Towards variable end-consumer electricity tariffs reflecting marginal costs: A benchmark tariff

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***Abstract*—A time-varying, hourly-based electricity tariff scheme for end-consumers is proposed that reflects truthfully marginal costs of electricity provision, based on spot market prices, and electricity transmission, based on actual T&D grid load levels. This tariff scheme is proposed as a benchmark for studying demand response (DR) of end-consumer. The tariff concept is applied to the situation in the city of Zurich, Switzerland, using time-series of the Swiss EEX power market spot prices and Zurich's yearly electricity load profile. A price spread analysis and a benchmark for measuring the economic incentive of variable electricity tariffs on the end-consumer side are presented.**

***Index Terms*—Electricity tariffs, real-time pricing (RTP), end-consumer electricity prices, electricity price spread, smart metering, demand response (DR).**

I. Introduction

A time-varying, hourly-based end-consumer tariff is proposed here that reflects truthfully marginal costs of electricity provision, based on spot market prices, and electricity transmission & distribution, based on actual transmission and distribution (T&D) grid load levels, for any given hour. The exemplary case is the situation in the city of Zurich, Switzerland, using time-series of the Swiss EEX spot market prices, the electricity load curve of the city of Zurich and the existing tariff structure of Zurich's public electricity utility (EWZ) for the time period March 2009 to March 2010 as the basis.

An intelligently designed time-varying tariff scheme can be an effective tool for influencing the actions of price-responsive end-consumers, a subset of demand response (DR), be it in the framework of demand-side management (DSM) schemes or smart-metering. All these end-consumers have in common that they are trying to minimise their cost function of electricity consumption. Therefore, a properly designed tariff scheme can be seen as a tool, because information about forecasted critical load situations and volatile spot market prices is straightforwardly priced into the proposed end-consumer tariff. In this context, the tariff scheme would act as a control signal, providing the necessary price information and hence the economic incentive for end-consumers to react accordingly. In the case of an end-consumer which is a participant of a DSM or smart metering scheme, by reducing, increasing or shifting his consumption. And in the case of a electric storage unit at the end-consumer side, be it in the form of electric vehicle batteries or other storage technologies [1], by charging or discharging at appropriate times. Within the proposed tariff regime, grid-friendly behaviour of end-consumers is rewarded.

The remainder of this article is structured as follows: Section II motivates the usage of variable end-consumer tariffs, Section III explains the construction procedure of the proposed variable tariff scheme and Section IV presents a price-spread analysis of this tariff scheme compared to other tariff schemes, evaluating benefits and draw-backs. Section V gives an outlook on plans for future analysis and concludes the here presented work.

II. Motivation for variable tariffs

Recent wide-spread deployment of smart meters in several European countries, for example in Italy and Sweden, has created the necessary prerequisite for the introduction of sophisticated time-varying tariff schemes for end-consumers. Since price-responsive consumers have an economic motivation to minimise their cost function for electricity consumption, a well-designed variable tariff scheme can align the individual interest of those consumers to behave cost-optimally with the superordinate aims of alleviating critical load situations. Furthermore, the recently occurring unusual price fluctuations at the spot markets, i.e. high negative spot prices [2], could be mitigated, since price-elastic loads can be seen as a crucial buffer in case of a mismatch in demand and supply.

The here proposed time-varying end-consumer tariff scheme is an effective tool for aligning individual interests and general interests, because information about predicted grid load situations and day-ahead spot market prices is embedded in the proposed end-consumer tariff. The time-varying tariff price vector effectively acts as a control signal for price-responsive loads. The larger the amount of price-responsive loads as a fraction of total load and the stronger the control signal, the higher the impact on the overall load shape and, hence, grid stability.

Simple high/low tariffs, also labeled peak/offpeak and day/night tariffs, have existed for years in many European countries, e.g. France, Germany and Switzerland [3]–[5]. Many variable tariff schemes that are in place at present have in common that electricity prices during the low price period are only about half that of prices during the high price period. Although these variable tariff schemes are simple in nature, they are nevertheless creating a strong economic incentive to shift certain dispatchable loads,

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especially thermal heat storage, i.e. electric water or space heating, from day to night time.

Simple variable tariffs with significantly varying price levels, but still easy for end-consumers to understand and use, where necessary at the time because end-consumers needed to take themselves the decision of when to shift, increase or decrease demand. This often happened and still happens by manually switching on or off thermal loads such as water and space heaters. More complex tariff structures would have overwhelmed end-consumers and practical implementations for automated electricity consumption optimisation and planning where not yet feasible. With the advent of ubiquitous and cheap computing and communication resources, these limitations have in principal disappeared. Sophisticated control entities for managing, for instance, loads of PHEV fleets [6], households [7] and buildings [8] have been proposed. Such controllers can benefit from time-varying end-consumer tariffs by incorporating the tariff's price signal directly into their optimisation strategy.

As the implementation of more complex tariff schemes is becoming increasingly feasible, the limitations of existing simple variable tariffs become more apparent: Traditional high/low tariff schemes do not truthfully reflect marginal costs for electricity provision and electricity transmission. Their variable price signal is merely a simplified approximation of long-term average costs for electricity procurement and grid operation.

With respect to the cost component for electricity provision, most end-consumer tariffs at present cannot be adapted to changing market situations: If spot market prices rise, utilities face additional market risk because higher costs cannot be passed along to end-consumers in a timely fashion. The opposite situation occurs for periods of falling spot prices, with end-consumers feeling uneasy about increasing profits for utilities and unchanged electricity prices for themselves. The proposed variable tariff has the advantage that price fluctuations at the spot market are passed along to end-consumers directly, decreasing market risk for electric utilities and increasing cost transparency for end-consumers. The flip side is that end-consumers in turn would face a market risk [9].

With respect to the cost component for electricity transmission, constant or simple end-consumer tariffs are not the best choice either. Since grid expansion projects are focused on existing and forecasted peak utilisation levels, reducing peak load and specifically peak load flows on transmission and distribution grids, can save large capital expenditures. Making better use of price-responsive loads makes thus economic sense. Constant and simple end-consumer tariff schemes can only be suboptimal in achieving this goal for the following reasons: Simple tariff schemes with only two different price levels per day create insufficient incentives for price-responsive consumers to behave more grid-friendly. Even though this is sufficient for shifting demand of loads with large thermal inertia, e.g. electric space and water heaters without significantly influencing the end-consumer's convenience. Many loads with relatively small thermal inertia and tighter temperature and/or convenience constraints, e.g. fridges and air-conditioning in offices, cannot take advantage of this. A typical fridge's ability to shift demand, for example, is limited to less than hour, if cooling temperature constraints are to be respected. Electric water and space heaters, on the other hand, can shift their electricity demand more flexible. Nevertheless, they would still benefit significantly from tariffs with shorter time intervals [10].

Variable tariff schemes with shorter time-intervals for different price levels, e.g. hourly-based, are more adequate for many appliances. Shorter time-intervals would therefore significantly increase the amount of potentially price-responsive loads in the grid. The simple variable tariff schemes in place at present are insufficient, if the goal is to optimally exploit the partially controllable load of price-responsive end-consumers for the purpose of grid stabilisation. In the context of rapidly increasing stochastic renewable generation shares, this is a significant untapped control potential.

Benefits of a spot/load-based tariff are thus manyfold:

- Active demand response by being price-responsive will be popular only if economic advantages, by adhering to such schemes, are clear and comprehensible for end-consumer. Variable electricity pricing schemes for end-consumer play the crucial role for creating this strong economic incentive.
- End-consumers can directly participate from price arbitrage opportunities at the spot market, hence are able to minimise their cost of electricity consumption. At the same time, electric utilities can minimise their market risk. If a sizeable part of a utilities' end-consumers would adhere to variable tariff schemes that are correlated to spot market prices, than the utility is less exposed to price risks at the spot market.
- Tariff prices that vary several times a day, not just between day and night time, create opportunities for much higher numbers of price-responsive end-consumers to participate in demand response schemes and to profit from arbitrage accommodation.
- A strong economic incentive is set for end-consumers to reduce consumption during critical peak load situations. In France, for instance, several methods that aim on reducing peak load have been implemented: Sending out alerts via radio, internet and text message to end-consumers in certain critical regions (Bretagne, Provence-Alpes-Côte d'Azur) [11], [12] and the introduction of day-based (low, medium, high load days) coupled with time-of-day-based (day/night) pricing schemes already in the 1990s [13]. The latter method also improves hedging of market risk.
- Wide-spread deployment of demand response schemes in the form of a considerable fraction of electricity demand becoming price-responsive, having at least a short-run price elasticity, would have a noticeable influence on spot market behaviour [14].
- Sudden price switches in high/low tariff schemes, i.e.

at the switching point between high and low price levels, may create grid security problems due to large-scale redispatch of generation capacity and changing load patterns. Decreasing the time slot length for different price levels to an, at least, hourly-based tariff would smoothen such discontinuities. This would have beneficial effects on grid security and power plant dispatch planning. An even smaller time slot length, i.e. 15 min. slots, has been suggested as an elegant means for further smoothen discontinuities [15]. This would, as a side-effect, also improve the potential for end-consumers to benefit from arbitrage accommodation, Section V.

The broader picture to this research question is that some European countries will make it obligatory for utilities to offer variable end-consumer tariffs in the near future, e.g. Germany in 2011 [16]. Other countries, such as France, already have more advanced variable tariff schemes [3]. Furthermore, the IEA has specifically recommended additional efforts to increase demand response for Switzerland [17]. The discussion of how sophisticated variable end-consumer tariff schemes can be designed intelligently is thus a near-term and relevant purpose.

III. Tariff construction

Other time-varying, hourly-based tariffs for end-consumers have already been presented and their effects analysed. A recent in-depth study, [18], considers a variable tariff that is based entirely on German spot market data (EEX). However, costs for grid utilisation, albeit an important part of total cost for electricity consumption, as well as concession fees and taxes are not directly represented. In Germany, for instance, only 20% of the average end-consumer electricity cost is for electricity provision, whereas 29% is for grid charges and 51% for government-mandated taxes, charges and other fees [19, p.137]. In most European countries, the cost component for grid usage is highest for end-consumers, whereas commercial and industrial consumers pay considerably less [19, p.142]. This is due to the much higher electricity consumption by the latter consumer groups, which diminishes the relative cost for grid utilisation with respect to the relative costs of electricity procurement.

For the case considered in this study, the city of Zurich in Switzerland and its public electricity utility (EWZ), all price components of the existing high/low tariff have been published transparently [4] and shown here in Table I. The cost of electricity provision over a full year is 41.0%, whereas costs for grid utilisation amount to 53.7% and concession fees to 5.4% (all weighted averages). Our principle assumption is that all significant cost components for electricity consumption need to be taken into consideration explicitly when constructing a variable end-consumer tariff. This is deemed crucial, if such a tariff scheme shall truthfully reflect existing cost structures. This becomes increasingly important, as soon as a significant fraction of end-consumers participates in variable tariff schemes.

Costs	**High tariff**		**Low tariff**		**Average tariff**	
	abs.	[%]	abs.	[%]	abs.	[%]
Electricity	7.50	40.5	4.00	42.1	5.94	41.0
Grid fee	10.00	54.1	5.00	52.6	7.78	53.7
Concession	1.00	4.5	0.50	5.3	0.78	5.4
Total cost	**18.50**	100	**9.50**	100	**14.50**	100

TABLE I
EWZ high/low end-consumer tariff scheme [4].
(Prices in Swiss franc centimes per kWh.)
High tariff: Mon.-Sat. 6-22h — Low tariff: Mon.-Sat. 22-6h and Sun. / public holidays.

The construction of the here proposed time-varying, hourly-based end-consumer tariff is as follows:

1) Time-series of spot market prices and load curves for the region in question, see Fig. 1, are used to calculate the average spot price and average grid load level. This is accomplished here by calculating averages for a preceding time-period, e.g. last year, but could also be realised by calculating moving-averages, i.e. continuously updating spot/load averages by considering the last 365 days ($i - 365$). In our case study, Swiss EEX spot market data and grid load data from the city of Zurich (Courtesy of EWZ) for the time period of 17 March 2009 to 16 March 2010 (365 days) have been used.
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, Table I.
3) The construction of the time-varying, hourly-based spot/load-based tariff is then accomplished straightforwardly using Eq. 1. (The index i corresponds to any hour of a given time period for which a tariff price vector shall be calculated).

$$\forall\ i \in \mathsf{Time\ Period},$$
$$\mathsf{Spot/Load\ Tariff\ (i)} := \left(\begin{array}{rc} & \alpha \cdot \frac{\mathsf{Spot\ price(i)}}{\mathsf{Spot\ price_{avg.}}} \\ + & \beta \cdot \frac{\mathsf{Load\ level(i)}}{\mathsf{Load\ level_{avg.}}} \\ + & \gamma \end{array} \right) \cdot \mathsf{Tariff_{avg.}}$$
$$\mathsf{with} \left\| \begin{array}{lll} \alpha & := & \%\,\mathsf{Electricity_{avg.}} \quad (= \ 41.0\%) \\ \beta & := & \%\,\mathsf{Grid\ utilisation_{avg.}} \quad (= \ 53.7\%) \\ \gamma & := & \%\,\mathsf{City\ concession_{avg.}} \quad (= \ 5.4\%). \end{array} \right\| \tag{1}$$

$$\sum_{i}^{1\,year} \texttt{cost(High/Low tariff)} = \sum_{i}^{1\,year} \texttt{cost(Spot/Load-based tariff)}$$
$$= \sum_{i}^{1\,year} \texttt{cost(Spot-based tariff)} \tag{2}$$

The construction procedure's result is a spot/load-based tariff time-series consisting of electricity prices for one year, 8760 hours ($= 365\,\mathrm{days} \cdot 24\,\mathrm{h}$), for the time period March 2009-10. The tariff is normalised with respect to the average price of the existing high/low end-consumer tariff (CHF 0.145/KWh [~€0.10/kWh]). Constant loads, e.g. fridges or lights that are always switched on, thus result in the same yearly electricity costs as under the tariff regime before, Eq. 2.

In this case study, the variable tariff's time-serie has been constructed *a posteriori* using existing historical data. However, day-ahead tariff construction can be implemented as well. Next day's EEX spot market prices are usually announced shortly after noon on a weekday. The day-ahead variable tariff price vector can be constructed and published in line with EEX spot prices. This leads to a varying prediction horizon for the variable tariff's day-ahead prices of a 12 h minimum, just before the announcement of the next day's EEX spot prices, to a 36 h maximum, just after the announcement. This may already be sufficient information for certain automated loads on the end-consumer side. Additionally, sufficiently accurate models for estimating day-ahead load curves and day-ahead spot market prices exist [20]–[22]. Using predictions of day-ahead, or even two-day-ahead, grid load levels and spot market prices can be used straight-forwardly to construct estimates of day-ahead (two-day-ahead) tariff price vectors. Controlled load on the end-consumer side can take these tariff price estimations into consideration for their optimisation.

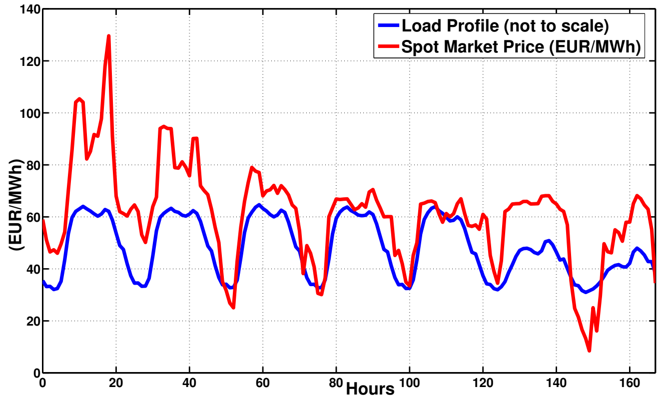

Fig. 1. Correlation between the EEX Swiss spot market prices (in €/MWh) and Zurich's load profile (Courtesy of EWZ). The reference time frame is the 3^{rd} week of January 2010.

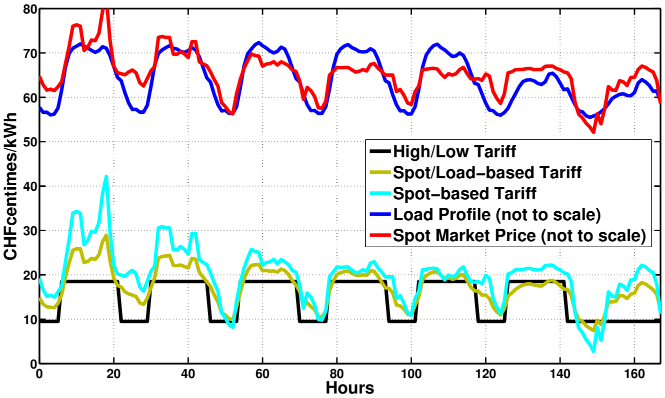

Fig. 2. Comparison of existing day/night tariff with two hypothetical variable electricity tariffs: Spot-based and spot/load-based tariffs.

IV. TARIFF ANALYSIS

Analysis of variable tariff schemes based solely on spot market prices (spot-based tariff) has been presented [18]. Since the important cost component for grid utilisation had been explicitly disregarded, the price volatility σ of a spot-based tariff considerably differs from the volatility of a tariff that combines spot market prices and grid utilisation levels (spot/load-based tariff). Analysis on economic incentives that are set for price-responsive end-consumers and their possible optimisation strategies are thus not directly comparable.

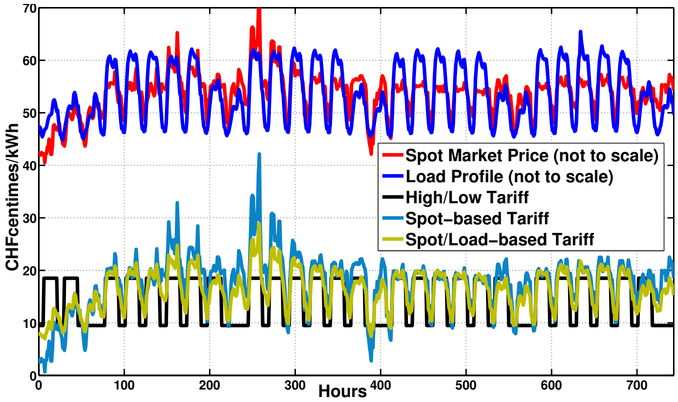

Fig. 3. Zurich's load curve - EEX spot prices - EWZ HT/NT tariff - spot-based tariff - spot/load-based tariff (January 2010).

One could argue that time-series of spot market prices and load curves are correlated with one another. Which would mean that simplified variable end-consumer tariffs based solely on spot market price variations can be deemed sufficiently good. On first sight this argument seems valid, since it can be shown that the correlation between Swiss EEX spot market prices and the load curve for the city of Zurich is indeed high, $R = 0.75$. However, when looking at quantitative data, i.e. a snap-shot time-series of spot prices and load curves, Fig. 1, it is obvious that subtle differences remain between both time-series. This is of importance in certain situations, when peak load is matched with relatively low spot market prices. This was the case, for example, during the night of 1 Mai 2008 in Germany [23]. Indeed, when comparing a spot-based tariff with a spot/load-based tariff, relative deviations over time are significant, Fig. 2–3. A spot-based tariff has a much higher variance σ^2 when compared to a spot/load-based tariff, $\sigma^2_{spot} = 36.92$ and $\sigma^2_{spot/load} = 16.34$. This difference in price variance is depicted in Fig. 4.

The theoretical potential, i.e. performance bound, for arbitrage accommodation on the end-consumer side can be calculated by using the concept of a generic storage unit. This storage unit with storage capacity Q_0 has ideal properties, meaning no cycle losses ($\eta_{cycle} = 0$) and fast charging/discharging rate P_0. As all tariffs dealt with here are hourly-based, the fastest charging/discharging time $t_{min.}$ is equal to shortest time interval, one hour. This leads to the simple relationship

$$t_{min.} = \frac{Q_0}{P_0} = 1\,\mathrm{h}. \tag{3}$$

The storage unit can best take advantage of arbitrage opportunities from hourly-based variable tariff schemes, since the unit can charge or discharge, without losses, its full storage capacity Q_0 for all possible combinations of hours within a chosen time slot length. As such, there are no technical or timing limitations to the optimal usage of this unit for price arbitrage. However, the notion of a minimum price spread, $\Delta P_{min.}$, is introduced here. It represents the marginal operation cost of the storage unit. The threshold thus defines what the minimum price difference between two hours in one time slot has to be in order to trigger a charge/discharge cycle of the storage unit. For a battery system, minimum cycle costs can be around $\Delta P_{min.}^{battery}$ = €0.05-0.08/kWh. For a dispatchable load that only shifts its demand in time, the value of $\Delta P_{min.}^{load}$ depends on convenience losses and whether or not the overall energy consumption increases as a result of demand shift. In the best case, $\Delta P_{min.}^{load}$ is zero.

Using the generic storage concept, some interesting results can be shown. The lower price variance of a spot/load-based tariff has a remarkable impact on the potential for arbitrage accommodation on the end-consumer side, as can be seen in Fig. 5–7. For instance, in Figure 5 it can be shown that the number of potential arbitrage occurrences in the course of a full year, expressed as a function of marginal storage operation costs, is higher for the spot-based tariff than for the spot/load-based tariff. This is an evident result, since the spot-based tariff has a significantly higher variance. In a simple high/low tariff scheme, arbitrage opportunities are limited to minimum price spreads that are at and below the difference of the defined high and low price level (step function). Figure 6 shows the number of potential arbitrage occurrences in the course of a full year, expressed as a function of time slot lengths. The optimal time slot length for a moderate price threshold that is appropriate for battery systems, is 14 hours. Intuitively, this seems valid as the storage unit then takes advantage of the different price price levels between day and night. For a load that shifts its demand, the picture is very different. In Figure 7, it is shown that for smaller $\Delta P_{min.}$ the optimal time slot length becomes smaller as well. In the case of a $\Delta P_{min.}^{load}$ = €0.01/kWh, the optimal time slot length is 3 hours. Optimal arbitrage strategies for dispatchable loads and battery systems are hence very different: For dispatchable loads, the strategy seems to be to seek as much arbitrage opportunities throughout a year even at relatively low price differences. For battery units the optimum seems to be to seek only the arbitrage opportunities with the highest price differences.

Comparing all tariff options, it can be shown that the here proposed spot/load-based tariff scheme exhibits the best correlation with both spot price and load curve time-series, Table II. This is an indication that the spot/load-based tariff price signal actually does act as a communication signal for end-consumers, truthfully relaying information on spot market price levels and grid load levels. This creates an important feedback in the system, acting against peak load levels as well as peak generation levels.

Tariff scheme	Spot time-series	Load time-series
	$R =$	$R =$
High/Low	0.55	0.80
Spot-based	1.00	0.75
Spot/Load-based	0.95	0.91

TABLE II
Correlation of variable tariff schemes with spot price and grid load time-series.

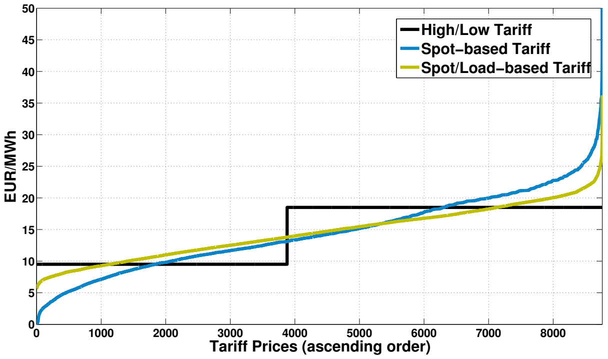

Fig. 4. Variable tariff schemes (sorted by price, one-year period).

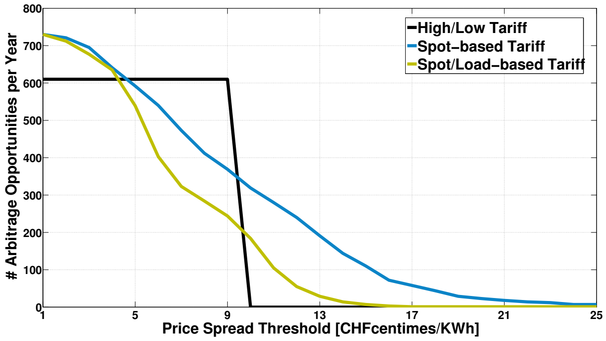

Fig. 5. Arbitrage accommodation — Suitable events per year vs. minimum price spread (time slot: 12 h).

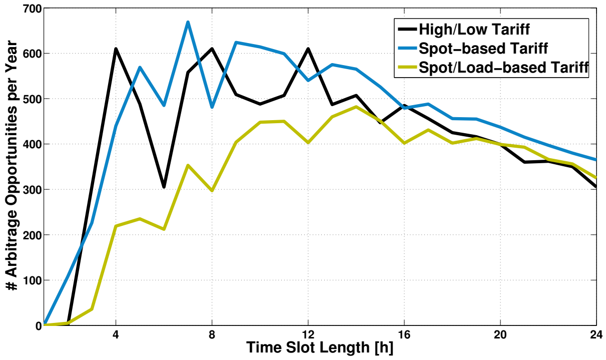

Fig. 6. Arbitrage accommodation — Suitable events per year vs. time slot length (Price spread ≥ CHF 0.06/KWh [€40/MWh])

V. Conclusion & Outlook

A method for constructing variable end-consumer tariffs that reflect truthfully the time-varying marginal costs of electricity provision and T&D grid utilisation has been presented. This tariff scheme is proposed as a benchmark for evaluating demand response effects of price-responsive loads on the end-consumer side. A variable, hourly-based end-consumer tariff has been constructed for the city of Zurich, Switzerland, using time-series of Swiss EEX spot prices and the city's yearly load curve. The proposed spot/load-based tariff scheme allows to find a consensus between the individual goal of an end-consumer to minimise the cost for electricity provision and the superordinate goal of reducing peak electricity demand and hence peak grid loads.

The properties of this variable spot/load-based tariff,

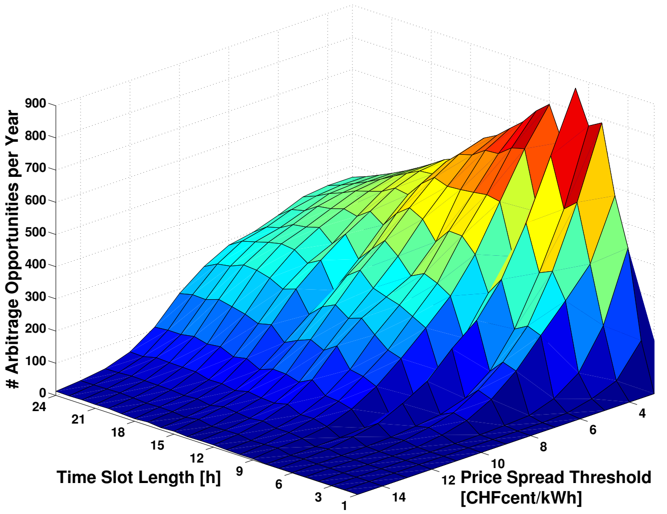

Fig. 7. Arbitrage accommodation — Suitable events per year vs. minimum price spread threshold and time slot length.

namely its suitability for price arbitrage accommodation and as an indicator for critical load situations, have been investigated. This has been done by introducing a theoretic benchmark that determines the maximal potential for arbitrage accommodation for a generic electricity storage unit, independent of any technical limitations. This is a measure of how strong the economic incentive for adhering to a near real-time variable electricity pricing scheme is in an ideal situation (performance bound). The actual performance of realistic end-consumer loads, with their varying limitations, can then be compared against this performance bound. Actual implementation of a variable tariff scheme will likely be different in practise. The here proposed benchmark is however of value for analysis, as it is tariff that most truthfully reflects marginal costs.

The outlook for this research topic is to analyse, if the proposed variable tariff system, applied to realistic end-consumers, can relieve grid congestion and hence increase the security margin of the electric grid, and how optimal arbitrage strategies look like.

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