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A More Realistic Heat Pump Control Approach by Application of an Integrated Two-Part Control

Maximilian Schulz [1,*], Thomas Kemmler [2], Julia Kumm [1], Kai Hufendiek [1] and Bernd Thomas [2]

[1] Institute of Energy Economics and Rational Energy Use (IER), University Stuttgart, 70565 Stuttgart, Germany; Julia.Kumm@ier.uni-stuttgart.de (J.K.); Kai.Hufendiek@ier.uni-stuttgart.de (K.H.)

[2] Reutlingen Center for Energy Research (REZ), Reutlingen University, 72762 Reutlingen, Germany; Thomas.Kemmler@Reutlingen-University.DE (T.K.); Bernd.Thomas@Reutlingen-University.DE (B.T.)

* Correspondence: maximilian.schulz@ier.uni-stuttgart.de

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Abstract: Heat pumps are a vital element for reaching the greenhouse gas (GHG) reduction targets in the heating sector, but their system integration requires smart control approaches. In this paper, we first offer a comprehensive literature review and definition of the term control for the described context. Additionally, we present a control approach, which consists of an optimal scheduling module coupled with a detailed energy system simulation module. The aim of this integrated two-part control approach is to improve the performance of an energy system equipped with a heat pump, while recognizing the technical boundaries of the energy system in full detail. By applying this control to a typical family household situation, we illustrate that this integrated approach results in a more realistic heat pump operation and thus a more realistic assessment of the control performance, while still achieving lower operational costs.

Keywords: heat pump control; distributed energy systems; heat pump scheduling; building energy system simulation

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1. Introduction

In 2017, the share of heat generation in final energy consumption in Germany was 90.0% in the private household sector, 59.7% in the business, trade and service sector and 73.5% in the industrial sector. The share of renewable heat is found to be only 12.8%, 6.7% and 4.7% respectively [1]. To achieve the German climate protection targets derived from the Paris Agreement, heat generation and supply need to be restructured in a more sustainable way. Heat pumps (HP), of which about 966,000 units are installed in Germany at the moment [2], are a viable technology for the sustainable supply of heat. They offer great potential for decarbonizing final energy consumption and could thus take on a central role in future energy systems (ES). In order to integrate this technology into the energy system with a high share of fluctuating renewables, especially when combined with photovoltaic (PV) systems, and to avoid critical distribution grid states, smart controls for the operation of heat pumps in building energy systems are required without affecting the comfort of the people living in the building.

Heat pump control approaches have been investigated in numerous publications especially in the last years, indicating their increasing relevance. A closer look into the literature shows the wide variety of developed approaches which, in our opinion, should be evaluated by their application in a real energy system. This requires a practically applicable control approach, which incorporates the basic principles of control engineering. As we will show in more detail below, this is a topic that is still neglected in many publications.

Therefore, as an introduction, we start with a brief but detailed overview of the basics of control theory and the resulting control approaches. Then, we present an analysis of the research subjects of the existing publications focusing the heat pump control (HPC) with a special look at their control approaches. Afterwards, we propose our definition of a heat pump control as an orientation point. Basically, we want to establish our understanding, that a heat pump control consists of two parts:

A controlling system which is responsible for scheduling the heat pump operation, and a controlled system realizing this schedule actually, resulting in the actual heat pump operation and energy system state. In order to investigate the application of the heat pump as precisely as possible, a real energy system should serve as this controlled system. With regard to the scientific investigation of control approaches, however, this is difficult to realize, which is why simulated energy systems may be a suitable solution. The coupling and interaction of the two systems should result in an optimal scheduling which is at the same time feasible for the real system.

One major aim of this work is thus to raise awareness that both subsystems have their relevance and should be considered regarding control approaches and their performances. Hence, we compare the results of our approach with the results of two other control approaches consisting of only one of the two systems each. Using the exemplary case of an energy system representing a typical single-family household, we want to illustrate the effects, which arise, in case one of the subsystems is ignored and compare it to the integrated control. In addition, there is the advantage that our control approach is modularly expandable in order to expand existing controls or to represent the real energy system even more accurately.

The structure of this paper is organized as follows: In Section 2, the basics of control theory and the usage of the term heat pump control in the literature is briefly reviewed in a quantitative way. Subsequently, we present our definition of the integrated control approach which highlights its two-part character. In Section 3, we describe our methodology as well as the energy system of a typical single-family household, to which the different control approaches will be applied. In Section 4, we present the results of the heat pump control approaches with focus on comparing different intensities of subsystem coupling. As a conclusion in Section 5, the relevance of considering the two-part characteristics of a HP control is highlighted.

2. Control of a Heat Pump

Initially, we aim to analyse the existing HPC publications regarding their control approaches. As a benchmark, we give a classification of the subject of the publications. For a better understanding of the theoretical basics of control, we provide a short exposition of existing control approaches first. We use these two steps to subsequently present our integrated two-part control (ITC).

2.1. Overview of Existing Control Approaches—The Control Principles

There are various approaches to the control of heat pumps, which we will present in more detail at this point. A detailed overview of the application of these control approaches in smart grids is provided by [3]. Besides the focus on the different approaches, the application opportunities and their varying targets are discussed, which we will not address further. Instead, we want to take a closer look at the control approaches.

Basically, a control always consists of a system that controls and a system that is controlled. According to the standard DIN IEC 60050-351 [4], these systems are called controlling system and controlled system. Regarding the system and control theory as a classical branch of the engineering disciplines, which is for example described in [5,6], the two systems are called controller and plant. Although we explain briefly the basics of control using these two references, we will refer to the denomination of the DIN standard.

The control of a system can be classified regarding the used information: If the controlling system receives feedback from the controlled system, it is called a closed-loop control (CLC), otherwise, when no information is fed back, it is called an open-loop control (OLC). This feedback is the result of processing the input control signal that the controlling system sends to the controlled system. The control signal usually may represent the result of an optimization problem, which can have different forms, e.g., a deterministic or stochastic formulation. This signal is then processed in the controlled system, which is a real physical energy system or might typically be modelled by differential equations. The formulation of these equations can be simplified by simulation programs.

One of the most frequently used methods for such a control approach is the model predictive control (MPC), which is usually compared to a rule-based control (RBC). RBCs define control rules, e.g., holding a defined parameter at a fixed set point. A MPC computes the future response of a con-trolled system by a trajectory of the input vector as the result of the optimization problem into the actual model state. MPC models therefore also consist of a controlling and a controlled system, thus exhibiting the mentioned two-part character, whereby the controlling system is also represented by an optimization problem. This problem is solved for a defined optimization target value in a finite horizon, whose first step is realized in the controlled system. Afterwards, the new state of the system is sent back to the controlling system as feedback [7]. For example, in [8], four rule-based controls (thermal control, time control, PV optimized control, predictive rule-based control) are compared with one MPC approach. Hereby, the MPC achieves 6–16% reduced operational costs, the RBC only from 2 to 4%, whereby the less complexity of the RBC should be considered. A general review to the comparison between MPC and RBC is given in [9].

Applied to the control of heat pumps, scheduling approaches aim to calculate a feasible schedule for the heat pump operation, therefore acting as a controlling system. This task can be carried out by heuristic or optimization models. Whereby heuristic models determine a valid solution for the schedule, the optimization model provides a valid and simultaneously optimal solution. These models consist of a target function that maximizes or minimizes a target value, and restrictions setting the framework for the optimization. Such target functions are exemplified mainly by cost optimi-zation, in some cases also by maximization of self-consumption or minimization of electricity cost. For optimization approaches, there are various methods applied. An overview is provided for example by [10] or [11]. Methods include e.g., Linear [12–14] or Mixed-Integer-Linear [15–17] Programming. There are also a number of approaches for heuristic scheduling reported, for example the application of a Monte Carlo algorithm with the target function of maximizing the self-consumption of PV power in [18] or to produce electricity on demand by CHP units in combination with a thermal energy storage (TES) in [19]. Reference [20], for example, uses heuristic scheduling for cost-minimization. In [21], the authors apply different heuristic rule-based algorithms to increase or lower the space heating set point. For example, if the current electricity price is below a certain level, the set point is raised and the heat pump is activated.

After this look at the task of scheduling in the controlling system, the focus is now on the operation of the resulting schedule in the controlled system. Fundamentally, every control system aims at a real application, in this case the heat supply of a real energy system by a heat pump. In most cases, this real application is extremely complex to realize, for example with regard to the time periods or the different configurations of the energy system to be investigated. Therefore, the energy system is mostly represented and simplified by a model which is based on differential equations. The major challenge regarding the controlled system is the modelling of the nonlinear system dynamics. In most cases these are represented by an approximate linearization to reduce the complexity of the resulting optimization problem. For example, in [7] the optimization model is extended stochastically to take weather uncertainty into account, whereby the interaction of the actual energy system, the control input and the weather is linearized. Reference [22] aims to minimize the electrical costs for the heat pump operation but neglects the nonlinear heat pump properties. As presented later, we model our controlled system for ease of usability and scalability by a simulation model which is also based on differential equation.

Therefore, many approaches that have been developed in the literature refer to the simulation of energy systems, especially of buildings, and therefore for the simulation of the controlled system.

At the same time, only few studies are carried out with real systems. The basic approach of such a simulation model intends to analyse the energy consumption. Therefore, they determine the energy losses and gains of a building by modelling external influences such as the outside temperature or solar radiation, the operation of heating systems in the building and their interaction accounted by energy flows. Reference [23] defines these approaches and compares twenty different models with regard to the respective features and properties considered. According to [24], simulation approaches can generally be divided into white-box and black-box approaches.

White-box models are designed to simulate the building in detail based on physical principles and thus e. g. determine the energy flows accurately on a high-resolution level. In contrast, black box models focus the regression of input and measured output data and are trained in such a way, that the building-specific behaviour can be derived from input data.

To summarize, a multitude of control, scheduling and simulation approaches of heat pumps in energy systems are described in the literature. This results in a variety of approaches, whereby we want to raise the awareness that a control always consists of two systems to avoid a lack in control accuracy. The influence of this effect will be investigated in the following.

2.2. Focus and Control Approaches of HPC Publications—The Research Gap

In advance of illustrating the applied control approaches in the publications, we aim for a better understanding of the subject of the publications regarding the control of heat pumps. Therefore, we conducted a meta-analysis using quantitative methods, analogous e.g., to [25]. We analyzed the publications in the Elsevier Scopus database with the search query 'heat pump control' in title in more detail. This analysis returned 610 results for the years 2014 to 2019. A list of these publications can be provided by the corresponding author upon request. Unfortunately, this service is no longer available from September 2019, which means that only 9 of 12 months of the year 2019 are considered. Therefore, we scaled the related key figures for 2019 to the entire year by a factor of 4/3 for better comparability. To carry out this meta-analysis, the abstracts of the publications were checked for keywords, which were assigned to categories, whereby multiple entries are possible. If at least one of the keywords is mentioned, the publication is assigned to a category.

The analysis focusing the subject of the publications resulted in 7 categories, with the keywords in Appendix A in Table A1: Performance/Efficiency, Technical improvements, Energetic efficiency, Cost savings, Flexibility, Sustainability and CO_2-/Greenhouse gas (GHG) emissions. The annual number for each category and the total number of publications are shown in Figure 1.

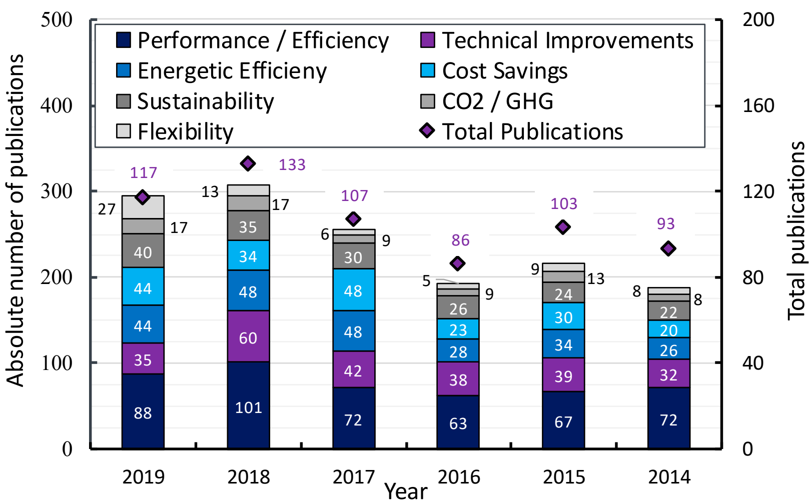

Figure 1. Number of keywords in the publications and absolute number of annual publications in the Elsevier Scopus database in the years from 2014 to 2019.

As seen in Figure 1, we can state that two-thirds to three-quarters of the annual publications deal with the subjects of efficiency and performance of heat pump controls. Hereby, a larger part of the publication deals with an improvement of energetic efficiency instead of cost reduction, whereby this difference has become smaller or even equal in recent years, so it could be deduced that the publications focus on the integration of heat pumps into the overall energy system via economic considerations such as the electricity price instead of efficiency improvements of local heat pump operation. Besides, a smaller part addresses this improvement in a technical-experimental way.

Over the years, there has also been a strong increase in publications focusing on flexible HP operation as well as on sustainability and reduction of CO_2- and greenhouse gases. This increase in publications related to flexibility strengthens the hypothesis of the rising relevance of the HP integration into the overall energy system. In conclusion, we can deduce that the application of heat pumps is increasingly seen as a vital instrument for a sustainable supply of heat and flexibility.

In the context of this meta-analysis, the publications were examined for further topics. We can state that mainly air source and ground source heat pumps are considered in the publications, water source heat pumps in contrast account for a small proportion (Figure A1). With a view to other technologies considered in the publications, the application of heat pumps is often, as expected, coupled with PV-systems and thermal storages. In this context, components of the heat pump itself, such as the heat exchanger or the compressor, are often also considered (Figure A2). A look at the investigated energy system shows that the heats pumps are predominantly operated in residential buildings and houses (Figure A3). To model these energy systems, TRNSYS is applied more often than Modelica or Simulink (Figure A4). The detailed figures are presented in Appendix B.

With regard to our focus on control, the publications have specially been examined for their control approaches by the following categories, with the specific keywords in Table A2 in Appendix A: Temperature control, Model predictive control, Rule-based Control, Open-loop control, Closed-loop control and Feedback. The results of this analysis are presented in Figure 2, subdivided by the year of publication:

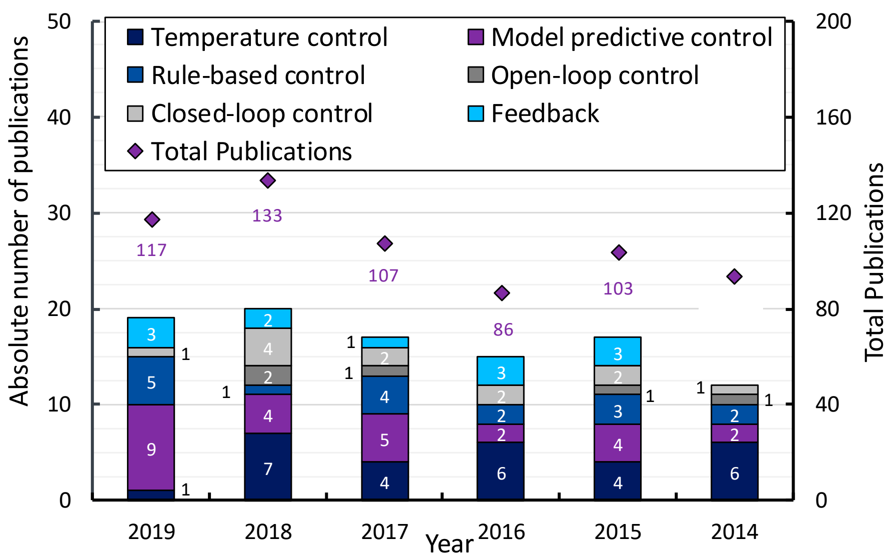

Figure 2. Number of control approaches in the publications and absolute number of annual publications in the Elsevier Scopus database in the years from 2014 to 2019.

Comparing the absolute numbers of Figure 2 to those in Figure 1, one may see that little attention has so far been paid to the basics of control theory. In our opinion this topic has not been investigated to its full extend. Over the years, we can identify a change from temperature controls to model predictive controls, which means a shift from rule-based to optimization control approaches. Only few publications deal with the open-/closed-loop control theory and the concept of feedback. In addition, there is no common mention of OLC or CLC and feedback in a publication. At the same time 243 publications deal with the term optimization. The majority of publications aiming at an optimal operation of the heat pump therefore show a lack of the control basics. Thus, we will demonstrate the self-exposed disadvantages of the respective control approaches in the following:

Temperature-controlled systems as quite basic systems lead to additional costs for the operator, which can be reduced by introducing predictive control approaches and optimizing the operation of the heat pump. Open-loop approaches, especially optimization models without feedback from the controlled system, do not consider the current state of the energy system. This results in a very rapid deterioration in performance and accuracy of the control, which however is not detected, if the controlled system is not part of the investigation. In many publications, the controlled system is only represented by restrictions for the optimization model. Thus, it is a part of the controlling system and not an explicitly modelled system. In the following chapter, we will explain why the controlled system should be considered as a stand-alone module to avoid this deterioration of the heat pump control accuracy.

2.3. The Integrated Two-Part Control

A heat pump control consists of two successive modules: the controlling system and the controlled system. First, the controlling system determines a heat pump schedule for a finite time in the future with a simplified time resolution. This system follows therefore a heuristic or an optimization model approach. The resulting schedule is communicated to the controlled system, which is the physical or a virtual building energy system, where the schedule is executed to the extent of the actual system restrictions. As already mentioned, if the controlled system, the energy system, cannot be observed in form of the real object, simulation is a viable option for investigating different control approaches. To adopt the schedule in real time, an additional controller is needed in the controlled system to ensure, that at no time the physical conditions are violated. This usually is a temperature-based control in the physical building energy systems. Therefore, the controlled system determines the actual operation of the heat pump, which might deviate from the schedule provided by the controlling system as well as the resulting state of the energy system.

The reason for deviations of the actual schedule from the schedule provided by the controlling system arises from disturbances affecting the controlled system, which are not considered by the controlling system. On the one hand, this results from simplifications made in the controlling system, e.g., simplified HP characteristics or discrete bounded time resolution. An explanation of these deviations resulting from the representation of a real system by a model is provided by [6]. The real system needs to be described in mathematical (in-)equalities in their full complexity, in order to make sure that the model achieves the same behaviour as the real system. In order to bypass this almost infinite number of equations with further challenges such as the extensive consideration of non-linearities, simplifications in the modelling must therefore be accepted to a certain extent.

On the other hand, the disturbances occur from the lack of information on the behaviour of the controlled systems during the control period as it lies ahead in time when the schedule is defined. By the application of the control, the schedule of the heat pump must already be set for at least the next time step, although the restrictions for calculating this schedule might still be uncertain. In our case, as will be shown later, this uncertainty in particular results from the behaviour of the people in the energy system, who have a decisive influence on the electrical and thermal load profile, as well as the external weather conditions, which determine the electricity generation of the PV system.

Figure 3 presents our concept of a two-part control for heat pumps applicable in a physical energy system.

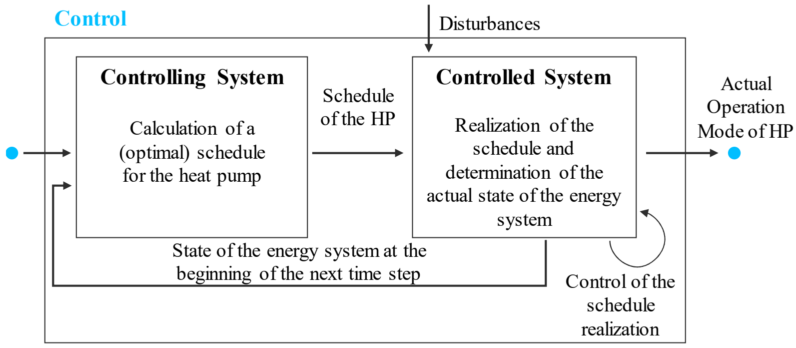

Figure 3. Integrated two-part control consisting of controlling and controlled system adapted according to DIN IEC 60050-351.

In conclusion, the scheduling itself and the effects of applying the schedule to the energy system must both be considered for an appropriate heat pump control. The task of scheduling is to generate an optimal, but also feasible schedule for the heat pump. Subsequently, the controlled system carries out the execution of this schedule affected by the disturbances of the actual HP operation and the resulting state of the energy system.

3. Methodology

As the essential content of this work, we want to increase the awareness that for evaluation of a heat pump control the investigated system needs to consist of the both subsystems as depicted in Section 2, the controlling system and the controlled system. Therefore, we illustrate und quantify the effects if the control only consists of one of the two modules. Although these effects seem obvious, most of the prior publications lack of this integrated control as shown before. Accordingly, it is questionable whether their theoretical performance will hold if they are applied to a real energy system.

If a simple heuristic RBC operates the heat pump in the controlled system, there are significant additional costs for the operator due to the suboptimal economic operation. If, on the other hand, the control system receives no feedback from the controlled system, the heat pump is controlled by an open-loop control. This quickly results in deviations between the calculated schedule and the real operation, which also ends up in a deterioration in performance and costs (which might be unnoticed, if the controlled system is not actively monitored). Accordingly, the results of the developed integrated two-part control serve as a benchmark to investigate the role of both subsystems for this control. By successively eliminating each of the subsystems, we quantify the differences in the technical and economical results.

The energy system used for this analysis represents a typical grid-connected single-family household with a thermal and electrical demand. Technical and economical details will be presented in Section 3.1. The actual controlled system is a Simulink energy system simulation for the building on a highly detailed technical level, further depicted in Section 3.2. The controlling system is the optimization model E2M2_DES, which generates cost optimal heat pump schedules. This model is described in more detail in Section 3.3. We successfully combine both systems to an integrated control unit, as shown in Section 3.4.

3.1. Characteristics of the Building Energy System

The controlled system is a simulation of the presumed building energy system of a virtual, typical single-family house, which we define in detail here. The assumed building is an insulated one-storey detached house with an area of 220 m^2. The building energy system comprises corresponding thermal and electrical energy demands and it is equipped with a system consisting of a PV plant, a heat pump and an electric heater for heat generation as well as a thermal energy storage. These individual subsystems for the generation and storage of thermal or electrical energy, with which the energy system under consideration is equipped, are hereafter referred to as components.

We obtain the thermal demand profile by simulating the space heating demand needed to keep the room temperature between 19 °C and 23 °C. For this, the building energy system simulation, depicted in more detail in the next Section 3.2, is executed in a temperature-controlled mode. This simulation was examined in Simulink. To obtain detailed results for the thermal demand profile, the time step of the simulation was set to a maximum of 150 s; the minimum step was up to 1ms. For simplification, the thermal demand consists of the demand for space heating only; we neglect domestic hot water demand for this case. The electrical load profile is presented by a measured electrical load profil of a single-family household in the german city Düsseldorf [18]. The annual electrical consumption of 3985 kWh_{el} is thereby typical for a household of this size. The PV generation profile stems from a PV-plant in the Stuttgart area scaled down to a capacity of 6.8 kW_p, which is the mean power of all PV-plants <10 kW_p installed in Germany between August 2017 and July 2018 [26]. These profiles hereby exhibit a resolution of 15 min. Figure 4 shows the daily mean value of the profiles.

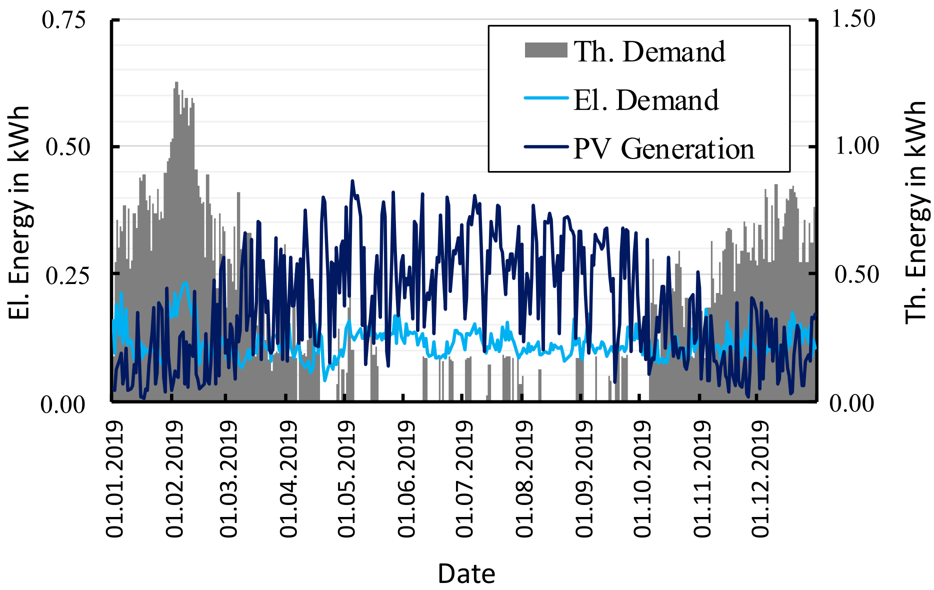

Figure 4. The main characteristics of the investigated energy systems as mean daily values: electric (light blue) and thermal demand of the household (grad) and b) the PV-generation (dark blue).

To cover the thermal demand, the building is equipped with the mentioned generating system. The assumed heat pump can modulate its thermal output power in a range between 30% and 100% of the installed power. Switched off, it has a minimum downtime of 5 min, switched on a minimum operating duration of 10 min.

Table 1 sums up the specific technical and economical properties of the energy system, the explicit coefficient of performance (COP) curve is shown in Figure A5 in Appendix C.

The application of the heat pump system described above serves to cover the electrical and thermal demand of the household. The specific application of the system is determined by each control approach individually, which will be described in more detail later.

Table 1. Technical and economical properties of the energy system.

Component	Property	Value	Unit
Household Load	Electrical Demand	3995	kWh_{el}/year
	Thermal Heat Demand	11,581	kWh_{th}/year
Photovoltaic System	Electrical Power	6.8	kW_p
	Electrical Energy	6545	kWh_{el}/year
Air Source Heat Pump	Electrical Power	2.4 (A7/W35)	kW_{el}
	Thermal Power	10.9 (A7/W35)	kW_{th}
	COP	4.5 (A7/W35)	–
Electric Heater	Electrical Power	5	kW_{el}
Thermal Energy Storage	Thermal Capacatiy	48.9	kWh_{th}
	Density	2000	kg/m^3
	Area	220	m^2
	Floor thickness	0.08	m^2
	Specific heat capacity	1000	J/kg/K
Ambient Temperature	Min./Max. Value	−13/33	°C
Coefficient of Performance (COP)	Min. Value		
	Max. Value		
Power Grid	Purchase Price	29.33	€ct/kWh_{el}
	Feed-In Tariff	12.60	€ct/kWh_{el}

3.2. Implementation of the Controlled System Module

The controlled system module is represented by parts of the control simulation model developed by the Reutlingen Center for Energy Research (REZ), which is described in more detail in [18]. This control model uses the MATLAB-Simulink of Mathworks (Natick, MA, USA), programming environment and basically consists of four blocks: Forecast, optimization, internal control and dynamic model. It determines the heat pump schedules using a heuristic Monte Carlo method combined with various target functions correcting possible physical failures by a closed loop control logic in the internal control subsequently. To perform the task of the controlled system, the internal control and the dynamic module blocks of the REZ model are used.

The internal control operates the heat pump according to the schedule with respect to the simulated physical data like the room temperature and the control rules. For example, when the controlled system reaches the maximum room temperature, the heat pump turns off even if there is a request by the schedule to run the heat pump. Therefore, the internal control is of higher priority compared to the schedule and ensures by this means the comfort of the people living in the building. Additionally, we can simulate a rule-based control using the REZ model without any provided heat pump schedule in a temperature-controlled mode. In this mode, we control the heat pump in a way that the room temperature varies within a predefined temperature range, only.

The dynamic model represents the physical components like the heat pump itself and the building. We took the basic models of the heat pump, the electric heater, the thermal energy storage and the simple house from the CARNOT Blockset [27] and modified them to fit the needs of our simulation model. The permitted range of the room temperature and the thermal mass of the buildings floor provide the flexibility for the heat demand. For this purpose, we modelled the floor as a multi-node system in a Simscape environment and integrated it in the simple house model of CARNOT Blockset. The heat generated is transferred to the room via the floor, which affects the room temperature. In combination, this system acts as a heat storage and provides a thermal capacity of 48.9 kWh.

3.3. Implementation of the Controlling System Module

The scheduling model E2M2_DES forms the controlling system. It consists of a mixed-integer linear programming (MILP) optimization model formulated in GAMS, which minimizes energy cost for a defined energy system by the calculation of optimal schedules for each of the components of the system. The components here comprise for example the heat pump or the photovoltaic system. The total cost $V_{CostTotal}$ of all components COMP in the energy system are minimized over all time steps T as:

$$V_{CostTotal} = \sum_{t\in T} \sum_{comp\in COMP} \begin{bmatrix} V_{C,StartUp_{t,comp}} \\ V_{C,FeedIn_{t,comp}} \\ V_{C,ElecPurch_{t,comp}} \\ V_{C,Charges_{t,comp}} \\ V_{C,VarOaM_{t,comp}} \\ V_{C,FOaM_{t,comp}} \end{bmatrix} \tag{1}$$

where $V_{C,StartUp}$ represents the costs for a start of a component comp, $V_{C,FeedIn}$ negative costs of the feed-in of electrical energy into the grid, $V_{C,ElecPurch}$ cost of the purchase of electrical energy from the grid and $V_{C,Charges}$ costs for charges on the consumption of electrical energy. Besides, fixed costs $V_{C,FOaM}$ and variable costs V_{CFOaM} for the operation and the maintenance of each component can be considered.

To meet the electrical or thermal demand, we define appropriate constraints to ensure the basic physical properties of the technical components. Hereby, the electrical balance equation is given as:

$$\begin{gathered} Load_{el,Sys} + \sum_{comp\in COMP} V_{el,Cons_{comp}} + V_{el,FeedIn} = \\ \sum_{comp\in COMP} Gen_{el,comp} + \sum_{comp\in COMP} V_{el,Gen_{comp}} + V_{el;Purch} \end{gathered} \tag{2}$$

In this way, it is ensured that, for each time step, the electrical load $Load_{el,Sys}$ of the energy system and the electrical consumption V_{elCons} of each technology comp is covered by the generation $Gen_{El,comp}$ of the non-controllable generation technologies, where the generation curve are given a priori, and the generation $V_{el,Gen}$ of the controllable generation technologies comp. If there is still a surplus of energy, this amount $V_{el,FeedIn}$ is fed into the grid; otherwise electrical energy is purchased from the grid as $V_{el,Purch}$.

The balance of thermal demand and generation is given as:

$$Load_{th,Sys} = \sum_{comp\in COMP} V_{th,Gen_{comp}} - \sum_{comp\in COMP} V_{th,Cons_{comp}} \tag{3}$$

Here the thermal load of the energy system $Load_{th,Sys}$ must be covered by the generated thermal energy $V_{th,Gen}$ of each technical component comp, reduced by the consumption of thermal energy $V_{th,Cons}$ of some component comp. Storage losses of some components are characterized as energy consumption. At the same time, the loading of the storage is modelled as energy consumption and the unloading as energy generation. Moreover, a mixed-integer variable allows considering the specific behaviour of each component. This way, regarding the heat pump, characteristic properties such as the minimum power limit, minimum down and operating times are explicitly modelled.

In addition, the model considers the economic and regulatory conditions of the local energy system and its interaction with the overall energy system, for example by an electricity price or a feed-in tariff. The Cplex optimizer solves the model defined in this way.

In order to calculate the cost-optimal schedule of the heat pump, we give perfect information about the time series for energy demand and PV generation in 15 minutes' resolution within the optimization period to the model. Using this information, we calculate the cost-optimal operation schedule of the heat pump for the control period. The result represents a cost-optimal schedule for the components.

3.4. Implementation of the Integrated Two-Part Control

To create the ITC according to Figure 3, we couple the two presented models E2M2_DES serving as the controlling model and the REZ model serving as the controlled system. E2M2_DES calculates with a finite optimization period an optimal HP schedule for the regarded energy system. We then transfer the schedule for the control period, which is usually shorter than the optimization period, to the REZ model. Subsequently, the REZ model executes the schedule within the energy system simulation as far as allowed by the technical restrictions and the comfort situation in the building. In case the schedule will violate these constrains, the internal control will temporarily ignore the schedule and replace it by a demand-oriented rule-based HP operation. At the end of the control period, we return the actual state, represented by the room temperature, of the controlled energy system to the controlling system represented as the energy level of the thermal energy storage given by its state of charge (SOC).

Based on this status information, the optimization module repeatedly calculates the schedule for the next control period, until the end of the investigation period is reached. Additionally, we document the optimal heat pump schedule as well as the actual operation (amongst many other data). Figure 5 provides an overview of the input data, the model interactions and the results. Here, we presented the energy system under investigation and the implementation of our control approach. In the following chapter, we will show the results of their application.

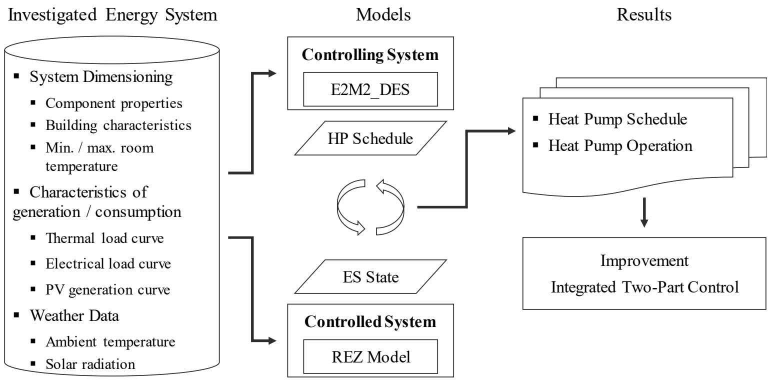

Figure 5. Concept of the integrated two-part control approach by coupling of the models E2M2_DES and REZ model.

4. Comparison of the Control Approaches

The methodology presented above allows us to apply the ITC to the specified energy system as well as to study the separate execution of both subsystem modules. In case of the separate execution of each of the submodules, the heat pump is considered firstly to be controlled either by the schedule of the controlling system at minimal cost without feedback from the actual energy system, referred to as scheduled control (SC). In the other case, the heat pump is controlled by the temperature rule-based control keeping the room temperature in the defined band, referred to as temperature control (TC). In order to evaluate the effects of applying the integrated two-part control approach, we compare the ITC and its heat pump schedule with each of the two scheduling control approaches together with the operational characteristics of the heat pump. In the first step, we want to illustrate the effect of an open-loop control, assuming no feedback is returned from the controlled system to the controlling system. Hereby, we firstly focus on the physical feasibility of the calculated schedule in the controlled system in the following chapter. Afterwards we evaluate the economic quality of the schedule.

4.1. Implementation of the Controlling System Module

In the first step, we compare the feasibility of the schedule of the controlling system without feedback from the actual system, in this case an open-loop control, to the ITC with feedback, hereby a closed-loop control. Feasibility is defined as how precisely the schedule can be realized in the controlled system. For this purpose, the heat pump schedule is compared to the heat pump operation.

For this analysis, the controlling system module E2M2_DES calculates an optimal yearly heat pump schedule with a rolling optimization period of two days (192 quarter hours) for the equivalent energy demand of the temperature-oriented heat pump operation. Afterwards, we investigate the yearly schedule with respect to its actual operation and feasibility in the controlled system. Therefore, we feed it into the REZ model and execute a simulation to check whether the schedule of the scheduled control (SC) fulfils the technical restrictions and the comfort situation. The ITC also simulates the operation of the heat pump for one year by exchanging schedules and the state of the energy system within each rolling step. Figure 6 depicts the resulting schedules and the operation of the heat pump for both cases for some exemplary days as well as the room and the ambient temperature.

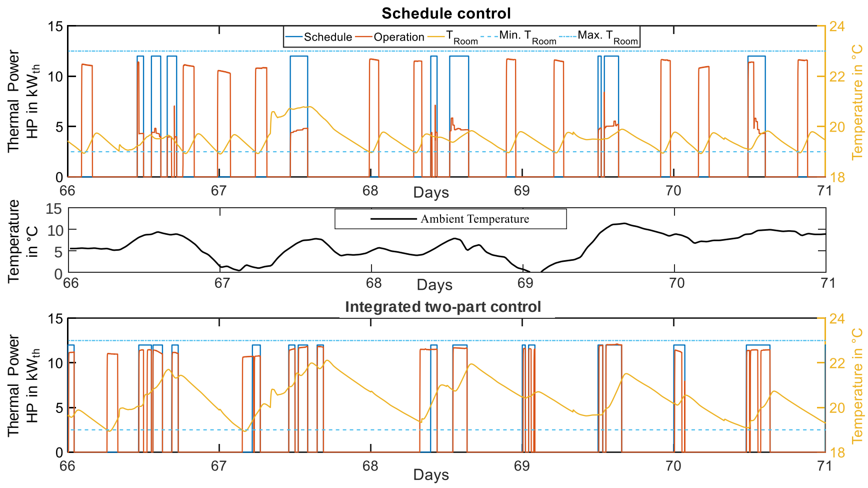

Figure 6. Comparison of the pre-set schedule and real operation mode and each resulting room temperature, on top the schedule and below the integrated two-part control, as well as the ambient temperature in between.

The Figure shows an exemplary segment of the one-year control period, given by the time period of day 66 to day 71. The solid blue line (Schedule) represents the thermal power of the HP schedule of the controlling system. The solid orange line (Operation) depicts the actual thermal power of the HP operation in the controlled system. On the secondary axis, the solid yellow line (T_{Room}) outlines the room temperature and the dotted light blue lines illustrate the minimum and maximum room temperature limits (Min./Max. T_{Room}).

The upper graph shows the schedule and its operation for the SC and the lower graph those for the ITC. The ambient temperature is plotted between the two graphs as black line. Clearly we can recognize the relation between increased heat demand of the building and lower ambient temperature. While the first three days exhibit a stronger temperature gradient and, on average, lower outside temperatures, from the middle of the second to the last day the temperature is about 10 °C.

With a view to the control approaches, it is obvious, that the actual heat pump operation deviates quite heavily from the optimal schedule in case of the scheduled control (upper graph). The non-scheduled starts of the heat pump, for example at the beginning of day 67, needed to avoid the room temperature declining below 19 °C, illustrate this result. This can be explained by the fact that the actual state of the building is represented in the optimization model only in a simplified way by the thermal demand profile and not by the actual room temperature. Thus, the optimization model can access this information with a temporal resolution of 15 min, only, for serving the heat demand. The controlled system, in contrast, operates with a temporal resolution of down to one second. If in one of these highly resolved time steps the temperature band is violated, the internal temperature control of the controlled system is activated immediately. Without coupling, the controlling system receives no feedback about these deviations in the actual energy system, which is why it continuously assumes a wrong state in the controlled system.

Therefore, we closed the feedback-loop by applying the ITC approach. In this case, the HP follows the given schedule very closely and the room temperature alternates within the predetermined range. We can recognize this improvement in the feasibility of the schedule by comparing the graphs in Figure 6 visually as well as by comparing the root mean square errors (RMSE). Whereas the RMSE of the scheduled and the actual operation for the SC is 1.10 kWh, the RMSE of the ITC is only 0.43 kWh. Simultaneously, it also becomes visible that the ITC's operation mode is clearly dependent on the outside temperature. The heat pump is activated especially at times of higher ambient temperatures, which means an increased COP and therefore less electrical energy is required for heat supply.

Hence, we demonstrated that the feedback of the state of the energy system in the ITC approach improves the feasibility of the heat pump schedule significantly. If there is no feedback, the schedule of the control system is more often ignored and replaced by a temperature-oriented, rule-based heat pump operation, which does not minimize costs. In conclusion, deviations and differences in modelling granularity affect the feasibility of the schedule calculated by the control system in the controlled system which can be improved by this feedback. This raises the question of the monetary effects of these deviations, which will be discussed in the next paragraph.

4.2. *Economic Quality of the Schedules*

As a second evaluation factor we investigate the cost of the heat pump operation in more detail. As mentioned above, in a first step we applied the controlled system to determine a temperature-controlled (TC) schedule for the thermal supply of the energy system without considering any economic information. This schedule serves as an upper benchmark for the costs. Afterwards, we evaluate the differences between an open-loop and closed-loop control, as described in the previous chapter.

E2M2_DES calculates a schedule as a controlling system without any feedback from the controlled system, but taking into account the price for the grid purchase as well as the feed-in tariff for the generated electrical energy in the controlled system (still abbreviated SC). Additionally, we carried out the yearly simulation by the ITC exchanging the information of the actual state of the energy system after every 24 h. As a consequence, each control approach results in a different operation of the heat pump in the controlled system. Due to this different operation of the heat pump, the self-consumption of the electric energy of the PV system for the heat pump and the electrical load, the grid purchase of electric energy for the heat pump and the electrical load as well as the feedIn of the electric energy from the PV system also differ for each control approach. These results of our simulation of the control approaches for the heat pumps are presented in Appendix D. Figure 7 summarizes these results through by the resulting operating costs for covering the heat demand and the self-consumption level (ratio of PV self-utilization to total electricity demand).

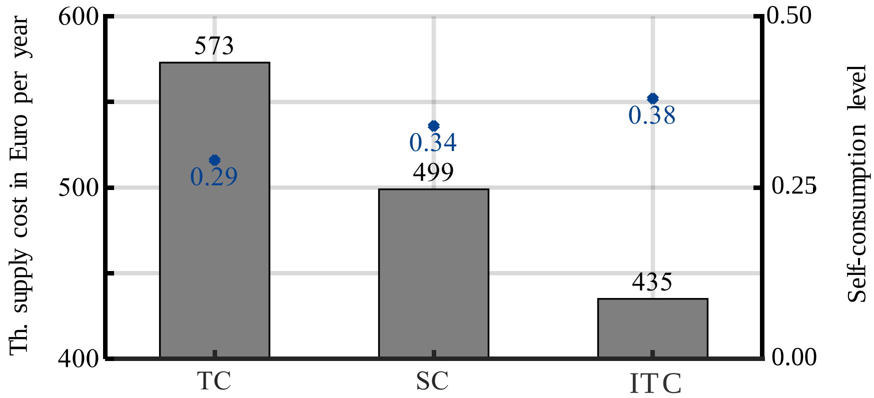

Figure 7. Yearly heat pump operating costs and self-consumption level of each control approach.

First, we can state—as expected and shown in many similar investigations outlined in Section 2—that the operating costs of an optimized heat pump schedule are significantly lower compared to the conventional rule-based system. While the costs of the SC are 74 Euro lower than the costs of the TC, the ITC is even 138 Euro lower. This can be explained by the increase in the level of self-consumption, indicating that more cost-effective PV power compared to electricity from the grid is consumed directly in the building. This increase in self-consumption results in particular from the improved operation of the heat pump, as can be seen in Figure A9 in Appendix D.

Although this means a slightly decrease of the self-consumption of PV electrical energy by the electrical load, the self-consumption of the PV electrical energy by the heat pump is increased by about a factor of 5 compared to the TC and by about a factor of 2 compared to the SC. In order to explain the different costs, we take a closer look at the amounts of energy required for heat supply, which are depicted in Figure 8 together with the median of room temperature in the building.

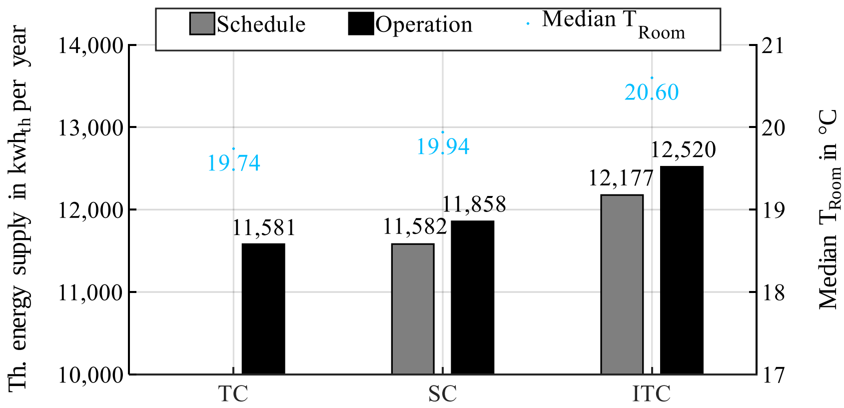

Figure 8. Amount of generated thermal energy of the scheduled and the real operation of the heat pump and median of the room temperature for each control approach.

Here, we recognize that the schedule of the SC generates almost exactly the amount of energy needed by the TC. As demonstrated in the previous section, however, there are deviations from this schedule in the actual operation, which is why the internal control must generate 276 kWh more of thermal energy. These deviations thus also affect the monetary result of SC. Although the ITC produces even more thermal energy, the costs for heat supply are still far below the costs of SC.

At the same time, the ITC allows for an improved utilization of the thermal capacity of the building as a storage, as can be seen in Figure 6. The median of the room temperature underlines this statement: The TC and the SC only slightly raise the room temperature above the lower permitted limit of 19 °C. The application of the ITC, on the other hand, results in a median room temperature of 20.60 °C, which also results in higher comfort for the people living in the building. This increase of room temperature is associated with a higher heat demand, which can be explained by increasing transmission losses. At the same time, though, the self-consumption level increases and the costs for thermal energy supply decreases, as shown in Figure 7. We can explain this by the fact that the ITC schedule can be realized better in the controlled system, whereby the actual operation of the heat pump follows this optimized schedule more precisely and therefore less temperature-related interventions occur. At the same time, the application of the ITC results in a 4% increase in the level of self-consumption. Due to this improvement, we can reduce the costs for heat supply by 64 Euro.

Finally, it can be concluded that an integrated two-part control approach, e.g., our presented approach in Section 2.3 enhances the operation of the heat pump in the investigated energy system. A simple temperature rule-based control of the heat pump guarantees a sufficient heat supply for the residents at all times, but at much higher costs. These additional costs can be reduced by using a control module based on an optimization module or a heuristic method, whereby the consideration of the feedback of the current state of the controlled system in the control system reduces these costs additionally.

5. Conclusions and Outlook

At this point we want to summarize the central insights and give an outlook on future fields of research.

5.1. Conclusions

In summary, with this presented use case we want to highlight the advantages of an integrated two-part character of a heat pump control in distributed energy systems. Our coupling of the models from IER and REZ into the integrated two-part control (ITC) allowed us to demonstrate the effects that arise in comparison to a heat pump control consisting of just one of the two modules only. As a result, the operation of the heat pump in the controlled overall system is improved, which can be recognized by the deviation between the schedule and operation of the heat pump by an RMSE of 1.10 kWh of the scheduled control to 0.43 kWh of the integrated two-part control. Furthermore, we reduce the costs over the period of one year by 138 Euro, compared to the temperature control (TC) and by 64 Euro, compared to the scheduled control (SC). In summary, by applying the ITC, we lower the costs of the respective control approaches by 24% (TC) and 12% (SC), based on the respective purchase costs. This cost reduction has an enormous potential for scalability to a large number of comparable energy systems, since in particular only the existing control software needs to be expanded and upgraded.

As explained before, just a minority of publications on heat pump control consider this integrated two-part character. Instead, if only a controlling system based on an optimization problem is applied to control the heat pump, the results overestimate the performance of the heat pump by neglecting the actual heat pump operation in the controlled system, which is always influenced by the presented disturbances. Without a controlling system, however, the potential of the heat pump application is not fully exploited. To avoid these disadvantages, a two-part control system can be applied by the implementation of a control system based on an optimization problem or a heuristic method combined with a controlled system e.g., implemented as an energy system simulation.

5.2. Outlook

Future research goals can aim at achieving an even better representation of real heat pump performance in the simulation model. With the use of Simulink, it is possible to adapt the simulation model as detailed as required. For example, the simple house model can be replaced by a multi-node model and thus the physical conditions can be represented in even more detail. This should increase the accuracy of the feedback to the optimization model of the IER, which should result in an even more realistic heat pump schedule.

This emerging field of research particularly yields at the scientific evaluation of control approaches. After all, each control approach should be evaluated based on its application in real energy systems, which thereby serve as the controlled systems. Each model of an energy system is thereby inevitably associated with deviations in the behaviour of a real system, which in turn influence the evaluation of the control approaches. Nevertheless, we want to appeal and conclude that a holistic evaluation of a control approach is achieved only, if the operation of the control in the controlled system, either in a simulated or real system, is also considered.

Author Contributions: Research concept and design, B.T. (heuristic approach, integration, benchmarking), K.H. (optimization approach, integration, benchmark); Conceptualization, M.S. (literature review, control concept, controlling system, model coupling), T.K. (controlled system and model coupling), J.K. (controlling system and model coupling); methodology M.S., T.K. and J.K.; software M.S. and T.K.; validation, M.S., T.K. and J.K.; formal analysis, M.S. and T.K.; preparation of results, M.S., T.K., J.K., K.H., B.T.; investigation, M.S. and T.K.; resources, IER and REZ; data curation, M.S. and T.K.; writing—original draft preparation, M.S. and T.K.; writing—revision and editing, J.K., K.H. and B.T.; visualization, M.S. and T.K.; supervision, J.K., K.H. and B.T.;

project administration, M.S.; funding acquisition, J.K., K.H., B.T. All authors have read and agreed to the published version of the manuscript.

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Appendix A

In our analysis of the focus as well as the considered control approaches of the publications regarding the control of heat pumps, their abstract has been checked for keywords. In the following Table A1, the key words of each category is shown for the analysis of the focus of the publications.

Table A1. Overview of the categories and the specific key words of the analysis of the subject of the publications.

Category	Keywords
Performance/Efficiency	efficiency, efficient, performance
Technical Improvements	experimental, test, tested
Energetic Efficiency	energy save / saving, energy consumption, power consumption, energy loss
Cost savings	cost, price, economic
Flexibility	flexibility, flexible, DSM
Sustainability	renewable, sustainable, environmental
CO_2-/greenhousegases	CO_2, Carbon dioxide, carbon, greenhouse gas, ghg

In the following Table A2, the key words of each presented category is given for the analysis of the control approach of the publications.

Table A2. Overview of the categories and the specific key words of the analysis of the control approaches of the publications.

Category	Keywords
Temperature control	thermostatically, temperature control
Model predictive control	model predictive, MPC
Rule control	rule controle, RBC
Open-loop control	open loop, OLC
Closed-loop control	closed loop, CLC
Feedback	feedback

Appendix B

In the context of the meta-analysis, we investigated the publications for some more details. First, we analyzed which heat source is used by the heat pumps. Here, we can state that air source and ground source heat pumps in particular are applied in the publications. Only few publications investigate the operation of water source heat pumps. The total numbers are presented in the following Figure A1.

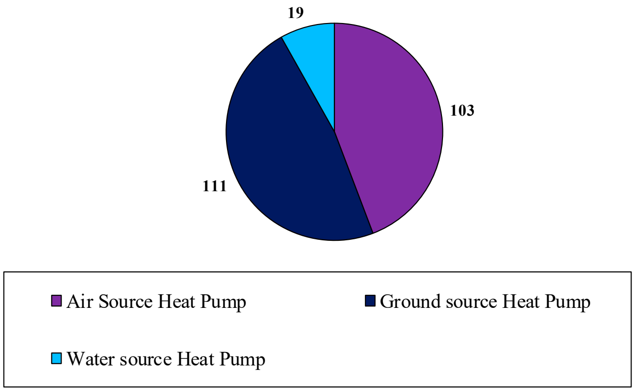

Figure A1. Number of publications divided according to the heat source used.

In addition to the consideration of the heat source used, the question arises which other technologies and components have been used in combination with the heat pump. The corresponding number of these technologies and components applied is shown in the following Figure A2.

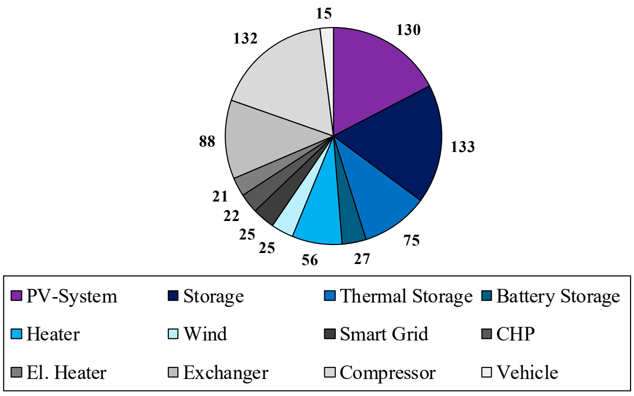

Figure A2. Number of publications subdivided according to the further components considered.

Here, we can see that heat pumps are mainly combined with PV-systems and heat storages, which is to be expected. Much more surprising is the fact that heat pumps are almost as often associated with wind energy as with the term smart grid. In addition to these other technologies under consideration, components of the heat pump itself are often mentioned in the publications, here the heat exchanger as well as the compressor.

Subsequently, it is interesting in which energy system the application of heat pumps is investigated. The result of this analysis is presented in the following Figure A3.

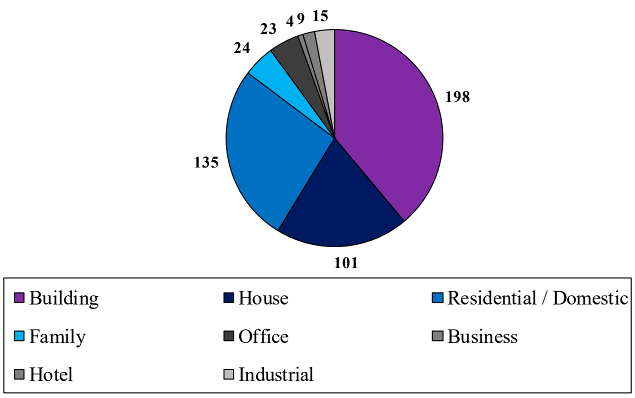

Figure A3. Number of publications subdivided according the investigated energy system.

Predominantly, buildings and houses are the main subjects of the investigation. considered in this context. These buildings are primarily used as residential buildings (categories Residential / Domestic and Family). The usage of heat pumps in office or business buildings or hotels as well as in industry is much less frequently investigated.

Finally, we analyzed how often the different models for the simulation of the energy system are mentioned in the publications. The corresponding result is shown in Figure A4.

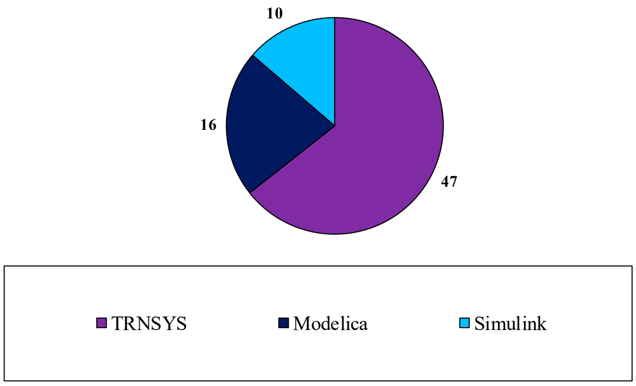

Figure A4. Number of publications divided according to the model used to simulate the energy system.

In almost two thirds of the time, TRNSYS is thereby the tool chosen to model the energy system. Modelia or Simulink are therefore used much less often.

Appendix C

In the following Figure A5, we present the coefficient of performance of the heat pump of the energy system under consideration depending on the ambient temperature.

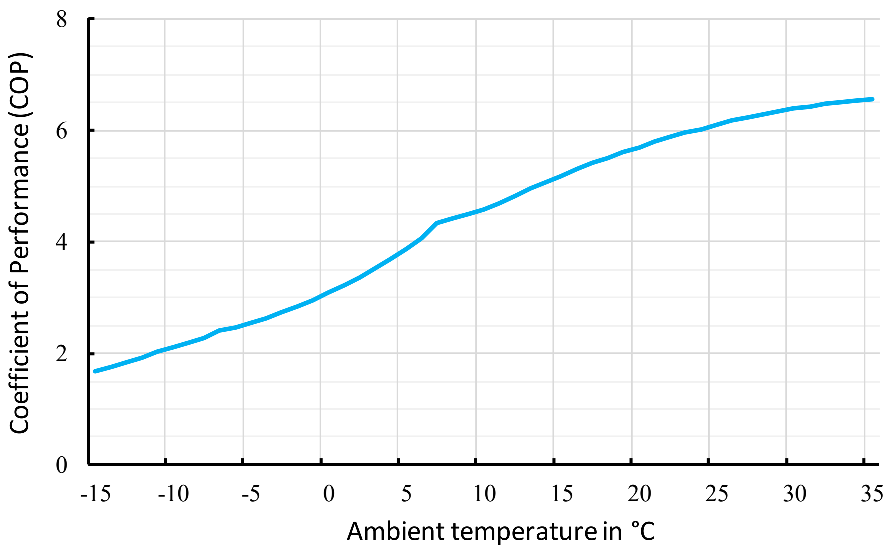

Figure A5. Number of publications divided according to the model used to simulate the energy system.

Appendix D

As a result of the application of the three control approaches, the heat pump operates in different ways. Consequently, the energy transfer between the PV system, heat pump and the public grid also varies. In the following, we present for each control approach the consumption of electrical energy by the heat pump and to cover the electrical load of the household, generated by the PV system or purchased from the grid, as well as the grid feed-in of the electrical energy of the PV system. Electric energy generated by the energy system is shown as a positive value, while electrical energy purchased from the grid is shown as a negative value. The following Figure A6 shows the key figures for the temperature control (TC):

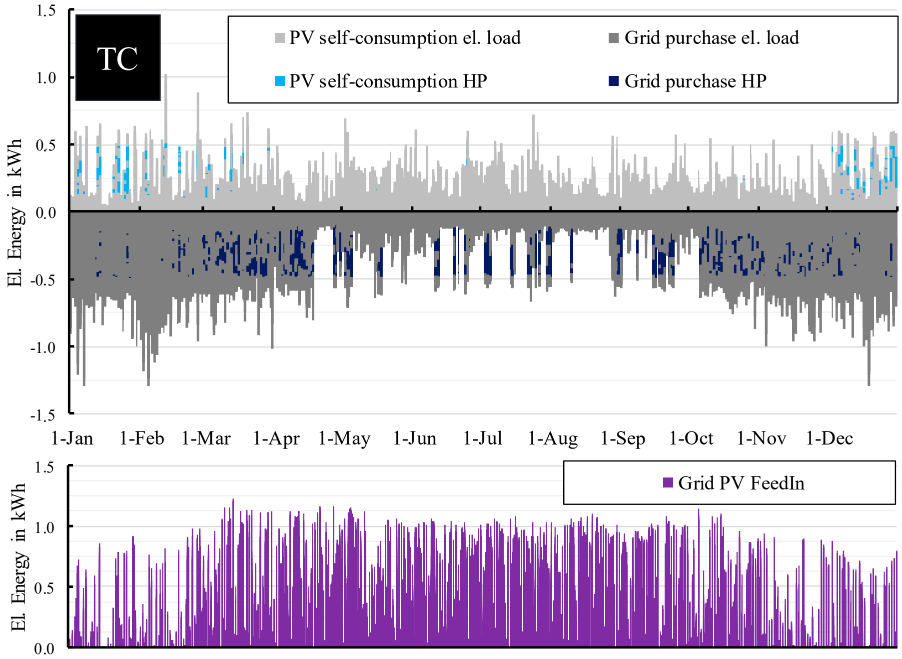

Figure A6. Energy transfer between heat pump, PV system as well as the grid, resulting from the temperature control.

The following Figure A7 shows these key figures for the scheduled control (SC).

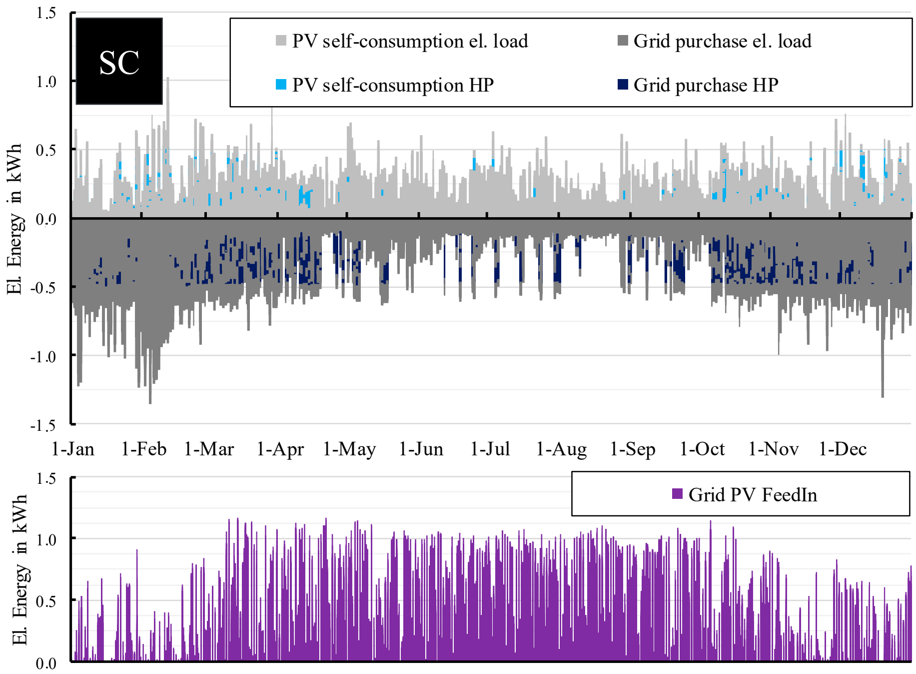

Figure A7. Energy transfer between heat pump, PV system as well as the grid, resulting from the scheduled control.

The following Figure A8 shows these key figures for the integrated two-part control (ITC).

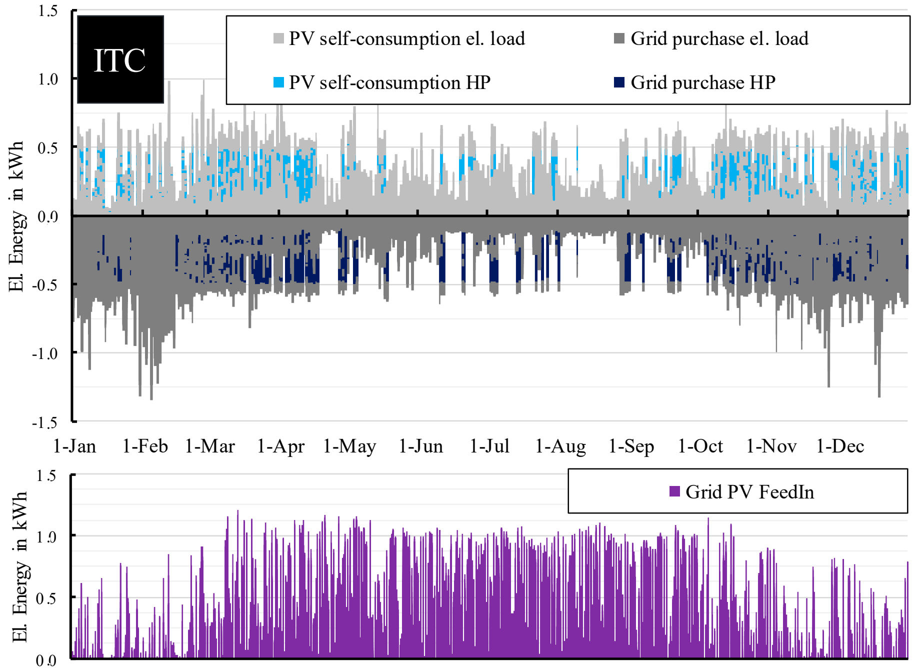

Figure A8. Energy transfer between heat pump, PV system as well as the grid, resulting from the scheduled control.

In the figures, the PV electrical energy consumed by the heat pump is shown in light blue. A visual comparison of the three figures easily demonstrates that the application of the ITC results in a significantly higher internal consumption of PV electrical energy by the heat pump than for the other two control approaches. In summary, we present the resulting annual energy transfer between the PV system, heat pump and the public grid of each control approach in Figure A9.

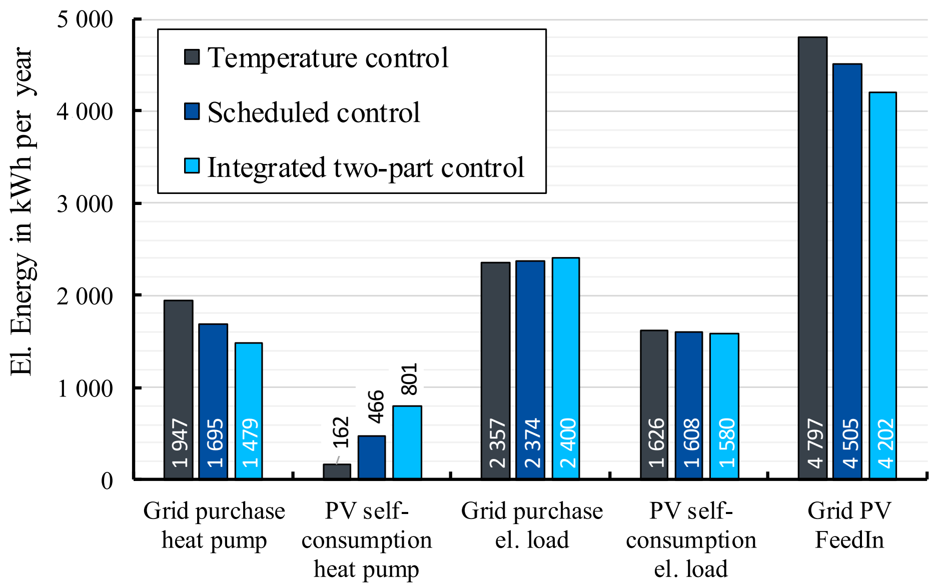

Figure A9. Annual sums of the energy transfer of each control between PV system, heat pump and public grid.

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