

# Operation of heat pumps for smart grid integrated buildings with thermal energy storage

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## Abstract

A small scale office building consisting of radiant heating, a heat pump, and a water thermal energy storage tank is implemented in an optimal control framework. The optimal control aims to minimize operational electricity costs of the heat pump based on real-time power spot market prices. Optimal control and reference control are compared investigating the operation of heat pumps in a future scenario. Due to enforced implementation of renewable energy generation, future power grids will require optimal control, especially for heat pumps combined with thermal energy storage.

The results of the optimization show that in the future scenario, heat pumps need to operate with high frequencies of ON/OFF switching and should be able to operate efficiently at partial load.

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Keywords: Thermal energy storage; heat pump; optimal control; smart grid; real-time pricing

## 1. Introduction

Buildings can serve to compensate intermittency issues caused by renewable integration [1]. Managing the electrical demand and communicating with the smart grid describe the most important tasks of smart grid integrated buildings [1]. Energy management systems of smart grid integrated buildings actively control electrical and thermal appliances to provide balancing and flexibility services to the grid operator [2,3]. Grid operators apply incentives to the building energy management system to receive direct or indirect demand response (DR) [4]. In this study, we focus on indirect DR, which is based on real-time prices [4]. Typical for real-time prices is a trading process between prosumer (building energy management system) and an electrical spot market [5]. The spot market offers an electricity price scheme for a predicted period. Based on the price offer, the building energy management optimizes the scheduling of set points (optimal control) for electrical and thermal appliances and provides a flexibility service to the grid [6]. The flexibility service indicates the ability to change the electrical demand profile [6].

A possibility to optimize the operations in the building energy management system is the implementation of model-predictive control (MPC) [7]. To provide optimal control input to the MPC, energy management systems include information about the prediction of occupancy, ambient temperature, relative humidity, wind speed, and solar radiation. Besides, the prediction of building dynamics and energy system dynamics create challenges to determine the optimal schedule of electrical and thermal appliances [7].

Building energy systems often consist of thermal energy storage tanks that can be enabled as flexibility sources in buildings using power-to-heat devices [8]. The most promising power-to-heat devices are electrical heat pumps (HPs) that can interact with thermal appliances such as thermal energy storage (TES) systems [3,9].

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This paper investigates the effect of optimal control on the operation of heat pumps. A heat pump, a stratified water tank as TES and radiant heaters are modeled for a small scale office building. Simulations of optimal control based on electricity spot market prices are performed to get a detailed insight into the scheduling of the HP and the TES tank. In contrast to other studies that assume simplified TES models in optimal control [10,11], this study considers the implementation of a more detailed water tank model. This model enables a more accurate investigation of the heating system.

The primary objective of this study is to find out how the results of the optimal control affect the HP operation regarding ON/OFF frequency and partial load behavior. Section 2 presents the models (weather forecasting and occupancy prediction, water tank, HP, building) considered in the optimization framework. Section 3 shows the results of the optimal control and discusses the effect on the HP operation.

## 2. Modeling framework

The modeling framework contains five major blocks, weather forecasting and occupancy prediction, water tank, HP, building, and control and optimization model.

### 2.1. Weather forecasting and occupancy prediction

The weather model uses TMY weather data from DeBilt, the Netherlands. A typical winter day in March is assumed with an average daily temperature of 3.7 °C. The occupancy affects the internal heat gains (lighting, computers, human bodies) of the building. For each floor of the building, the maximum internal gains of 100 W of lighting, 400 W of computers, and 960 W of human bodies are identical to an occupancy probability of 1. The occupancy probability  $\epsilon_t$  also relates to zone temperature set points and is presented for this case study as follows:

$$\epsilon_t = \begin{cases} 0, & T_{zone,set} = 15 \text{ }^{\circ}\text{C}, & t = 0 - 6, 19 - 24 \\ 0.1, & T_{zone,set} = 15 \text{ }^{\circ}\text{C}, & t = 6 - 7 \\ 0.5, & T_{zone,set} = 20 \text{ }^{\circ}\text{C}, & t = 7 - 8, 12 - 13, 18 - 19 \\ > 0.7, & T_{zone,set} = 21.5 \text{ }^{\circ}\text{C}, & t = 8 - 12, 13 - 18 \end{cases}$$

More information about the weather and occupancy model can be found in a previous case study [12].

## 2.2. Water thermal energy storage tank

A stratified water tank of 0.5 m<sup>3</sup> is modeled, which can be seen in figure 1. During the charging, inflow takes place at the top and outflow at the bottom. During the discharging, when heating power is provided to the building, inflow takes place at the bottom and outflow at the top. For charging and discharging, the volume flow is assumed to be constant at 1 m<sup>3</sup>/h.

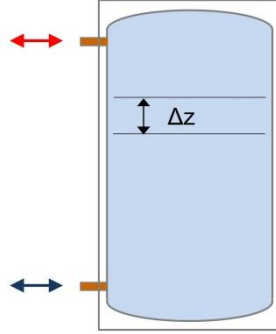


Fig. 1. Design of the stratified water tank including vertical spatial discretization  $\Delta z$ .

The mathematical formulation of the water tank presents a one-dimensional convection-diffusion problem assuming a vertical temperature distribution  $\partial T / \partial z$ . The model calculates convection and diffusion as follows:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} - u \frac{\partial T}{\partial z}, \quad 0 \leq z \leq H, \quad 0 < t \leq t_{max} \quad (1)$$

$$\alpha = \frac{\lambda}{\rho c_p}, \quad (2)$$

with the speed of the water flow  $u$ , the thermal properties  $\alpha$ , the spatial coordinate  $z$ , the height of the tank  $H$ , the time  $t$ , and the maximum time  $t_{max}$ . The simulation solves the convection-diffusion problem numerically using the Crank-Nicolson scheme as finite difference (FD) method. This approach has been used by previous case studies validating the heat and mass transfer dynamics of a water tank [13–15]. To reduce the thermal losses to the environment, insulation material of 0.032 m thickness and 0.033 W/(mK) of thermal conductivity is used for the water tank [16].

## 2.3. Heat pump

The HP model is an interpolation function considering condenser outlet, evaporation inlet temperature, partial load and coefficient of performance (COP) to determine the electricity power consumption and the thermal power. The values are derived from manufacturer data from Dimplex air-water heat pumps as can be seen in figure 2 [17]. The manufacturer data show a maximum thermal output of 20 kW and a maximum condenser outlet temperature of 60 °C. In the simulation, the HP can operate in three different modes, charging the water tank, providing heat to the building, and simultaneously delivering heat to the water tank and the building. Thereby, the condenser outlet temperature determines the inlet temperature of the water tank and the inlet temperature of the radiant heater.

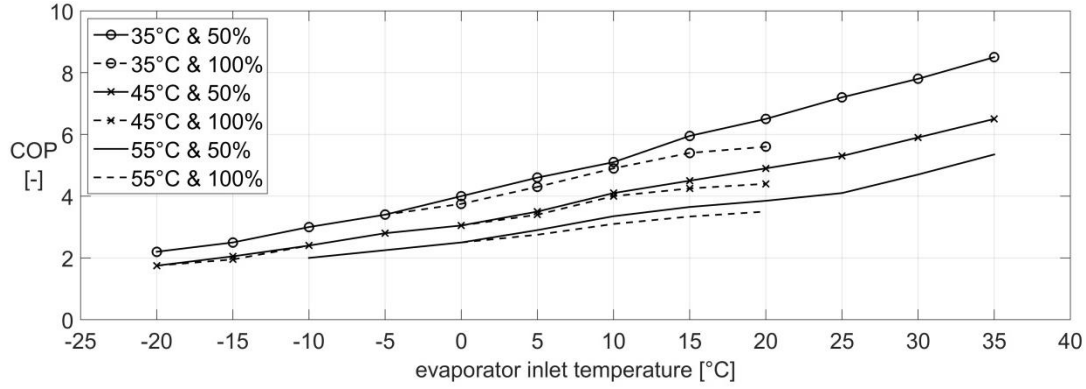


Fig. 2. Performance of the heat pump (HP). The coefficient of performance (COP) is a function of evaporator inlet temperature for different condenser outlet temperatures (35 °C, 45 °C, 55 °C) and different load levels (50 %, 100%) [17].

## 2.4. Building

A small scale office building with two floors and 135 m<sup>2</sup> per floor is modeled (Figure 3). The building elements are constructed of concrete (0.73 W/mK; 921 J/kgK; 1920 kg/m<sup>3</sup>) and external mineral insulation (0.04 W/mK; 830 J/kgK; 90 kg/m<sup>3</sup>) (Table 1) [12]. The building model is an advanced resistance-capacitance (RC) network which includes a thermal model of the building and an external heat flux model representing the heat exchange between the building and the ambient environment [18]. In the thermal model of the building, conduction in walls, convection, and radiation between walls and zones are simulated using constant heat transfer values. In the external heat flux model, internal gains, building system, solar gains, etc. are considered. Solar radiation is included as heat gain to facades, windows and internal building elements such as the zone air and internal walls. The building model was validated in comparison with EnergyPlus [18]. The model can be downloaded from [18] and implemented as Matlab toolbox, namely BRCM (building resistance-capacitance modeling) toolbox. Currently, the building model provides internal gains using constant heat flux per square meter floor area. In this study, a radiant heating system is added to the external heat flux model which takes into account heat exchanger inlet and outlet temperatures and temperature dependent heat transfer coefficients between radiators and zone temperatures.

Table 1. Building structure

Building elements	Materials	Thickness [m]
External wall	Mineral insulation; concrete	0.05; 0.30
Internal wall	Concrete	0.15
Ceiling, Floor	Concrete	0.25

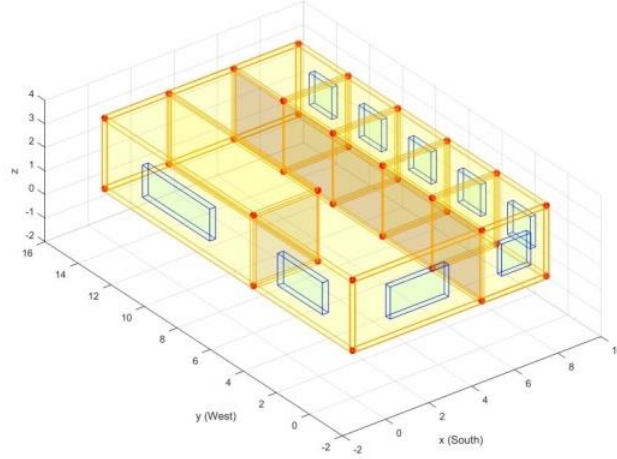


Fig. 3. First level of the small-scale office building model.

### 2.5. Control and optimization

The case study simulates reference control and optimal control. In the reference control, no TES is used and the HP is turned on whenever heating demand is required. In the optimal control, the water tank is combined with the HP to find the optimal path for charging and discharging the storage tank. The scheduling problem takes into account a dynamic optimization of a 24 h planning horizon. The optimization model connects the weather and occupancy forecasting, the water tank, the HP and the building model. The optimization methodology chosen in this case study is dynamic programming (DP) that can include linear and nonlinear models. Based on the work of Bertsekas et al. [19] DP is described as the following:

$$J(x_0) = \min_{\pi} J_{\pi}(x_0) \quad (3)$$

$$J_{\pi}(x_0) = E[g_N(x_N) + \sum_{t=0}^N (x_t, \mu_t(x_t), \varepsilon_t)] \quad (4)$$

$$x_{t+1} = f_t(x_t, u_t, \varepsilon_t), \quad t = 0, \dots, N-1 \quad (5)$$

with  $u_t \in U_t(x_t)$ ,  $\pi = \{\mu_0, \dots, \mu_{N-1}\}$ ,  $u_t = \mu_t(x_t)$ ,  $\mu_t(x_t) \in U_t(x_t) \forall x_t$

where  $f_t$  is the system,  $t$  the discrete time,  $N$  the planning horizon,  $x_t$  the states (storage temperature, zone temperatures, wall temperatures, etc.),  $u_t$  the controls (HP operation, TES charging and discharging),  $U_t$  the control constraints,  $\varepsilon_t$  the random parameter (occupancy probability),  $J(x_0)$  the optimal cost function and  $J_{\pi}(x_0)$  the expected costs with the policy  $\pi$  at  $x_0$ . The policy for the DP accounts for the costs of the electricity power consumption of the HP. This study considers two different real-time price schemes (figure 4) that are taken from the Dutch APX (Amsterdam power exchange) power spot market. The schemes represent regular prices for the heating season excluding taxes.

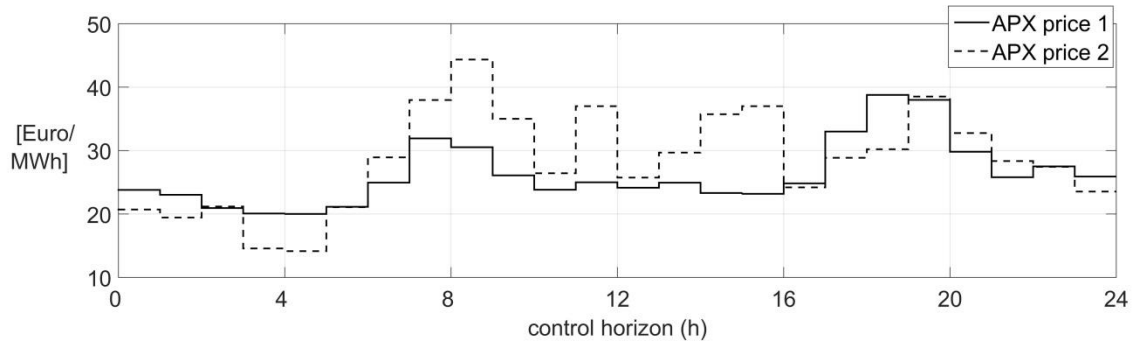


Fig. 4. APX (Amsterdam power exchange) prices from the Dutch power spot market excluding taxes.

### 3. Simulation results

Matlab was chosen as a simulation platform. For the simulation of the HP model, building model and water tank model, a simulation time step of 1 second is used. The simulation time step is chosen to reduce the truncation error of the finite difference scheme applied to the water tank model. For the simulation of the control actions, 15-minute time steps are assumed to keep the start-stop cycles of the HP at a maximum of four times per hour. The simulations are performed for a reference case, optimal control case 1 based on APX price 1 and optimal control case 2 based on APX price 2. The results of the simulations show the scheduling of the TES and the HP (section 3.1) and discuss the HP operation (section 3.2).

#### 3.1. Scheduling of the water tank and the HP

Figure 5 shows the reference control in which the heat pump responds to a feedback control covering the heating demand of the small scale office building. The thermal power of the HP (dark green graph in the upper diagram) is identical to the heating demand of the building (red graph in the upper diagram) because no storage tank is considered in the reference control. As can be seen in figure 5, the zone temperatures (brown graph) always satisfy the comfort temperature (yellow graph). After 24 hours, the zone temperatures decrease to a minimum of 19 °C affected by the wall temperatures of the heavy-weight construction of the office building.

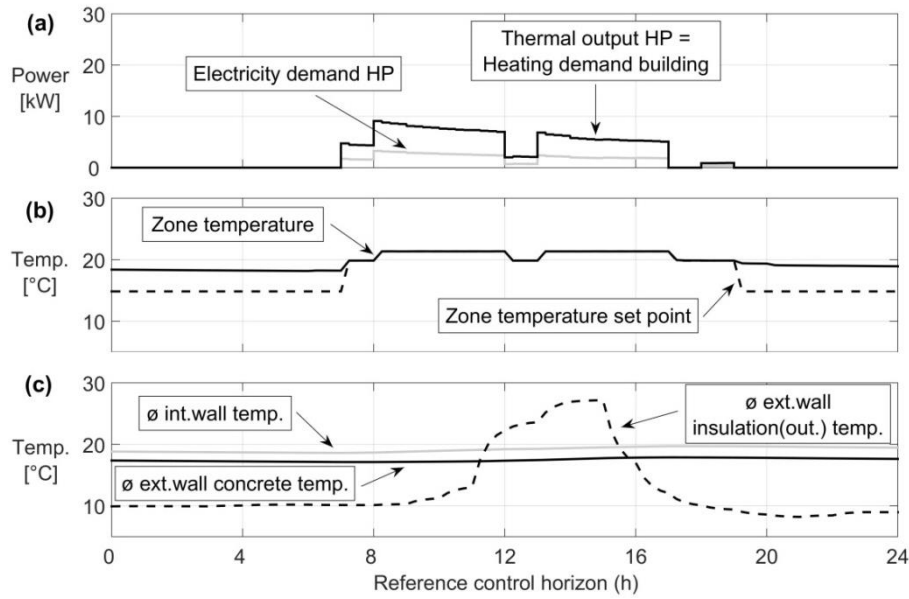


Fig. 5. – Reference case, simulation results; HP covers the heating demand of the building. (a) heating demand of the building, heat transferred from the HP to the building, and power consumption of the HP; (b) average zone temperature and zone temperature set point; (c) average temperature of the insulation at the outer surface of the external walls, average temperature of the concrete at the inner surface of the external walls, average temperature of the concrete of the internal walls.

Figure 6 shows the simulation results for the optimal control case 1. The HP charges the water tank during periods of relatively low electricity prices. The water tank discharges during periods of relatively high electricity prices and provides heating to the building. The optimization results indicate a maximum loading state of 45 % during the 24 h prediction horizon. It is shown that a small price variation between 10.00 and 12.00 can result in significant charging power values. For this period the maximal thermal output of the HP is a limitation of the maximum charging power of the water tank.

Figure 7 shows the simulation results for the optimal control case 2. The water tank reaches the maximum loading state of 54 % at 5 am, which is doubled compared to the results of case 1 as shown in figure 6 at 5 am. This is because the price scheme “APX price 2” gives lower electricity prices between 3 am and 5 am compared to the “APX price 1” scheme. For this charging period, it can be seen in figure 7 that the thermal HP power is a limitation of the charging power.

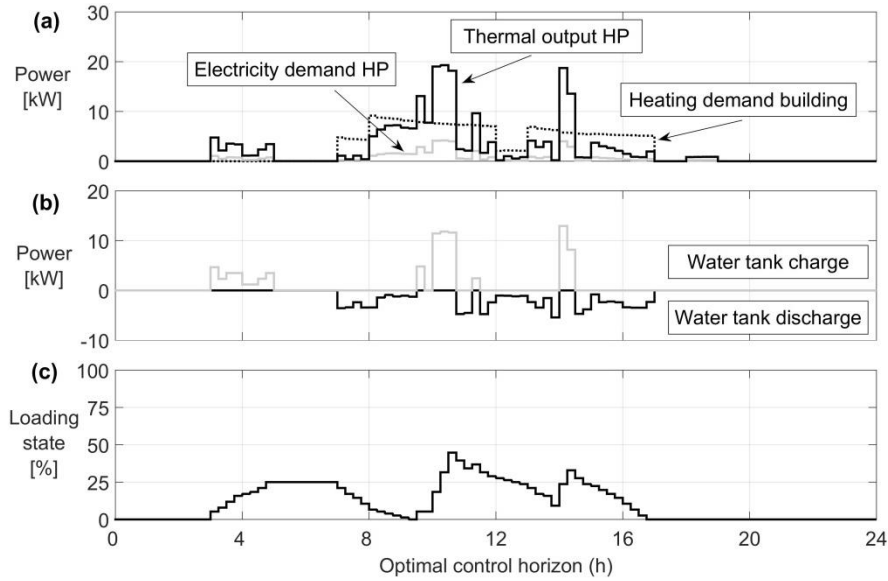


Fig. 6. – Optimal control case 1 using APX price 1, optimization results of the water thermal energy storage; (a) heating demand of the building, heat transferred from the HP to the building, and power consumption of the HP; (b) heat transferred from the water tank to the building (discharging) and heat transferred from the HP to the water tank (charging); (c) loading state of the water tank.

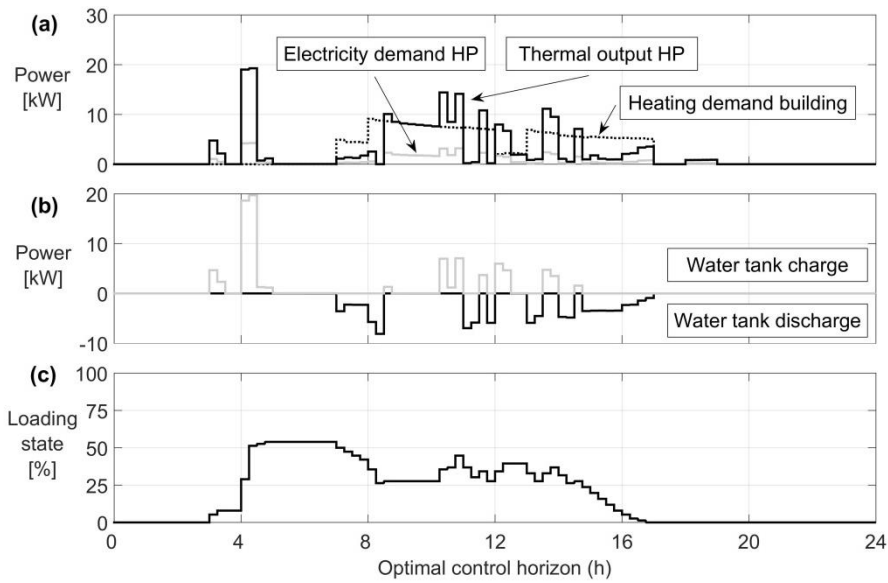


Fig. 7. – Optimal control case 2 using APX price 2, optimization results of the water thermal energy storage; (a) heating demand of the building, heat transferred from the HP to the building, and power consumption of the HP; (b) heat transferred from the water tank to the building (discharging) and heat transferred from the HP to the water tank (charging); (c) loading state of the water tank.

### 3.2. HP operation

The optimal path of the HP includes power consumption, evaporation temperature, condensation temperature, and COP. For the power consumption of the HP, a power profile is calculated for a 24 h prediction horizon. The power profile indicates whether the HP operates in full or partial load providing heating to the building and TES tank. For each control time step of the 24 h prediction period, the power consumption is calculated (Figure 5 and 6). The power consumption can be divided into 0.2 kW steps between the minimum power of 0.2 kW and the maximum power of 4.4 kW. Counting the numbers of control time steps (15 min time steps) for each step of the



power consumption gives the electrical power distribution. Figure 8 shows the power distribution of the HP for the three cases.

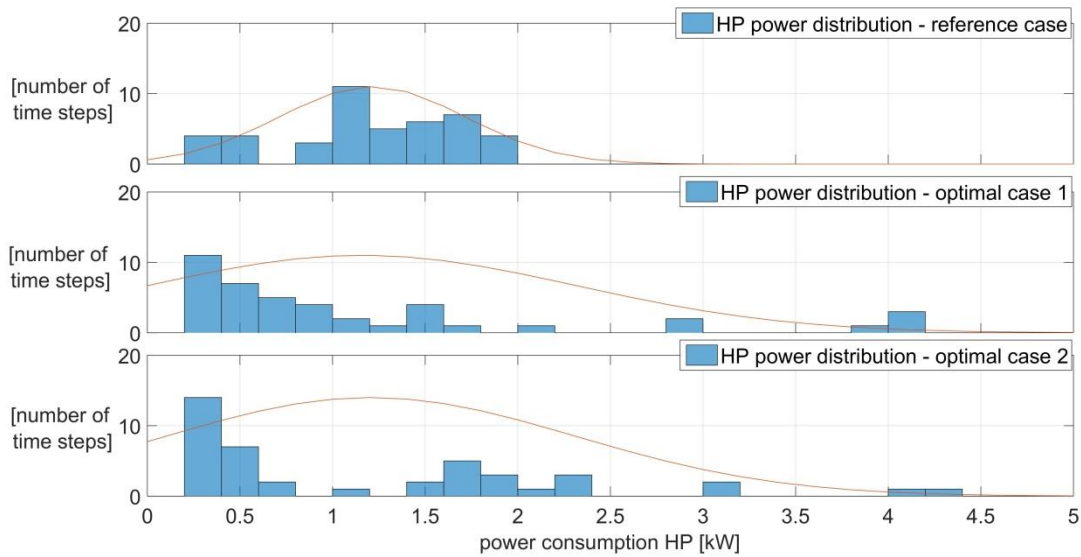


Fig. 8. – Electrical power distribution of the HP based on the results from the reference case (upper diagram), the optimal control case 1 (centered diagram) and the optimal control case 2 (lower diagram). The blue bars show the number of 15 min. control time steps for each power step. The red graphs illustrate the normal distribution of the power consumption.

For the reference case, it can be noted that a maximum of 2 kW of HP power consumption can be sufficient to cover the heating demand of the small scale office building. It is to emphasize that the value of 2 kW of electricity consumption applies for a typical day in March and for a heavy-weight office building with the initial simulation conditions as shown in figure 5. Between the minimum of 0.2 kW and the maximum of 2 kW, the power range of 1-1.2 kW occurs 11 times which means that the HP operates 2 h and 45 min between 1-1.2 kW. Similarly, the normal distribution of the power consumption peaks at 1.2 kW.

For the optimal case 1 and 2, the HP operates between 0.2 and 4.4 kW. The maximum occurs during periods of relatively low electricity prices charging the TES tank. During the operation of the HP, it can be seen that the HP works for the longest period during the day in a power range of 0.2-0.4 kW, 2 h and 45 min for optimal case 1 and 3 h and 30 min for optimal case 2. For both optimal cases the normal distribution peaks at 1.2 kW.

For the three cases, an average COP is listed in Table 2. The COP values marginally vary around 4.5 because the HP primary performs at a lower condenser outlet temperature of about 35 °C.

Table 2. Results of the heat pump operations

Control	ON/OFF times [-]	COP [-]	24h - Costs [€]	24h - Cost savings [%]
Reference feedback control	2	4.57	2.27	-
Optimal control based on APX 1	10	4.55	1.26	44
Optimal control based on APX 2	10	4.47	1.47	35

Table 2 also provides information about the frequency of switching ON/OFF for the HP. It can be seen that optimization of electricity costs (optimal case 1 and 2) results in a five times larger number of turning the HP on and off. Table 2 shows the operational costs of electricity consumption of the HP for the 24 h control horizon. The cost savings realized by the optimal control of the HP are 35 % and 44 %.

#### 4. Discussion

The building model, TES tank model and HP model used in the optimization framework, can represent the typical dynamic behavior of a building equipped with HP and TES tank. For the building model, a radiant heater based on inlet and outlet temperatures was added to the standard BRCM toolbox to simulate the heating system. For the TES tank model, a finite difference approach using a Crank-Nicolson scheme was applied to simulate conduction and diffusion in a stratified water tank that is in a good agreement with previous studies. For the HP model, an interpolation function was implemented to simulate the relation between condenser temperature, evaporator temperature, partial load, COP, and power consumption.

We used dynamic programming that is an effective optimization methodology. By systematically simulating the state space, an optimal solution for scheduling of the TES tank and the HP can always be found. Nevertheless, as the state space or the number of control variables increase, the computational complexity might impede quick optimization results.

Optimal control of the HP reduces the total operational electricity costs. Based on APX prices, 35 % and 44 % of electricity cost savings were realized. It is to emphasize that other financial costs such as lifetime costs, lifecycle costs and maintenance costs for the HP and taxes were not considered. In this study, the main focus was to show how the results of the optimal control using real-time prices affect the HP operation. Using real-time power spot market prices is a common approach to represent real-time pricing for minimizing the total operational electricity costs of an HVAC system that includes HPs. It can be assumed that these prices will have a different profile in the future. Nevertheless, current spot market prices are already affected by the increase of renewable integration which emphasizes the use of this methodology.

#### 5. Conclusion

A conventional feedback control and an optimal control are simulated for a building equipped with HP and TES tank considering 15 minutes of control time steps. The HP can provide heating to a TES tank and the building. By discharging the TES tank heating can also be delivered to the building. Minimizing the total operational costs of electricity usage results in a higher frequency of turning the heat pump ON and OFF. This contradicts to the common requirements of maintaining ON/OFF times of HPs as low as possible. When it comes to the implementation of real-time pricing in real-time control, future heat pumps should be more flexible adapting higher frequencies of ON/OFF times.

As a result from the optimization, real-time prices also affects the power consumption of the HP during operation. At each time step of the 24 h prediction horizon, the power consumption indicates whether the HP performs in partial or full load. The results of the optimal control show that the HP uses the full power spectrum between 0.2 kW and 4.4 kW of electrical power. For the optimal control, the HP operates for a relatively long period during the day at the lower bound of electrical power consumption (0.2 – 0.4 kW). During periods of relatively low electricity prices, the upper bound of the thermal output of the HP restricts the charging power of the TES tank. It can be concluded that future heat pumps should be able to operate efficiently for a wide range of electrical power consumption. Especially if HVAC systems consist of water thermal energy storage tanks, HPs should have flexible and high charging power. However, investments for more flexible HPs must be compensated by electricity cost savings.

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