SUITABLE NETWORK TARIFF DESIGN FOR THE GRID INTEGRATION OF DECENTRALIZED GENERATION AND STORAGE

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ABSTRACT

This paper aims at proposing a network tariff design suitable for the grid integration of high amounts of decentralized generation and storage units. The analysis is based on a consistent set of criteria and is carried out from two perspectives. Firstly, a DSO perspective is assumed. For this purpose, real cost and consumption data for the distribution grid of the city of Zurich is used. Secondly, the analysis is carried out from the perspective of an individual customer equipped with a PV-plus-battery system. It is evaluated how this customer can actively adapt to different network tariff structures. Based on the overall results, an adequate network tariff structure is proposed.

INTRODUCTION

ewz is the electricity supplier and distribution system operator (DSO) of the city of Zurich. It supplies electricity to roughly 220’000 customers and is owned by the municipality of Zurich. In 2008, the citizens of the city of Zurich voted in favour of pursuing the goals of the 2000-Watt society. The formulation of the 2000-Watt society concept in the municipal code of the city of Zurich refers both to the reduction of the overall continuous energy usage to no more than 2000 Watts per person and to the reduction of the carbon footprint to no more than 1 ton CO_2 equivalent per person [1]. The 2000-Watt society concept takes into account all primary energy carriers (renewable and non-renewable).[1]

In this context, the amount of distributed generation (DG) and more specifically photovoltaic (PV) plants installed in the distribution grid of the city of Zurich has already significantly increased during the last years and is expected to grow continuously in the future. This advance of decentralized generation allows customers to cover an increasing part of their consumption with their own behind-the-meter production facilities. Consequently, the quantity of electrical energy purchased from the grid decreases. In addition, the cost of battery storage systems has been constantly declining over the last years and further significant cost decreases are expected in the near future. With the increasing cost-effectiveness of PV and battery systems, the maximization of behind-the-meter self-consumption is likely to become a viable and attractive solution for a broad range of customers; for a minority of customers, grid parity of combined PV and battery systems is already a fact or will materialize soon [2]. The increasing self-consumption challenges today’s network tariff structures which are usually primarily based on volumetric kWh charges. This paper addresses this challenge and tries to give qualitative and quantitative insight regarding the effects of different network tariff designs both from a DSO and an individual prosumer perspective.

CONCEPTS OF GRID TARIFF DESIGN

A suitable network tariff design for the grid integration of a growing amount of decentralized generation and storage units has to take into account that these units in combination with self-consumption schemes lead to a decrease in the amount of energy purchased from the grid. This has several effects. Firstly, the revenues of the DSO are reduced because grid tariffs are usually volumetric (kWh charge), either exclusively or at least to a large extent. Hence, the DSO is unable to cover its cost in the short-term with the existing tariffs. This is problematic because cost recovery is essential for ensuring future investments necessary for a reliable and safe grid and for the further integration of decentralized generation. In order to recover its costs in the medium- and long-term, the DSO must increase its volumetric tariffs. In this way, customers without PV plants pay more and thus subsidize those who benefit from self-consumption. This means that cost-reflectiveness and fairness are threatened. The more electricity is self-generated and self-consumed, the stronger this subsidy effect becomes. Therefore, this relationship is sometimes referred to as “death spiral” [3].

A further drawback of volumetric tariffs is that they do not represent the real drivers of grid costs. Grid costs are mainly determined by the demanded capacity and cannot be mapped to purely energy-based tariffs in a cost-reflective way. Thus, they often fail to provide the right incentives for grid cost efficiency to end consumers [4].

1 For further information, see www.2000watt.ch.

In the following sections of the paper, we investigate possible solutions to the above mentioned issues through a suitable network tariff design without restricting ourselves to today's regulatory framework. We confine our analysis to network tariffs, i.e. we do not discuss possible adjustments of other components of the electricity tariff, e.g. the tariffs for supplied electricity or charges for financing feed-in tariff systems.
For a structured and consistent evaluation of different network tariff structures (e.g. volumetric, capacity-based and a combination of both), the following criteria, which are mainly based on the Eurelectric paper "Network tariff structure for a smart energy system", are used [5]:

- Cost-reflectiveness and fairness
- Non-discriminatory cost allocation
- Incentives for providing grid-oriented flexibility
- Adequate recovery of DSO costs (short-, medium- and long-term)
- Stability and predictability
- Transparency and comprehensibility
- Easy implementation

The criteria cost-reflectiveness and fairness imply that network tariffs should reflect the costs incurred by serving each customer. These costs are mainly capacity-driven. Non-discriminatory cost allocation means that the tariff design should not discriminate certain customers of the same customer group. This means, for example, that the same tariffs should apply within a DSO's supply area for customers of the same type. Incentives for providing grid-oriented flexibility can be provided in different ways, e.g. by critical peak pricing or a rate rebate for customers willing to let their supply be interrupted during limited periods. An adequate recovery of DSO costs is essential to ensure a reasonable return on capital for network investments in the past as well as for incentivizing future investments. Stability and predictability of network tariffs is important for customers in order to be able to foresee future tariffs and thus to minimize investment uncertainty. Transparent and comprehensible network tariffs ensure a low complexity for customers. And last but not least, network tariffs should be easy to implement for the DSO both regarding technical and process requirements (e.g. metering and billing).
The above listed criteria will be used in the following to qualitatively and quantitatively assess the impacts of different network tariff structures on DSOs and on active prosumers equipped with PV-plus-battery systems.

NETWORK TARIFF DESIGN AND CALCULATION (DSO PERSPECTIVE)

In the first part of this section the calculation of the network tariffs is described. We then evaluate the recovery of the DSOs costs for three different tariff structures: 1) a volumetric tariff based on the consumed energy (kWh charge), 2) a capacity-based tariff depending on the consumer's maximum power demand per month (kW charge), and 3) a mixed tariff combining both volumetric and capacity-based components. For the implementation of the capacity-based and the mixed tariff, measurements of the customers' monthly demand peaks, e.g. via smart meters, are required. The process followed for the network tariff calculation can be seen in Figure 1. The development of the expected revenues of the DSO is quantified for three different points of time; they are referred to as basis scenario showing the situation today, mid-term and long-term scenario.

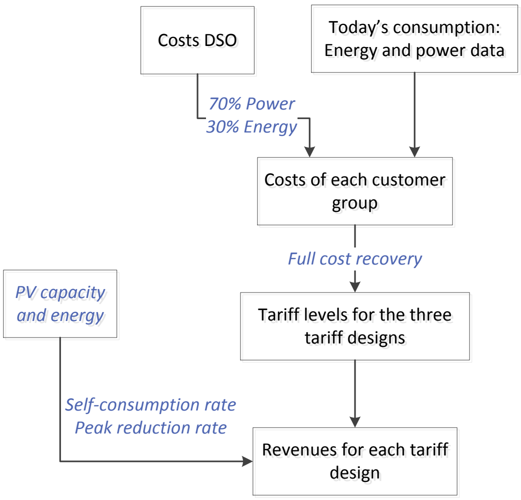

Figure 1. Process for the calculation of the tariffs and the evaluation of the DSO revenues. Assumptions are written in blue.

Methodology

In order to calculate the level of the network tariffs, the total costs of the grid have to be allocated among the different customers groups in a fair way. For example, customers with high consumption connected to the medium-voltage level create different costs than private households in low-voltage level. Even within the same voltage level, different customer groups might be defined by the DSO in order to map the differences in the relative administrative costs. The goal of such customers' fragments is to create cost-reflective tariffs. Therefore, the first step in the tariff calculation is to allocate the total costs based on the maximum power and on the energy consumption of each customer group. As shown in Figure 1, the total costs are allocated 70% based on their maximum power demand and 30% based on the energy consumption. These factors have been chosen because maximum power demand is the main driver of DSO costs as it determines the required installed grid capacity and consequently the required investments. The costs of each customer group combined with its consumption result in the corresponding levels of the network tariff components for each tariff design (volumetric, capacity-based and mixed). In any case, full cost recovery is assumed for the calculation of the tariff levels.
In order to evaluate the effectiveness and fairness of the

tariffs in the future, the net energy consumed by customers from the grid needs to be calculated assuming a certain increase in the installed PV capacity in the city. The assumed load and PV data are given in Table 1. A certain percentage of the energy produced from PV plants will be used for self-consumption; the amount of energy taken from the grid will thus decrease. Also a small reduction in the maximum power demand of the end users is assumed due to natural simultaneity of consumption and production (no batteries assumed). The factors used for the calculation of self-consumption are given in Table 2. The self-consumption rate is expressed as a percentage of the PV production and the peak reduction as a percentage of the maximum power demand. As a next step, the future revenues of the DSO are calculated based on the net consumptions.

	Load	PV[2]		
		Basis	Mid-term	Long-term
Peak power [MW]	520	11.5	320	800
Energy [GWh]	2896	11.5	320	800

Table 1. Assumptions for peak power and yearly energy of load and PV for the three considered points of time.

	Mid-term	Long-term
Self-consumption rate	60%	80%
Maximum power demand reduction (yearly average)	3%	5%

Table 2. Parameters for the calculation of the net energy consumption.

The level of costs related to energy supply and grid usage for the three network tariff designs for a typical single-family house in the city of Zurich (without a PV plant) can be seen in Figure 2. As it can be seen, the part of the DSO cost (grid usage) being recovered through the volumetric component and through the capacity-based component of the tariff varies among the three tariff designs. In the mixed tariff, the grid usage part consists of the capacity-based and the volumetric component which both have a weight of 50%.

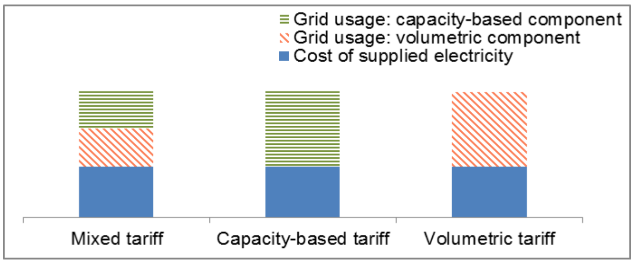

Figure 2. Cost components per network tariff design for a typical private household without PV plant.

2 The long term PV potential is derived from the solar map of the city of Zurich. A yearly PV production of 1000 kWh/kW$_p$ is assumed.

Comparison of the different grid tariff designs

In a next step, the evolution of the expected revenues from the three grid tariff designs in the city of Zurich is evaluated. For that, we assume constant grid costs, constant tariff levels and constant consumption over time. In doing so, we are able to analyze the impact of increasing PV generation and thus increasing self-consumption in the city of Zurich on the grid tariff revenues of ewz.

Figure 3 shows that there is a small loss in revenues over time for the capacity-based tariff, a moderate loss for the mixed tariff and a significant loss for the volumetric network tariff. In order to ensure cost recovery, the significant gaps created in the case of the volumetric and mixed tariff would have to be compensated by periodical increases in the tariff levels. These increasing tariffs levels would particularly impact customers not benefitting from self-consumption. In this way, the fairness and cost-reflectiveness of the tariffs would be threatened. At the same time, the frequent adjustments of the tariff levels by the DSO necessary for ensuring cost recovery would lead to instability and would endanger the predictability for customers.

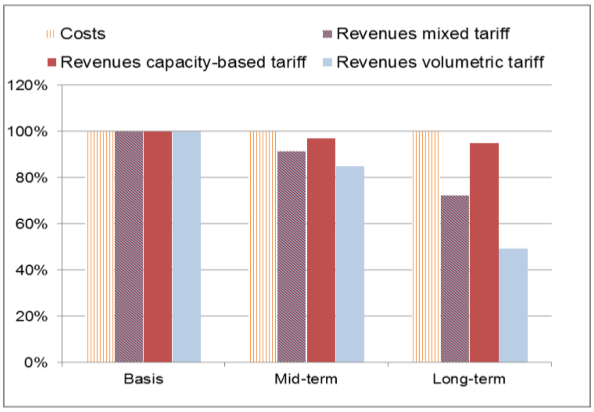

Figure 3. Cost and revenues resulting from the different grid tariff designs for today (basis) and for the mid- and long-term horizon.

It is important to note that our study has been made for the city of Zurich. Thus, the underlying load density is relatively high. Therefore, the reduction of energy consumed from the grid is moderate even with 80% self-consumption assumed in the long-term (see Table 2). The results would be even more pronounced in rural areas or in cities with lower load density.

Of course, there are many uncertainties which might change the results described above. One of these uncertainties is related to the individual reactions of active prosumers to the different tariff designs. This aspect will be discussed in the following section.

EFFECTS OF DIFFERENT TARIFF STRUCTURES ON ACTIVE PROSUMERS

A household in the city of Zurich with a PV plant is

chosen in order to examine the effect of the proposed tariff structures on a real prosumer.
The impact of a battery system on the electricity costs is also examined and an optimization problem is formulated aiming at minimizing the total electricity cost from the prosumer's point of view. The algorithm assumes a perfect knowledge of the future PV production and load demand profiles. Eventually, the three proposed tariff structures are investigated for three different PV - battery storage system configurations.

Modelling

Real load and PV 15-minutes time series data of a single-family house from 2013 in the distribution grid of ewz are used in order to examine the potential behaviour of the customer to the proposed tariff structures. The prosumer characteristics are listed in Table 3.

Prosumer characteristics	
Peak load demand	9.1 kW
Peak PV production	9.4 kW
Battery capacity / power rating	10 kWh / 10 kW
Battery roundtrip efficiency	90%
Min. / max. battery state of charge	10% / 90%

Table 3. Prosumer characteristics.

The three different system configurations investigated are shown in Table 4. In case A, no PV or batteries are considered, while in case B the existing PV system is taken into account. In both cases A and B, the prosumer has no control over the electricity costs since PV production is weather-dependent and no load shifting potential is assumed. On the other hand, in scenario C, the prosumer can actively influence his electricity usage by modifying the battery dispatch aiming to minimize his total costs. Thereby, a perfect knowledge of the future load demand and PV production curves is assumed.

Case	PV	Battery
A	-	-
B	Yes	-
C	Yes	Yes

Table 4. Investigated cases.

Optimization problem

The objective of the optimization problem is to minimize the customer's total yearly electricity costs consisting of the sum of the 12 monthly capacity-based costs for the grid usage and the volumetric costs (grid usage plus energy supply) for the whole year. A tariff based on current market prices is assumed for the remuneration of the prosumer for his surplus energy being fed into the grid. The resulting objective function is presented in (1), while the equations (2) - (7) describe the constraints.

$$\min\left\{\sum_{i=1}^{12} T_{G_C} P_{imp,i}^{max} + \sum_{t=1}^{N_t} (T_{G_V} + T_E) E_{imp,t} - T_R E_{exp,t}\right\} \quad (1)$$

$$\text{s.t.} \quad P_{PV,t} - P_{L,t} - P_{B_{ch},t} + P_{B_{dis},t} = P_{inj,t} \quad \forall\, t \quad (2)$$

$$0 \leq P_{B_{ch/dis},t} \leq P_B^{max} \quad \forall\, t \quad (3)$$

$$E_B^{min} \leq E_{B,t} \leq E_B^{max} \quad \forall\, t \quad (4)$$

$$0 \leq P_{B_{ch},t} P_{B_{dis},t} \leq a \quad \forall\, t \quad (5)$$

$$E_{B,t} = E_{B,t-1} + P_{B_{ch},t} n_B + \frac{P_{B_{dis},t}}{n_B} \quad \forall\, t \epsilon [2..N_t] \quad (6)$$

$$E_{B,1} = E_B^{min} + P_{B_{ch},1} n_B \quad (7)$$

where N_t is the number of time steps per year; T_{G_C} and T_{G_V} are the capacity-based and volumetric grid usage tariffs, respectively; T_E indicates the energy supply tariff and T_R represents the remuneration tariff for the surplus energy; $P_{imp,i}^{max}$ is the maximum monthly power demand; $E_{imp,t}$ and $E_{exp,t}$ are the energy import and export, respectively; $P_{PV,t}$ is the PV generation, $P_{L,t}$ is the power demand, $P_{inj,t}$ is the power injection while $P_{B_{ch},t}$ and $P_{B_{dis},t}$ denote the battery charge and discharge power, respectively; P_B^{max} is the battery power rating; $E_{B,t}$ is the battery's state of charge (SOC), while E_B^{min} and E_B^{max} are the minimum and maximum allowable values of the battery's state of charge; n_B is the battery efficiency and a is a very small number, here equal to 10^{-11}. Constraint (1) corresponds to the power node balance. Constraints (3) and (4) set the limits of the battery charge/discharge and state of charge. A simultaneous battery charge and discharge is prevented with constraint (5), (6) and (7) describe the battery dynamics.

Results

The results of the optimization for case C for both the volumetric and the capacity-based tariff are presented in Figure 4. The mixed tariff leads to the same behaviour as the capacity-based tariff and is not presented for that reason.

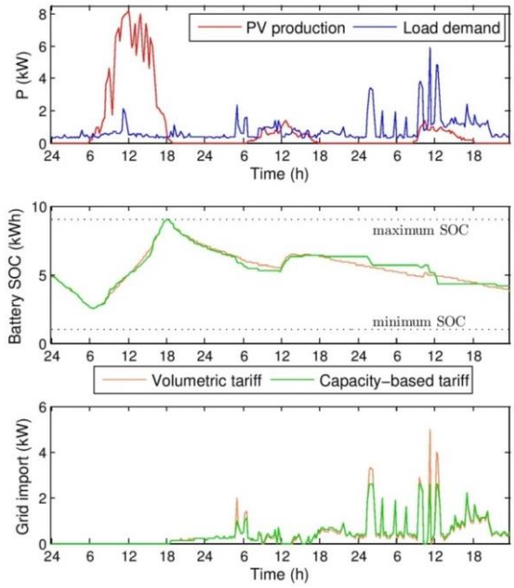

Figure 4. Comparison between volumetric tariff and capacity-based tariff for 3 days in April for case C.

For the visualization of the results we have chosen three consecutive days in April with different load demand / PV infeed situations. A high PV infeed can be seen on the first day, while load demand peaks have been recorded during the third day. On the first day, the two tariffs show a similar behaviour, since the PV infeed is sufficient to cover the load demand and no grid imports are needed.
A different behaviour can be observed on the third day. More specifically, in case of the capacity-based tariff, the battery is used for the shaving of the load peaks aiming at the minimization of the grid usage capacity component.
A comparison of the total yearly costs that the prosumer would have to bear per tariff structure and per system configuration is presented in Figure 5. The consideration of the PV plant in case B results in a cost reduction of up to 32% in case of the volumetric tariff. The use of the battery (case C) as a means to minimize the electricity costs leads to a further reduction in the total yearly costs. The maximum cost reduction by means of the battery can be observed in the case of the capacity-based tariff, where the total yearly costs are reduced by 75% in comparison to case A.

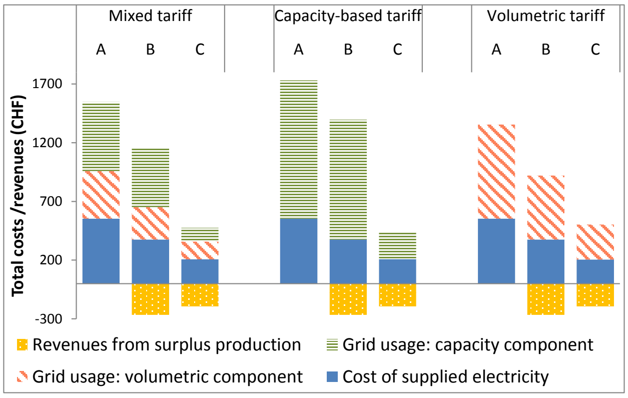

Figure 5: Yearly prosumer costs and revenues per system configuration and per tariff structure.

In this paper a perfect knowledge of the future demand and production curves is assumed. This means that the prosumer would exactly know in advance when the load peaks would occur and how high they would be. In a realistic situation, although real-time algorithms could be used for the scheduling of the battery dispatch, the cost-saving potential by using the battery would be nevertheless smaller.
The results show that, if no batteries are taken into account, the capacity-based tariff represents a good solution from a DSO perspective considering the cost recovery criterion. This holds both for an individual customer (cases B in Figure 5) as well as when considering the city of Zurich (Figure 3). With a battery, however, prosumers can significantly reduce their costs in all tariff designs. For the prosumer considered in our analysis, this potential is even higher with the capacity-based tariff (see Figure 5). In Figure 6, the power node balance for case C during the three chosen days in April is depicted for the capacity-based tariff.

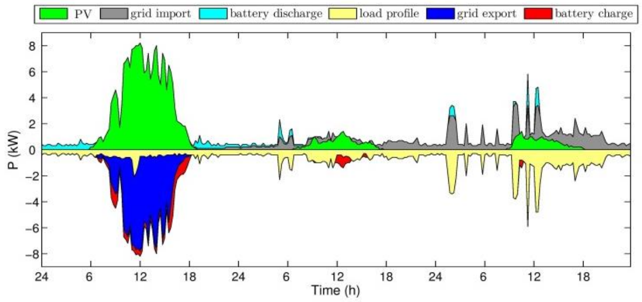

Figure 6. Power node balance during 3 consecutive days in April for the capacity-based tariff (case C).

CONCLUSIONS AND OUTLOOK

We investigated how to design network tariffs being suitable for the grid integration of a high amount of decentralized generation and storage units. Our quantitative analysis for the whole city of Zurich as well as for an individual prosumer shows that a capacity-based grid tariff would be suitable in terms of fairness, cost recovery and most of the other criteria if only the potential effect of increasing distributed generation (in our case PV) is taken into account. If it is additionally assumed that a high share of prosumers will be equipped with battery storage systems, then this is not true anymore. Such prosumers can actively react to all tariff designs proposed in this paper and can thus significantly save costs under all circumstances. This is good news for prosumers. However, from a DSO or regulatory point of view, it means that with none of the grid tariffs proposed in this paper the whole formulated set of criteria can be met in a future with high amounts of decentralized storage. We thus conclude that a future grid tariff design being suitable for the integration of both decentralized generation *and* storage should not only be based on maximum power demand and/or electricity consumption. Instead, it should reflect the increasingly bidirectional usage of the grid, i.e. it should not only be based on the peak demand but also on the peak infeed caused by grid users.

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