Building Control and Storage Management with Dynamic Tariffs for Shaping Demand Response

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***Abstract*—The results from a proof-of-concept study combining modern building automation systems (BAS) with dynamic electricity tariffs are presented. The use of a building automation system that optimizes the electricity demand of a retail end-consumer while managing a local battery unit and respecting all comfort constraints, e.g., on room temperature, illuminance, and indoor air quality, is proposed. The optimization is done in a fully automated fashion, i.e. without any need of action from an external operator. The study focuses on the situation of end-consumers in the city of Zurich, Switzerland. Demand shifting as well as effects on the cost of electricity consumption for different retail consumer groups, i.e. households and offices using their typical usage profiles are assessed. In-house battery systems are introduced as additional means of electricity demand flexibility. Extensive simulations (500+ full-year simulations) are performed for different building types, battery types, and usage profiles. The overall load shifting effect on the aggregated load curve of the city of Zurich is evaluated.**

***Index Terms*—Demand Response (DR), Dynamic Electricity Tariffs, Model Predictive Control (MPC), Smart Metering, Power System Flexibility.**

I. Introduction

Ongoing developments in the power systems sector, namely the rapid deployment of fluctuating renewable energy sources (RES), the power market liberalization as well as the envisioned wide-spread deployment of smart meters in many countries worldwide, show that electricity utilities as well as end-consumers are facing significant changes in the near future. Especially smart metering in combination with dynamic electricity tariffs may change profoundly how electricity is consumed and billed [1]. A shift in consumption profiles due to dynamic tariffs also influences electricity markets, as demand becomes increasingly price-responsive. A larger demand elasticity can be expected to lead to different bidding strategies at the spot markets and, over the long term, lower wholesale electricity prices [1], [2].

In this investigation it is shown how the additional information in the form of dynamic electricity tariffs, a strong economic incentive, can be used in building control for shaping demand profiles of retail end-consumer groups, i.e. shifting thermal loads like heating and cooling in households and offices. The effects that demand response (DR) has on overall electricity consumption and electricity costs of these consumer groups are assessed for different electricity tariff schemes via hourly-based simulations over the course of a full year. The setup (electricity prices, grid loading, weather, occupancy) is adapted to the situation in the city of Zurich, Switzerland.

Since the building itself constitutes a thermal storage, there inherently exists the possibility to shift electricity demand of thermal appliances from periods of high prices (or grid loading) to periods of low prices (or grid loading), respectively. Only part of the load in a building can be shifted in time, e.g., heating can, lighting cannot. The degree of shifting depends predominantly on the usage profile and the thermal inertia of a given building type. A building's thermal inertia is higher in case of a heavy building envelope than in case of a light building envelope. However, there are means to increase the effect of demand shifting by introducing additional thermal or electric storages in a building. The focus here is on evaluating the effect that the presence of an additional (electric) storage has on a building's electricity demand from the grid in an exemplary simulation setup.

The expected advantages are twofold: On the one hand, having a battery as an additional degree of flexibility should enable consumers to better hedge against electricity tariff peaks, leading on average to lower costs for their electricity demand from the grid. On the other hand, the geographically dispersed deployment of small storage units in buildings in combination with the proposed dynamic electricity tariff can help to further reduce the buildings' electricity demand from the grid at times of high overall grid loading. In this study the potential of demand shifting with and without additional electric storage is estimated, including an assessment of electricity costs. The beneficial effects that the here discussed DR measures would have, if fully deployed in the residential and commercial sector in the city of Zurich are illustrated.

II. Problem description

An overview of the problem setting and the corresponding electricity flows is given in Fig. 1. The building has some electricity demand which can be directly met by consuming electricity from the grid (u^{de}). Alternatively, the demand from the building can be met by consuming electricity by (partially) discharging the battery (u^{dis}).

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In order to recharge the battery, the battery consumes electricity from the grid (u^{ch}). This problem becomes more complex if time is taken into account. Given that the price of electricity is time-varying, the building automation system automatically determines at each time step k the electricity flows u_k^{de}, u_k^{dis}, and u_k^{ch} (as well as some other settings) depending on the electricity tariff, the electricity demand in the building and the state-of-charge of the battery. This decision is made based on predictions, i.e. using predicted electricity prices as well as information about the thermal storage of the building (building model) and the electric storage (battery model). The electricity tariff, the models and the computation of the decision, i.e. the controller, are described in the next three sections.

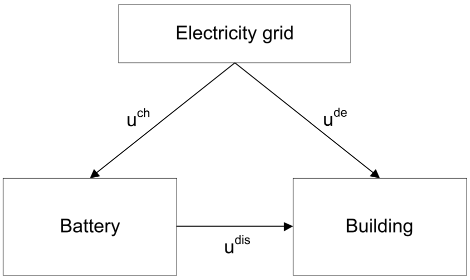

Fig. 1. Overview of electricity flows.

A. *Electricity tariffs*

In the investigation three different tariff schemes are used for the building control simulations: a *constant* electricity tariff c_k^{con}, a typical *peak/ off-peak* tariff c_k^{pop}, and a recently proposed *dynamic* tariff c_k^{dyn} [3].

Tariff	**Description**
c_k^{con}	constant tariff
c_k^{pop}	peak/ off-peak tariff
c_k^{dyn}	dynamic tariff

TABLE I
OVERVIEW OF ELECTRICITY TARIFFS. THE INDEX k DENOTES THE TIME DEPENDENCY, I.E. c_k IS THE TARIFF AT TIME k.

All tariffs are based on the price regime for electricity provision, transmission as well as fees and taxes that are currently charged by the local utility "Elektrizitätswerk der Stadt Zürich" (ewz) in the city of Zurich, Switzerland. For the *constant* tariff, a time-independent fixed rate for electricity consumption based on the average electricity costs is assumed (CHF 0.147/kWh). As *peak/ off-peak* tariff, the existing ewz tariff scheme is used, in which electricity prices during night time and on Sundays as well as public holidays (Mon.-Sat. 22h-6h, Sun. 0h-24h – CHF 0.095/kWh) are about half of the prices as during week-days (Mon.-Sat. 6h-22h – CHF 0.185/kWh) [4].

The *dynamic* tariff used here is a recently developed time-varying, hourly-based tariff that reflects the true marginal cost of electricity consumption, i.e. the sum of the time-varying cost components for electricity provision and transport as well as fixed cost components in the form of fees and taxes (all given on a per kWh basis) [3]. This tariff scheme is used here as a dynamic benchmark tariff for assessing and evaluating the demand response potential of price-responsive loads on the end-consumer side. It is based on time-series of Swiss spot market prices (Swissix) as traded on the European Energy Exchange (EEX) [5] and a generic electricity load curve, reconstructed from grid load measurements (full-year time series, 15 min sampling) of the city of Zurich. The reference year is 2007. The construction of the dynamic tariff is as follows:

1) Time-series of spot market prices and load curves are used to calculate the average spot price and average grid load level for the given time period.
2) The relative weights of the individual cost components of electricity consumption, e.g. α, β, and γ, are calculated using tariff data from ewz [6]. The average electricity price for the constructed full-year time-series is $c_{\text{avg}} = \text{CHF } 0.1465/\text{kWh}$.
3) The construction of the spot/ load-based tariff is then accomplished using (1). More details on the tariff construction can be found in [3].

The hourly dynamic electricity tariff c_k^{dyn} is defined as

$$c_k^{\text{dyn}} := \left(\alpha \cdot \frac{\text{Spot price}(k)}{\text{Spot price}_{\text{avg}}} + \beta \cdot \frac{\text{Load level}(k)}{\text{Load level}_{\text{avg}}} + \gamma\right) \cdot c_{\text{avg}} \tag{1}$$

$$\text{with} \left\| \begin{array}{lll} \alpha & := & \%\,\text{Electricity}_{\text{avg}} \\ \beta & := & \%\,\text{Grid utilization}_{\text{avg}} \\ \gamma & := & \%\,\text{City concession}_{\text{avg}} \end{array} \right\| ,$$

where k is the hourly time step and c_{avg} is the average tariff price. For the considered case, α, β, and γ are 41.0 %, 53.7 %, and 5.4 %, respectively.

This tariff scheme and how it can be applied in building control is further discussed in [7]. An illustration of all three tariff schemes as well as Swiss spot market prices and grid loading in the city of Zurich over the third January week of 2007 (15–21 January 2007, 7 days = 168 hours) are depicted in Fig. 2.

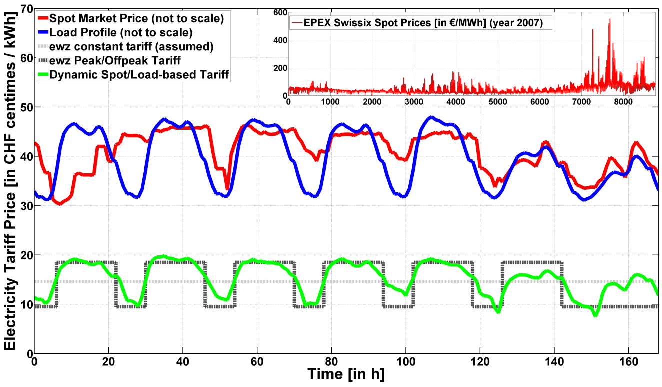

Fig. 2. Evolution of spot prices, grid load and tariff schemes (constant, peak/ off-peak as well as dynamic tariff).

B. Modeling

In order to describe the behavior of the end-consumer, a model of the building and automation system in the building as well as a description of the battery are needed. The modeling is detailed in the following.

1) Building and automation system: As building and automation system model, the model from [7], [8] is used.

$$
\begin{aligned}
x_{k+1} &= Ax_k + Bu_k + B_v v_k + ... \\
&\quad + \sum_{i=1}^{5}[(B_{vu,i}v_k + B_{xu,i}x_k)u_{k,i}] \\
y_k &= Cx_k + Du_k + D_v v_k + \sum_{i=1}^{5}[(D_{vu,i}v_k)u_{k,i}] \ ,
\end{aligned} \tag{2}
$$

where $x_k \in \mathbb{R}^n$ is the state representing the room temperature and temperatures in the walls, floor and ceiling at time step k. $u_k := \begin{bmatrix} u_{k,1} & u_{k,2} & u_{k,3} & u_{k,4} & u_{k,5} \end{bmatrix}^T$ is the control input to the building consisting of

$$
\begin{aligned}
u_{k,1} &= \text{blind positioning } [-] \\
u_{k,2} &= \text{electric lighting } \left[\text{W/m}^2\right] \\
u_{k,3} &= \text{chiller } \left[\text{W/m}^2\right] \\
u_{k,4} &= \text{cooling tower } [-] \\
u_{k,5} &= \text{radiators } \left[\text{W/m}^2\right] \ ,
\end{aligned} \tag{3}
$$

and the corresponding input constraints can be written as

$$
Su_k \leq s \ , \tag{4}
$$

with $S \in \mathbb{R}^{q \times 5}$ and $s \in \mathbb{R}^q$.

The system output $y_k := \begin{bmatrix} y_{k,1} & y_{k,2} & y_{k,3} \end{bmatrix}^T$ is given as

$$
\begin{aligned}
y_{k,1} &= \text{room temperature } [^\circ\text{C}] \\
y_{k,2} &= \text{room illuminance [lux]} \\
y_{k,3} &= \text{ceiling surface temperature } [^\circ\text{C}] \ ,
\end{aligned} \tag{5}
$$

and the corresponding (possibly time-varying) output constraints can be written as

$$
G_k y_k \leq g_k \ , \tag{6}
$$

with $G_k \in \mathbb{R}^{r \times 3}$ and $g \in \mathbb{R}^r$. Here, v_k represents the weather and internal gains (people, equipment). The model sampling time is 1 hour. The numerical values for the considered building example as well as a more detailed description of the building and automation system can be found in [7], [9].

The building model is based on physical parameters and by varying these parameters different building types can be represented, e.g., a heavy construction type and a light construction type or a building with large windows and with small windows. The variation results in buildings with different thermal storage capacities. The influence of these different thermal storage capacities on the demand response is a central aspect in this investigation.

2) Storage device: The influence of a thermal storage device is already addressed by changing the building type and considering different thermal storage capacities. Therefore, only an additional electric storage is modeled. As electric storage device a Li-ion battery, which has a high cycling efficiency, is used. The parameters defining the battery are taken from [10]. A generic model for grid-connected energy storage is taken from [11] and given as

$$
\zeta z_{k+1} = \alpha \zeta z_k + \eta^{\text{ch}} u_k^{\text{ch}} - \frac{1}{\eta^{\text{dis}}} u_k^{\text{dis}} \ , \tag{7}
$$

where $z_k \in [0, 1]$ describes the state-of-charge (SOC) of the battery at time step k (in %), ζ is the capacity, the term α reflects the internal loss of the battery and is given as 0.99992 (i.e. 0.008 % of the current charge is lost in every time step [10]). u_k^{ch} denotes the charging of the battery, and u_k^{dis} the discharging of the battery at time step k. The efficiencies for battery charging η^{ch} and discharging η^{dis} are both set to 90 % ($\eta^{\text{cycle}} = \eta^{\text{ch}} \cdot \eta^{\text{dis}} = 81\,\%$) [12].

The battery's SOC is constrained to lie between 20 % and 100 % in order to limit premature battery deterioration from deep discharges

$$
0.2 \leq z_k \leq 1.0 \ . \tag{8}
$$

The rate of battery charge/ discharge is limited to ± 2 kWh

$$
0 \leq u_k^{\text{ch}} \leq 2.0 \ , \tag{9}
$$

$$
0 \leq u_k^{\text{dis}} \leq 2.0 \ . \tag{10}
$$

The cost of battery usage consists of fixed costs and variable costs (numerical values are taken from [10]). In this study only the variable costs of battery usage, the so-called cycling costs for charging/ discharging the battery system are considered. The reason is that fixed costs (investment costs) can be expected to change profoundly and the importance of fixed costs can shift, e.g., if subsidies are given. The variable costs are chosen to be

$$
c^{\text{var}} = 0.045 \text{ CHF/ kWh} \ . \tag{11}
$$

In the optimization scheme it is assumed that only charging the battery is incurring costs, whereas no costs are incurred for discharging (see MPC problem).

3) Linearization and model augmentation: At each time step, a form of Sequential Linear Programming is applied [13] and the building model in (2) is linearized around some nominal trajectory [7]. Let $u_k^g \in \mathbb{R}^5$ denote the control inputs applied to the building using electricity from the grid and let $u_k^b \in \mathbb{R}^5$ denote the control inputs applied to the building using electricity from the battery. The linearized building model is then augmented with the battery model, where the new state vector is $\bar{x}_k := \begin{bmatrix} (x_k)^T & (z_k)^T \end{bmatrix}^T \in \mathbb{R}^{n+1}$ and the new control input vector is $\bar{u}_k := \begin{bmatrix} (u_k^{\text{g}})^T & (u_k^{\text{b}})^T & u_k^{\text{ch}} & u_k^{\text{dis}} \end{bmatrix}^T \in \mathbb{R}^{12}$. The augmented model is given as

$$
\bar{x}_{k+1} = \bar{A}\bar{x}_k + \bar{B}\bar{u}_k + \bar{E}v_k \ , \tag{12}
$$

with appropriate matrices $\bar{A}, \bar{B}, \bar{E}$. An overview of the control inputs is given in Fig. 3.

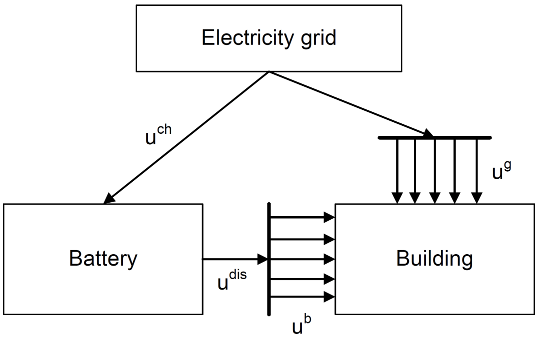

Fig. 3. Overview of control inputs, the building's direct electricity consumption as well as the charging/ discharging electricity flows.

The following relations are assumed:

$$u_k = u_k^{\mathrm{g}} + u_k^{\mathrm{b}} \ , \tag{13}$$

$$u_k^{\mathrm{dis}} = \xi^T u_k^{\mathrm{b}} \ , \tag{14}$$

$$u_k^{\mathrm{de}} = \xi^T u_k^{\mathrm{g}} \ , \tag{15}$$

where $\xi \in \mathbb{R}^5$ is a scaling vector representing the different efficiencies of the actuators. The products $\xi^T u_k^{\mathrm{b}}$ and $\xi^T u_k^{\mathrm{g}}$ denote the electric usage of all actuators at time step k (originating from the battery and the grid, respectively).

C. Model predictive control for buildings

In order to compare the different tariff schemes and investigate the need for an additional storage device, the optimal building response is computed by applying Model Predictive Control (MPC), a well-established methodology for constrained control problems [14].

In MPC, at each time step k a measurement of the current state x is taken, a mathematical model of the building is used to predict the future behavior of the building, and an optimization problem is solved to compute the optimal control inputs over a predefined prediction horizon N [15]. Energy costs, constraints originating from respecting comfort or limitations of actuators, as well as predictions about future weather and occupancy can be readily included in the optimization problem. From the optimal control input vector $\bar{\mathbf{u}} = [\bar{u}_0^T, \ldots, \bar{u}_{N-1}^T]^T \in \mathbb{R}^{12N}$, only the control input of the first time-step $\bar{u}_0^T$ is actually applied. The process then moves one step forward and the procedure is repeated at the next time step [7].

The optimal control input $\bar{\mathbf{u}}^*$ is computed by solving the MPC problem

$$\begin{aligned} \bar{\mathbf{u}}^*(x_0) := \arg\min_{\bar{\mathbf{u}}} \sum_{k=0}^{N-1} & c_k^{\mathrm{tariff}} u_k^{\mathrm{de}} \ + \ (c_k^{\mathrm{tariff}} + c^{\mathrm{var}}) \cdot u_k^{\mathrm{ch}} \\ s.t. \quad & S(u_k^{\mathrm{g}} + u_k^{\mathrm{b}}) \le s \\ & G_k y_k \le g_k \\ & x_0 = x \\ & (8), (9), (10), (12), (13), (14), (15) \ . \end{aligned} \tag{16}$$

III. Investigation setup

The demand response (DR) investigation addresses three main questions. It is assessed:

1) How much electricity demand can be shifted in households/offices by using the building's thermal storage capacity alone?
2) How much electricity demand can be shifted further when using additional electric storage?
3) What are the effects of a wide-spread demand response in the case of the city of Zurich (effects on aggregated load curve)?

In the investigation, the simulation parameters describing the building type, battery type, and tariff scheme are varied. A detailed list of the parameters and possible values is given in Table II. Furthermore, in order to create an aggregated load curve, three different usage profiles for both households and office are considered: Since work and commuting patterns differ, e.g., employees may arrive in the office sometime between 7 am and 9 am, a reference usage schedule is applied, which is then shifted by ±1 hour to create two additional profiles. In total, all parameter variations resulted in 576 hourly-based full-year simulation cases. In the simulations, any occurring public holidays have been neglected. Furthermore, the simulated year has been shortened to 360 days.

All simulations have been performed for the year 2007 and the city of Zurich. The weather data is obtained from observations by MeteoSwiss, the Swiss meteorological service [16]. The weather prediction that is used in the MPC setup is assumed to be perfect, i.e. the weather prediction is equal to its realization. For an analysis on MPC with real (i.e. imperfect) weather predictions and possible adjustments in the MPC setup, see [8]. The occupancy data is based on definitions in the building standards [17] for offices, with the exception that the occupancy level was held constant during the day. For households, the occupancy and vacancy times are the opposite of the ones for offices (reflecting that people are assumed to be at home when they are not in the office and the other way around). The prediction of the occupancy used in the MPC controller is again assumed to be perfect.

In order to compute the aggregated load curve of the city of Zurich, it was necessary to investigate the split of electricity consumption in Zurich. The total electricity demand of the city is 2983 GWh, of which

- the residential sector (i.e. households) accounts for 700 GWh (23.5 %),
- the commercial sector (i.e. offices) accounts for 1441 GWh (48.3 %) and
- the industry sector as well as the remaining other consumption account for 842 GWh (28.2 %).

The combined residential and commercial sector represents thus 71.8 % (or 2141 GWh) of the total electricity demand of Zurich. Most of this electricity usage takes place in either residential or office buildings. All electricity consumption data has been taken from the statistics department of the city of Zurich [18].

The electricity demand profiles obtained from the 576 full-year simulation runs have been scaled in order to match the electricity consumption of the residential, ser-

TABLE II
Overview of simulation parameters.

Building type	
Building usage	household, office
Building construction type	heavy (65 %), light (35 %)
Window area fraction	high (20 %), low (80 %)
Internal gains level	high (50 %), low (50 %)
Battery type	
No battery	-
Small battery	1 kWh
Medium battery	3 kWh
Large battery	5 kWh
Tariff scheme	
Constant tariff (con)	
Peak/ off-peak tariff (pop)	see Sec. II.A
Dynamic tariff (dyn)	
Schedule	
Normal schedule	on time
Early schedule	1h early
Late schedule	1h late

vices, and industry sectors. The calculated electricity demand time-series from the simulation runs for 'household usage' have been aggregated and scaled in order to match the demand of Zurich's residential sector. Analogously, the electricity-demand time-series from the simulations runs for 'office usage' were aggregated and scaled to fit the demand of Zurich's services sector. For both sectors, the distributions of building characteristics, i.e. construction type, window area fraction and internal gains, as established based on [9]) have been used (Table II). For the industrial sector, a standardized load profile for industrial costumers (BDEW G0) has been used [19] and scaled-up accordingly to the given consumption values.

IV. Results

In the following, the simulation results are presented and discussed. First, the ability of shifting load demand when using only the thermal capacity of the building is assessed. Second, the ability of shifting load demand is assessed in case electric storage in the form of battery units (small/medium/large) is available in addition. Third, the overall effect of load shifting in the residential and commercial building sector on the aggregated load curve of the city of Zurich is analyzed.

A. *Shifting electricity demand using thermal inertia only*

By using the thermal capacity of a building alone, a building's average daily peak demand can be reduced by 4.1 % (peak/ off-peak) to 5.6 % (dynamic) compared to the constant tariff. This varies clearly with the usage profile (household or office) and the inertia of the building envelope. Using the dynamic tariff, the peak reduction ranges from 19.1 % for an office with a heavy building envelope to 1.9 % for a household with a light building envelope. Applying the peak/ off-peak tariff instead, a slightly smaller peak reduction occurs. Results for both tariff options are illustrated in Fig. 4.

The electricity consumption for heating, cooling, and lighting in the here considered benchmark buildings over the course of a full year shows only slight increases: Using the dynamic tariff from 0.15 % (heavy building envelope) up to 0.7 % (light building envelope) and using the peak/ off-peak tariff from 0.02 % (heavy) up to 0.8 % (light). The average increase in electricity consumption is in both cases around 0.5 % over a full year.

The electricity cost for the here considered benchmark buildings over a full-year period is as follows: In case the dynamic tariff scheme is applied, the cost-minimizing building controller can reduce electricity costs by 2.2 % (no battery) to 9.2 % (large battery), when compared to the consumption-minimizing building controller. For the peak/off-peak tariff, costs can be reduced by 2.6 % (no battery) to 5.1 % (large battery). An illustration of these results is given in Fig. 5. Comparing the relative electricity cost reductions, the cost-minimizing building controller performs better for the dynamic than for the peak/off-peak tariff (except for the case of no battery storage).

Note that the analysis and its results differ from earlier work presented in [7]. Whereas in earlier work the cost performance of the same building controller for different tariff schemes has been compared, here the cost performance of different building controllers for the same tariff scheme (peak/ off-peak or dynamic) is compared.

B. *Shifting electricity demand using electric storage*

Using an electric storage in addition to the building's thermal capacity for shifting electricity demand should result in a higher overall electricity consumption than the original demand shifting losses using thermal inertia alone ($\approx$ 0.5 %). This is due to the additional energy losses occurring in the battery unit. These are mostly cycling losses caused by charging/discharging the battery with an assumed round-trip efficiency $\eta = \eta^{\text{ch}} \cdot \eta^{\text{dis}} = 90\,\% \cdot 90\,\% = 81\,\%$. A smaller part is caused by the slight internal losses within the battery system that occur over time. The larger the battery system, the higher the overall losses from both effects (dynamic tariff: from 0.5 % [no battery] to 1.8 % [large battery], peak/ off-peak tariff: 0.5 % [no battery] to 1.1 % [large battery]). The losses in the case of a dynamic tariff are higher as the battery is more intensely used, i.e. more battery cycling occurs.

Additional electric storage leads to a significant further reduction of average daily peak demand. Using the peak/ off-peak tariff, peak reduction evolves from 4.1 % (no battery) to 15.7 % (large battery). Using the dynamic tariff, peak demand is reduced from 5.6 % (no battery) to 24.1 % (large battery) when averaged over all building types (heavy/light building envelope, etc.) and usage profiles (households/ offices). The peak reduction is markedly higher when using the dynamic tariff instead of the peak/ off-peak tariff as shown in Fig. 6. Furthermore, it can be seen that for both tariff options the reduction effect of the peak demand levels off when the battery unit becomes larger. After some maximum possible peak reduction a further increase in battery size has no effect.

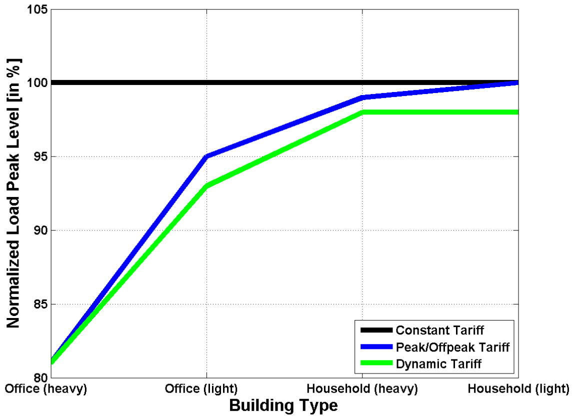

Fig. 4. Averaged daily load peak as a function of building envelope and usage profile.

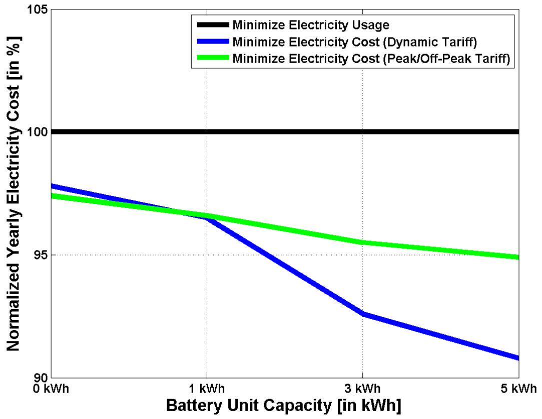

Fig. 5. Normalized yearly electricity consumption costs for different optimization goals.

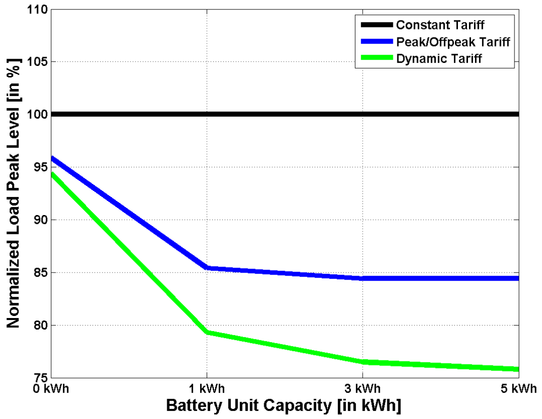

Fig. 6. Averaged daily load peak for different battery sizes.

C. Effect of the electricity demand shifting in the building sector on the aggregated grid load curve of the city of Zurich

The price-sensitive building automation system tries to shift consumption of the residential and commercial sectors away from peak demand periods. The degree of freedom of such shifting actions depends primarily on the energy storage capacity of the building, be it thermal storage, i.e. the building's thermal inertia (more generally also heat storage systems), or electric storage, i.e. a battery.

1) In case *no additional battery unit* is used, a slight load shifting effect is observable when looking at the averaged electric loading over the course of one full year (dynamic tariff: peak reduction of 4.4 % at 12am and 3.5 % at 6pm), as illustrated in Fig. 7.

2) In case a *small-sized battery unit* is used: somewhat larger load shifting effect is observable when looking at the averaged electric loading over the course of one full year (dynamic tariff: peak reduction of 11.5 % at 12am and 8.4 % at 6pm). A shift of load demand towards early morning, i.e. the time period of low electricity prices and lowest aggregated grid loading, is visible as shown in Fig. 8.

3) In case a *medium-sized battery unit* is used, an even larger load shifting effect is observable when looking at the averaged electric loading over the course of one full year (dynamic tariff: peak reduction of 14.5 % at 12am and 15.7 % at 6pm). A significant shift of load demand towards the early morning hours is visible, Fig. 9.

4) The largest shifting potential is observable for the simulation cases using the *large-sized battery unit* (dynamic tariff: peak reduction of 16.5 % at 12am and 17.5 % at 6pm). The load demand is shifted mostly towards early morning hours. Furthermore, during noon time (12am), when the global peak load demand occurs in Zurich, the building sector using the dynamic electricity tariff has its local demand minimum for day-time hours, which is around 6 % lower in comparison to the demand level when using the peak/ off-peak tariff for the same time frame. This behavior is illustrated in Fig. 10.

The load shifting from peak to off-peak hours, triggered by high electricity prices and/or high overall grid loading, is the more effective the more storage capabilities (thermal or electric) are available to the building controller. Increasing thermal or electric storage capacities markedly improves the building controller's demand shifting capabilities and hence adds to the reduction of electricity demand during peak load hours.

Numerical results regarding load demand reduction for the two most prominent daily peak hours, i.e. 12am and 6pm, are given in Table III. The mean daily consumption values for these peak hours over the full simulation year (360 days) have been calculated as:

$$P_{\text{mean}}(k) = \frac{1}{n}\sum_{i=1}^{n} P(k)_i \quad , \tag{17}$$

where n corresponds to 360 days (the length of the truncated full-year simulation) and $P(k)_i$ is the real power P demanded by the aggregated load profile in the k-th

Tariff	**Load at 12am [%]**			**Load at 6pm [%]**		
	Mean	Med.	Max	Mean	Med.	Max
Constant						
All cases	100	100	100	100	100	100
Peak/off-p.						
No Battery	95.5	98.5	97.1	98.3	104.9	97.6
Small Bat.	92.0	97.6	92.9	98.6	100.0	99.8
Medium Bat.	91.0	97.6	90.6	97.8	100.0	99.2
Large Bat.	89.3	97.6	90.0	96.9	99.5	96.9
Dynamic						
No Battery	95.6	98.5	95.0	96.5	100.0	95.2
Small Bat.	88.5	97.6	99.4	91.6	93.4	88.1
Medium Bat.	85.5	97.6	99.9	84.3	87.3	64.9
Large Bat.	83.5	97.6	99.9	82.5	86.3	64.9

TABLE III
Comparison of relative Peak Load Demand for different tariff schemes and battery sizes.

hour of day i. Calculations of other metrics, i.e. P_{median} and $P_{\max}$, have been made accordingly. The consumption profile for the case of a constant electricity tariff has been used as the reference value, i.e. *a priori* defined as 100% in the analysis of all metrics (mean/median/maximum).

D. Discussion of simulation load profiles

In the here performed simulation only a part of the total electric load demand of buildings is considered and modeled, namely the load demand due to the HVAC system (heating, cooling, ventilation) and due to lighting needs. Load demand from appliances such as PC workstations (in offices) or kitchen appliances (in households) are not considered. This explains, for example, the obvious load demand 'gap' during working hours in Fig. 7–10. Electricity demand usually has one of its daily peaks during lunch time due to high electricity demand in kitchens. This effect and others cannot be observed in the here presented load profiles, simply because such load types have not been simulated. Arguably, the loads from most of these appliances are not shiftable, i.e. people are hardly willing to cook at other times, because of the electricity price, hence load shifting would only be possible with batteries for these load types.

V. Conclusions and outlook

The here presented extensive simulation study shows that building automation systems (BAS) can effectively be combined with dynamic electricity tariffs for reducing peak electricity demands. The result is an electric load demand profile that behaves price-responsive within the given operation framework, which is set by constraints such as room temperature bounds and others. The building control system takes advantage of the degrees of freedom offered by inherent capacities of thermal storage, e.g. building inertia, and electric storage, e.g. batteries. The load demand reduction for the aggregated level of the city of Zurich, using the dynamic tariff, ranges from 3.5 % (no battery) to 17.5 % (large battery) and, using the peak/ off-peak tariff, from 1.7 % (no battery) to 10.7 % (large battery) for typical peak hours (Table III).

Assessing the demand response (DR) capabilities of the building sector for reducing peak electricity demand on an aggregated level is a useful exercise, as effective peak load reduction measures have several benefits: These benefits range from the deferral of investments in the electricity grid as well as peak generation capacity to providing additional flexibility to intra-day and day-ahead power markets since the load demand is – partially – rendered price-responsive. Deferral of grid and peak capacity investment, fully or partially, constitutes a major benefit to system operators as the estimated total investment need for electricity grid infrastructure as well as generation capacity worldwide until the year 2035 has been estimated by the International Energy Agency (IEA) to be of the magnitude of \$17 trillion (WEO reference scenario) [20]. Reducing or deferring only 1 % of this need would still affect an investment volume of \$170 billion. In this study, an aggregate peak reduction of 1.7 % to 17.5 % (depending on tariff scheme) was achieved. As further research direction, the role of micro generation units can be assessed. Distributed generation for buffering peak load demand on the end-consumer side has intentionally been left outside the scope of this work.

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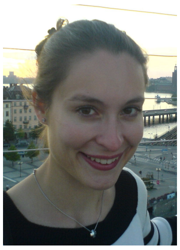

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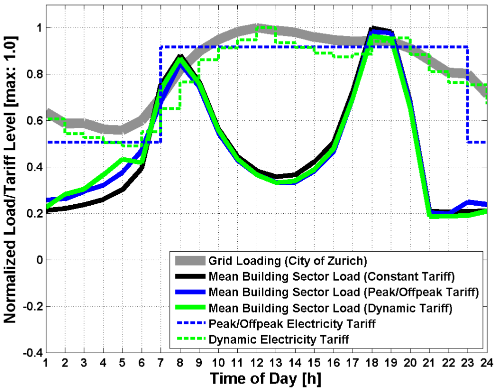

Fig. 7. Aggregated load curve – City of Zurich (no battery unit).

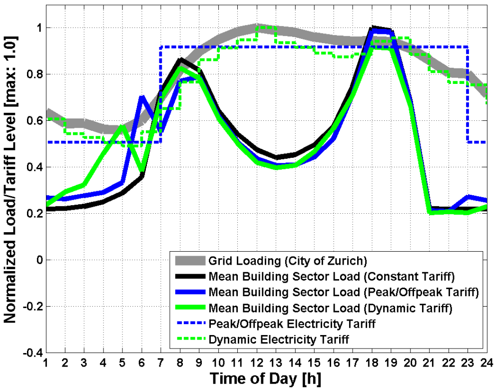

Fig. 8. Aggregated load curve – City of Zurich (small battery).

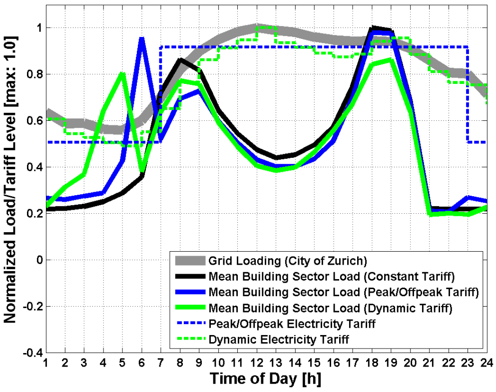

Fig. 9. Aggregated load curve – City of Zurich (medium battery).

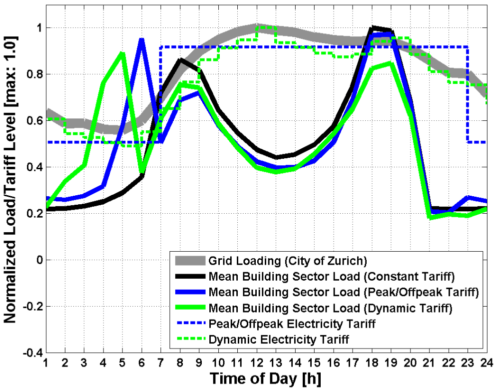

Fig. 10. Aggregated load curve – City of Zurich (large battery).