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Heat pump systems with photovoltaics: Influence of the control strategy on the optimal design

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Abstract:

Electrifying the heat supply of buildings is key to mitigate climate change. Inhere, photovoltaic and heat pump systems are promising technologies. Studies indicate that an increase in self-consumption is economically beneficial. Coupling photovoltaic with heat pump systems enables the aspired increase of self-consumption, especially in combination with thermal energy storages. The coupling of the systems is influenced by the control strategies, for which rule-based and model predictive-based approaches exist. Research finds that optimal control methods heavily depend on the system design and vice versa. Contrary to these interdependencies, current design guidelines neglect a possible influence of photovoltaics on the design of the heat pump system.

To analyze a possible influence on the optimal heat pump system design, we apply nonlinear, dynamic simulation-based optimization to find the optimal design of the heat pump system for three different cases: no photovoltaic, no supervisory control, and a state-of-the-art supervisory control. The model consists of the whole building energy system, including the building envelope, radiators, a heat pump, a photovoltaic, and a grid connection. The dynamic simulation covers a whole year. To obtain generalizable results, we conduct optimizations for varying boundary conditions, including changes in weather and photovoltaic roof area.

Consistent over all boundary conditions, results indicate that cost optimal heat pump system design does not change for current price assumptions. However, maximizing the thermal energy storage is vital to obtain maximal costs savings compared to the case with no photovoltaic system. Thus, for different price assumptions, the optimal design will change.

Keywords:

Simulation-based Optimization, Rule-based Control, Dynamic Simulation, Modelica, Design of Experiments

1. Introduction

The residential building sector accounts for 25 % of Germany's CO_2 emissions [1]. To reduce these CO_2 emissions, electrification of the residential building heating sector is vital. Inhere, heat pumps (HPs) and photovoltaic systems (PVs) are essential technologies [2–5].
Heat pumps are able to provide space heating (SH) and domestic hot water (DHW) using electrical energy. Besides refrigerant leakage, operational emissions depend on the emission factor of the used electrical energy [5].
PVs generate generate emission-free electricity during operation. Typically, a higher self-consumption leads to faster pay-off rates. Combining heat pumps and PV, synergies arise. While the heat pump can utilize the emission-free electricity, the self-consumption and, thus, viability of PV increases as well [2, 3]. However, this effect is impeded by asynchronous supply and demand of residential buildings on a daily and seasonal timescale. At daytime, the PV generates more electricity due to solar radiation; simultaneously, the heat pump requires less, as the heat demand decreases. In summer, the PV generates overall more electricity; but the heat pump, if only used for heating, requires electricity only for DHW applications.

Several storage technologies are suitable to overcome this issue. Battery storages enable a shift of emissions-free PV-generated electricity to more useful times, while thermal energy storages shift the heat pump operation to more useful times. As a storage medium, water or the building's mass may be used. In residential heat pump systems, water-based thermal energy storages are already used for several reasons: Storing DHW [6], buffering defrost cycles [5], limiting on/off cycling at part load [6], or acting as a hydraulic separator to enable different mass flow rates [7]. Hence, using the existing water-based storages is a viable option compared to the capital-cost-intensive invest into a battery [2, 3, 8].

Minimizing costs and emissions requires optimizing the design and control of the heat pump, the PV, and the thermal energy storage. Researchers use advanced design and control methods to achieve optimality, such

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as supervisory model predictive control (MPC) [9] or simulation-based optimization of heat pump systems [5]. However, these advanced methods are not state-of-the-art [10, 11]. In practice, rule-based design and control methods are applied [4,6,12]. With an expected service-life of around 20 years [12], each suboptimal design of a building energy system today impedes the climate goals of Germany for 2045 [13]. Additionally, the market share of heat pumps in the German building stock is only 5 % [14]. To enable a fast ramp-up of heat pump systems in the building stock, practitioners require simple rules for design. For control, manufacturers will presumably not open up the internal control interfaces to external energy management systems. In Germany, a heat pump is considered Smart-Grid-Ready (SG-Ready), if it allows four modes: (1) block the heat pump, (2) normal operation, (3) turn-on request, and (4) turn-on command [15]. The latter two may increase setpoints in the local control of the heat pump and, hence, indirectly the compressor frequency [16]. Hence, current state-of-the-art heat pumps only support mode-based supervisory controls. Resulting, this contribution focuses on ready-to-use, rule-based design and control methods for heat pump systems with photovoltaic.

In the following, we review contributions regarding (1) rule-based design approaches and (2) rule-based control approaches. In this review, we focus on heat pump systems with PV using thermal energy storages.

1.1. Rule-based design approaches

Research contributions highlight the importance of a correct heat pump and thermal energy storage size [2, 5, 10, 17]. As central guideline in the European Union, the EN 15450 provides rules for sizing heat pump systems based on the bivalence temperature T_{Biv}, the heat demand at nominal outdoor air temperature, and further assumptions for space heating as well as DHW usage [6]. German guidelines follow similar approaches relying on the bivalence temperature for design [12]. The bivalence temperature affects the sizing of the heat pump and, thus, invest and operational costs. Furthermore, the space heating storage is sized with a factor depending on the heat demand $V_{\dot{Q}_{\mathrm{Bui}}}$ between 12 and 35 l kW^{-1}. Despite the influence of T_{Biv} and $V_{\dot{Q}_{\mathrm{Bui}}}$ on the design, current guidelines require both T_{Biv} and $V_{\dot{Q}_{\mathrm{Bui}}}$ as an input [6, 12]. Recommendations depending on the boundary conditions, like weather or building envelope, are not given. Additionally, a potential influence of PV on the rule-based design is neglected.

In research, several contributions aim at an optimized design of heat pump systems. They highlight that the operational phase determines the optimal design. Consequently, they perform annual simulations and integrated design and control optimizations. While heat pump and storage sizes are varied, the influence of PV is not assessed. [5, 10, 17]

Designing heat pump systems with PV, Kemmler and Thomas [2] vary heat pump and storage sizes for different buildings and technologies, always considering PV and an MPC. However, MPC is not yet state-of-the-art. Huang el al. [18] perform a design optimization for a system containing PV, heat pump, thermal energy storage, and electric vehicles using simulation-based generated load profiles as an input. This impedes the control analysis and a possible influence on the optimal design. For PV-thermal systems, Miglioli et al. [19] state optimal design heavily depends on the boundary conditions. They advise to size the heat pump independent from the PV-thermal sizing, as summer operation is dominant for the optimal sizing of solar-based technologies.

Overall, contributions either do or do not consider PV for the optimal design of the heat pump system. A direct comparison between using PV and using no PV in optimal design is only given by Fischer et al. [20]. They analyse the impact of PV on the optimal heat pump system design using mixed-integer linear programming. Varying boundary conditions, they find that the heat pump size does not change with PV. Moreover, the thermal energy storage size changes only slightly. Therefore, they follow that current guidelines are sufficient. However, they assumed optimal control and simplified component models, highlighting the need for detailed simulations in their outlook.

1.2. Rule-based control approaches

Fischer et al. [4] compare control approaches for heat pump systems with PV. Both predictive and non-predictive controls are considered. While predictive controls are more efficient, current state-of-the-art heat pump rely on non-predictive, rule-based approaches. However, the non-predictive, rule-based controls applied in [4] or [21] use the compressor frequency as an actuator, which is not state-of-the-art.

Rule-based supervisory controls using setpoint changes follow the same principle: If enough PV surplus is present, thermal storage setpoints are increased - either by a fixed temperature difference, or to a maximal value [3, 4, 8, 21]. Both Haller et al. [8] and Pinamonti et al. [3] first increase DHW setpoints and later space heating setpoints. Pinamonti et al. [3] go further and activate the building inertia as well.

In general, the optimal values for these controls depend on the design of the system [4, 22]. For instance, different contributions find that increasing the storage volume is not necessary to achieve an increase self-consumption with good control values [8,21]. However, these results depend on price assumptions and storage

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insulation levels.

1.3. Research questions

The review on rule-based design and control approaches shows their mutual dependence. However, it is not apparent to what extent PV and the use of a state-of-the-art supervisory control may influence the optimal design of the heat pump system [2–5, 8, 10, 18, 19, 21].

Therefore, we conduct an analysis by means of detailed annual simulation-based optimization aiming to answer two questions:

1. *Does the existence of PV affect the optimal design of residential, retrofit heat pump systems?*
2. *Does the usage of a state-of-the-art, rule-based control for PV surplus affect the optimal design of residential, retrofit heat pump systems?*

To answer these questions, the remainder of the contribution is structured as follows: Section 2 presents the simulation model, rule-based control approach, and the study design to analyse the influence of PV on the design. In Section 3, we analyse the results. Section 4 presents limitations and implications of this contribution. In Section 5, we summarize the findings and highlight future research prospectives.

2. Methods

2.1. System model

As motivated in Section 1, we focus on retrofit residential buildings in the German building stock. Following current guidelines [6], a typical building energy system consists of: A heat pump and heating rod (HR) connected in series; a space heating storage connected in parallel; a separate DHW storage with an internal heat exchanger connected in parallel; radiators to transfer heat to the rooms; analogue thermostatic valves which control the volume flow through each radiator to ensure thermal comfort; and rule-based controllers.

We model this system using the open-source Modelica library BESMod [23]. In here, components, control, and building envelope are modelled in a dynamic, nonlinear fashion:

- **Heat Pump**: Air-to-water heat pump with Propane as refrigerant [24, 25].
- **Heating Rod**: Ideal heater with a constant efficiency of 97 % [5, 25].
- **PV**: Model from [26] based on manufacturer data [27] with 133 $\mathrm{Wp/m^2}$ maximum power peak (MPP) per area.
- **DHW storage**: Indirect heat exchanger and a constant volume of 125 l [6, 25].
- **Space heating storage**: Directly charged storage with a volume depending on $V_{\dot{Q}_{\mathrm{Bui}}}$ [6].
- **Radiators**: Model according to EN 442 [25, 28] with a nominal supply temperature of 55 °C.
- **Building envelope**: The reduced order approach from the AixLib [25] is used, which is coupled to TEASER [29].

In the following, we highlight the control approach of the building energy system. As in literature, we separate the control into two layers: supervisory and local control.

2.1.1. Supervisory control

Rule-based, non-predictive supervisory control approaches in literature follow the basic principle of [3, 30]. As we analyse a retrofit building with low mass and radiator transfer system, only overheating of the DHW and space heating storage are considered.

Figure 1 depicts the implemented control logic. The electrical surplus power, $P_{\mathrm{el,Sur}}$, acts as an input. The electrical subsystem calculates the surplus based on current PV generation and all electrical power demands of the heat pump system.

Then, a hysteresis checks if the current surplus exceeds the upper hysteresis limit $P_{\mathrm{el,Hys}}$. The lower hysteresis limit is 0 W. Current research uses the minimal electrical power of the heat pump, $P_{\mathrm{el,HP,Min}}$ as a value for $P_{\mathrm{el,Hys}}$ [21]. At the same time, [4] highlights that the control strategy and component sizing is strongly interconnected. As $P_{\mathrm{el,Hys}}$ essentially defines the number of times the supervisory control overrides the local control, we vary the value as a fraction $f_{\mathrm{HP,PV}}$ based on the heat pumps nominal electrical power $P_{\mathrm{el,HP,Nom}}$, which is given in datasheets at rated conditions A2W35:

$$P_{\mathrm{el,Hys}} = f_{\mathrm{HP,PV}} \cdot P_{\mathrm{el,HP,Nom}} \tag{1}$$

If surplus exceeds the threshold, the control increases the DHW storage setpoint to $T_{\text{set,DHW,PV}}$. If the measured DHW storage temperature from the uppermost layer $T_{\text{mea,DHW}}$ exceeds this setpoint, the control increases the space heating storage setpoint by $\Delta T_{\text{SH,PV}}$. Using a winter mode from September until April, space heating is never affected during summer period.

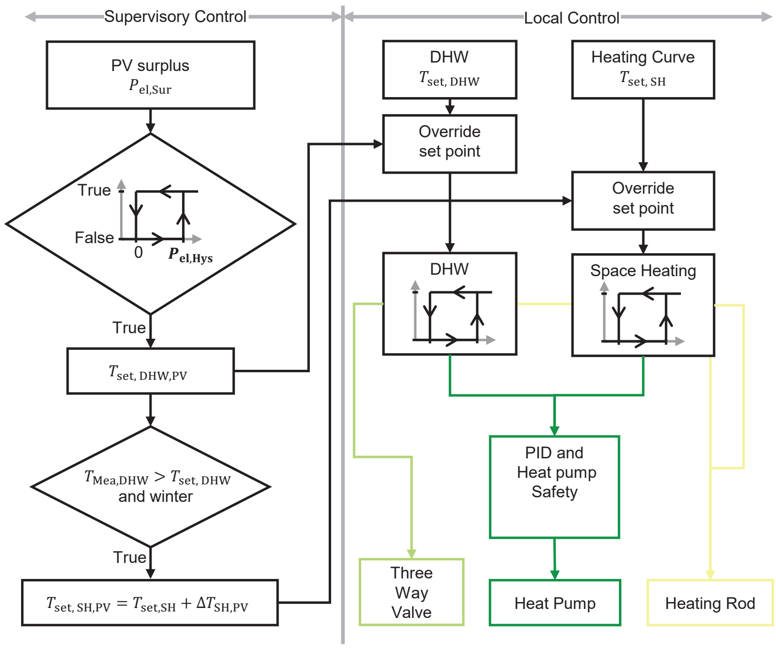

Figure 1: Rule-based supervisory and local control logic following the approaches in [3,30,31]. Colors indicate the flow of the lines.

The supervisory control only changes the setpoints of the local control. Three parameters may be changed: $f_{\text{HP,PV}}$, $T_{\text{Set,DHW,PV}}$, and $\Delta T_{\text{SH,PV}}$. We performed a separate control optimization for a single guideline-based design using the same model. Here, the values $T_{\text{Set,DHW,PV}}$ =60 °C and $\Delta T_{\text{SH,PV}}$ =15 K are pareto-optimal for relevant objectives (cf. Section 2.2.3.). The detailed analysis of this control optimization exceeds the scope of this contribution. It is noteworthy that 60 °C is also the maximal value used by [21].

As the parameter $f_{\text{HP,PV}}$ dictates to what extent surplus may be used, we include this parameter in a design and control optimization (cf. Section 2.2.2.).

2.1.2. Local control

A local controller actuates the different components based on these setpoints.

The local control follows the approach in [31] and is depicted in the right part of Figure 1. Two hystereses decide whether the heat pump and heating rod turn on or off for space heating and DHW. DHW has priority over space heating. For the heating rod control, the time-based approach from [5] is used. If the lower hysteresis limit is violated for more than 30 minutes, the control activates the heating rod. A PI controller actuates the heat pumps compressor frequency based on the set and measured values in the system. Moreover, a safety controller ensures minimal runtime, off-time, and limits the maximal number of starts per hour to three [24].

2.2. Study design

The research question's answers depend on uncertain economic parameters (i.e., electricity tariffs) and involves multiple relevant objectives, for instance, costs, emissions, efficiency or self-consumption. To evaluate multiple scenarios and objectives, we use a full-factorial design of experiments to evaluate every possible combination of discrete optimization variables [32]. Factors of the full-factorial design are different boundary conditions (cf. Section 2.2.1.) and optimization variables (cf. Section 2.2.2.). Section 2.2.3. highlights relevant objectives for our analysis.

Using discrete variables leaves untapped potential. For instance, a 9.48 kW heat pump could be the global optimum; whereas the discrete choice for a 10 kW heat pump is only near-optimal. However, manufacturers only offer discrete component sizes anyway. Thus, insights on whether these discrete choices change is

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sufficient to answer the question if the optimal design changes. If the continuous optimum is of interest, a surrogate-based optimization approach can be applied to efficiently search for it [33].

2.2.1. Boundary conditions

The boundary conditions may influence the findings in this contribution. To limit the complexity of the study, we only vary certain boundary conditions. In the following, we motivate our choices.

Weather

The system design according to guidlines [6, 34] depends on the nominal outdoor air temperature $T_{\mathrm{Oda,Nom}}$, which is defined by the buildings's location [35]. Additionally, the solar radiation at different locations may influence the design of a heat pump system with PV. Thus, we define three weather cases: cold, average, and warm. We extract these cases from the German guideline DIN 4710 [36], which seperates Germany into 15 climatic regions. For weather data, the test reference year *average* is selected for each location provided by Germany's Meteorological Services [37].
Using this data, we calculate $T_{\mathrm{Oda,Nom}}$, the minimal temperature $T_{\mathrm{Oda,Min}}$, the mean temperature $T_{\mathrm{Oda,Mean}}$, and the sum of direct and diffuse radiation on a horizontal plane H_{Glo}. Based on the values, we select the coldest (Fichtelberg), warmest (Bremerhaven), and average (Bad Marienberg) region based on $T_{\mathrm{Oda,Nom}}$. Table 1 lists all four relevant characteristics for the three regions. With cumulative global radiation between 931.59 kW h m^{-2} in Hamburg and 1123.95 kW h m^{-2} in Weihenstephan, the selected locations represent a typical range of global radiation in Germany.

Table 1: Values for relevant characteristics of climatic regions in Germany.

Region	$T_{\mathrm{Oda,Mean}}$ in °C	$T_{\mathrm{Oda,Nom}}$ in °C	$T_{\mathrm{Oda,Min}}$ in °C	H_{Glo} in kWh/m^{2}a
Bremerhaven	9.8	-7.8	-10.2	1023.8
Bad Marienberg	7.8	-11.0	-17.6	955.8
Fichtelberg	3.4	-16.1	-18.4	984.2

Building Envelope

For the building envelope, we select a non-renovated building from the construction period 1983 with a net-floor-area of 156.25 m^2 from the German TABULA standard [38]. Using TEASER, the envelope model is generated [29].

The roof has a total area of 72.9 m^2 and two sides, each with a tilt of 35°. One half is south-facing, the other half north-facing. As south-facing installations are a common recommendation, we focus on this orientation [39]. Using 100 % of the south-facing roof, the MPP equals 4.8 kW.

User

Besides weather and building envelope, user profiles may influence the optimal design of the system. At the same time, user profiles are inherently uncertain and stochastic. To neglect a possible influence of stochastic profiles, we assume deterministic profiles based on guidelines.
For DHW, Profile M according to European Union Regulation 811/2013 [40] is used.
For internal gains, standard profiles from TEASER are used [29]. However, we neglect the influence of internal gains on the electricity demand. All available PV electricity may be used for the heat pump system. This either represents a tenant-landlord scenario or a best-case scenario, where homeowners adjust their appliances usage in favour of the heat pump. While the latter is not realistic, it maximizes the possible influence of PV on the heat pump system, and, thus, its optimal design.

2.2.2. Design and control optimization

Table 2 lists the factors and levels of the integrated design and control optimization. Following findings in recent literature, we use 1 K levels for the bivalence temperature, as this parameter has the highest influence on efficiency, cost, and emissions [5, 17].
Aside from the aforementioned factors, we enable and disable the supervisory control. Combined with the roof area usage factors, this leads to three cases which we use to analyse the influence of PV and the control strategy on the optimal design of the heat pump system:

1. *No PV*: Reference case with no PV and no supervisory control
2. *No Control*: PV but no supervisory control
3. *Control*: PV and a rule-based supervisory control

Case 2 applies when components of different manufacturers are used which are not able to communicate with a supervisory control.

Overall, 2640 annual simulations are run, with an average computation time of 15 min[1].

Table 2: Full-factorial design for the design and control optimization

Factor	Values	Number of levels
Weather	Fichtelberg, Bad Marienberg, Bremerhaven	3
Roof area usage	0 %, 50 %, 100 %	3
Supervisory Control	Disabled, Enabled	2
$f_{\mathrm{HP,PV}}$	10 % to 100 %	4
T_{Biv}	−16 °C to 5 °C	20
$v_{\dot{Q}_{\mathrm{Bui}}}$	$5\,\mathrm{l\,kW^{-1}}$ to $100\,\mathrm{l\,kW^{-1}}$	4

2.2.3. Objectives

As the invest decision of a homeowner may depend on more than one objective, we analyse the optimal design with regard to multiple objectives.

Besides costs and efficiency, the self-consumption rate and the self-sufficiency degree are often used as characteristic values for the evaluation of systems with PV [30].
Emissions are not analysed in detail within this contribution. However, the full-factorial design enables a post-analysis of further objectives.

Economics

The cost functions for annuity of the heat pump system follow [10, 41]. Inhere, invest, operation, and maintenance costs are considered.
As we want to analyse a possible change in the heat pump system design if PV is used, we explicitly neglect the investment in PV. In reality, the economic viability of PV depends on the self-consumption rate, which is influenced by household appliances. As we neglect those, assessing economic viability of PV is not within the scope of this contribution.

Further, we assume current electricity tariffs from Germany, with 36.06 $\mathrm{ct_{EUR}/kWh}$ for electricity consumption and 8.2 $\mathrm{ct_{EUR}/kWh}$ for feed-in.

Efficiency

The seasonal coefficient of performance $SCOP_{\mathrm{Sys}}$ indicates the annual efficiency of the heat pump system. To incorporate the whole system, we define the $SCOP_{\mathrm{Sys}}$ according to an energy balance around the building energy system:

$$SCOP_{\mathrm{Sys}} = \frac{\int_{0\mathrm{a}}^{1\mathrm{a}} (\dot{Q}_{\mathrm{SH}}(\tau) + \dot{Q}_{\mathrm{DHW}}(\tau))d\tau}{\int_{0\mathrm{a}}^{1\mathrm{a}} (P_{\mathrm{el,HP}}(\tau) + P_{\mathrm{el,HR}}(\tau))d\tau} \tag{2}$$

Inhere, $\dot{Q}_{\mathrm{SH}}$ is the building's space heating demand, $\dot{Q}_{\mathrm{DHW}}$ is the DHW's demand, as well as $P_{\mathrm{el,HP}}$ and $P_{\mathrm{el,HR}}$ the heat pump's and heating rod's electrical power consumption, respectively.

Self consumption rate

The ratio of directly used PV electricity $W_{\mathrm{el,PV,use}}$ and the generated PV electricity $W_{\mathrm{el,PV}}$ defines the self consumption rate SCR [39]:

$$SCR = \frac{W_{\mathrm{el,PV,use}}}{W_{\mathrm{el,PV}}} \tag{3}$$

In literature, the SCR is commonly used to evaluate design and control approaches for PV systems [3, 4, 8].

Self-sufficiency degree

The ratio of directly used PV electricity $W_{\mathrm{el,PV,use}}$ to the total electricity demand defines the self-sufficiency degree SSD [39]:

$$SSD = \frac{W_{\mathrm{el,PV,use}}}{W_{\mathrm{el,tot}}} = \frac{W_{\mathrm{el,PV,use}}}{W_{\mathrm{el,PV,use}} + W_{\mathrm{el,Grid}}} \tag{4}$$

[1] Intel(R) Xeon(R) CPU E5-1650 v3 @3.50GHz, 32 GB DDR3 RAM, 64 bit, SSD hard drive

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3. Results

We separate the results of the design and control optimization into two cases. First, we analyse if the existence of PV changes the optimal design. Second, we highlight the influence of the design on the optimal control parameters.

3.1. Influence of PV on the heat pump system design

Figure 2 illustrates three cases for the medium weather case and a south-facing PV installation with 100 % roof area usage. For all other cases, the absolute values change, but the relative deviations are comparable. Thus, we focus on this case for our analysis.
First, the optimal design does not change; neither when using no supervisory control, nor when using a supervisory control. Second, the relative objective space, i.e. the gradients, does not change between the cases. This observation holds for all simulated boundary conditions. Thus, for the current price assumptions (cf. Section 2.2.3.), PV does not influence the optimal design of the heat pump system.

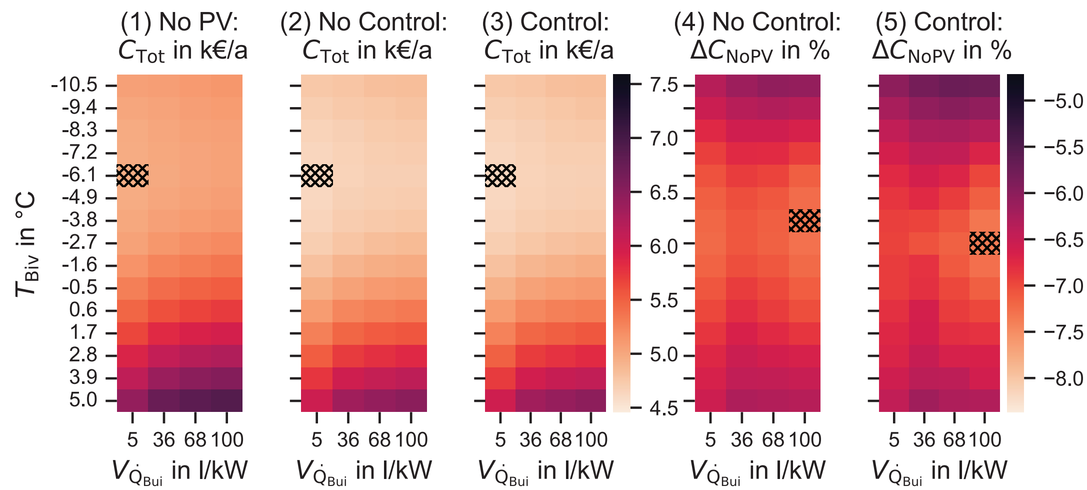

Figure 2: Optimal total costs over T_{Biv} and $V_{\dot{Q}_{Bui}}$ for the three cases (1) *No PV*, (2) *No Control*, and (3) *Control*. Furthermore, the percentage change in total costs compared to case *No Pv* ΔC_{NoPV} for the cases (4) *No Control*, and (5) *Control* is depicted. Results are for location Bad Marienberg and a south-facing PV installation with 100 % roof area usage. The hatched cell indicates the optimal design.

Looking at further differences in the objective space, Figure 2 also depicts the change in total costs compared to the case *No PV*. For these boundary conditions, the case *No Control* yields cost reductions between 5.8 % and 7 %, while the case *Control* obtains cost reductions between 5.7 % and 7.3 %. Over all boundary conditions, the case *No Control* obtains cost reductions between 5.3 % and 7.7 %, while the case *Control* obtains cost reductions between 2.6 % and 7.9 %. With 0.3 % additional cost reduction, case *Control* is only slightly better than case *No Control* for the highest cost reduction. At the same time, case *Control* achieves lower cost reductions in some cases compared to case *No Control*.
Consistent over boundary conditions, the highest cost reductions are achieved with smaller heat pumps and larger thermal energy storages compared to the economic optimum.

Figure 3 illustrates four important metrics to explain why the optimal design changes. Inhere, the self-sufficiency degree *SSD* closely resembles the cost reductions. Essentially, the *SSD* is a superposition of the self-consumption rate *SCR* and the system efficiency $SCOP_{Sys}$.
First, the *SCR* increases with bigger thermal energy storages and smaller heat pumps. Bigger thermal energy storages enable a better exploitation of surplus electricity. Smaller heat pumps lead to higher times of heating rod usage t_{HR} and, thus, an increased electricity demand. This increased electricity demand increases the chance of PV electricity being used and, therefore, the *SCR*.
Second, the $SCOP_{Sys}$ decreases with smaller heat pumps and increases slightly for bigger storages, as the local control requires the heating rod less frequently. For small storages and monovalent heat pumps, the $SCOP_{Sys}$ decreases slightly. Suboptimal PID-values lead to this decrease.

The results in this section hold for the optimal control value $f_{PV,HP}$. The following section analyses how the optimal values of $f_{PV,HP}$ change with the design.

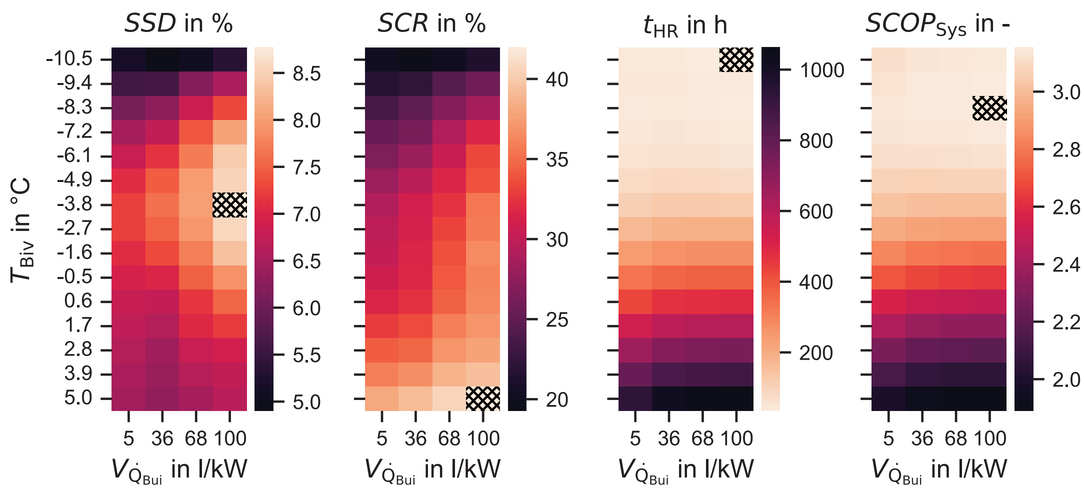

Figure 3: Optimal values for the *SSD*, *SCR*, heating rod on-time t_{HR}, and $SCOP_{Sys}$ over T_{Biv} and $V_{\dot{Q}_{Bui}}$ in case *Control*. The results hold for location Bad Marienberg and a south-facing PV installation with 100 % roof area usage. The hatched cell indicates the optimal design.

3.2. Influence of the design on the optimal control

The control parameter $f_{HP,PV}$ defines the threshold to increase setpoints and, thus, use surplus electricity. Figure 4 illustrates the optimal settings for $f_{HP,PV}$ depending on different designs of heat pump and storage, as well as relevant objectives. For cases with multiple optima, especially for monovalent designs (minimal T_{Biv}), the maximal value of $f_{HP,PV}$ is used.

Looking at total costs, settings equal or greater than 40 % are optimal. For bivalence temperatures around −6 °C, the lowest values of 40 % are optimal for larger storages. This design is concurrent with the highest cost reduction through the control. Thus, to achieve the highest cost reduction, the supervisory control needs to be included into the optimization problem.

Focusing on the efficiency, maximal values of $f_{HP,PV}$ maximize the $SCOP_{Sys}$. Only for the smallest heat pump, where the efficiency is already low, smaller values of $f_{HP,PV}$ are advisable. Looking further at *SSD* and *SCR*, minimizing $f_{HP,PV}$ is advisable. These findings hold for different boundary conditions considered in this study.

4. Discussion

Before discussing the implication of our results, we highlight limitations in the methods applied.

4.1. Limitations

The results show that the applied rule-based control is better or worse for different designs compared to using no control. Overall, not more than 0.3 % of costs are additionally saved due to the supervisory control. We optimized the set-temperatures in a separate study and the threshold in our design and control optimization. Including the set-temperatures may yield further saving potential. However, as the separate operational optimization is conducted for designs close to the optimal design, we do not expect the optimal design to change. In contrast to [3], we do not consider space cooling. Further, we study colder climates and buildings with a DHW share of only 5 % to 8 %. As Fischer et al. [21] point out, DHW is the dominating factor for PV. Our study confirms these results. Fischer et al. study a DHW share of 16 % [21], Pinamonti et al. of 23 % up to 48 % [3]. While investigating higher DHW shares might benefit the supervisory control, it does not affect the optimal rule-based design according to current guidelines [6]. In here, the DHW storage volume is fixed by demand. However, future studies should check if an optional over-sizing factor could be introduced to guidelines to increase self-sufficiency for heat pump systems with PV.

Furthermore, the rule-based control in current research are either based on digital thermostats or the ability to control the compressor frequency. Especially the latter is not given for the current SG-Ready label. Thus, we follow that the rule-based control is plausible for current state-of-the-art retrofit systems in Germany.

A further limitation in the methodology is the assumption that PV is only used for the electricity demand of the heat pump system. In reality, household appliances decrease the PV surplus. This further minimizes the chance of the heat pump system to use cheap PV electricity. While not relevant to our research questions

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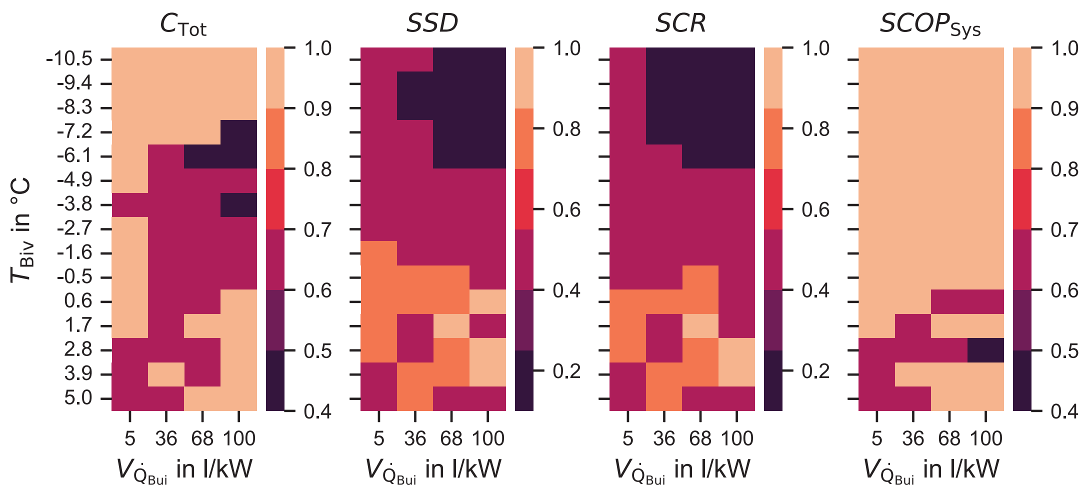

Figure 4: Optimal control values for $f_{HP,PV}$ with regard to the optimal objective values given in Figure 2 and Figure 3. Values are given over T_{Biv} and $V_{\dot{Q}_{Bui}}$ and hold for location Bad Marienberg with a south-facing PV installation and 100 % roof area usage.

regarding the change in optimal design, realistic internal gain profiles should be used if an optimal design for a specific case is required.

Our results are consistent for varying weather data and PV areas. However, other boundary conditions such as the ratio of roof area to heating demand may influence the results. For our cases, PV surplus is mostly available during spring, summer, and autumn. For better-insulated buildings with a larger roof, the surplus usage and, thus, the optimal design may change. The same holds true for the orientation of PV. West- or east-facing installations with different tilts could benefit PV surplus during heating season. Last, the usage of a battery or dynamic energy tariffs could impact the heat pump and thermal energy storage design.

Aside from control and boundary conditions, only some components of the dynamic simulation model are empirically validated [24]. The others follow white-box model approaches or are verified using comparative validation [25]. As the thermal energy storage enables the efficient exploitation of PV surplus, experimental validation should be carried out.

4.2. Implications

Keeping the limitations of this study in mind, three implications for current practice arise.
First, optimal design of the heat pump does not change when using PV with no or ineffective supervisory controls. While minor changes in T_{Biv} occur depending on the price assumptions, heat pumps are only available in discrete steps anyway.
Second, for current price assumptions, the optimal design of the storage does not change. However, to maximize PV usage, the thermal energy storage should be maximized. This contradicts the optimal design without PV, where the economic optimum is always at minimal storage volumes. However, other factors, such as defrost or utility blocking times may require the need of a larger thermal energy storage for space heating. Thus, simply minimizing the storage volume is not advisable when combining PV with heat pumps. Third, the four discrete options of the SG-Ready-Label do not enable a substantial increase of self-sufficiency. Hence, different interfaces for supervisory controls, such as the compressor speed, should be opened for external access.

5. Conclusion

This contribution analyses the influence of PV on the optimal design of heat pump systems for retrofit buildings using state-of-the-art rule-based controls. Applying annual simulation-based optimization of design and control using detailed Modelica models, we highlight findings and implications for practice and research:

1. At least in retrofit, PV does not influence the optimal heat pump size for the used rule-based controls. For current practice, neglecting PV is a valid assumption in current guidelines [6]. However, advanced control strategies could change the optimal design in future systems.

2. PV does not affect the cost-optimal thermal energy storage size. However, optimal storage sizes change

when changing price scenarios or objective functions. Thus, PV should be considered when sizing the thermal energy storage. The same could apply for the DHW storage, as DHW enables an efficient PV usage during summer.

3. Future studies should incorporate additional boundary conditions and technologies. Different DHW profiles, internal gains, or PV installations may impact the influence of PV on the optimal design.

4. Future research should develop simplified design rules - both for rule-based controls and system design. First, assessing advanced approaches as in [4] for different designs is advisable. Afterwards, design-independent rules should be extracted to enable a fast and optimal planning of building energy systems.

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Nomenclature

Symbols

- T Temperature, °C
- ΔT Temperature difference, K
- $V_{\dot{Q}_{Bui}}$ Volume per heat demand, $\mathrm{l\,kW^{-1}}$
- f factor, −
- P_{el} Electrical Power, W
- W_{el} Electrical Energy, W
- $W_{el,PV,use}$ Self-used electrical energy, W
- $W_{el,Grid}$ Electrical energy taken from grid, W
- C_{Tot} Total costs, €/a
- $\dot{Q}$ Heat flow rate, W
- t Time period, −
- H_{Glo} Global horizontal diffuse and direct radiation, $\mathrm{kWh/m^2a}$
- SCR Self-consumption level, %
- SSD Self-sufficiency degree, %
- $SCOP_{Sys}$ Seasonal coefficient of performance for whole system, −

Subscripts and superscripts

- *HR* Heating rod
- *HP* Heat pump
- *PV* Photovoltaic
- *SH* Space Heating
- *MPP* Maximum Peak Power
- *MPC* Model Predictive Control
- *Bui* Building
- *Oda* Outdoor air
- *DHW* Domestic Hot Water
- *tot* total
- *SG* Smart-Grid
- *Sur* Surplus
- *Hys* Hystereses
- *Nom* Nominal
- *Mea* Measured
- *set* setpoint

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