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Flexible Use of Residential Heat Pumps - Possibilities and Limits of Market Participation

HEMF Working Paper No. 2/2018

by

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Flexible Use of Residential Heat Pumps – Possibilities and Limits of Market Participation by Jessica Raasch

Abstract

The increased amount of electricity supply from intermittent renewable energy sources leads more and more to high price volatility in electricity spot markets. An increasing share of generation is less dispatchable than in the past, and therefore higher amounts of flexible demand, which can be adjusted towards supply, are required. Even residential consumers are potential market participants, if the smart equipment of buildings and the electricity grid are readily available.

This paper investigates the possibility for heat-pump operators to participate in spot markets. Especially problems and possible benefits are investigated when uncertainties in ambient temperatures or prices are considered. Therefore an optimization model, including an air-to-water heat pump, a storage tank and the heated building is implemented in MATLAB. In order to investigate the heat-pumps operation according to optimized heat-supply schedules. Along different scenarios, an agent-based model is used. Namely operations with day-ahead and intraday market participation are investigated, using historical EPEX spot electricity prices for 2014.

Results show that uncertainty is a critical issue when private consumers participate in electricity markets. Even with a certain amount of system flexibility, there are tight operational constraints for the heating device, which are hard to fulfill. Short-term decisions including responses to current information are required. The system behavior is acceptable with very shortterm decision making, namely a hourly reoptimization with intraday-market participation. Further on, benefits can be yielded, when a combination of procurement before (day-ahead) and adjustments in the very short term (intraday) are applied.

Keywords: Heat-Pump Operation, Flexible Consumption, Residential Market Participation, Spot-Market Bidding.

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Content

Abbreviations

H	optimization time horizon
$\dot{m}_{wc(,t)}$	mass flow (at time t)
$P_{el(,t)}^{max}$	maximum electric power (at time t)
p_t	price at time t
$\dot{Q}_{HP(,l)}$	heat supply heat pump (at time l)
$\dot{Q}_{HP(,t)}^{max}$	maximum heating power (at time t)
$\dot{Q}_{HR(,l)}$	heat supply heating rod (at time l)
$\dot{Q}_{sol(,t)}$	solar gains of building (at time t)
$T_{amb,t}$	temperature (at time t)
$T_{f(,l)}$	temperature floor (at time l)
$T_{i(,l)}$	temperature indoor (at time l)
$T_{st(,l)}$	temperature storage tank (at time l)
$T_{wc(,l)}$	temperature circulating water (at time l)
$T_{wc,r(,l)}$	temperature returning water (at time l)

1 Introduction

The current electricity system is undergoing significant changes, especially due to increasing amounts of infeed from renewable energy sources. This generation depends significantly on environmental conditions and is therefore volatile and not dispatchable. This results in a physical system, which is more complex to operate. Further consequences are reflected in changed market features: E.g. the level of EPEX spot market prices in the bidding zone Germany/Austria has dropped during recent years, while endconsumer prices went up due to increasing additional charges (especially the EEG levy for RES generation has grown, cf. [1]). Consequently the task to balance demand and supply becomes more and more complex. But also a high potential for a profitable spot market participation of flexible bidders is given. Higher amounts of flexible market participants could facilitate the coordination of demand and supply. Particularly end consumers - in case of flower market entry barriers and given suitable incentives - could contribute to balancing the system by participating in the competitive market. Yet, defining the term "flexibility" in electricity systems is a not obvious. Various system participants have a certain degree of flexibility, e.g. to shift load, to control infeed or to adjust technical conditions for electricity transmission. However, primary objectives of electricity consumers and generators are independent from physical grid requirements and there are typically various restrictions for behavior adjustments for grid users. According to [2], limitations arise particularly from (1) a limited range of possible actions, (2) the necessity for fast reactions and (3) the uncertainty of favorable conditions.

For residential grid users a supply of flexibility becomes more and more feasible. The development of smart equipment of grids, households and private electric devices makes bidirectional communication as well as response to received signals viable.[1] Therefore small-scale consumers and producers are increasingly enabled to enter e.g. the wholesale electricity market. These improved conditions may enable a large amount of individual demand units to react to e.g. weather-dependent supply situations. Instead of taking the demand curve as inflexible, here a balance can be achieved by a higher degree of adaptability in a more liquid market.

The problems and obstacles related to adequate incentives as well as the potential of flexibility supply from residential consumers are discussed in the literature, e.g. by

[1] Various field tests, including smart equipment and integrated residential users, have been carried out during recent years, cf. e.g. [3] and [4].

[5] and [6] . Especially the operation of thermal energy storages is promising, e.g. according to [6].

The relevance of integrating residential users into the market and the design of incentives is analyzed by several authors: E.g. [7] introduce a pricing mechanism aiming at the integration of residential generators into balancing markets, while [8] and [9] discuss contracts or market mechanisms for smallscale consumers in order to react to present supply situations. Yet, consumers are not specified further and thus individual restrictions are neglected. [10] in contrast focus on the specific load behavior of electric vehicles. A day-ahead price mechanism here aims at a total demand profile without extreme peaks. The behavior of small-scale consumers in existing markets is analyzed e.g. by [11] and [12]. The authors state, with regard to the Dutch resp. the Iberian day-ahead market that electricity costs can be reduced, in case an aggregator provides adequate incentives and thus smartly coordinates individual consumption. In [13] similar results are obtained for the specific case of heat-pump consumption with view to the day-ahead market in UK. Again an aggregator, aiming at a smart coordination of participants, has to collect individual information and has to coordinate individual users to act for acommon goal.

At a technical level, heat pumps can be interpreted as thermal capacity providers and have therefore great potential to supply residential consumption flexibility. Such a heating system is operated by electric power and can be activated partly independently from heating needs. The building itself has a certain heat capacity, and an additional thermal storage tank can help to decouple electricity consumption and heat supply further. E.g. [14] state that heat pumps are suitable and beneficial components for an energy system characterized by high amounts of intermittent renewables, when combined with cogeneration and wind power.

On the other hand, there are specific restrictions, which reduce flexibility of these systems. Heat pumps are originally designed to supply a building with heat and a certain level of comfort for the inhabitants has to be kept necessarily. Particularly in the case of residential heat-pump operators, storage capacities of the building and the thermal storage tank are limited. Therefore the necessity of an acceptable temperature has to be considered as a constraint when flexibility is to be provided or the operation is scheduled according to competitive prices. Further on, several uncertainties affect the decision on optimal heat-pump operation, since a schedule has to be planned in advance. The system consisting of a heat pump, possibly a thermal storage tank and a building is complex, especially since the operation states of all components and all time steps are interdependent. An optimal operation

schedule has to consider these interdependencies. The optimal operation is strongly impacted by the ambient temperature: heat losses are a function of the difference of indoor and ambient temperature, but also the efficiency of heat pumps depends on the available source temperature, which is equivalent to the ambient temperature in case of air-to-water heat pumps. Scheduling the heat operation in advance implies the need of a temperature forecast and leads to a certain amount of uncertainty. In addition, consumption costs can be uncertain, depending on the underlying market or pricing system. (cf. e.g. [13])

Specific requirements for heat-pump operation and the resulting available flexibility are analyzed in various context situations in the literature. E.g. [15] and [16] investigate residential generators and heat pumps, aiming at an optimal private consumption. In [17] and [18] pricing and market models are introduced to induce a smart flexibility utilization. Thereby goals are a grid-oriented operation respectively the reduction of peak load.

Another issue to keep in mind is the uncertainty of relevant parameters, such as prices and ambient temperatures. As the level of required heat supply and occurring heat losses have to be estimated as precise as possible, an optimal operation can be scheduled adequately only in the short term. Against this backdrop, spot markets as day-ahead and intraday markets might be suitable markets for heat-pump participation.

E.g. a beneficial integration of heat pumps is stated in [19] for the Austrian spot market in 2011. In [20] a control mechanism for heat pumps and air conditioning is introduced in order to analyze benefits of participation in the ERCOT market in Texas. Here a variation of the set point, representing the interior comfort temperature, is allowed to gain flexibility. The authors conclude that the market participation of heat pumps has welfare-increasing effects by reduction of the system's electricity costs and by cutting of load peaks while the level of comfort is only slightly decreased. [21] computes a positive outcome for multi-family heat pumps when the operation is driven by the price signals observed at the Swiss intraday and balancing markets. The intraday market is the underlying market for heat pump integration also in the Danish case in [22]. Yet, instead of direct participation of individual heat-pump operators, the authors assume that an aggregator has to match the flexibility of several residential heat-pump operators.

German spot markets promise to offer a similar potential for flexible consumption for the following reasons. Day-ahead prices are characterized by a relatively low level but

high volatility, since renewable energy sources supply a significant amount of electricity (cf. [1]). And [23] state an increased liquidity of the intraday market during recent years, so that acting nowadays in these markets is less risky and more and more attractive.

This paper presents a detailed analysis of heat-pump operators, who participate in German competitive electricity markets, namely the day-ahead and the intraday market. The focus is set on specific heat-pump restrictions, while existing market-entry conditions as well as additional trading costs are neglected. Thus, the comfort conditions, which need to be fulfilled, are regarded firstly and flexibility is achieved by an optimally dispatched thermal storage tank. In case internal interdependent system restrictions have to be considered, the choice of purchase time steps is not a simple one. Therefore a detailed heating system consisting of an air-to-water heat pump, a thermal storage tank and the heated building is considered. The operation of the observed heating system is optimized against given historical spot market prices. The optimization is formulated as a linear problem in MATLAB. Further on, a simulation of optimal schedules, reoptimization and resulting system states is carried out within an agent-based model. Thus, a realistic operation taking into account uncertain ambient temperatures is modeled. The possibilities and the potential benefits are compared for the participation in the day-ahead and the intraday market, and additionally for a combined procurement in both markets. It turns out that uncertainties are significant obstacles for private consumers and therefore a very short-term decision making is advisable.

The remaining paper is organized as follows: Chapter 2 introduces the system of heat pump and building as well as the corresponding optimization problem. The simulation environment, which is an agent-based model and includes the mentioned optimization, is presented together with implemented foresight assumptions and several scheduling strategies. In Chapter 3 the test-case data are drawn (determining the heating system and the simulation time span) and concrete market participation variants are described. These include a pure day-ahead-market participation, an intraday-market participation and a bidding strategy combining both markets. Results are presented in Chapter 4, where the fulfillment of system and comfort restrictions as well as economical benefits are evaluated in detail. Chapter 5 concludes.

2 Methodology - Heat-Pump Operation

The considered heating system consists of an air-to-water heat pump, a thermal storage tank and the heated building (see Fig. 1). The building is heated by means of

under floor heating, which is fed from the storage tank. In case the heat output of the heat pump is too low, a heating rod may supply additional heat in the thermal storage tank. The opportunity for night setback is neglected here, and warm water is not heated by the heat pump.

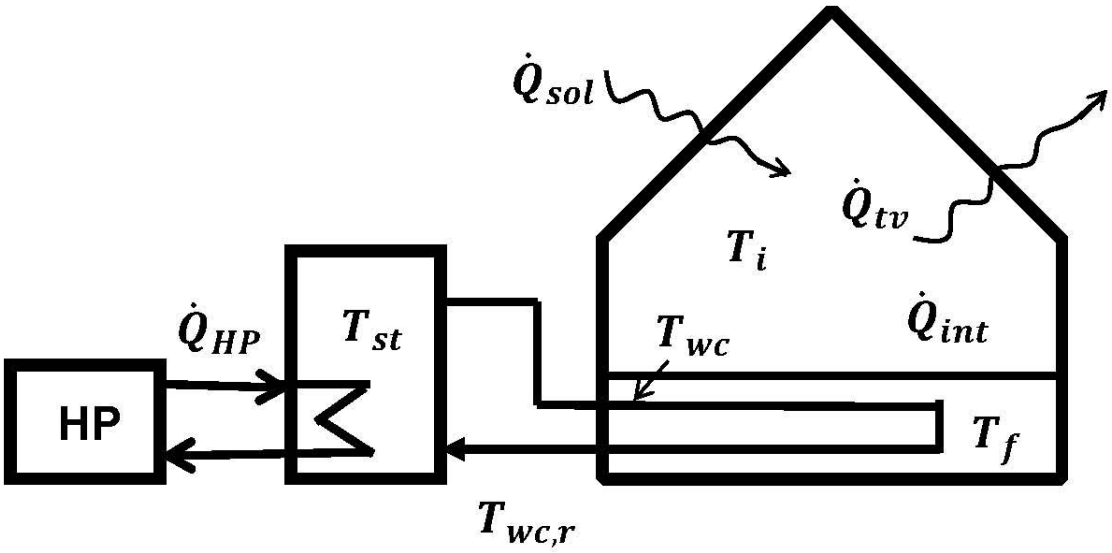


Figure 1: Heating System

Air-to-water heat pumps are characterized by the utilization of ambient air. Thus the available heating power $\dot{Q}_{HP}^{max}$ as well as the required electric power P_{el}^{max} vary with the current ambient temperature T_{amb}. Additionally the supply temperature T_S, entering into the thermal storage buffer, affects the electricity demand. Characteristic curves to model these relationships can be approximated by quadratic equations (cf. [24], p.2):

$$\dot{Q}_{HP}^{max} = a_1 + a_2 T_{amb} + a_3 T_S + a_4 T_{amb} T_S + a_5 T_{amb}^2 + a_6 T_S^2 \quad (1)$$

$$P_{el}^{max} = b_1 + b_2 T_{amb} + b_3 T_S + b_4 T_{amb} T_S + b_5 T_{amb}^2 + b_6 T_S^2 \quad (2)$$

In order to control the indoor temperature T_i, which is a affected implicitly by the heat supply (from heat pump and eventually heating rod) $\dot{Q} = \dot{Q}_{HP}(+\dot{Q}_{HR})$, the thermal behavior of the whole system has to be modeled. Namely the temperatures of the storage tank T_{st}, the circulating water of the underfloor heating T_{wc}, the floor temperature T_f and the returning water within the pipe system $T_{wc,r}$ are of interest: Thereby the thermal storage temperature T_{st} is mainly a ected by the adjoining temperatures of the tank's surrounding (T_{sur}, assumed to have

a fix value of 15˚C, e.g. in a relatively cool basement room) and the return flow temperature $T_{wc,r}$.[2] The temperature of the water circuit T_{wc} depends on its delta to the floor temperature and to the thermal storage temperature. Beside the exchange with the water circuit temperature, the floor temperature is affected by the indoor temperature, while the latter one is reduced by losses due to the ambient temperature T_{amb}, but can be increased also by heat gains through solar radiation and internal gains ($\dot{Q}_{sol}$ and $\dot{Q}_{int}$). Finally the return temperature $T_{wc,r}$ is driven by the heat exchange with the floor and heat inflow from the storage tank. The amount of exchange is respectively affected by the size of surfaces and the thermal characteristics of adjacent materials, which can be seen in detail in the following formulas (based on [25]):

$$\rho_w c_w V_{st} \dot{T}_{st} = \dot{Q} - S_{st} C_{hl} (T_{st} - T_{sur}) + \dot{m}_{wc} c_w (T_{st}^{av} - T_{wc,r}) \quad (3)$$

$$c_w m_{wc} \dot{T}_{wc} = U_{p,f} A_{pipe} (T_f - T_{wc}) + \dot{m}_{wc} c_w (T_{st}^{av} - T_{wc,r}) \quad (4)$$

$$\rho_{ce} c_{ce} V_f \dot{T}_f = -U_{p,f} A_{pipe} (T_f - T_{wc}) - U_{bui} A_{bui} (T_f - T_i) \quad (5)$$

$$C_{bui} \dot{T}_i = U_{bui} A_{bui} (T_f - T_i) - H_{tv} (T_i - T_{amb}) + \dot{Q}_{sol} + \dot{Q}_{int} \quad (6)$$

$$m_{wc} c_w \dot{T}_{wc,r} = -\dot{m}_{wc} c_w (T_{st}^{av} - T_{wc,r}) - U_{p,f} A_{pipe} (T_f - T_{wc}) \quad (7)$$

Thereby the mass flow $\dot{m}_{wc}$ as to be determined, while material-dependent factors such as specific heat capacities c_w, c_{ce} and densities ρ_w, ρ_{ce} for water and cement are given (see Table 1). In addition, building-specific parameters affect the interrelationship of the temperatures: C_{bui} is the building's heat capacity (including indoor air), A_{bui} is the heated area, V_f is the volume of the (cement) floor, A_{pipe} stands for the surface of the pipe system, m_{wc} for the mass of the water circuit, $U_{p,f}$ is the heat exchange coefficient between pipe and floor, U_{bui} the heat transition coefficient (aggregation of all building components which separate the inside from the outside) and H_{tv} represents the coefficient of transmission and ventilation losses. V_{st} and S_{st} are the volume and surface of the thermal storage tank and C_{hl} its heat loss coefficient.

2.1 Optimization – Scheduling the Heat-Pump Operation

An optimal heat-pump operation aims at buying electricity when prices are low, while a certain level of comfort is maintained. The latter one is measured with the delta of indoor temperature and a comfort temperature T_{comf} of 20˚ C. A dead band of two

[2] The average storage temperature $T_{st}^{av} t$ is used as simplification, here. The temperature varies with the layer within the tank, which is not mapped in detail here. The average temperature is assumed to be the average of allowed minimum and maximum storage temperature.

degrees, symmetrically distributed around the set point is defined as an acceptable indoor temperature.

ρ_w	density of water	$1000\ kg/m^3$
c_w	specific heat capacity water	$1.164\frac{Wh}{kgK}$
ρ_{ce}	density of cement	$2000\ kg/m^3$
c_{ce}	specific heat capacity cement	$0.28\frac{Wh}{kgK}$

Table 1: Physical Properties

As initial information the time horizon for optimization, the current state of system temperatures as well as prices and (forecasted) ambient temperatures for the specified time horizon are required. To ensure that values with acceptable prediction accuracy enter into the optimization, the time horizon is chosen to be at most 24 hours. But depending on available price information, even a shorter planning period can be chosen.

Based on the received ambient temperature information, the required mass flow for each hour is determined initially. Here the corresponding losses, reduced by available gains, and the heat transport parameters are considered. $\dot{m}_{wc,t}$ for hour t is given by

$$\dot{m}_{wc,t} = \frac{H_{tv}\left(T_{comf} - T_{amb,t}\right) - \dot{Q}_{sol,t} - \dot{Q}_{int,t}}{c_w(T_{st}^{av} - T_{wc,r,o})}, \tag{8}$$

where $T_{amb,t}$ is the (forecasted) ambient temperature in hour t, $T_{wc,r,0}$ the last available information on the return temperature of the circulating water. In case of values exceeding a previously defined minimum or maximum value, $\dot{m}_{wc,t}$ is set to the corresponding value.

With given mass flow the above defined relationship of system temperatures is linear in heat supply and system temperatures. Thus, the optimization problem can be formulated as a linear problem, which is implemented in MATLAB. Variables of the problem are then temperature values ($T_{st}, T_{wc}, T_f, T_i, T_{wc,r}$) and heat supply values ($\dot{Q}$) for each time step. It is to decide on $\dot{Q}$ for each hour, depending on corresponding prices. The equations (3) - (7) describe in discretized form equality restrictions on the temperature changes between time steps. Additionally, inequality restrictions have to be included in order to maintain comfort and storage conditions. The maximum available heat capacity $\dot{Q}_{HP}^{max}$ HP and the corresponding electric load P_{HP}^{max} are determined for each hour in advance according to equations (1) and (2). (Information

on the ambient temperature is assumed to have an hourly resolution, while the thermal behavior can be simulated with a finer resolution in order to avoid instable system dynamics due to inadequate discretization.). The heating rod has a constant level of efficiency. Yet, in this model the heating rod is dispatched only in case the heating capacity of the heat pump is insufficient to meet the required heat level over the total time horizon considered.[3] Internal gains can be determined for each hour in advance, too. Being a result of individual inhabitant behavior (heat gains from humans and active devices), internal gains are difficult to predict precisely. Therefore a constant average value is assumed, which is based on the heated building area ($\dot{Q}_{int} = \frac{5W}{m^2} \cdot A_{bui}$, cf. [26], p. 84). Gains due to solar radiation are given as exogenous input (see Chapter 2.2).

In detail, the linear optimization problem is defined as follows: The objective function includes the costs for the heat supply summed over all time steps, implying a specific electric load:

$$\sum_{l=1}^{N \cdot H} p_t \cdot \frac{P_{HP,t}^{max}}{\dot{Q}_{HP,t}^{max}} \cdot \dot{Q}_{HP,l} \cdot \Delta t, \tag{9}$$

where $H$is the optimization horizon and N the number of finer time steps of length Δt per hour. (This finer resolution is used for the thermal behaviour simulation.) The hour t of the current simulation step l is then given by $t = \lceil l \cdot \Delta t \rceil$. p_t is the exogenous price information and $\dot{Q}_{HP,l}$ is the heat pump's heat supply, chosen for time step l. In case of required additional heat supplied by the heating rod, the objective function is supplemented by the following term:

$$\sum_{l=1}^{N \cdot H} p_t \cdot \frac{1}{\eta_{HR}} \cdot \dot{Q}_{HR,l} \cdot \Delta t, \tag{10}$$

where η_{HR} is the efficiency of the heating rod and $\dot{Q}_{HR,l}$ is the chosen additional heat supply of time step l.

The thermal dynamics of the building and heating system form equality restrictions. The thermal system's behavior equations (see (3) - (7)) are thereby included in a discretized version for every time step modeled:

[3] This makes a difference only in case of negative prices as the efficiency of the heat pump is throughout significantly better. From a pure economic point of view, wasting energy at negative prices is optimal. Yet if the observed prices are distorted by some regulatory settings (e.g. mandatory take-off of renewable electricity), limiting the use of electricity may still be beneficial in a longer term system view.

$$\rho_w \mathrm{c_w V_{st}} \frac{\mathrm{T_{st,l}} - \mathrm{T_{st,l-1}}}{\Delta \mathrm{t}} = \dot{Q}_{HP,l} + \dot{Q}_{HR,l} - S_{st} C_{hl} \left(T_{st,l-1} - T_{sur}\right) - \dot{m}_{wc,t} c_w (T_{st}^{av} - T_{wc,r,l-1})$$

$$\mathrm{c_w m_{wc}} \frac{\mathrm{T_{wc,l}} - \mathrm{T_{wc,l-1}}}{\Delta \mathrm{t}} = U_{p,f} A_{pipe} \left(T_{f,l-1} - T_{wc,l-1}\right) + \dot{m}_{wc,t} c_w (T_{st}^{av} - T_{wc,r,l-1})$$

$$\mathrm{\rho_{ce} c_{ce} V_f} \frac{\mathrm{T}_{f,\mathrm{l}} - \mathrm{T}_{f,\mathrm{l-1}}}{\Delta \mathrm{t}} = -U_{p,f} A_{pipe} \left(T_{f,l-1} - T_{wc,l-1}\right) - U_{bui} A_{bui} \left(T_{f,l-1} - T_{i,l-1}\right)$$

$$C_{bui} \frac{\mathrm{T}_{i,\mathrm{l}} - \mathrm{T}_{i,\mathrm{l-1}}}{\Delta \mathrm{t}} = U_{bui} A_{bui} \left(T_{f,l-1} - T_{i,l-1}\right) - H_{tv} \left(T_{i,l-1} - T_{amb,t}\right) + \dot{Q}_{sol,t} + \dot{Q}_{int,t}$$

$$m_{wc} c_w \frac{\mathrm{T_{wc,r,l}} - \mathrm{T_{wc,r,l-1}}}{\Delta \mathrm{t}} = -\dot{m}_{wc,t} c_w \left(T_{st}^{av} - T_{wc,r,l-1}\right) - U_{p,f} A_{pipe} \left(T_{f,l-1} - T_{wc,l-1}\right),$$

for $l = 1, \dots, N \cdot H$. Further on,

$$\dot{Q}_{HP,l}, \dot{Q}_{HR,l}, T_{st,l}\ T_{wc,l}\ T_{f,l}, T_{i,l}, T_{wc,r,l}$$

for $l > 0$, are variables corresponding to time step l.[4]

Due to technical restrictions and in order to maintain the comfort conditions, the following inequality restrictions have to be fulfilled as well: The heat-pump output can be chosen in each time step only within the range of zero and the heat capacity:

$$0 \leq \dot{Q}_{HP,l} \leq \dot{Q}_{HP,t}^{max}, \ \ for\ l = 1, \dots, N \cdot H, \tag{11}$$

where $t = [l \cdot \Delta t]$.

In case of possible supply from the heating rod, the minimum and maximum heat capacity have to be reflected as well:

$$0 \leq \dot{Q}_{HR,l} \leq \dot{Q}_{HR}^{max}, \ \ for\ l = 1, \dots, N \cdot H. \tag{12}$$

Additionally, the thermal storage tank is facing several limits: A declining storage temperature beneath a specific minimum temperature T_{st}^{min} would imply effectively that heat supply to the building would fail and is therefore avoided. An upper limit for the storage temperature is modeled by T_{st}^{max}. This restriction reflects the fact that at some point more heat supply does not imply an increasing storage temperature. This is due to the fact that the heat pump can deliver heat effectively to the storage tank only in case of positive gap between supply temperature of heat pump and storage temperature. Thus, additional inequality restrictions are given as follows:

$$T_{st}^{min} \leq T_{st} \leq T_{st}^{max}, \ \ for\ l = 1, \dots, N \cdot H. \tag{13}$$

Finally, the comfort conditions are formulated as follows:

[4] The equations belonging to $l = 1$ differ slightly from the latter ones, as the initial temperatures $T_{st,0}, T_{wc,0}, T_{f,0}, T_{i,0}$ and $T_{wc,r,0}$ enter as parameters instead of being variables.

$$T_{comf} - \Delta_{TBand} \leq T_{i,l} \leq T_{comf} + \Delta_{TBand}, \quad for\ l = 1, \dots, N \cdot H, \tag{14}$$

Where $T_{comf} = 20$ and $\Delta_{TBand} = 1$.

A function f that computes an (optimal) heat-supply schedule is the result. Input data are the optimization time horizon H, price data, ambient temperature data and solar-gain data for that time horizon as well as the current states of system temperatures:

$$\mathrm{f}\left(\mathrm{H}, \vec{p}, \vec{T}_{\mathrm{amb}}, \vec{Q}_{sol}, \mathrm{T_{st,0}}, \mathrm{T_{wc,0}}, \mathrm{T_{f,0}}, \mathrm{T_{i,0}}, \mathrm{T_{wc,r,0}}\right) = \left(\dot{Q}_{HP,1}, \dots, \dot{Q}_{HP,H}\right), \tag{15}$$

where $\vec{p} = (p_1, \dots, p_H), \vec{T}_{\mathrm{amb}} = (T_{amb,1}, \dots, T_{amb,H})$ and $\vec{Q}_{sol} = \left(\dot{Q}_{sol,1}, \dots, \dot{Q}_{sol,H}\right)$

are vectors containing hourly data, respectively for prices, ambient temperatures and solar gains. In case heat demand can only be served by additional heat from the heating rod, the output is defined by

$$\left(\dot{Q}_{HP,1}, \dots, \dot{Q}_{HP,H}, \dot{Q}_{HR,1}, \dots, \dot{Q}_{HR,H}\right).$$

2.2 Simulation

As a simulation framework an agent-based model is chosen. A JADE-based multi-agent simulation is used including a heat-pump agent, which represents the combination of heat pump and heated building. Within this agent, the invoking of the optimization algorithm f (see (15)) and the following operation (based on the same thermal-behavior equations) are executed. This framework enables the execution of various simulations: the impacts of possible forecast errors, i.e. differences between predicted and realized ambient temperatures, can be represented. But also cases with perfect forecast can be simulated. Additionally, the agent can apply the optimization model in two ways: either a heat supply schedule is computed in advance (e.g. once per day) or a rolling planning repeats the optimization (e.g. hourly).

Additionally the framework includes agents, which provide required information: A market agent sends vectors of price data and a weather agent provides current weather data (ambient temperature and solar radiation). Data are provided hourly. The structure of known prices (or price forecasts) depends on the chosen market context. Therefore, assumptions on price information are explained in Chapter 3.1 resp. 3.2. The weather agent is based on an implementation by J. Kays and A. Seack (cf. [27], [28]), who develop an agent-based model for distribution grid planning purposes.

Based on provided solar radiation data, the heat-pump agent then determines building specific solar gains: The computation here is similar to the effective solar radiation reaching photovoltaic panels in [28], (p. 79). The computation is executed for all

facades of the building and corresponding window areas $A_{w1}, A_{w2}, A_{w3}, A_{w4}$ and is corrected by average reductions due to e.g. glazing and incidental shadowing ($F_F, F_S, F_C, F_W, g_{senk}$ according to [29], p. 213).

With extremely warm indoor temperatures, it is assumed that inhabitants shade the windows, so that additional warmth from solar radiation is avoided. Consequently, solar gains are set to zero in hours with initial indoor temperatures which approach the upper limit by 0.1 K.[5]

2.2.1 Foresight Modes

Simulation with Perfect Foresight. For simulations with assumed perfect foresight, prices as well as ambient temperatures and solar radiation are assumed to be known in advance. Required weather data are stored as parameters of the heat-pump agent.

Simulation under Uncertainty. Usually relevant input data, such as weather data, are not known in advance. Thus, simulations which show effects of uncertainties on heat pump operation can be applied. In order to simulate weather forecasts and their deviations a simple myopic forecasting scheme with updating is used, since actual forecasts are not easily available for sites with historical weather records. The heat-pump agent stores the weather agent's data with assignment to the corresponding hour of day as historical data, noted $T^{hist}_{amb,1}, \dots, T^{hist}_{amb,24}$. When receiving current information on the temperature T_{amb,t_0}, the delta Δ_{t_0} to the last known temperature for this hour (which is from the previous day) is computed as follows:

$$\Delta_{t_0} = T_{amb,t_0} - T^{hist}_{amb,t_0},$$

where t_0 is the current hour of the day. The ambient temperatures $T^{fc}_{amb,t}$ for the subsequent 24 hours are then assumed to be shaped as the historical data, but shifted by the estimated level change:

$$T^{fc}_{amb,t} = T^{hist}_{amb,t} + \Delta_{t_0}, for\ t = 1, \dots, 24.$$

For solar radiation a myopic forecast is applied, using the historic data directly as forecasts. Thus, the occurrence of the same solar data as during the bygone 23 hours for the following 23 hours is assumed.

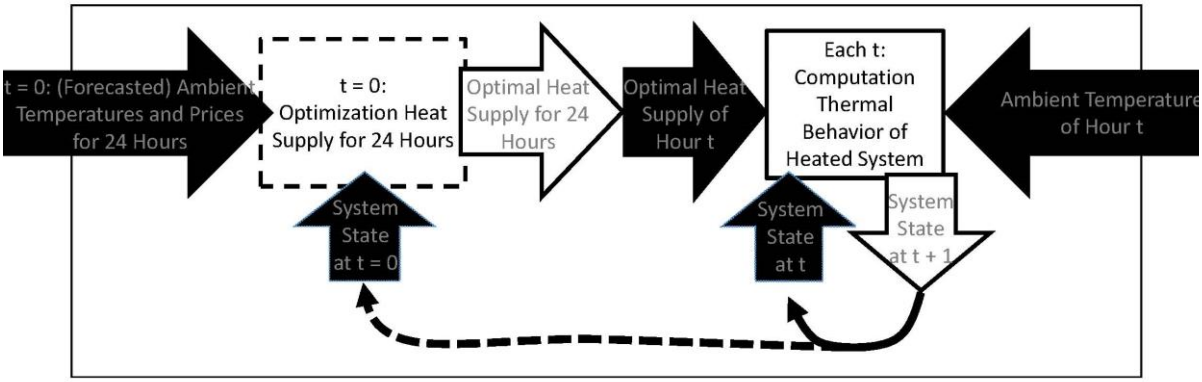
2.2.2 Scheduling Strategies

In order to reflect possible uncertainties on weather data, two simulation modes are implemented concerning the sequence of optimization and operation. An ex ante

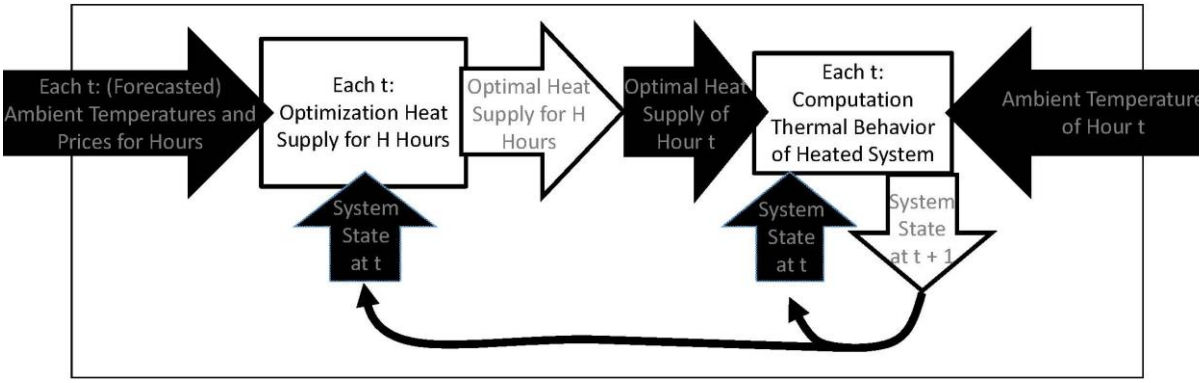
[5] The possibility to cool the building is not regarded, as the focus is set on flexible heat supply, which is given particularly in winter months.

determined operation for 24 hours as well as an hourly rolling planning for variable time horizons can be chosen.[6]

Scheduling in Advance. Every day at midnight, the optimization algorithm is invoked and the operation is scheduled for the following 24 hours. The operation is carried then out according to the previously scheduled plan. (See Fig. 2a, where dashed lines indicate daily process steps, while continuous lines show hourly steps.)



(a) Scheduling in Advance and Operation



(b) Hourly Rolling Planning and Operation

Figure 2: Schemes of Scheduling Strategies

In the presence of uncertainties, a predetermined schedule may turn out to be not optimal or even infeasible in actual operation - e.g. because the actual heat supply has to be higher than anticipated to keep indoor temperatures within the comfort range. In order to cope with such problems or prevent them, the following heuristic modifications to both the optimization and the simulation models are proposed -

[6] These scheduling methods correspond naturally to existing market structures – namely the auction based day-ahead market and the continuous trading of the intraday market.

partly as precautions in order to avoid violations on operation limits, and partly as instantaneously required adjustments.

For the *optimization* the following modifications are implemented:

1) The given restrictions in the optimization model may be changed in order to gain a more robust operation in case of uncertainty. Notably imposing tighter storage temperature limits in the optimization, allows to use additional leeway in storage operation to fulfill all original restrictions during operation, even when heat requirements occur unexpectedly.
2) Another possibility to gain some flexibility in operation, is to modify the mass flow in the heating system compared to the optimal mass flow as given in (8). In order to cope with situations with too much or too little heat in the system, the mass flow may thus be lowered or increased by a factor of 2 for up to four time steps.
3) As a fall-back option also a heuristic is implemented. When an optimal solution cannot be achieved in acceptable computation time, then the estimated heat supply of the full time horizon is distributed equally to each hour.

During the *simulation* of the heat-supply operation the following modifications are permitted (e.g. deviations between scheduled plan and effective heat-pump operation):

(a) In case the realized ambient temperature is lower than the forecasted one, the available maximal heat capacity $\dot{Q}_{HP}^{max}$ is lower, too. As a consequence, the planned heat supply for a specific hour cannot be delivered fully. The heat supply is set to the minimum of the currently available heat capacity and scheduled heat supply of that hour. (The amount of demanded electricity is assumed to be constant. This seems to be legitimate, as the maximum electric power consumption is only weakly dependent on ambient temperatures.)

(b) When temperature forecasts are badly wrong, then the earlier scheduled heating plan may fail to fulfill the restrictions concerning storage and comfort conditions.

(i) When the indoor temperature is too high/low in a specific time step, then the previously defined mass flow (see (8)) is lowered/increased by a factor of 2 (but not below a minimum $\dot{m}_{wc}^{min}$ or above a maximum $\dot{m}_{wc}^{max}$ size for the mass flow). This correction is chosen when the

indoor temperature approaches the indoor temperature limits by less than 0.1 K.

(ii) When the storage temperature is close to violations (i.e. the temperature approaches the limits by 0.5 K), then instantaneous adjustments of heat supply from the market are assumed to be possible. Namely, additional electricity purchase or the resale of previously bought electricity is carried out by setting the heat supply to $\dot{Q}_{HP}^{max}$ or 0.

(iii) As adjustments of mass flow lead to a quicker or slower heat supply from the thermal storage tank, an additional measure, which combines the two aforementioned adjustments, is implemented: if the storage temperature is relatively low/high (i.e. the limits are approached by 4 K) and simultaneously the indoor temperature is close to be too low/high at the beginning of an hour (i.e. the limit is approached by 0.2 K), then a mass flow adjustment and a following storage temperature violation are likely. Therefore heat supply is assumed to be necessary resp. superfluous and thus set to $\dot{m}_{wc}^{max}$ resp. 0.

Hourly Rolling Planning. In case of the rolling planning, the optimization is carried out in each hour for a certain time horizon (see Fig. 2b). On an hourly basis, the following steps take place: prices and price forecasts are received from the market agent for a certain time horizon, temperature forecasts maybe computed and the optimization function f is applied for the given time horizon. Due to typical lags between the reception of information and effective operation, the optimization schedule is determined for the operation, starting with the following hour. The actual heat supply in each hour is then done according to the latest schedule available. Thus, only the very first scheduled hour of each optimization is carried out, taking place in the next hour.

In comparison to the strategy `Scheduling in Advance' as described before, there are less adjustment possibilities required as the used information are newer. Yet, the following adjustments may be called: optimization adjustments as described in (1), (2) and (3) are possible as well as operation deviations due to less available heat or instantaneously required mass flow variations (see (a) and (b)(i) above).

3 Test Case

An application for the described agent-based simulation with optimized heat-pump operation is carried out for a sample heat pump, which heats a single-family house (according to a model given in [30], p. 38). The building has one floor and a partly heated basement, the roof space is unheated. In total the heated area is 110 m² and the corresponding air volume 272.9 m³. Further detailed data are given in Table 2.

C_{bui}	building heating area	$7982\ Wh/K$
A_{bui}	heated area	$110.5\ m^2$
A_{w1}	area window to the north	$4.49\ m^2$
A_{w2}	area window to the east	$3.87\ m^2$
A_{w3}	area window to the south	$5.82\ m^2$
A_{w4}	area window to the west	$0\ m^2$
V_f	volume floor	$6.63\ m^3$
A_{pipe}	surface pipe system	$27.87\ m^2$
m_{wc}	mass water circuit	$123.85\ m^2$
$\dot{m}_{wc}^{min}$	minimum mass flow	$50\ kg/h$
$\dot{m}_{wc}^{max}$	maximum mass flow	$1200\ kg/h$
$U_{p,f}$	heat exchange coefficient (pipe to floor)	$78.42\frac{W}{m^2K}$
U_{bui}	heat transmission coefficient (building in-/outdoor)	$13.33\ \frac{W}{m^2K}$
H_{tv}	coefficient transmission/ ventilation losses	$282.23\ W/K$
V_{st}	volume storage tank	$3.52\ m^3$
S_{st}	surface storage tank	$36.88\ m^2$
C_{hl}	heat loss coefficient storage tank	$0.48\frac{W}{m^2K}$
T_{st}^{min}	minimum storage tank temperature	$28°C$
T_{st}^{max}	maximum storage tank temperature	$39°C$
η_{HR}	level of efficiency heating rod	0.98
$\dot{Q}_{HR}^{max}$	thermal capacity heating rod	$3\ kW$

Table 2: Parameters Thermal System

The heating system considered consists of a heat pump with thermal nominal capacity of 9 kW and electrical nominal capacity of 1.86 kW (Panasonic WH-SDC09F3E8, the system is dimensioned with regard to the nominal ambient temperature in Essen

(Germany) and additional supply from a heating rod, cf. [31]). Parameters the for temperature depending thermal and electrical capacity, as defined in (1) and (2), are listed in Table 3. In order to yield high flexibility, a constantly high level of 42 ˚C is chosen for the supply temperature. The volume of the thermal storage tank and the supply temperature have significant impact on the opportunity to operate the heat pump independently from building heat demand. This is due to the fact that the storage tank can take more heat, when its volume increases (and thus its thermal inertia) and when the upper bound of storage temperature (related to the supply temperature) is higher. Preceding investigations have shown that the thermal storage-tank volume V_{st} beyond 3.52 m³ and the supply temperature T_S above 42 ˚C does not yield additional benefits.[7] Thus, the data for supply temperature and tank volume are fixed at the mentioned levels. The storage tank then has a surface S_{St} of 36.88 m² (a combination of eight equal units of the system PAW-TE0E3STD is considered).

$\dot{Q}_{HP}$		P_{el}	
a_1	$10.12\ kW$	b_1	$0.811\ kW$
a_2	$-0.003\ kW/°C$	b_2	$-0.058 kW/°C$
a_3	$-0.015\ kW/°C$	b_3	$0.055\ kW/°C$
a_4	$0.001\ kW/°C^2$	b_4	0
a_5	$-0.002\ kW/°C^2$	b_5	0
a_6	0	b_6	0

Table 3: Parameters Heat Pump

Regarding the market context, two simulations are carried out. In order to apply information with adequate accuracy, only short-term trading is taken into account, namely participation in a day-ahead and an intraday market are simulated.

In order to obtain stable simulation results for the thermodynamic system, the time resolution for the optimization of the heat-pump operation is chosen to be a two-minute pace in the MATLAB code, i.e. $\Delta t = \frac{1}{30}$. The optimization performance is more robust, when heat supply is chosen for each two-minute-time-step, too. Yet, as market transactions are assumed to be hourly contracts, heat supply as well as corresponding electric load are finally defined as average values for each hour.

[7] The investigations to determine supply temperature and storage-tank size are carried out in the context of an average daily profile of ambient temperatures around 0°C and constant prices. As a market participation in general is to be investigated, the focus is set on flexibility here, and therefore a high storage volume is chosen without consideration of the investment costs.

For all scenarios the simulation is performed for the first quarter of 2014. Here market operations can be observed for both a `real' winter month and a relatively warm March, implying also a relatively high level of temperature volatility.

3.1 Day-Ahead Market

For the day-ahead market simulation it is assumed that prices for the following day are known at midnight and procurement can be settled for the whole day then. As simulation mode the `Scheduling in Advance', described in Chapter 2.2.2, is applied. That is, at midnight a presumably optimal heat-supply operation for the following day is scheduled and followed as closely as possible. Price information is provided previously as a vector of day-ahead prices from the market agent. Data is given by historical day-ahead EPEX spot prices for 2014. Thus, day-ahead trading of heat-pump operators is analyzed without consideration of uncertainty in prices nor market-entry barriers for small-scale consumers nor transaction fees. The aim is to analyse the theoretical potential for the participation of heat-pump operators in real spot markets.

In case improperly estimated heat capacity or thermal behavior lead to the need of instantaneous adjustments of the heat-supply operation (modelled as described in (b)(ii) and (iii)), an additional intraday-market contract is assumed to be concluded. In case of uncertainty (i.e. uncertain weather data), the restrictions of the optimization are chosen tighter than properly required (see $\tilde{T}_{Sp}^{\min}, \tilde{T}_{Sp}^{\max}, \tilde{T}_{i}^{\min}$ *and* $\tilde{T}_{i}^{\max}$ in Table 4).

	Day-Ahead	Intraday
$\tilde{T}_{Sp}^{min}$	$32\,°C$	$29\,°C$
$\tilde{T}_{Sp}^{max}$	$35\,°C$	$38\,°C$
$\tilde{T}_{i}^{min}$	$19.5\,°C$	$19\,°C\ (= T_{i}^{min})$
$\tilde{T}_{i}^{max}$	$20.5\,°C$	$21\,°C\ (= T_{i}^{max})$

Table 4: Adjustment Parameters

3.2 Intraday Market

In order to simulate the participation of a heat-pump operator in an intraday market, the simulation mode `Hourly Rolling Planning' (see Chapter 2.2.2) is chosen. Price data from the intraday market is provided each hour. Again a vector of prices is given, but the number of prices varies and therefore also the time horizon for heat-supply optimization. A decreasing number of prices is available throughout the day, as only contracts for all following hours within the same day are traded in the EPEX Spot intraday market. Yet, at 3 p.m. the market for the following day opens. Therefore

again prices for the next 24 hours can be taken into account for an optimal schedule. Except a price for the current hour is lacking in each case. This is due to the fact that contract conclusion and execution may be at minimum 30 minutes apart. As mentioned above (see Chapter 2.2.2) the optimization is done for a period starting the following hour, while heat-supply operation of the current hour is executed according to the previously determined schedule.

Historical price data are again used as input: for each scheduling hour, the weighted average price of contracts traded in that period in the EPEX Spot intraday market are used as price expectations for the hours of the planning horizon. The price for the next hour is assumed to be the actual price of delivery, which can be chosen for a contract or not. In contrast, no actual trading is considered for the following hours. The size of the price vector (and correspondingly the planning horizon H) depends on the current time as the optimization is carried out for at most 24 hours but also at most until gate closure.

In addition, the same simplifications concerning market participation of residential consumers are made as for the day-ahead market simulation. Particularly, market liquidity is assumed to be sufficient, so that contract partners for trades are always available. In case of uncertainty the storage temperature range is again chosen tighter than properly required (see $\tilde{T}_{Sp}^{min}$ and $\tilde{T}_{Sp}^{max}$ in Table 4).

3.3 Combined Bidding

Another application attempts to make use of the benefits of both described strategies: the planning in advance, which fulfills the schedule (in theory) without corrections (but is rather critical under uncertainty) on the one hand, and the rolling planning, which reschedules optimal solutions using newest information on the other hand. Here first a day-ahead procurement for the following day is carried out according to the schedule determined in advance. Subsequently, changing electricity quantities are bought or sold in the intraday market after reoptimization. The heat-pump operation, including possible adjustments, is carried out similarly to the intraday application. In terms of implementation the only difference to the intraday simulation is an additional optimization each day, which has no effect on the applied heat-supply operation.

This strategy is expected to be advantageous due to the following reasons: First, a greater choice between two prices should lead to lower procurement costs (even if future prices are uncertain and may not be locked in the setting described here). A procurement in advance allows to avoid purchasing of currently required electricity. Even more, it is possible to sell electricity in some cases, when prices are high.

The costs of procurement are computed after the simulation including both the day-ahead procurement and the effective heat-pump operation supplied from the intraday market.

4 Results

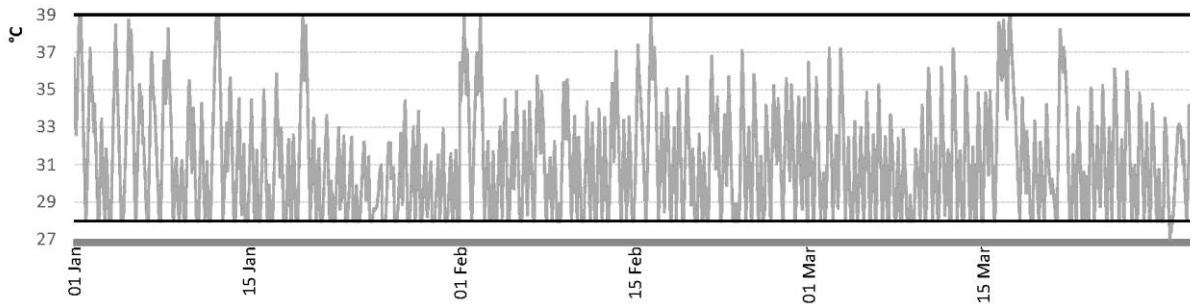
From the outset it can be stated that comparisons of procurement costs obtained for various market applications are not biased by schematic differences in price levels, as the EPEX spot day-ahead and intraday market have nearly the same mean price for the investigated time period (3.350 ct/kWh for the day-ahead, 3.349 ct/kWh for the intraday market). Concerning the volatility of prices, the intraday market is slightly advantageous for participants with purchasing and reselling intentions as there are on average greater price spreads (the standard deviation is 14.7 ct/kWh for the day-ahead compared to 17.59 ct/kWh for the intraday market).

The simulated time range is from January to March. Thereby January and February represent a rather typical heating period, while in March heat supply is required as well, but there are also some hours of relatively high temperatures. With -5.15 °C as lowest and 23.85 °C as highest ambient temperature the temperature range is quiet large. The highest temperatures difference within one day occurs on 30 March with 25 °C. Remarkably, on this day the maximum of 23.85 °C is reached, which exceeds the accepted indoor temperature of 21°C.

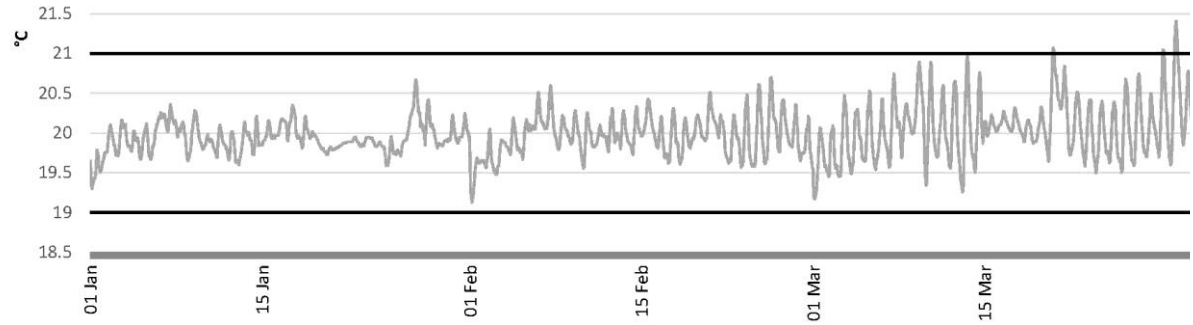
4.1 Simulation with Perfect Foresight

Obviously, the simulations with perfect foresight are rather theoretical ones, but serve as pre-analysis to check the operation functionality and to compare the scheduling strategies disregarding the impact of uncertainty. Especially basic differences between the described scheduling strategies may be identified and the impact of weather conditions on operation patterns can be observed therewith.

Day-Ahead Market. For the day-ahead-market application Fig. 3 shows the obtained values for the constrained temperatures, i.e. storage and indoor temperature. Only a few small violations of the imposed temperature limits are observed in March. The reasons for these violations are discussed below. As a mean procurement price 2.791 ct/kWh is realized (compared to an average price of 3.350 ct/kWh on this market).



(a) Storage Temperature Behavior and Limits



(b) Indoor Temperature Behavior and Limits

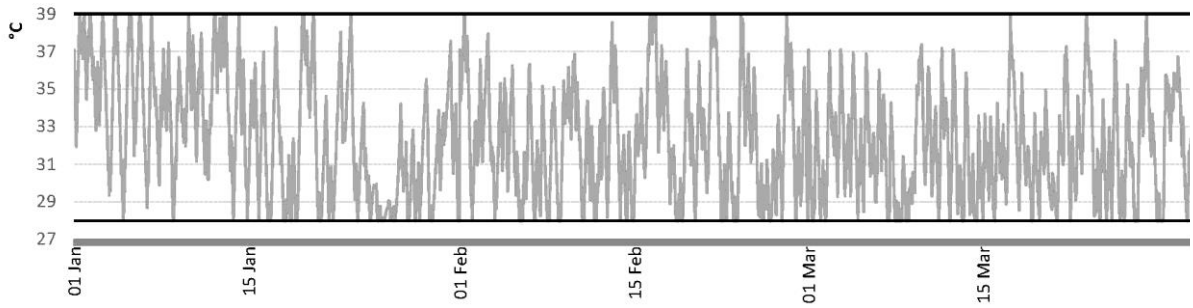
Figure 3: Temperature Performance Day-Ahead-Market Application under Perfect Forecast

In an additional computation 2.709 ct/kWh is determined as a lower limit for the procurement price in the same market and weather context. This price holds under the assumption of maximum within-day flexibility, i.e. when total daily heat demand is allocated as far as possible - given the heat capacity of the heat pump - to the lowest market prices of the day. Hence the realized price in the context of perfect foresight is only 3% higher than the price with full flexibility, indicating that the system-depending restrictions for storage and indoor temperature are rather low obstacles from an economic point of view.

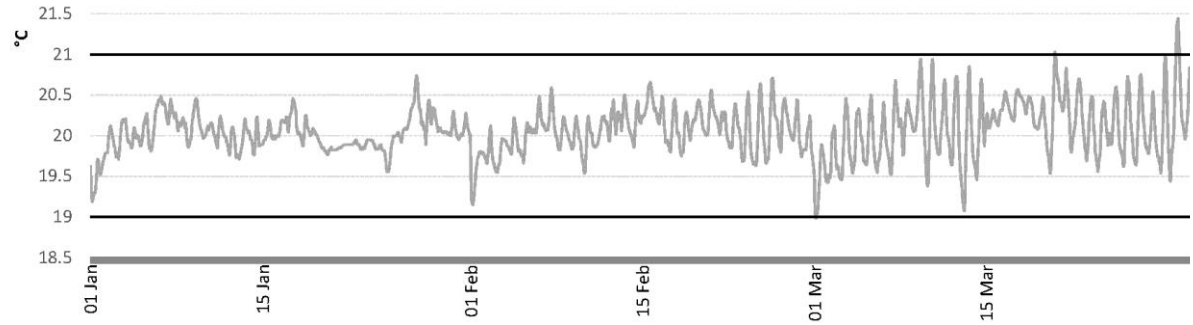
The observed constraint violations occur only in in hours with high ambient temperatures and large temperature spreads. On 30 March no optimal solution can be found and instantaneous corrections with short-term heat supply occur twice. Nevertheless, violations of the lower storage temperature limit cannot be avoided in the cold morning hours. And later on, ambient temperatures of more than 23 °C imply a violation of the upper indoor temperature limit. Further slight violations of the same temperature limit (12 times) are due to relatively high outdoor temperatures (above 20 °C) combined with missing cooling possibilities and the system's inertia.

Intraday Market. In case of the intraday-market application, the system and comfort constraints are fulfilled nearly throughout the whole simulation period (see Fig. 4).

Violations occur only on 30 March for the indoor temperature (too high), when it comes to the mentioned high ambient temperatures. Again, the performance is more difficult for the spring month March: On three days heuristic schedules have to be called. In the end, these substituting schedules operate the system in a way that no deviations between scheduled and effective operation are needed. Thus, no adjusting mechanisms are required to fulfill all restrictions in case of the intraday-market operation. The frequently updated information and the avoidance of subsequent faults due to repeated reoptimization lead to a more robust strategy in the context of critical weather conditions.



(a) Storage Temperature Behavior and Limits



(b) Indoor Temperature Behavior and Limits

Figure 4: Temperature Performance Intraday-Market Application under Perfect Forecast

The price paid per kWh is about 2.690 ct/kWh in average, where the market's mean price is 3.349 ct/kWh. The theoretical procurement price with maximal flexibility, which is computed similarly to the day-ahead case above, is 2.550 ct/kWh. I.e., the realized price with perfect foresight implies with a deterioration of 5% again only a limited loss due to technical and comfort restrictions.

Noteworthy, the consumed electricity is higher for the case of the reoptimizing intraday application. While the optimization in advance (within the day-ahead market)

ends up with 2772 kWh for the three simulation months, the reoptimizing mode implies a consumption of 2805 kWh.[8]

4.2 Simulation under Uncertainty

Day-Ahead Market. A more realistic simulation for the day-ahead-market application is done with uncertain ambient temperatures. Naturally the performance of the heat-pump operation turns out to be significantly worse. Especially the maintenance of technical and comfort restrictions is critical: From January to February the upper indoor temperature limit is violated slightly in 9 cases. The temperature ranges are 28.05 °C to 37.83 °C for the storage tank and 19.03 °C to 21.02 °C for the indoor temperature. As before, the performance for March is more critical: Mainly due to high indoor temperatures the number of violations increases to 51 for the period January to March (where 43 violations belong to the upper indoor temperature limit) and the ranges for storage and indoor temperatures are extended to 26.65 °C to 37.85 °C resp. 18.83 °C to 21.8 °C. Even with mass flow variations and instantaneous heat supply adjustments these violations cannot be avoided. Significant violations of indoor temperatures are due to inaccurate estimates of ambient temperatures (there are hours with deviations of up to 17K) so that they cannot be absorbed by mass flow adjustments. Violations of the storage temperature limits occur during longer periods of under- resp. overestimated ambient temperatures and subsequent mass flow variations, with the consequence of too slow or too quick storage discharging.

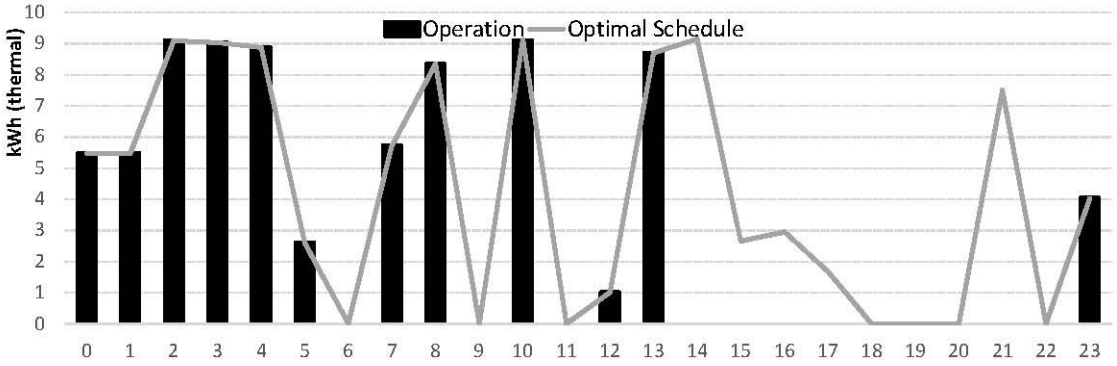
Intraday adjustments of the precomputed schedule take place in 141 of 2160 hours. Thus, the procurement price now is increased significantly to 3.298 ct/kWh. In comparison to the theoretical price with full flexibility this is a deterioration of 22% (see also Table 5). Still, the realized price is below the market mean. But additionally it is to note that the consumption in total is increased in comparison to the operation with perfect foresight assumption. Due to adjustments of mass flow, instantaneous heat supply and subsequent deviations between optimal schedule and operation, now 2864 kWh are consumed, where before 2772 kWh were required.

An example of schedule adjustments due to improperly estimated ambient temperatures is illustrated for 9 March (see Fig. 5a and 5b). Estimations at midnight, which are too low throughout the day, lead to an optimal schedule at midnight, which has to be adjusted from 2 p.m. onwards by heat-supply interruptions.

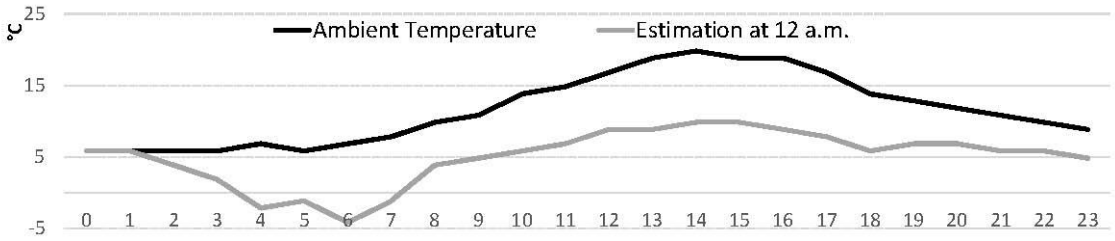
[8] The reason for deviating electricity amounts may be the higher price volatility of intraday prices: Then prices have a relatively deeper impact than ambient temperatures and therefore the achieved COP on average is declined.

	Day-Ahead $[ct/kWh]$	**Intraday** $[ct/kWh]$	**Combined Bidding** $[ct/kWh]$
Market Mean	3.350	3.349	
Theoretical Price	2.709	2.550	
Perfect Foresight	2.791	2.690	2.608
Under Uncertainty	3.298	2.762	2.684

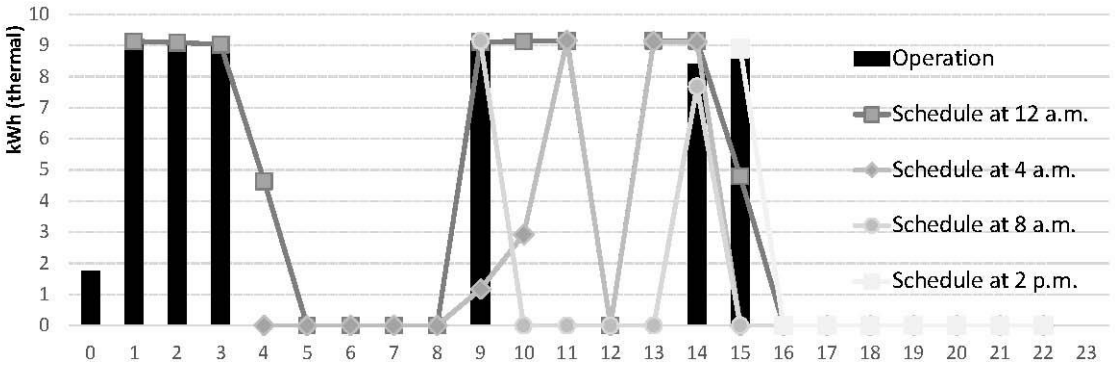
Table 5: Comparison of Prices



(a) Day-Ahead: Optimal Schedule at 12. a.m. to 11 p.m. and Operation



(b) Ambient Temperatures and Estimation at 12 a.m.



(c) Intraday: Optimal Schedules from hour t onwards (scheduled in hour t-1) and Operation

Figure 5: Optimal Schedules for 12 a.m. to 11 p.m. on 9 March and Adjustments

In sum, one cannot stick to the optimal schedule, and the average procurement price deteriorates here significantly compared to the perfect foresight simulation. Planning one day in advance turns out to be a long period for residential heating with myopic weather forecasts as inaccurate estimates lead to violations of given restrictions and

rather bad economic results. Even the numerous adjustment mechanisms cannot guarantee a satisfactory performance within the predefined constraints. Thus, planning in advance is theoretically a good solution, but not practicable in the end - at least in the absence of accurate weather forecasts.

Intraday Market. Waiving the assumption of perfect foresight has less consequences for the case of the intraday-market application. Naturally, the reoptimizing strategy can respond to inaccurate estimates better. The performance for the restricted storage and indoor temperatures is acceptable in this case (ranging from 28.05 °C to 39.0 °C resp. 19.06 °C to 21.64 °C for the full period from January to March). High indoor temperatures are occurring only in three days of March (18th, 20th, 30th), where ambient temperatures are high or relatively high and badly estimated over a period of a few hours. Some adjustments of the mass flow are called and avoid further violations. As an illustration of the intraday performance in comparison to the one of the day-ahead operation, schedules and effective operation are displayed in Fig. 5c also for 9 March. The optimal schedule at 12 a.m. is based on the same weather information as the corresponding day-ahead plan, and is valid for the hours from 1 a.m. onwards. It coincides with the operation (black bars) for the first three time steps, so that the following hourly optimal schedules are omitted in the illustration. Effectively deviating schedules are computed at 4 a.m., 1 p.m. and 2 p.m. as displayed (belonging to the periods beginning at 5 a.m., 2 p.m. resp. 3 p.m.). Updated information on ambient temperatures lead to reductions of supplies scheduled earlier and to rescheduled supply time steps, each the result of new optimal decisions. Previously estimated low ambient temperatures can be corrected and an excess of heat supply avoided, while later on, an earlier heat supply takes into account that following hours (e.g. early morning hours of the next day) are expected to require more heat.

In the end, a procurement price of 2.762 ct/kWh is realized, which is 8% above the theoretical price with full flexibility. Abandoning the perfect foresight assumption, leads therefore to a further deterioration by only 3 percentage points. (For a comparison of prices see also Table 5.)

Total consumption increases again in comparison to the simulation under perfect foresight (2827 kWh instead of 2805 kWh). Yet, consumption as well as procurement price and performance degradate significantly less with uncertain information than in the case of the day-ahead-market application.

Combined Bidding. The combined bidding makes use of the theoretically beneficial day-ahead procurement, which becomes practicable with the additional hourly intraday-market participation.

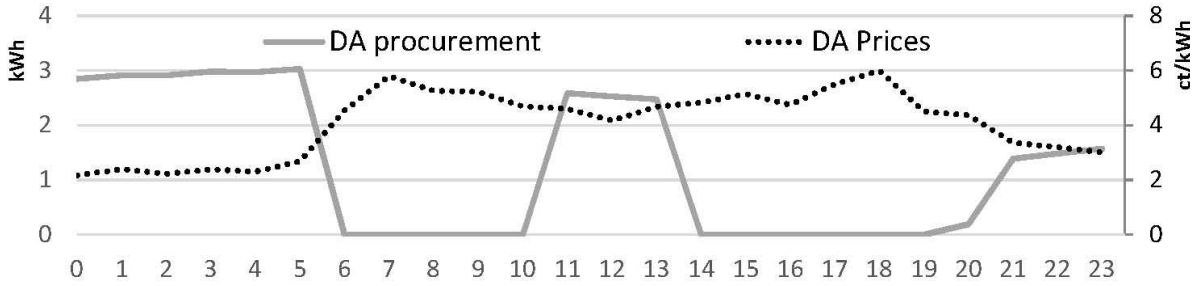
As a result a final procurement price - implying costs and earnings of the day-ahead and the intraday trading - of 2.684 ct/kWh is realized (where the pure intraday participation reached 2.762 ct/kWh).[9] Thus, even the realized price with assumed perfect foresight is outperformed (see Table 5).

Yet, the dual purchasing (and possible reselling) improves the balance on a daily basis not in every case: In 49 out of 90 cases, the final price per kWh is reduced when combined bidding is applied, while the other cases lead to a higher daily price per kWh. As an example with a benefit, the day-ahead (DA) and intraday (ID) tradings on 10 February are illustrated (see Fig. 6a and 6b). In this case, at midnight scheduled and effectively demanded electricity are in total nearly the same, and at the end of the day the combined bidding leads to 37.63 ct cheaper heat supply then the pure intraday procurement. Fig. 6a shows the day-ahead procurement and corresponding day-ahead prices. Fig. 6b displays beside intraday prices of 10 February (dotted line) the effective intraday operation (coinciding with the intraday procurement in case of pure intraday-market application, see grey line) as well as the intraday trading after day-ahead procurement in case of combined bidding (black line). It can be observed that a coincidence of a low day-ahead price and an intraday price peak corresponds to intraday reselling in case of combined bidding (see 3 a.m., 11 a.m., 12 p.m., 1 p.m.), while the pure intraday application simply avoids procurement.

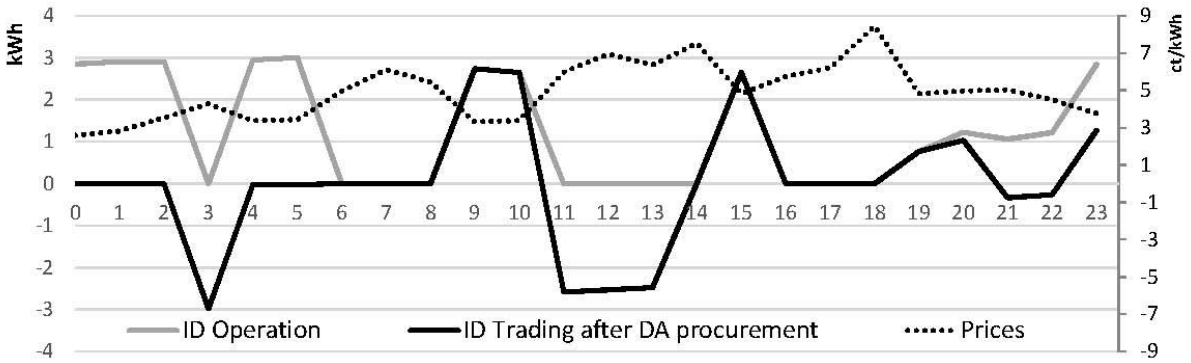
In fact, the main difference between intraday trading and combined bidding is that opportunities to resale electricity are given and thereby procurement is on average cheaper than reselling. Table 6 provides an overview over all combinations of day-ahead (DA) and intraday (ID) prices in a simplified manner. Assuming that a strict price limit is given for the day-ahead trading as well as one for the intraday trading (so that procurement takes place if and only if prices are lower than the mentioned price limit), the table shows operation decisions and their consequences. It turns out that only the cases with `DA Price $\leq$ DA Price Limit' imply changes in comparison to the pure intraday trading. But given this assumption, the first case (`ID Price $\leq$ ID Price Limit') has as result on average neither benefits nor losses. The second case (`DA Price $\leq$ DA Price Limit', `ID Price > ID Price Limit') implies a benefit for one single time step in the

[9] Total consumption or the system's temperature behavior do not change in comparison to pure intraday participation as the effective operation is the same as the one for intraday operation without preceding day-ahead procurement.

most cases.[10] In sum, benefits are more likely than losses and therefore the combined bidding is generally advantageous compared to pure intraday trading.



(a) DA Procurement



(b) ID Operation and ID Procurement

Figure 6: Combined Bidding

	DA Price ≤ DA Price Limit	***DA Price > DA Price Limit***
ID Price ≤ ID Price Limit	*decision to buy DA* *decision to buy ID* *→ effectively no ID procurement* *≫ beneficial if DA price < ID price* *≫ 0 benefit on average*	*decision against buying DA* *decision to buy ID* *→ effectively no ID procurement*
ID Price > ID Price Limit	*decision to buy DA* *decision against buying ID* *→ reselling DA procurement* *≫ beneficial in most cases* *(as DA price is low, ID prrice high)*	*decision against buying DA* *decision against buying ID* *→ no difference to pure ID trading*

Table 6: Combination of Day-Ahead and Intraday Price Levels

[10] Conclusions are valid only if compared procurement amounts are equal and price limits are strict (which is not exactly the case when results are observed in detail). Yet, highlighted tendencies seem to be legitimate. Further more, the conclusion of the likeliness of benefits in the latter described case can be sharpened with tighter assumptions: Assuming additionally that DA and ID price limits are the same, then a profit from procuring and reselling is a fact, and not only more likely, for this time step.

5 Conclusion

This paper analyzes electricity-market participation of residential heat-pump operators as heat appliances (in aggregation) have a high flexibility potential. At the same time, a single operator, who is a private consumer, has strict restrictions and typically less sophisticated prediction tools.

Therefore a system consisting of heat pump, storage tank and building, operating in the context of a market situation is implemented as a MATLAB optimization model. In order to implement a realistic application for this optimization, which allows to modify number, types and parameters of observed participants easily, an agent-based model is used.

In order to investigate the critical issue of uncertain information, various market situations are simulated. Besides the comparison of theoretical perfect foresight situations and realistic error-prone forecasts, the participation in two real markets with different time span between contract and delivery time are modeled. Namely, participations in the short term EPEX Spot markets (day-ahead and intraday) are investigated for January to March 2014. Further on, a combined bidding strategy, which includes both markets, is investigated and resulting average procurement prices are compared.

Results show that a simple participation of residential consumers in day-ahead markets is problematic in terms of practicability. Single small-scale consumers have strict restrictions and limited prediction tools. Thus, uncertainties lead to unsatisfactory results in a market with a daily planning horizon. The day-ahead-market application shows that the operation performance is insufficient in terms of respecting constraints in storage and indoor temperatures as well as in the resulting supply plan. Shorter term decisions with continuously updated information are a feasible alternative, as shown with an intraday-market application under uncertainty.

From an economical point of view, the mean intraday procurement price can be improved with a combined bidding strategy: A day-ahead procurement in advance of an intraday trading according to hourly reoptimized schedules lowers the procurement price from 2.762 ct/kWh to 2.684 ct/kWh. In the end, the combined bidding reaches a better price than the intraday-market participation with assumed perfect forecast. Thus, the critical issue of uncertainties is fully compensated. In contrast, a day-ahead operation under realistic conditions results not only in significantly worsened procurement prices but also fails to respect operational limits

in critical situations. Consequently, our results indicate that a market participation for residential consumers is conceivable only when including the very short term markets.

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