Demand-Side-Management Potentials for Heat-Pumps in Residential Buildings

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Abstract

The rollout of volatile renewable energies, within the European Union creates a need for flexibility, which in turn can be solved with Demand-Side-Management. Heat pumps in single-family houses can contribute by adapting their consumption towards price signals, boosting the integration of renewable energies at the same time. Studies so far only focus on Nearly-Zero-Energy-Buildings neglecting the potential of buildings with lower energy standard.

This paper illustrates the load shifting potential of two reference-building types by the means of thermal simulation. Therefore, a designed control unit adapts the operation times of the heat pump according to spot market price signals while simultaneously sustaining indoor comfort. The results show remarkable cost reductions achieved by load shifting for both cases. In addition, the approach of this study facilitates the projection of Demand-Side-Management potentials of whole regions.

Introduction

In November 2018, the European Union (EU) intensified their climate targets for 2030 aiming now inter alia for a 32% share of renewable energies related to the final energy consumption (Arias Cañete, 2018). To achieve this goal, capacities of the supply-dependent generators like photovoltaic and wind turbines need a massive rollout. To ensure the security of supply, the exploitation of several flexibilities within the supply chain is eminent. In this matter, the EU indicates significant potential of consumers to interact with energy markets in order to optimize the energy costs and the time of consumption (Demand-Side-Management, DSM). In private households, heat pumps (HP) are supposed to be suitable for DSM strategies (European Commission, 2017).

Furthermore, the guideline for Building Efficiency towards 2030 received an update in July 2018. As it was before, new buildings have to meet the “Nearly-Zero-Energy” Standard the latest by 2021 in the whole EU (European Union, 2018). The modifications are now addressing long-term refurbishment strategies for the existing building stock.

In this context, researchers from Germany, Luxembourg, Belgium and France investigate such DSM strategies for HPs in single-family houses within the INTERREG project “Power-to-Heat for the Greater Regions Renewable Integration and Development“(PTH4GR²ID)

(INTERREG VA, 2019). The idea is to use thermal storage and the inertia of the building in order to displace the HPs operating times while simultaneously sustaining indoor comfort criteria. This flexibility allows for a pooled interaction with short-term electricity markets in order to optimize the end consumer prices and hence allows boosting the integration of renewable energies.

The present work illustrates the above-mentioned strategy by comparing simulated results for two single-family houses that are representative for the future building stock in central Europe. The first building model meets the requirements of a “Nearly-Zero-Energy-Building” (NZEB) while the second meets the minimum refurbishment requirements by the state of Luxembourg. Both houses are equipped with an “air-to-water“-HP.

Method

Control concepts that include DSM strategies usually apply optimisation techniques (Vardakas, Zorba, & Verikoukis, 2015).

In this context, Killian and Kozek (2018) present an approach to optimally operate a low energy office building using a fuzzy model predictive controller (FMPC). Hereby, the FMPC achieves higher comfort and reduced costs compared to a rule based controller. A state-space model of order five is used to describe the building mathematically.

Robillart et al. (2018) apply a time-continuous optimisation method to develop a real time controller able to deploy heating power in a cost efficient way. The building energy software COMFIE was used to obtain the thermal model of a residential passive house. To enable a fast convergence of the optimisation algorithm, the balanced truncation method is applied to reduce the building’s model complexity.

The flexibility of residential floor heating systems in two residential NZEBs is investigated by Vandermeulen et al. (2017). The simulation setup foresees a coupling between Modelica and Matlab. In this context, Modelica is used to emulate the NZEB buildings, whereas Matlab determines the optimal control strategy of an “air-to-water” HP using a mixed integer linear programming (MILP) approach. The simulation does not foresee a thermal energy storage to buffer space heating energy.

The present work analyses the DSM potentials by means of thermal simulation, by coupling the software TRNSYS (University of Wisconsin, 2019) with a predictive

controller written in Matlab (MathWorks, 2019). While NZEB are pre-designed for DSM concepts because of their high thermal inertia, their impact on the renewable integration is today still limited since the total energy consumption is quite low and NZEBs represent just a small share of the total building stock. One question that arises is: How suitable is the DSM concept for the existing building stock that also in the future will rarely reach NZEB standards? Because HPs are not suitable for non-insulated buildings, generally at least a mid-level energy standard is required. In fact, HPs are mostly used either in new buildings or in refurbished buildings.

A direct comparison of these two building types with a standard simulation, applying a non-flexible regulation strategy, allows evaluating the suitability for DSM in terms of energy costs and energy efficiency. The applied heating system in the simulation represents common implementations.

Currently there are no flexible electricity price tariffs for HPs (besides Day and Night ones), allowing DSM strategies for the renewable integration. If and when flexible electricity tariffs apply, the HP can adjust its behavior according to price signals. The most liquid market DSM can address is the Day-Ahead market of the EPEX Spot that operates in central Europe (EpeX Spot, 2019). Lower electricity prices are supposed to be an indicator for a high market share of renewable energies considering that their variable costs are the least. A DSM adaption based on these market prices therefore helps the integration of renewable energies, especially when these prepossess a more dominant role and temporary surpluses and shortages of the electricity production become habitual. The study uses historical market data of 2017 that for future applications is supposed to be replaceable by forecasts.

Reference Buildings

Nearly-Zero-Energy-Building

The first reference building represents a NZEB conform to the EU requests for new residential houses. The heated floor area is 173.5 m². The heat transmission coefficients of the building envelope are shown in Table 1 (Lichtmeß and Viktor (2014))

Table 1 Coefficients of heat transmission for the NZEB

Component	U-Value
External Wall	0.12 W/m ² K
Roof	0.10 W/m ² K
Floor	0.14 W/m ² K
Windows	0.62 W/m ² K

The building is a medium heavy construction and has an effective heat storage capacity C_{eff} of 15.6 kWh/K (90 Wh/m²K, DIN 18599) leading to a time constant τ of 161 h. A ventilation system with heat recovery (85% efficiency) provides a constant air exchange rate. The building envelope is designed using SketchUp and then

imported into TRNSYS. The building is divided into four thermal zones for the sake of better accuracy.

Refurbished Building

The second reference building (hereafter referred to as RB) represents the existing stock refurbished in line with the minimum standards in terms of heat transfer coefficients of the building envelope, by the State of Luxembourg (Grand Duchy of Luxembourg, 2016). The corresponding heat transmission coefficients are shown in Table 2.

Table 2 Coefficients of heat transmission for the RB

Component	U-Value
External Wall	0.32 W/m ² K
Roof	0.20 W/m ² K
Floor	0.32 W/m ² K
Windows	1.34 W/m ² K

Since these parameters result from EU guidelines, there is a consistency to other EU state regulations with similar climate zones. The heated floor area of 190 m² is divided into four thermal zones. The construction type is medium heavy as well, leading to a C_{eff} of 17.1 kWh/K and a τ of 60 h. The air exchange rates are the same as for the NZEB but with only one but important difference, that there is no heat recovery in operation.

TRNSYS Model

The simulations are carried out using the software TRNSYS. The reference buildings are equipped with air-to-water HPs heating a thermal energy storage (TES) unit as shown in Figure 1. The HP operates according to a performance diagram of a real HP. At the operating point A2/W35, the thermal output is 5 kW while the electricity input is 1.32 kW. For the RB, the HP performances are scaled by the factor two in order to facilitate the comparison.

Figure 1: Scheme of the heating system in TRNSYS

HP systems usually have small TES units to extend the operation interval. At the same time, the TES allows a certain flexibility between heat consumption and heat production, providing the flexibility required for DSM. In this study, the TES is kept rather small (200 l insulated water tank for NZEB, 400 l for the RB) to simulate a closer approximation to existing heating systems. The

heating circuit has four loops, each supplying a floor heating system (FHS) that is communicating with one thermal zone of the building. The thermostats in the zones regulate the room temperatures around 21°C. ISO 7730 indicates operative indoor temperatures between 20°C and 24°C during the heating period as a necessity for thermal comfort. This paper regards the air temperatures of the simulation and considers these below 20°C as discomfort that needs to be avoided. Internal gains caused by occupation are taken into account according to a three-person household. The flow temperature of the heating circuit is adjusted according to the outside temperatures by mixing it with the return flow. The simulation uses real weather data from the city of Luxembourg for the year 2017.

While in the Standard Simulation, the HP receives control signals depending on a fixed temperature hysteresis in the storage tank, for the optimization process, an extension of this temperature band helps gaining flexibility for taking advantage of varying electricity prices. The maximum temperature allowed in the storage tank is 55°C, the minimum temperature in each time step is the desired flow temperature, which depends on the outside temperature. The simulation uses historical price data from central Europe's energy day ahead market (EPEX Spot) of 2017 to demonstrate the impact of the optimization.

For the optimization, TRNSYS is interfaced with the MILP model written in Matlab. This program receives several parameters from TRNSYS as input describing the system, such as the TES dimensions or the heating load curve of the building. The predicted heat demand is essential for the controller's accuracy. In case of an underestimation, the temperatures in the TES can drop below the desired heating temperatures, resulting in discomfort in the thermal zones. In the opposite event, if the TES temperatures are higher than necessary, the HP's efficiency decreases resulting in higher costs. The present work uses simulation results to create a simplified heat demand curve. Although the precision of the results is good enough to demonstrate the DSM concept, the authors are convinced to improve the controller's accuracy by using a different approach. Model predictive controls often use accurate climate data to predict every possible influence on the heating system such as exact solar radiation gains. While this approach leads to good results in theory, it is eminent for practice applications to react to deviations such as forecast discrepancies or the influence of unexpected user behavior. Thus, a generic approach with the integration of disturbances might be a better concept for real life applications.

The controller uses the system inputs, weather data and market data in order to create a forecast of the best heating strategy for the next 12h, giving control signals to the HP as output. The time interval of one signal is 10 min, so in one hour the HP receives six signals. After one hour, the controller takes the TES temperatures as feedback in order to recalculate the optimization for the next 12h. The simulation is then carried out over the entire heating period (01.Jan-30.April and 01.Oct.-31.Dec.).

Mixed Integer Linear Programming Model

The following sub-chapters present the mathematical modelling for each component used in the controller, to determine the optimal scheduling.

Air-To-Water Heat Pump Model

The electricity input and thermal output of the HP is computed as a function of the primary and secondary side temperature.

The electrical and thermal characteristics of the HP are described with commercially available performance data (Viessmann, 2018). The HP's performance maps contain information for the flow temperatures 35°C, 45°C and 55°C in reference to outdoor temperatures between -15°C and 20°C. Performance characteristics for flow temperatures beneath 35°C are set to those of 35°C, so that in total, four sampling points are used to describe the HP's electrical input $\dot{P}_{HP,t}$ and thermal output $\dot{Q}_{HP,t}$ during every time step t .

Values lying in between the sampling points are determined through linear interpolation. To do so, positive weights $\lambda_{i,t}$ are used for each sampling point. The sum of these weights is equivalent to the binary commitment status $S_{HP,t}$ of the HP for each time step.

$$S_{HP,t} = \lambda_{1,t} + \lambda_{2,t} + \lambda_{3,t} + \lambda_{4,t} \quad (1)$$

The weights are further computed, using the top layer temperature $T_{TES,t,1}$ of the thermal energy storage (TES), the maximum possible temperature of the TES $T_{TES,max}$ and the surrounding temperature of the TES $T_{TES,surr}$. The following equation is used to ensure that the HP's flow temperature is superior to the first layer temperature of the TES for $S_{HP,t}=1$.

$$T_{TES,t,1} - (1 - S_{HP,t}) \cdot T_{TES,max} \leq \lambda_{1,t} \cdot T_{TES,surr} + \lambda_{2,t} \cdot 35 + \lambda_{3,t} \cdot 45 + \lambda_{4,t} \cdot 55 \quad (2)$$

Furthermore, special ordered set 2 (SOS2) are used for all weights, to ensure that at most two adjacent weights are unequal to zero (Williams, 2013).

The electricity input and thermal output of the HP are finally computed using equation (3) and (4), with $\dot{Q}_i$ and $\dot{P}_i$ being the performance at a given sampling point. The positive weights $\lambda_{i,t}$ are applied to enable operating points of the HP, which occur between the sampling points $\dot{Q}_i$ and $\dot{P}_i$.

$$\dot{Q}_{HP,t} = \lambda_{1,t} \cdot \dot{Q}_{35} + \lambda_{2,t} \cdot \dot{Q}_{35} + \lambda_{3,t} \cdot \dot{Q}_{45} + \lambda_{4,t} \cdot \dot{Q}_{55} \quad (3)$$

$$\dot{P}_{HP,t} = \lambda_{1,t} \cdot \dot{P}_{35} + \lambda_{2,t} \cdot \dot{P}_{35} + \lambda_{3,t} \cdot \dot{P}_{45} + \lambda_{4,t} \cdot \dot{P}_{55} \quad (4)$$

Thermal Energy Storage Model

Thermal energy storage units are generally modelled as either perfectly stirred or perfectly stratified. This work applies a perfectly stratified TES with three layers. Each layer l has a specific height and volume and is bound to a lower and upper temperature threshold $T_{TES,surr}$ and $T_{TES,max}$ respectively. Due to the fact that the operating condition of the HP is described with a binary variable, every interaction resulting in a multiplication between the HP mass flow $S_{hp,t} \cdot \dot{m}_{L,nom}$ and given layer temperature $T_{TES,t,l}$, leads to non-linearities, which are circumvented with the following approach.

$$S_{HP,t} \cdot T_{TES,surr} \leq \vartheta_{TES,t,l} \leq S_{HP,t} \cdot T_{TES,max} \quad (5)$$

$$(1 - S_{HP,t}) \cdot T_{TES,surr} \leq T_{TES,t,l} - \vartheta_{TES,t,l} \leq (1 - S_{HP,t}) \cdot T_{TES,max} \quad (6)$$

Equation (5) says that the auxiliary temperature $\vartheta_{TES,t,l}$ equals zero when the HP is off, while equation (6) ensures that $\vartheta_{TES,t,l}$ equals $T_{TES,t,l}$ if the HP is switched on. The thermal power coupling between the HP and the TES is realized using equation (7) with c being the thermal capacity of the fluid.

$$\dot{Q}_{HP,t} = \dot{m}_{L,nom} \cdot c \cdot (\vartheta_{L,out} - \vartheta_{TES,t,l}) \quad (7)$$

During the time increment Δt , the energy balance of each layer with the mass $m_{TES,l}$ is established using convective heat transfer $\dot{Q}_{conv,t,l}$, laminar conductive heat transfer $\dot{Q}_{cond,t,l}$ and conductive heat losses $\dot{Q}_{losses,t,l}$.

$$m_{TES,l} \cdot c \cdot (T_{TES,t,l} - T_{TES,t,l})/\Delta t = \dot{Q}_{conv,t,l} + \dot{Q}_{cond,t,l} - \dot{Q}_{losses,t,l} \quad (8)$$

A more elaborate MILP-formulation of the convective and conductive heat transfer mechanisms can be found in (Schütz, Harb, Streblow, & Müller, 2015).

The thermal demand of the building $\dot{Q}_{SH,t}$ is covered by a floor heating system. The massflow within the SH circuit at a given time step is $\dot{m}_{sh,t}$. The flow temperature is equivalent to the TES top layer temperature $T_{TES,t,1}$. The return flow temperature $T_{sh,out,t}$ of the SH circuit is finally calculated with equation (9).

$$\dot{Q}_{SH,t} = \dot{m}_{sh,t} \cdot c \cdot (T_{TES,t,1} - T_{sh,out,t}) \quad (9)$$

The first layer of the TES is subject to further temperature constraints:

$$T_{HC,t} \cdot sh_t + T_{TES,surr} \cdot (1 - sh_t) \leq T_{TES,t,1} \leq T_{TES,max} \quad (10)$$

The binary variable sh_t indicates a demand for space heating at a given time step. If $sh_t = 1$, the top layer of the TES has to be greater than or equal to the heating curve temperature $T_{HC,t}$.

Objective Function

The objective of the optimization consists in minimizing the total cost over a certain scheduling horizon. The costs stem from the HPs electricity consumption. The objective to be minimized is given in equation (11) with $p_{elec,t}$ the electricity spot market price at a given time step.

$$\text{Min}(\sum p_{elec,t} \cdot \dot{P}_{HP,t} \cdot \Delta t) \quad (11)$$

Co-Simulation Interface

The aforementioned MILP-model is applied to compute the optimal scheduling for a time frame of 12 hours. The scheduling horizon is discretized into intervals of 10 minutes, which results in 72 time steps in total. The scheduling horizon is recalculated on hourly basis. The optimization is carried out with Gurobi 8.1 and the Matlab toolbox Yalmip (Efberg, 2004).

The dataflow between TRNSYS and Matlab is displayed in Figure 2. TRNSYS communicates a 12-hour weather and electricity price forecast to Matlab/Gurobi. At the beginning of each scheduling horizon, TRNSYS provides the starting temperatures for the MILP TES layer temperatures. The heating load forecast is based on a heat demand curve. Matlab/Gurobi computes the HPs control signals and communicates them to TRNSYS.

Figure 2: Dataflow between Matlab/Gurobi and TRNSYS

Results

Nearly-Zero-Energy-Building

In the Standard Simulation, the heat demand of the NZEB is 21 kWh_{th}/m²a. As shown in Figure 3, the electricity costs for the HP over the heating period are 43.89 € (3.76 Ct/kWh_{el}). These costs however just represent the direct acquisition costs on the spot market. End consumer prices in the EU also include interest margin, grid fees as well as taxes and contributions that differ in each country.

Figure 3: Comparison of the Standard Simulation and the Controller Simulation of the NZEB

With the DSM controller, these costs decrease by 11.4 %. The average price per kWh is reduced to 3.28 Ct/kWh_{el}. The electricity consumption of the HP increases by 1.4 % because the controller allows higher temperatures in the storage tank, leading to HP performance losses and heat losses of the tank itself. Since the minimum temperatures in the TES are equal to the desired flow temperatures, the controller also allows lower temperatures than the fixed hysteresis of the Standard Simulation, leading to energy savings. Figure 4 displays the temperature profile of two thermal zones for the two coldest months of the simulation, showing that both simulations only have one very short period of discomfort for one zone due to outdoor temperatures of -11°C.

Figure 4 Room temperatures of the NZEB simulations

The temperatures in the controller simulation are almost identical, illustrating that the desired flow temperatures were reached. Therefore the controller does not lead to any discomfort.

Refurbished Building

In the Standard Simulation, the RB has a heat demand of $109 \text{ kWh}_{\text{th}}/\text{m}^2\text{a}$. The electricity costs for the HP over the heating period are 210.51 € which corresponds to $3.72 \text{ Ct/kWh}_{\text{el}}$ (Figure 3). With the DSM controller, the costs decrease by 10.9%. The average price reduces to $3.56 \text{ Ct/kWh}_{\text{el}}$.

Figure 5 shows that also for the RB the comfort criterias were predominantly met, except for times with very low outside temperatures. The total hours of discomfort hardly increase due to the controller.

Figure 5 Room temperatures of the RB simulations

Forecast discrepancies for the heat demand of the building can cause TES temperatures below the desired flow temperatures. These temporal mistakes are mostly compensated by the inertia of the floor heating system and the building envelope. Nevertheless one conclusion is, that with decreasing inertia, the requirement for an accurate heat demand forecast increases.

Displacement of operating hours

The cost reduction implies that the controller manages to shift operating intervals of the HP towards times with

lower electricity prices. Figure 6 illustrates its functionality by showing how the HP avoids high price periods. The first graph displays the TES temperature in the upper layer, the second part of the diagram shows when the controller sends a run signal to the HP. The diagram on the bottom indicates the electricity prices the controller reacts on.

Figure 6: TES temperature, control signals and electricity prices for one day (NZEB)

The functionality is clarified further, when the analysis is extended over the entire heating period. For this purpose, the 24 hours of each simulation day are classified in six four-hour price levels, the four most expensive intervals being summarized in Level 1 and the lowest price intervals being in Level 6. In the next step, the relative amounts of the HP operation intervals (10 min) related to the total amount of operation intervals for the Standard Simulation and the simulation with the controller are allocated to these categories. The sum over the entire heating period then leads to the results in Figure 7.

Figure 7: Shift of operation intervals achieved by the controller

For the NZEB, the shift of operation intervals from high prices to low prices is evident. The relative use of the lowest prices increases by 7.8% while the relative use of the highest prices decreases by 4.5%. The total amount of operating intervals in Level 1 decreases by 35% compared to the Standard Simulation while the ones in Level 6 increase by 32%. This illustrates, that the NZEB

facilitates an efficient displacement of HP operation intervals.

In direct comparison, the RB shows the same effect but due to the higher energy demand, the shift between the different levels is only possible to a lesser extend. The price intervals as shown in Figure 6 rarely have abrupt rises and decreases. By consequence, the shift of operation intervals is less visible in Figure 7 because it mostly happens between adjacent price intervals that nevertheless lead to the savings displayed in Figure 3. The total amount of operating intervals in Level 1 decreases by 9% while the ones in Level 6 increase by 4%. For both building types, the flexibility potential will increase if TES tanks with a higher capacity are applied.

Interpretation

The suitability of NZEBs for DSM is confirmed. Their high thermal inertia and the low energy demand allows a cost effective displacement of the HP operating hours. In this case study, the applied controller already saves 11.4% of the energy acquisition costs on the spot market due to flexible consumption. The rather small size of the TES does not allow exploiting further saving potentials. The physical storage capacity is limited, so temperatures in the tank rise fast, forcing the HP to run in less efficient operating points while trying to take advantage of price signals. This leads to higher electricity consumption and therefore counteracts the savings. Nevertheless, the designed heating system that represents current applications already shows significant potential for DSM. The controller successfully manages to diminish the use of the price peaks.

Since DSM decreases the need for other energy storage alternatives, its efficiency needs to be competitive towards these options. In comparison to a battery storage (efficiency 90-97% (Zapf, 2017)), the overconsumption of 1.4% caused by DSM is reasonable but as mentioned before, higher TES capacities will even reduce the overconsumption and therefore improve the energy efficiency. However, the cost savings over time must be further investigated.

In comparison, the RB saves 10.9% in relation to the Standard Simulation. The controller also manages to avoid price peaks but to a much lesser amount since its higher energy demand in combination with the limited TES capacity does not allow to avoid high price periods that hold up for several hours. The absolute cost savings are with 23 € a lot higher compared to the NZEB (5 €) as the absolute energy costs are higher as well. Since the flexibility of the RB is relatively lower, the application of TES tanks with larger capacities must be further investigated in order to exploit the energy shifting potentials.

Projection of DSM Potentials

The case study shows that not just the NZEB but also buildings refurbished to a certain energy standard, and equipped with HPs can contribute to the integration of renewable energies by DSM. In order to determine a full potential for DSM of a region, an analysis of the building stock is necessary. In Luxembourg for example, the

number of single-family-houses that correspond to the reference buildings of this case study is round about 20.000 in 2017 (ca. 17 % of the residential building stock) (Klein & Peltier, 2017). If the concept applies to all these buildings, an installed HP capacity of ca. 150 MW_{el} is available for DSM. These HPs are then capable of avoiding the price peaks as shown in this case study. Due to population growth and by consequence a high demand in new residential buildings, the number of suitable buildings will increase to ca. 63.000 in 2030 (Haas & Peltier, 2017). By consequence, the overall potential for DSM will rise to ca. 450 MW_{el}. In relation to the predicted peak demands of 950 MW_{el}-1.300 MW_{el} in the public electrical grid of Luxembourg, DSM can have a significant impact (Creos, 2018). In reality, these potentials of course will not be fully available since for example not every building will be equipped with a HP. To refine these potential estimations, data on the market share of HP systems is gathered in order to define trend scenarios. Similar lines of thinking allow calculating DSM potentials for other regions in central Europe.

Conclusion and Outlook

The present work illustrates that HPs in single-family-houses can contribute to the integration of renewable energies by adapting their consumption based on external signals like price changes for instance, without compromising on indoor comfort. While several studies already identified the suitability of NZEB for DSM, it is shown here, that not optimal insulated buildings have significant DSM potentials as well.

Further studies regarding the subject of HP DSM will focus on improving the results. One task is to improve the controller, mainly by the design of accurate heating load forecasts so that it is easily applicable to any building. Another important task is then to find the optimized dimensions for TES systems that use the DSM strategy based on several criteria like economic feasibility, investment costs, energy efficiency and renewable integration. In combination with larger TES capacities, the optimization horizon is extendable as well.

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