{Q}_{prod}$, $\dot{Q}_{load}$ produced and consumed thermal power of the system in kW

The contribution factor $f_{D,HP}$ of the heat pump is an important index and is defined as follows:

$$f_{D,HP} = \frac{Q_{HP}}{Q_{load}} \qquad 4$$

The gas consumption Q_{Gas} of the peak load boiler is calculated from the residual output to be covered by Eq. 5. The efficiency of the boiler η_{boi} is assumed to be constant and independent of temperature. 106% is assumed as a typical value for a condensing boiler.

$$Q_{Gas} = (1 - f_{D,WP}) * Q_{prod} * \eta_{boi} \qquad 5$$

In contrast to VDI 4645, the balance limit with regard to electricity consumption W_{el} is defined narrowly and only includes the compressor output, as all other consumers such as pump and fan power are regarded as inevitable expenditure.

$$W_{el} = f_{D,HP} * Q_{load} * SEER \qquad 6$$

$SEER$ seasonal energy efficiency ratio (results from a weighted average of the COPs of the heat pump)

As the COP (coefficient of performance) of an air-to-water heat pump is anything but constant, the formulation with instantaneous values is used for the following considerations (index t for the time step under consideration):

$$P_{el} = f_{D,WP,\mathrm{t}} * Q_{prod,\mathrm{t}} * COP_t \qquad 7$$

The final energy consumption as an important criterion for the energy benchmark in Germany is calculated according to Eq. 8:

$$EEV = Q_{Gas} + W_{el} \qquad 8$$

Preliminary considerations for efficient operation

A decision must be made at each time step concerning the most effective method of providing the currently required heat output. This can deviate from the building's current demand due to thermal inertia of the building masses (>400 kWh/K) and the buffer storage (47 kWh).

While the efficiency of the boiler can be assumed to be constant, this is not the case for the air-to-water heat pump. Its efficiency depends on the source and sink temperature. The source temperature in this system is the outdoor temperature T_{oda}, the sink temperature corresponds to the heating water supply temperature $T_{HP,sup}$. (The index t at the COP is omitted in the following equations wrt to readability.)

$$COP = f(T_{oda}, T_{HP,sup}) \qquad 9$$

As described above, a constant supply temperature is required in the described system, only the dependency on the outside air temperature remains. According to the 2nd law of thermodynamics, the upper limit of the efficiency of a heat pump is the Carnot efficiency. The instantaneous COP is reduced by the Carnot efficiency (Eq. 10)

$$COP = \eta_{Carnot} * COP_{Carnot} = \eta_{Carnot} * \frac{T_{HP,sup}}{T_{HP,sup} - T_{oda}} \qquad 10$$

For each kWh to be generated, a decision must be made as to which generator is more efficient (in relation to the selected KPI of costs or primary energy). In each case, the generator with the lower expenditure (according to Table 2) should be selected. For the heat pump, the capacity limit might be reached beforehand (Figure 1), in this case the boiler must supplement the missing capacity as a peak load generator, regardless of whether this is efficient.

Table 2 specific effort

	Heat pump	Boiler
Costs	$\frac{k_{K,el}}{COP}$	$\frac{k_{K,gas}}{\eta_{Boiler}}$
Primary Energy	$\frac{k_{PE,el}}{COP}$	$\frac{k_{PE,gas}}{\eta_{Boiler}}$

The $COP_{threshold}$ is defined as the COP of the heat pump at which the specific effort for generation with heat pump and boiler are equal.

$$COP_{thresh} = \frac{k_{i,el}}{k_{i,gas}} * \eta_{Boiler} = f_i * \eta_{boi} \qquad 11$$

If the expected COP at the time step under decision is above the threshold COP_{thresh} (according to equation 11), the heat pump should be used; if it is lower, the boiler should be used. The greater the expense factor ratio f_k,i between electricity and gas (Table 1), the higher the COP of the heat pump must be in order to be the efficient choice, Table 3 shows this.

Table 3 KPI Expense factors ratios f_k,i

KPI	f_k,i	COP_{thresh}
Costs (K)	0,3/0,11 = 2,73	2,89
Primary energy (PE)	1,8/1,1 = 1,64	1,73

Resulting Energy concept

In order to amortise the investment of the heat pump and to demonstrate compliance with the 65% criterion in accordance with the the German building regulation (GEG), the aim is to achieve a high contribution factor of the heat pump.

The achievable contribution factor is limited due to the design of the heat pump. The contribution factor is made up of the amount of heat to be generated monovalent above the bivalence temperature amended by the share from bivalent parallel operation below the bivalence temperature.

According to Figure 3, 52% of the contribution factor results from the bivalence point of 5°C for monovalent operation. The remaining 48% of the annual heating energy is generated below an outdoor air temperature of 5°C and should also be covered as much as possible by the heat pump.

A balanced hourly analysis of the load, achievable heat pump output (Figure 1) in combination with the heating energy assigned to the outdoor temperature (Figure 3) results in a maximum contribution factor of 76% for the heat pump. The corresponding load profiles are shown in Figure 4.

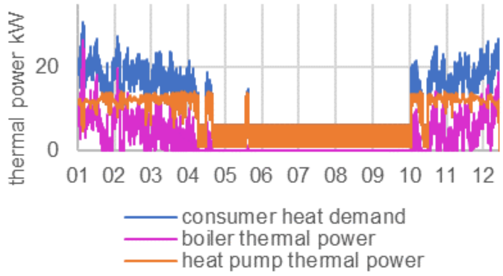

Figure 4 Load profile and generation capacity over the annual period

The preliminary considerations show that it is not always sensible to maximise the coverage of the heat pump, i.e., to operate it at its capacity limit or with exactly as much output currently required. To show this effect three different control strategies are implemented.

Implementation of the Energy Concept – Control Strategies

No overarching system controller is used; rather, the integrated controllers of the two generators, boiler and heat pump, must be properly coordinated in order to enable sensible control of the system.

It is assumed that both generators have a hysteresis control ("CTRL_OO") for switching on and off. A downstream PI controller ("CTRL_PI") is used to control the partial load state.

Three control strategies for bivalent-parallel operation at outdoor temperatures below 5°C are analysed. They differ in terms of the supply temperature set point of the heat pump $T_{HP,sup,set}$:

R1) The heat pump is operated its capacity limit in order to reach the supply temperature set point of the system ($T_{load,sup,set}$ = 55°C). The supply temperature set point of the heat pump is therefore also ($T_{HP,sup,set}$ = $T_{load,sup,set}$ = 55°C).

R2) The heat pump is operated with a constant supply temperature set point (e.g. $T_{HP,sup,set}$ = 52°C) below $T_{load,sup,set}$. Continuous additional heating by the gas boiler is required.

R3) $T_{HP,sup,set,t}$ is determined depending on the outside temperature. At time steps where $T_{HP,sup,set,t} < T_{load,sup,set}$, additional heating by the gas boiler is required.

$$T_{HP,sup,set} = min\langle T_{load,sup,set} | T_{HP,thresh} \rangle \quad 12$$

If, in addition to a constant efficiency of the boiler η_{boi}, constant effort factors $k_{i,j}$ (Table 1) and a constant Carnot quality factor η_{Carnot} of the heat pump are assumed, a supply temperature threshold can be determined from the above-mentioned limit COP_{thresh} as a function of the current outdoor temperature:

$$T_{HP,thresh} = COP_{thresh} * T_{oda} / (COP_{thresh} - \eta_{Carnot}) \quad 13$$

The load supply temperature setpoint of $T_{load,sup,set}$=55°C is used as the setpoint for both controllers of the peak load boiler. The measured value is the actual storage tank temperature at the level of the system outlet.

The setpoint for both heat pump controllers is the constant (R1, R2) or variable (R3) supply temperature set point of the heat pumps. The supply temperature in the heat pump charging circuit is measured as the actual value. A continuous circulation in this circuit must be guaranteed for this to be measured.

Simulation

Model Description

The simulation was carried out facilitating a Modelica model in the Dymola environment. Figure 5 shows the model.

The AixLib.Fluid.HeatPumps.HeatPump model was used for the heat pump, which was parameterised with the actual characteristic curves (thermal output $\dot{Q}_{HP}$=f(T_{oda},$T_{HP,sup}$) and electricity consumption P_{el}=f(T_{oda},$T_{HP,sup}$)) of a commercially available heat pump (Lambda EU-15L).

The demand side model was created by the authors and is highly simplified. The heat demand is modelled as a function of the outside air temperature as given in Figure 1. The mass flow decreases at partial load condition (T_{oda}>-10°C), but not to the same extent as the heat demand. As the outdoor air temperature increases, the realisable temperature spread decreases. The mass flow behaviour was modelled according to the measured behaviour of the real system. The thermal inertia of the demand side was taken into account indirectly by using hourly average values - no explicit modelling was carried out. The demand side model would therefore be unsuitable for evaluating load shifting potential.

The boiler model was also created by the authors based on the AixLib.Fluid.BoilerCHP.BoilerNoControl model. The control strategies were implemented using custom made models. No complex algorithms were implemented, only hysteresis and PI controllers were used. The necessary sensors were modelled according to available measurement points in the real system.

The model does not yet take into account evaporator frosting and blocking times by the electricity utility. Variable electricity tariffs and the model-predictive control have also not yet been implemented.

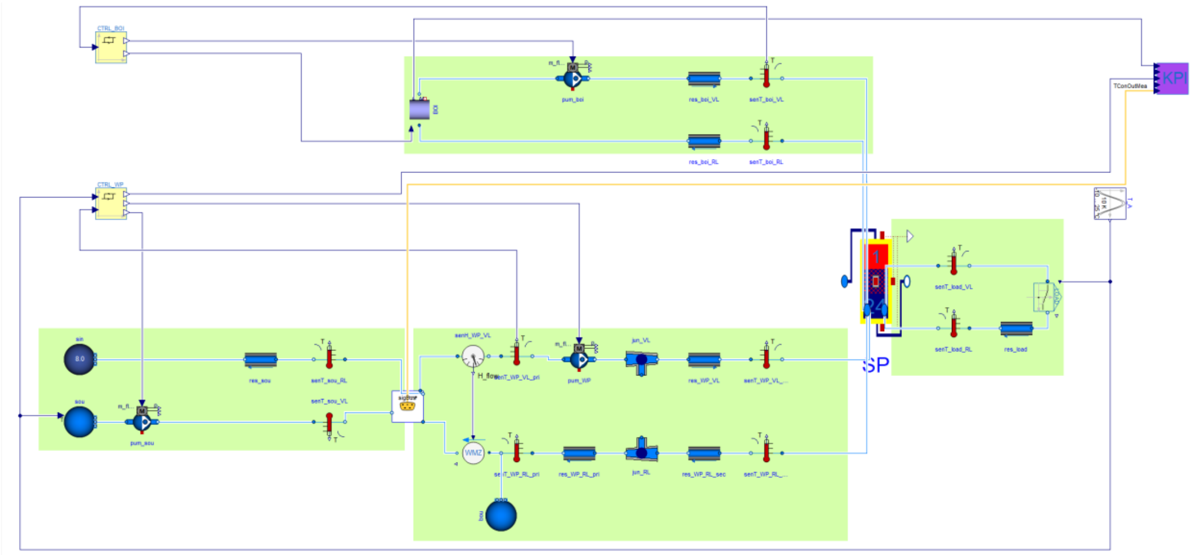

Figure 5 Modelica Model for the Case Study: Dymola Environment was used, custom made components based on the AixLib were facilized.

The variant study was carried out using the Python interface of the Dymola simulator. The runtime of the annual simulations is heavily dependent on the parameterisation of the controllers and takes between two and twenty minutes on a standard desktop PC.

Experiment 1: Comparing Control Strategies

First of all, the three control strategies were investigated, with different top-level parameterisation for the strategies R2 and R3, for the hysteresis' and PI controllers' standard parametrisations as highlighted in Table 5 and 6 were used.

Table 4 shows the results. Along with both KPIs (costs and non-renewable primary energy), the contribution factor and the seasonal energy efficiency rate of the heat pump are given. Since the end energy consumption (EEV), which is a sum of all purchased energies (electricity and gas) is an important KPI in German energy legislation it is given in the table as well.

Strategy R2 has been investigated with two different $T_{HP,sup,set}$ of 52°C and 55°C. The latter corresponds to the supply temperature set point of the system and the results should therefore be similar to these of R1. Small deviations result from a different placement of the temperature sensors used.

Strategy R3 has been investigated with two different COP_{thresh}, while 2.89 results from the expense factors for gas and electricity given in Table 1 and 3 for the KPI costs, 3.5 would be appropriate for a higher ratio between electricity and gas expenses. The KPI non-renewable primary energy results in a COP_{thresh}=1.73. This was not included in the variant study, as the heat pump examined achieves such a COP even under the most unfavourable operating conditions, i.e., at the minimal outdoor air temperature of -15°C.

Table 4 Comparison of variant of the control strategies with standard parametrisation (minimum and maximum highlighted in bold)

	SEER	$f_{D,HP}$	EEV MWh/a	Costs €/a	PEV_nr MWh/a
R1	3,52	81,2	24,9	5427	37,3
R2-55	**3,50**	**81,4**	25,0	5453	37,4
R2-52	3,60	81,1	**24,7**	**5339**	**36,8**
R3-2.89	3,50	81,4	25,0	**5453**	37,4
R3-3.5	**3,72**	**71,5**	**28,2**	5350	**39,3**
MAX/MIN	106%	114%	114%	102%	107%

The differences between the control strategies in terms of the KPIs are as expected: the higher the contribution factor of the heat pump, the lower the SEER achieved. Low contribution factors of the heat pump cause high final and primary energy consumption, as a lot of gas is used. There are hardly any differences in terms of operating costs.

Experiment 2: Finetuning Parametrisation of Hysteresis' and PI controllers

For the control strategy R3 with COP_{thresh}=2.89, various combinations of the parameterisation of the hysteresis controller have been examined in accordance with Table 5.

Table 5 Analysed parameterisations Hysteresis controller (bold: standard values)

$dT_{on,boi}$=	0 / 2 / 5 /**10** K
$dT_{off,boi}$ =	**0** / 5 /10 K
$dT_{on,WP}$ =	0 / 5 /**10** K
$dT_{off,WP}$=	0 / 2 / **5** /10 K

The highlighted combination turned out to be favourable, both in terms of primary energy consumption and costs. The parameterisation of the PI controllers was then varied for this parameter set according to Table 6.

Table 6 PI controller parameterisations investigated (bold: standard values)

$k_{CTRL,boi}$	0.1, 1, **10**
$Ti_{CTRL,boi}$	0.01, 0.1, 1, **10** s
$k_{CTRL,WP}$	**0.0001**, 0.001, 1.0
$Ti_{CTRL,WP}$	0.1, **30**, 3000 s

More than 100 combination of the parameters in tables 5 and 6 have been investigated: Varying the parameterisation of the hysteresis and PI controller results in greater differences in contribution factor $f_{D,HP}$, seasonal energy efficiency ratio SEER, operating costs and PEV than between the control strategies with standard parameterisation (Table 4). Table 7 shows the range from 100% (minimum achievable value) to 117% in terms of operating costs and even up to 139% in terms of primary energy consumption.

Table 7 Characteristic values for R3-2.89 with different parameterisations

	SEER	$f_{D,HP}$	EEV MWh/a	Costs €/a	PEV_ne MWh/a
Min	3,22	45,7	24,3	5179	36,2
Max	3,88	81,8	40,1	6069	50,1
MAX/MIN	121%	179%	165%	117%	139%

Figure 6 compares the two KPIs primary energy consumption and operating costs for the variants of the parametrisation of hysteresis' (blue) and PI-Controllers (orange), the 5 different variants of control strategies (as given in Table 4) are also shown (red). It can be concluded that the parameterisation of the hysteresis has a greater influence than that of the PI controller. However, changes in the parameterisation of the PI controller (proportional gain k and reset time Ti) enable a decoupling of PEV and costs. All variants in Figure 6 have the same investment costs.

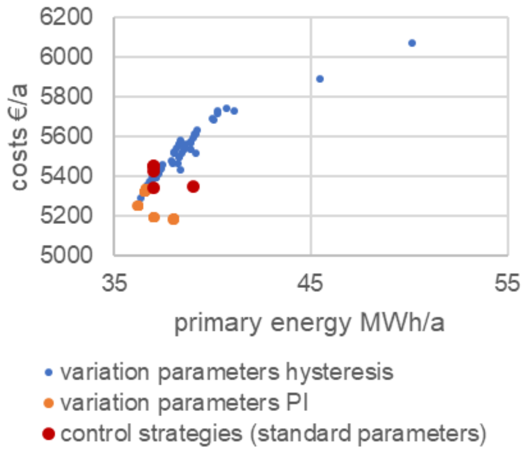

Figure 6 Operating costs and primary energy consumption of the different control variants

Conclusion

Preliminary considerations on suitable operating strategies for bivalent-parallel operated air-to-water heat pumps showed that an outdoor air temperature dependent specification of the heat pump supply setpoint temperature $T_{HP,sup,set,t}$ ensures the most efficient operation with regard to the selected KPIs (R3). However, depending on the characteristic curves of the heat pump, similarly good KPIs might be achieved with simpler control strategies (R1/R2). Table 4 shows that this is the fact for the heat pump examined in this study - the differences in operating costs are small.

The economic optimisation with regard to energy costs or the use of non-renewable primary energy require different top-level parametrisation of R3 (COP_{thresh}). Assuming the latter criterion as representative for a macro-economic perspective it can be concluded that the price signal does not set the right micro-economic incentives - a plant operator must decide in favour of one of the two KPIs as a target value.

The controller parameterisation (top level parametrisation of strategies R2 and R3, as well as the finetuning of Hysteresis and PI-controllers as shown for R3) has a considerable impact on the KPIs of a system. While the top-level parameterisation of the control strategies was only carried out within sensible ranges based on preliminary technical considerations (only 5 variants in Table 4), the parameterisation of hysteresis and PI controllers was varied over a very wide numerical range (more than 100 combination from tables 5 and 6). The resulting variations in the KPIs are therefore also significantly more widespread. It can be assumed that the fluctuation range of the KPIs would also be significantly widened with regard to the top-level parameterisation of the control strategies if no technical pre-restriction of the parameter space had been made. The study showed that KPIs were up to 39% exaggerated due to unfavourable parameterisation, this shows the relevance of controller parameterisation. If the optimal parametrisations cannot be identified on the basis of preliminary technical considerations, simulation is a suitable method for identifying this by means of variant studies.

As simulation models always contain simplifications, the realization of the KPIs should be checked in the operating phase. The system model provides a suitable benchmark for this.

Table 7 shows an operating cost saving potential between the cheapest and most expensive variants of just under €900 per half-year (given the prices for gas and electricity in Table 1), which can be realised without any hardware investment. In order to realise this potential, however, it is necessary to carry out the simulation. Without simulation, a mediocre operating strategy might be achieved, so that savings of approx. €1000 per year appear realistic for the example system. With a targeted ROI within 3 years, the cost of determining the optimum control strategy (using simulation) and implementing it (by parameterising the system controller) should not exceed €3000. With current simulation environments and libraries and a suitable toolchain for variant studies, this seems ambitious but possible.

The investigations were carried out for a heating system whose design had already been based on simulation and therefore matched the demand of the building supplied very well. Many heating systems are considerably oversized and it can be assumed that there is much greater potential for optimising such systems through controller parameterisation.

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