Demand response optimized heat pump control for service sector buildings

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SPECIAL ISSUE PAPER

Demand response optimized heat pump control for service sector buildings

A modular framework for simulation and building operation

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Abstract With an increasing amount of volatile renewable electrical energy, the balancing of demand and supply becomes more and more demanding. Demand response is one of the emerging tools in this new landscape. Targeting service sector buildings, we investigated a tariff driven demand response model as a means to shave electrical peak loads and thus reducing grid balancing energy. In this paper is presented a software framework for load shifting which uses a tariff signal for the electric energy as minimization target. The framework can be used both on top of an existing building management system to shift heat generation towards low-tariff times, as well as to simulate load shifting for different buildings, heat pumps and storage configurations. Its modular architecture allows us to easily replace optimizers, weather data providers or building management system adapters. Our results show that even with the current TOU tariff system, up to 34 % of cost savings and up to 20 % reduction in energy consumption can be achieved. With Sub-MPC, a modified MPC optimizer, we could reduce computing times by a factor 50, while only slightly affecting the quality of the optimization.

Keywords ICT in buildings and housing · Building energy operating systems · Heating devices and energy networks · Demand response · Dynamic electricity prices · Load shifting · Simulation · Building automation

1 Introduction

In the wake of the COP21 conference in Paris, profound changes in the electricity production market are expected [1]. The driving force for these changes is the increasing share of renewable energies mostly depending on weather conditions. It opens numerous questions about the electric grid stability, matching production to demand, energy storage solutions and energy efficiency. The electricity systems in developed countries worldwide are transforming towards a more decentralized power generation with a growing share of renewable sources with fluctuating production levels as shown in [2]. Given the traditional centralized power generation regime, also grid stability and security of supply are in the responsibility of transmission system operators (TSO) like Swissgrid and distribution system operators (DSO), which try to cut peaks and minimize balancing energy by using load clipping and direct load control (DLC, i.e. remotely switching off loads during peak demand periods, as in [3–6]). As the production becomes more and more decentralized now and in future, the decentralized response to the electricity demand—known as demand response (DR)—through non-static energy tariff signals emerges to be a valuable instrument to achieve self-stabilizing energy grids (e.g. [7]).

Demand response has been investigated in various studies and projects for residential buildings (e.g. [6,8–10]) and industrial facilities (e.g. [5,11,12]). They have shown that DR needs to be supported by automation to yield sustainable results. However, for residential buildings in Switzerland, penetration with building automation systems and smart meter infrastructure is still low. In contrast, the majority of service sector buildings (SSB), e.g. office buildings, schools or shopping centres, are equipped with building management systems (BMS) as well as smart meters already today. Additionally, the thermal heating of SSB represents a substantial

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part of the SSBs' integral energy consumption. If produced by a heat pump, it becomes an electrical load highly flexible in time and therefore suitable to load shifting (LS) [13]. But there is almost no research available about this building type. To fill that gap, we focus in this paper on commercial buildings equipped with heat pumps for heating.

While a lot of demand response research is already published [14–16], very little [17] has arrived on the market in real buildings. Here, iHomeLab specifically addresses this shortcoming: In order to push towards the deployment of such technologies, we have developed a framework as an extension to industrial level BMS (using BACnet) that adds LS capabilities. The framework is able to carry out simulations for LS optimization before its operation in real buildings. This dual use approach is expected to cut development costs and lowering failure risks in the transition from simulation to real building operation, thus targeting a major step towards integration.

In this paper, we present our framework and use its simulation mode to demonstrate the effectiveness on LS for different SSB building types, tariff systems and optimization approaches. To promote demand response, the framework relies on different modular optimization strategies. Focusing our DR optimization strategy on supplying the right amount of heating energy to the building, we are able to use a simplified energy consumption model of SSBs which is fairly easy to configure. To enable LS, the following system parameters are taken into account: tariff regimes, weather conditions, building occupancy, heat generation capabilities (including storage), building characteristics, and user comfort.

2 Framework

2.1 Scope overview

Our work focuses on SSB that are already equipped with a BMS. The developed framework is designed to be used both for simulation of electrical load shifting and for enhancing the existing BMS in this respect. It does not replace the BMS or part of its control, but rather sits as an extension "on top" of it. By solely optimizing the way the heat storage is filled and managed, all consumers of heat in the building continue to work under the regime of the BMS, being oblivious to the change. The framework achieves electrical load shifting purely by minimizing energy costs, without any further external control signals.

As a basis for decisions, a tariff signal for the electrical energy is used. By setting tariffs, the provider can influence the system, but has no direct control over it. This is a paradigm change from a centrally controlled system to a decentral, incentive-based system. Its cost effectiveness depends heavily on the shape and characteristics of the chosen tariff system. Therefore, iHomeLab has compared different tariff signals, see Fig. 2. However, a tariff signal to trigger load shifting is not the only approach. Peak limitation, maximization of own PV consumption, avoiding or maximizing consumption in specific time slots, etc. are other possible optimization targets that could easily be achieved due to the framework's modular setup.

In our approach, the operation of the heat pump and the heat storage tank are optimized. Details about distributing the heat in the building are left to the BMS. The building is treated as a whole, i.e. modelled as a single room that summarizes the properties of the building. By doing so, our system can be customized for a specific building with fewer parameters than other approaches and therefore with a shorter set-up time than other optimizing systems.

2.2 Implementation

The core part of the framework is programmed in Java. To achieve a very loose coupling of its parts, all modules can be started separately, reading their input from and writing their output to JSON files. For the optimizers and for the building simulation, MATLAB/Simulink [18] is used: The Java module prepares the input files, and then calls MATLAB scripts via the MATLAB production server. The MATLAB scripts read the JSON input, execute and store their output again as JSON files. To speed up execution, the MATLAB production server is kept alive between calls in simulation mode.

In detail, the framework consists of the following modules as shown in Fig. 1:

- *WeatherReader* Checks if there is a new weather forecast available, and if so, loads it from the FTP server of e.g. MeteoSwiss, converts it into our JSON format and stores it locally.
- *TariffReader* Same as WeatherReader, but for tariffs. As there is not yet a tariff signal for Switzerland available online, we read the tariff from a file in a format that has been provided by Swissgrid.
- *BuildingReader* This module is used only when controlling a real building. It reads values such as temperatures or schedules from a BMS and stores them in our JSON format. We have implemented a concrete implementation for the Siemens Desigo BMS, reading values from BACnet objects via a local OPC server. Therefore it could be easily adapted to other BMS that are based on BACnet.
- *BuildingWriter* Also this module is only used for a real building. It sends values such as set-point temperatures or heat pump switching signals to the BMS. Like the BuildingReader, it communicates via the OPC server using BACnet objects.
- *SimulatedBuildingWrapper* This module is used only in case of a simulation. It collects all the input for the simu-

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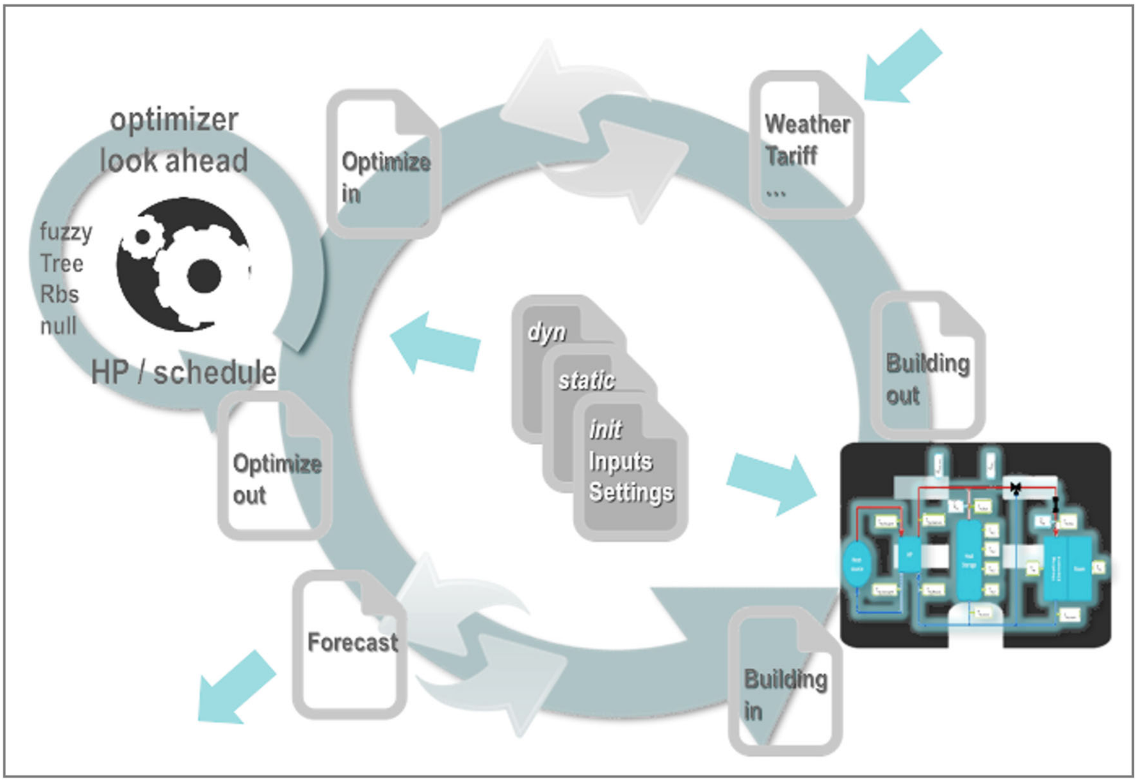

Fig. 1 Schematic interaction of the software modules, with their inputs and outputs

lation, uses MATLAB to simulate the building behaviour for a defined timespan and saves the new building status to a file.

- *Optimizer* Combines input data (weather, tariff, building data), then starts a MATLAB script to find an optimized control signals for the BMS and to calculate the corresponding predicted electricity consumption. Several optimizers have been implemented.
- *Controller* A central module which calls the others following a defined schedule. There are two implementations: one for controlling a real building and one for simulations.

These software modules can be used in two ways: On the one hand, they can be used with a building model in order to simulate, test and compare various building types and building equipment, optimizers and tariff signals. Simulations are configured in JSON files and allow batch execution. On the other hand, the modules can be used to enhance an existing building management system by sending recommendation signals to the heat pump in order to foster DR induced load shifting.

2.3 Optimizer implementations

The Optimizer module is the core component responsible for DR. Based on the tariff signal for the next 24 h, on the weather forecast and on the current state of the building, the optimizer calculates the control signal for the heat pump for the next time period. Its task is thus to balance the heat pump operation with the heat storage tank temperature while covering the needs of the building (respecting comfort zones for temperature) and shifting loads to low tariffs.

Optimal control of buildings has already been researched and is often solved by using a model predictive control approach (MPC), e.g. [19]. Unlike typical approaches, we do not want to take control over the building by e.g. controlling every valve (we leave this to the BMS), but we rather transmit suggestions to the BMS on when to activate the heat pump.

On top of the reference case where the framework has no effect on the building, we have implemented three different strategies:

1. an MPC controller.
2. a sub-optimal MPC controller (Sub-MPC).
3. a fuzzy logic controller.

The first two rely on a model of the controlled building. They predict the energy consumption of the building and search for optimal heating sequences in the given prediction horizon. The MPC controller uses the building model to test different solutions and to evaluate their quality. The optimization problem can be formulated as a mixed-integer programming

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problem with constraints and subject to the dynamics of the system:

$$\begin{aligned}&\min_u \; price \cdot u^T\\ &\text{s.t.}\;\; T_{store}(t) \leq T_{thrHS} \quad \forall t,\\ &\qquad T_{lowerCF} < T_{room}(t) < T_{upperCF} \quad \forall t.\\ &\qquad \dot{x} = f(x,u,d)\end{aligned}$$

Where *price* denotes the el. tariff vector and u the (binary) switching sequence of the heatpump. T_{store} is the temperature of the heatstorage tank and T_{thrHS} its upper limit. $T_{lowerCF}$, $T_{upperCF}$ denote the lower and upper comfort boundaries for the room temperature T_{room}. System dynamics are brought in through $\dot{x} = f(x,u,d)$. The problem is then solved either with a brute force algorithm or with an A* tree search algorithm. The Sub-MPC controller uses a heuristic derived from the model to include the dynamics of the system in linear constraints U_j, that give the lower limit of number of intervals the heatpump is required to run up to the interval j. The comfort is implicitly included through the U_j.

$$\begin{aligned}&\min_u \; price \cdot Q \cdot u^T + \sum_{i=1}^{h} e_i\\ &\text{s.t.}\;\; e_i \geq 0,\\ &\qquad \sum_{k=1}^{j} u_k = U_j + e_j \quad \forall i = 1 \ldots h,\end{aligned}$$

where Q denotes the weight matrix and e_i the costs for the 'soft' constraint on the switching sequence. This simplification drastically reduces the solution search space compared to the first approach. The branch-and-bound algorithm from YALMIP [20] is used to solve the resulting mixed-integer linear programming problem. The fuzzy logic controller is the only one not directly depending on a building model. It is composed of six rules that are designed to promote LS.

3 Simulation methodology

iHomeLab uses the developed framework and the different optimizers in simulation mode to assess the LS potential for typical buildings in Switzerland.

3.1 Building models

The two building models have been designed using the parameters of buildings SFH15 and SFH100 as defined in [21]. The heat pump (HP) and the heat storage tank (HS) have been chosen according to the characteristics of these buildings, see Table 1.

The two buildings have the advantage of representing a wide spectrum of existing buildings with the first fulfilling the requirement for the "Passivhaus" [22] and the "Minergie P" [23] labels and the second corresponding to a typical "non-renovated existing building" [21].

Table 1 Main characteristics of the two modelled buildings

Type	HP power	HS size	Space heating energy demand
SFH15	4.66 (kW)	0.77 (m^3)	15 (kWh/m^2a)
SFH100	15.4 (kW)	2.65 (m^3)	100 (kWh/m^2a)

The HP power is calculated for a heat source of 5°C and the heat load is taken for the climate of Strasbourg [21]

In addition to the physical properties, these models need so-called dynamic parameters: weather data, temperature set points, ventilation schedules, and internal gains. Appropriate weather data (outdoor temperature and solar radiation) have been acquired from Meteo-Swiss for the city of Lucerne, Switzerland. For the temperature set-points, we assumed 21 °C during business hours (Mo-Fr) and 18 °C for the remaining periods. The ventilation follows a similar scheme and is active only during business hours. For the internal gains (e.g. heat from people, computers, etc.), we generated a profile assuming the buildings were used only on weekdays. A density of 0.15 persons per m^2 was taken to calculate the amount of people in the office. The arrival and departure of the employees follows a daily-randomized schedule accounting for "early" and "late" workers. For optimizers requiring a model, the same inputs have been used except that the historical measured weather data was replaced with the corresponding forecasts.

3.2 Tariff signals

The optimizers require an electrical tariff signal which they can use as optimization criterion to promote demand response. For the simulations, we used 3 of the 5 cost neutral tariff signals developed in [13], namely Time Of Use (TOU), critical peak pricing (CPP+) and real time pricing spread (RTP+). They are shown in Figure 2.

As "Real Time Pricing" we understand a price signal which reflects the expected overall consumption and is announced the day before (a 24 h forecast every 12 h). Price differences are accentuated to increase load shift behavior.

Having these different signals, we want to explore their impact on DR and understand whether the introduction of complex tariffs such as RTP+ is really needed.

3.3 Simulation matrix

With the mentioned inputs and models, we then performed a batch of simulations, mixing buildings models, tariff signals and optimization strategies, always comparing to a reference case (with no optimizer, same tariff and same building model). The performed simulations cover three weeks during January 2014 (05.01.14– 26.01.14) and allow us to get infor-

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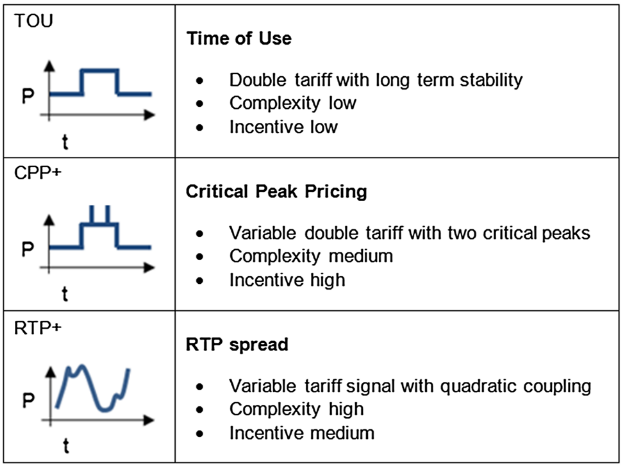

TOU	**Time of Use** • Double tariff with long term stability • Complexity low • Incentive low
CPP+	**Critical Peak Pricing** • Variable double tariff with two critical peaks • Complexity medium • Incentive high
RTP+	**RTP spread** • Variable tariff signal with quadratic coupling • Complexity high • Incentive medium

Fig. 2 Summary of the different tariff signals used for our simulations. For more details about the actual levels and the design process, readers should refer to [13]

mation about the heating energy consumption, cost, comfort in the building and the repartition of the electrical load with respect to tariff (high, mid and low tariff). The chosen timespan has the advantage to have days with big temperature differences. The difference in energy content of the storage tank between the initial and final state has been accounted for by adding the cost for the corresponding energy difference using the mean electricity price.

4 Results and discussion

Figure 3 shows the behaviour of the system, with and without our framework, for the SFH15 building and an RTP+ tariff during four consecutive days (Sun.–Wed.).

Figure 4 compares the load shift behaviour and cost reduction of all optimizers for three tariff models and both building types. The relation between cost reduction and energy use savings is depicted in Fig. 5 for SFH15 and in Fig. 6 for SFH100. Calculation times required for the optimizers Sub-MPC and MPC is depicted in Fig. 7. Numerical values from the simulations are provided in Table 2.

Our simulations show that all optimizers succeed in realizing load shifting by avoiding high tariff times and moving these loads to mid (where applicable) or low tariff times. An example is shown in Fig. 3. The heating needs of the building are highest during the night because the SFH15 building is well insulated and during the day, its occupants contribute a significant amount of the required heating needs. Without the framework, the HP is switched on (shaded areas) whenever the temperature in the storage (HS) reaches a lower threshold, and switched off when the upper threshold has been reached. With the framework, the price (staggered curve) is taken into account, so the HP is preferably used during low tariff times. The framework also keeps an overall lower temperature in the storage and thus minimizes losses from the storage. As a consequence, even the energy consumption was reduced in most cases when using the framework, contrary to initial expectations.

Figure 4 compares the load shift behaviour for the three tariffs and for the two buildings. All combinations have been simulated with all optimizers (reference, Fuzzy, Sub-MPC and MPC). For each of the combinations, the reference case energy demand was set to 100 %, so the next three bars show how the load has been shifted from the high to the low and/or middle tariff. The resulting cost reduction is displayed with the separate bars on the right side. We see that all optimizers succeed in shifting load towards periods with lower tariffs.

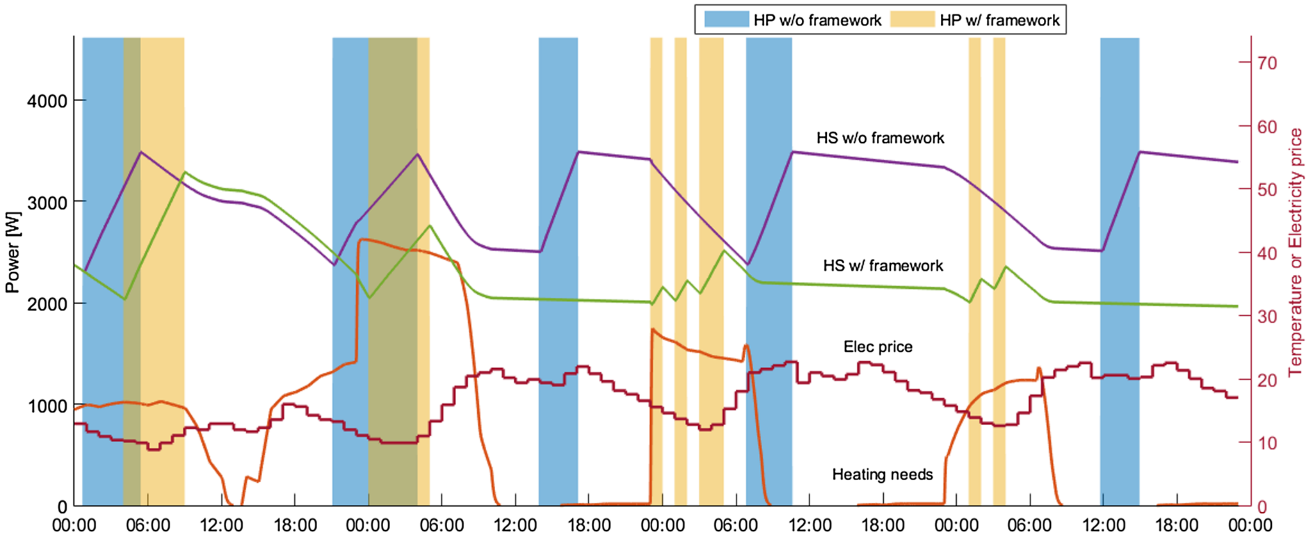

Fig. 3 Heat pump operation times and storage temperature with and without our framework, for the SFH15 building and an RTP+ tariff during four consecutive days (Sun.–Wed. extracted from a longer simulation)

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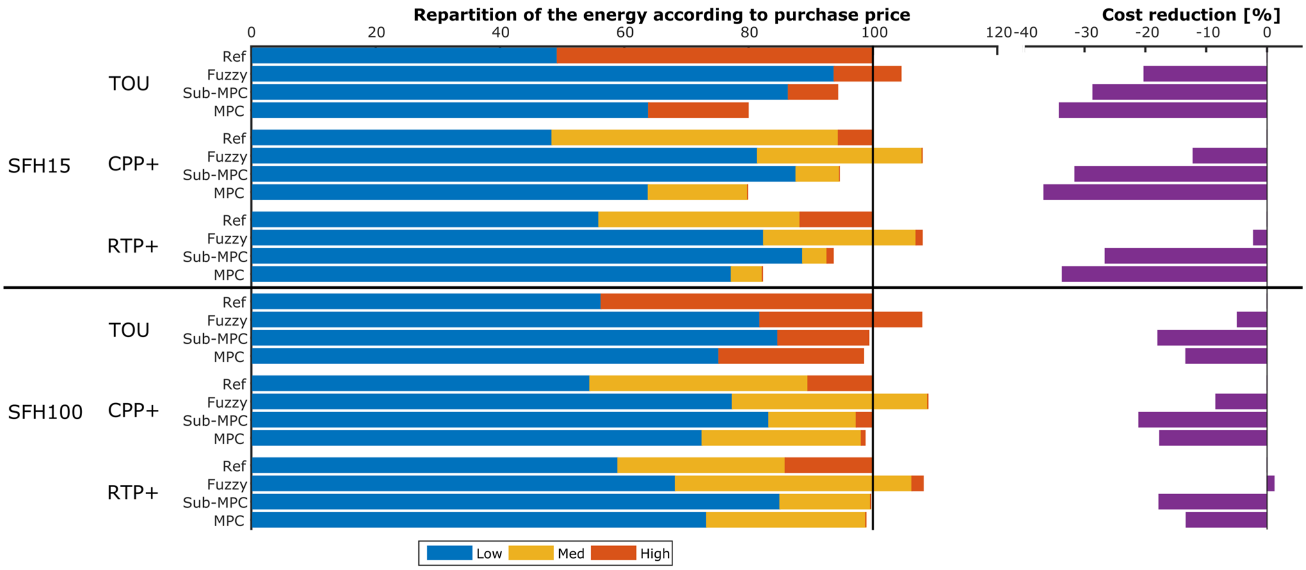

Fig. 4 Comparison of load shift behaviour and cost reduction of all optimizers for three tariff models (TOU, CPP+, RTP+) and both buildings (SFH15, SFH100). For detailed numbers, see Table 2

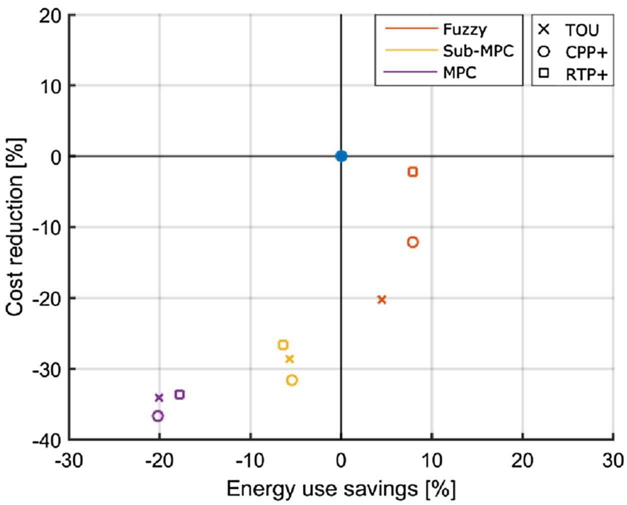

Fig. 5 Relation between cost reduction and energy use savings for the SFH15 building, for three tariffs (TOU, CPP+, RTP+) and three optimizers MPC, Sub-MPC, Fuzzy

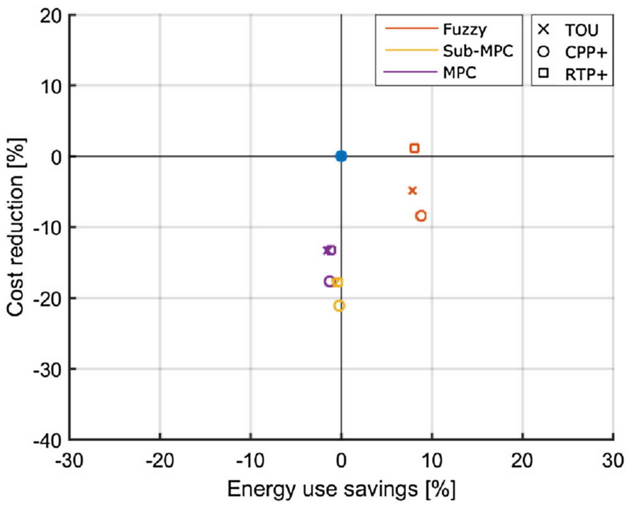

Fig. 6 Relation between cost reduction and energy use savings for the SFH100 building, for three tariffs (TOU, CPP+, RTP+) and three optimizers MPC, Sub-MPC, Fuzzy

Interesting is the fact that while MPC is best in saving energy, Sub-MPC is in most cases more successful in shifting the load into the low tariff times (only exception is TOU in SFH15). The Fuzzy optimizer increases the energy consumption and therefore is not as successful as the other optimizers in saving costs.

The relation between cost reduction and energy use savings is depicted in Fig. 5 for SFH15 and in Fig. 6 for SFH100. Looking at the results for building SFH15 (Fig. 5; Table 2), which uses very little energy already, we find that MPC still achieves an impressive amount of savings: 33–37 % of costs and 18–20 % of energy. This is mainly due to the fact that this algorithm will heat the storage only to the required temperature shortly before the heat is needed, which greatly reduces energy losses from the storage. Sub-MPC reaches cost savings of 27–32 %, but only 5–6 % of energy savings. With the use of rather conservative assumptions in the optimization problem, this comes as no surprise. The Fuzzy optimizer is able to save up to 20 % of costs, but its performance depends on the tariff model. It also has the disadvantage of increasing the energy consumption.

In building SFH100, both MPC and SUB-MPC are able to achieve cost reductions up to 18 and 21 %, respectively. Their relative energy consumption savings are smaller than in SFH15 (max. 2 %), but as SFH100 uses much more energy than SFH15, the absolute energy savings are still valuable.

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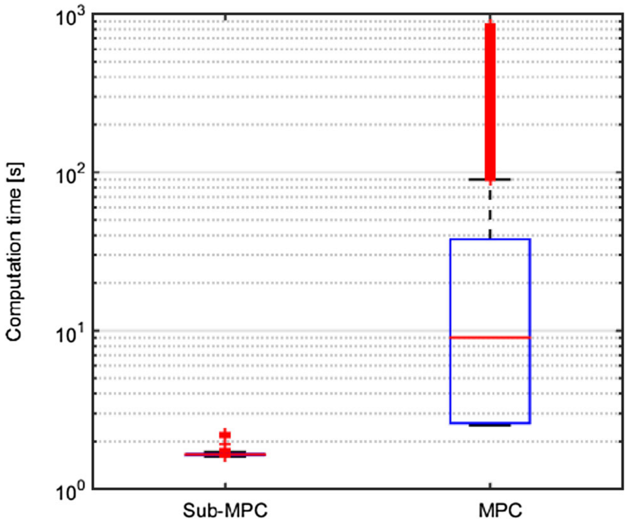

Fig. 7 Boxplot of the required computing time to perform one time step (1 h) in the building simulation for the optimizers Sub-MPC and MPC

The biggest cost reduction is achieved in most cases with CPP+ tariffs, closely followed by TOU. The effectiveness of RTP+ varies for different combinations of building and optimizer. It seems that clearer differences between high and low energy costs lead to better cost optimization results.

While MPC and Sub-MPC render similar savings in costs and energy consumption (with MPC being only slightly better), their requirements on computing power are very different as shown in Fig. 7. In average, on a regular desktop PC, Sub-MPC needs 1–2 s to find a solution, while MPC uses 100 s or up to 2500 s under certain circumstances. Therefore, in many cases Sub-MPC should be preferred over MPC, especially if calculation time is limited.

5 Conclusion

iHomeLab achieved the goal to develop a framework for shifting electrical loads by minimizing energy cost, that can be used both for simulation as well as to enhance existing

Table 2 Cost reduction, energy consumption reduction and load shift behaviour of all optimizers for three tariff models (TOU, CPP+, RTP+) and both buildings (SFH15 top, SFH100 bottom)

	Cost (%)	Energy (%)	High tariff reduction (%)	Shifted load (%)
SFH15				
TOU				
Fuzzy	−20	5	−79	79
Sub-MPC	−29	−6	−84	84
MPC	−34	−20	−69	69
CPP+				
Fuzzy	−12	8	−100	49
Sub-MPC	−32	−5	−100	87
MPC	−37	−20	−100	69
RTP+				
Fuzzy	−2	8	−92	42
Sub-MPC	−27	−6	−92	89
MPC	−34	−18	−100	89
SFH100				
TOU				
Fuzzy	−5	8	−40	40
Sub-MPC	−18	−1	−67	67
MPC	−13	−2	−47	47
CPP+				
Fuzzy	−8	9	−100	31
Sub-MPC	−21	−0	−77	64
MPC	−18	−1	−94	42
RTP+				
Fuzzy	1	8	−87	3
Sub-MPC	−18	0	−100	65
MPC	−13	−1	−100	38

Column “High Tariff Reduction” shows the reduction of energy consumption during high tariff times, column “Shifted Load” during both high and middle tariff times

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BMS. On the one hand, the framework can communicate with a Siemens Desigo BMS, by reading and writing BACnet objects through an OPC server. On the other hand, we have used the framework successfully to simulate various combinations of building types and building equipment, optimizers and tariff signals. These simulations have yielded interesting results. For example, we are able to demonstrate that remarkable cost savings as well as reduced electricity consumption could be possible even with the current metering equipment and tariff systems (i.e. TOU). There is no need to wait for political changes or new structures or rules in the energy market in order to start with load shifting in suitable SSBs.

The optimizers in our system work with a simplified building model. Nevertheless, we achieve remarkable cost savings up to 37 %, with energy savings up to 20 %, while keeping comfort constraints. Because our system requires less configuration effort than optimizers relying on detailed building models, the setup of our system should be easily feasible for HVAC engineers. Future application of the framework will validate this approach.

Up to now, we can state that, if our framework is used, great effects can be reached with relatively little additional installation and configuration effort. However, it is clear that load shifting can only be achieved if the building is equipped with heat storage appropriate to the building size. If the heat pump were to stay switched off during high tariff times, the storage should be big enough for about 4 h of the usual heat demand. Depending on the specific application and climate conditions, the storage dimensioning can be calculated more precisely. In addition, the building itself (its heater, heavy walls, etc.) can be used as storage, a fact that we have not used so far in this work.

Our framework depends on the electrical heat generation equipment of the building. While not applicable to buildings with oil or gas heating, our framework can still be used in simulation mode to find suitable dimensioning for heat pump and storage when refurbishing the building with a heat pump. Similarly, it can be used when planning new buildings, to prepare effective load shifting already in design phase with suitable dimensions for the heat pump and storage.

All optimizers achieve their biggest cost reduction with CPP+ tariffs, closely followed by TOU. This leads to the conclusion that the clearer differences are between high and low energy costs, the better the cost optimization results will be. TSO wanting to stimulate load shifting and peak shaving should therefore consider introducing CPP+ tariffs rather than RTP+ or similar tariffs.

Our goal was to achieve load shifting through cost optimization while keeping the comfort. In addition, the system can easily be adapted to other optimization goals due to its modular setup. It can be used for peak limitation or for maximization of own PV consumption, but also for avoiding or maximizing consumption in specific time slots. All this can be achieved by changing the objective function in the optimizer. The modularity of the framework also permits to easily plug in new versions or enhance it for other weather services or other BMS. The currently implemented BMS adapter module for Siemens Desigo is based on BACnet objects, so for other BMS that are also working with BACnet, the basic functions are already included.

Starting from this work, further research directions could be the extension of the methodology to cooling in summer and actively controlling humidity. A worthwhile extension could also be the inclusion of the building itself (i.e. its floors, walls and heating pipes) as storage and to adapt the optimization accordingly. Finally, to verify the straightforward set-up and to proof the stability of operation, our framework must be installed and verified in real buildings as a next step.

Overall, our demand response approach through a decentralised load shift management system helps shaving load peaks and filling load valleys. It is easy to set up and requires neither fundamental changes in the political or economical landscape nor roll-out of smart-meters nor a smart-grid infrastructure to start with. Therefore, it is an important contribution for the present that helps to stabilize the future energy landscape.

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