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Network charging schemes and self-supply: instruments to prevent self-reinforcing dynamics

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Network charging schemes and self-supply: instruments to prevent self-reinforcing dynamics

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Abstract

Self-supply can destabilize the finance of a distribution network. This paper analyses under which circumstances the tariff structure of a distribution network is stable or unstable under pressure of self-supply and provides recommendation how to change the tariff structure to restore stability if it is unstable. This paper analyses the occurrence of self-reinforcing dynamics in relation to volumetric network tariffs and surcharges in networks with a high propensity for self-supply. We model the level of self-supply endogenously depending on profitability and explore network tariffs that avoid an unstable dynamic for investments into self-supply in the system. Analysed tariff modifications concern the energy and load split, the extent of netting, and a variation in cost pass-through to lower network levels. Adding to the recent literature, we explore the option to calibrate tariff parameters predetermined as well as endogenously linked to self-supply levels in the network. We find endogenously determined modifications of load- and energy split and variations in the cost pass-through from upper network levels between parallel grids most promising to prevent a self-reinforcing dynamic. The analysed modifications also open up the possibility to calibrate a new, sustainable level of self-supply and to incorporate uncertainties in the tariff design.

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Keywords: network tariffs, electricity distribution, prosumers

JEL-classification: L11, L94, Q41

1 Introduction

With rooftop photovoltaics on the rise, are we facing a vicious circle pushing consumers away from electricity distribution networks? And if so, what is a stable approach to promoting distributed renewable energy generation? These are the key questions for the following analysis.

Due to strong political support and decreasing investment cost for photovoltaics (PV), consumers increasingly generate at least part of their electricity themselves and on-site. Incentives for self-supply now stem from saved system cost, like network charges (e.g. Fh ISE 2020) rather than from support schemes. Self-supply unlocks an alternative to supply from the grid and reduces total withdrawal from the network. Yet, network supply still serves as backup. Hence a self-supplier may require the same capacity as a conventional user but uses it far less. Network charges finance the provision of the network. They often account to a large proportion for energy consumed from the grid and only to a smaller extent for capacity held available. In contrast, network cost is deemed largely related to the network's capacity and rather independent from utilization. Hence, self-supply does not necessarily reduce overall network cost. Yet it often reduces self-suppliers' contribution to cost recovery.

Figure 1 illustrates schematically the effect of volume-based cost distribution of fixed network cost in view of self-supply. Overall network cost is depicted as the width of the bars remains constant regardless of the amount of prosumers (P).

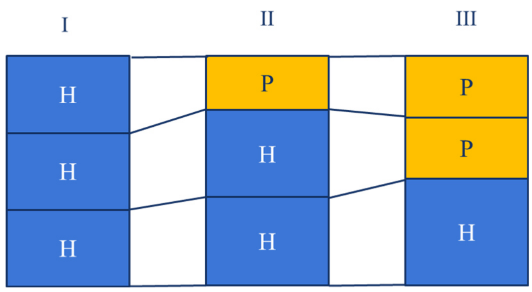


Figure 1: the spiral of increasing prosumer shares and avoidable cost in three stages

In the first stage, all households (H) withdraw the same and hence pay the same. Then the first household becomes a prosumer, withdrawing less from the grid. Part of the cost assigned in the first stage is hence avoided by the prosumer in the second stage. This is made up for by adding cost to the remaining households proportionally to their new share of withdrawals. As a consequence, the cost to be saved by investing in self-supply is larger in the second stage than in the first. This encourages a second household to become prosumer. In the third stage, the remaining household now accounts for an even larger share of shrinking withdrawals and is therefore assigned even more cost. Consequently, his incentive to prosume, i.e. the avoidable cost, has increased even further in the third stage. The existing prosumer from the second stage is also assigned additional cost but is still saving as compared to his pre-self-supply state.

The example illustrates that the incentive for self-supply is propelled by previous investments into on-site generation. The more prosumers there are, the more attractive it becomes for regular households to prosume. In an extreme case, this dynamic reinforces itself until all users have become prosumers.

This paper explores what charges and circumstances lead to such self-reinforcing dynamics. A model analyses the occurrence of instability in the financing, particularly for volumetric charges and surcharges in combination with a high propensity for self-supply in the network. The objective is to model investment into self-supply according to profitability and identify conditions for a system in which self-supply increases but then stalls at a higher level. We analyse options to stabilize the system on a sustainable level of self-supply and verify them in a case-study based on the German framework.

We model three alternative charging approaches, that potentially stabilize the system, namely changing:

- the energy-load split

  Under the initial assumption of rather volumetric charges, one measure is to increase the load share, charging proportionally to user peak load.

- the rebate for self-supply

  The cost which can be saved via self-supply exhibits an indirect rebate. Tariff design can reduce this rebate by accounting not strictly for energy withdrawn from the grid.

- the allocation of cost from upper network levels between parallel grid areas

  Assuming initially that cost is cascaded downwards from higher to lower grid levels, altering the tariff scheme can reduce cost in one network and shift it to another.

The paper is organised as follows: After the introduction, section 2 gives a brief overview of the relevant literature and section 3 introduces the model and the framework of the analysis. Section 4 presents a general analysis based on the model. We first discuss the relation between sustainability and efficiency and then introduce the alternative charging approaches in detail. The section also provides a theoretical analysis of their suitability to re-establish a stable equilibrium. Section 5 follows with a case-study based on exemplary input data for Germany. Finally, section 6 concludes on preconditions of a spiral effect and on the suitability of the charging approaches in practice. It also features a brief outlook on the impact of future trends in the electricity sector on the conclusions.

2 Background and literature

The ideas and analysis in this paper add to the literature on electricity and network tariffs in connection with self-supply. For a good synopsis on the historical evolution of economic theory on tariff design, we refer to the literature review in Simshauser (2016). Picciariello et al. (2015a) provide a comprehensive overview of the more recent literature concerning distribution network tariffs and the challenges with respect to distributed generation.[1]

The debate on the so-called utility death spiral raised interest in electricity tariffs and network pricing to prevent unwanted self-reinforcing dynamics from self-supply. The term refers to the notion that utility-based electricity supply may become obsolete with competition from increasing self-supply via distributed generation. Given the fact that network cost is rather independent of the number of users, self-supply could start a spiral of losing more and more users due to rising specific cost as depicted in figure 1. As described in the theory of network externalities (e.g. Katz & Shapiro 1985, Farrell & Saloner 1986 or more comprehensively Cabral 2000), the system may lock-in to self-supply with an increasing number of user decisions even if overall efficiency advocates a larger share of network-based supply. In standard literature on network externalities utility is often the sum of a constant stand-alone utility and a network utility proportional to the number of users. Analogously, in our model the profitability of self-supply is correlated to the share of prosumers in the grid.

Since the threat of self-reinforcing self-supply was enlisted as a disruptive challenge to electricity supply (EEI 2013), the concept of massive grid deflection due to distributed generation has been analysed in scientific literature with respect to integrated electricity rates as well as unbundled network charges. Costello & Hemphil (2014) acknowledge the significance of technological innovation and update their analysis on rising electricity rates and bypass via self-supply from 1987 accordingly. Felder & Athawale (2014) argue that while increases in PV-based self-supply may diminish utility revenues, overall efficiency and

[1] Pollitt (2018) supplements an account of network tariffs in the context of cost-reflectivity, taxation, platform markets and (multilateral) business models.

societal benefit should be the measure of policies concerning emerging self-supply. Conclusions from case studies concerning the likelihood of a spiral effect vary greatly. Bustos et al. (2019) for example find significant indication for massive grid deflection due to PV deployment in Chile even without subsidies while Prata & Carvalho (2017) eliminate the option for their case study of Portugal. Consistently, Laws et al. (2017) conclude that the occurrence of a veritable death spiral depends largely on factors outside a utility's control such as high PV adoption rates and low expectations for return on investment.[2] Therefore, we employ a model, where prosumers evolve based on a mix of incentives in addition to those from network tariffs and where the propensity for self-supply varies regionally between different subnetworks.

Notwithstanding the likelihood of disruption, many authors observe in case studies and study analytically the distributive effects from self-supply in status quo (e.g. Prata & Carvalho 2017, Schittekatte et al. 2018, Clastres et al. 2019,) and cross-subsidies as deviation from cost-reflective charges (e.g. Picciariello et al. 2015b, Simshauser 2016, Nijhuis et al. 2017, Passey et al. 2017). Many of them evaluate changes in tariff structure to improve cost recovery (Young et al. 2019, Clastres et al. 2019), acceptance, and fairness (e.g. Nijhuis et al. 2017, Neuteleers et al. 2017, Passey et al. 2017) and economic efficiency via cost-reflectiveness (e.g. Picciariello et al. 2015b, Simshauser 2016, Nijhuis et al. 2017, Passey et al. 2017). In contrast and in line with Prata & Carvalho (2017), the main criterion for our analysis preventing a self-reinforcing dynamic in grid areas with a high propensity for self-supply. The electricity distribution system may settle at a self-supply share significantly higher than status quo. Yet, changes in network tariffs are evaluated concerning their ability to stabilize the customer base before all users become self-suppliers. We explore three distinct tariff variations: (1) concerning the energy and load split, (2) the extent of netting between on-site generation and consumption, and (3) a variation in cost pass-through to subnetworks.

Volumetric or energy-based charges are historically common for utility and network pricing especially towards smaller network users (EU 2015, CEER 2020). They are rather predictable and simple (Nijhuis et al. 2017) but have been identified as a main reason for potentially excessive self-supply (Picciariello et al. 2015b, Simshauser 2016, Bustos et al. 2019)[3]. Many studies have linked volumetric charges and particularly netting individual

[2] In fact, the conclusions from Prata & Carvalho (2017) are strongly linked to their assumption of up to 30% of households considering self-supply as an option and on variations of the respective installation cost.

[3] Interestingly, Laws et al. (2017) who examine net-metering not only for grid tariffs but for all volumetric parameters influencing self-supply, including subsidies and energy remuneration find that it reduces

generation and consumption to poor cost-reflectiveness (e.g. Picciariello et al. 2015b, Simshauser 2016) and high cost increase for passive network users (e.g. Schittekatte et al. 2018). The existing studies consider net-metering as a binary variable. By modelling a rebate for self-supply we consider a sliding scale of billing at one extreme all consumption regardless of the source of supply and at the other extreme netting all on-site generation. Additionally, we explore the interaction of netting on network charges recovering cost specific to the network area and of netting for energy cost and surcharges which are largely independent of local consumption levels.

Load- or capacity-based network charges have been advocated as increasing predictability and simplicity, and thus acceptance, yet they are cost-reflective only if based on coincident, not individual or connected capacity (Passey et al. 2017, Nijhuis et al. 2017, Brown & Sappington 2018). Neuteleers et al. (2017) support the acceptance and fairness of capacity charges based on a survey among network users. Young et al. (2019) and Clastres et al. (2019) additionally advocate capacity charges to ensure cost-recovery for network operators where revenue adequacy is not inherent to network tariffs. However, capacity charges are found to lead to larger price increases for passive than for active consumers compared to a status quo with regular volumetric pricing (Schittekatte et al. 2018). Prata & Carvalho (2017) additionally consider that users might increase their connected capacity to accommodate excess generation. Under these circumstances they find that the enlarged capacity rate base levels out the initial distributive effect. To add to the existing assessment of load-based charging, in this paper we propose an option to calibrate a sliding scale between volume- and load-based charges by predetermination as well as endogenously linked to self-supply levels in the network.

Regional variations in network tariffs have hardly been considered with respect to self-supply. Hintz et al. (2018) compare distributional effects and regional variation for transmission charges in Germany in view of increasing self-supply. Their analysis is based on scenarios of exogenously determined self-supply levels. To analyse potentially self-reinforcing self-supply in certain subnetworks, we model the level of self-supply endogenously instead. Rather than limiting regional variations, we explore the option of embracing them and adjusting the cost pass-through from higher network levels in order to limit excessive incentives for self-supply in network areas that are already under pressure.

the likelihood of a self-reinforcing dynamic. This is in line with our findings in section 5 that adjusting the energy rebate for self-supply can have reverse effects for network tariffs than regarding other surcharges.

3 Model

We employ a model to analyse the profitability of investment into self-supply with different charging schemes. The model consists of two network levels populated with two types of users: regular households (H) and prosumer households (P) with PV for self-supply. Network cost is assigned to single users or between network areas on energy and /or peak load.

Prosumers withdraw less energy than they consume as some energy is generated on site. Prosumers' peak load, however, is the same as regular users. We assume that household peak load occurs in the evening when PV self-supply does not interfere. Regular households can invest in PV and thus become prosumers themselves. These investments depend on profitability, i.e. savings minus the cost of self-supply. Savings stem from reducing electricity delivery from their supplier through the network and are comprised of saved electricity cost, saved taxes and surcharges and saved network charges.

There are several concepts to account for the energy reduction through self-supply, most prominently coincident and net metering. While consumption remains the same, the withdrawal from the grid is reduced whenever consumption and self-generation coincide. Hence, energy withdrawn from the network is lower than energy consumption. In addition, prosumers inject energy into the grid whenever self-generation is larger than consumption.

What users actually pay depends on metering. We distinguish the following two types of metering. *Coincident metering* accounts for the energy actually withdrawn from the grid at any moment. Hence consumption is netted for coincident generation only. With *net metering*, consumption is reduced not only by coincident generation but by all energy generated over a certain period. Hence with net metering billed energy is even lower than withdrawn and consumed energy. Figures 2 illustrates these concepts.

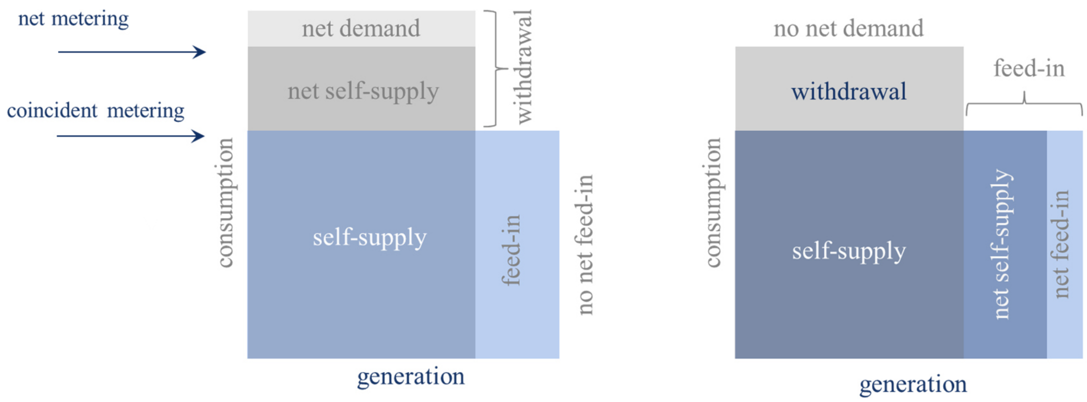


Figure 2: different concepts for billed energy with self-supply

The profitability of investment into self-supply (π) is derived as the difference between savings (S) from self-supply and cost of self-supply (C_S) (see formula (1)). Formula (2) shows savings to consist of

- saved network charges (s_N),
- saved energy-based surcharges (s_S) and
- saved energy cost (s_E).

Cost in the case of PV-based self-supply is only investment cost (see formula (3)), maintenance is considered very small and therefore neglected. Profitability as well as savings from network charges and surcharges and cost are a function of the share of self-supply in the model network, denoted by α.

$$\pi(\alpha) = S(\alpha) - C_S(\alpha) \quad \textbf{(1)}$$

$$S(\alpha) = s_N(\alpha) + s_S(\alpha) + s_E \quad \textbf{(2)}$$

$$C_S(\alpha) = C_I(\alpha) \quad \textbf{(3)}$$

The main term for the analysis in this paper are saved network charges (s_N). We consider only use-of-system charges because connection charges are usually not related to users' usage pattern. We assume that the annual network charge for a single user (P_N) consists of an energy-based and a load-based component as presented in formula (4).

$$P_N = q_u \cdot \frac{C_N \cdot e}{Q(\alpha)} + L_u \cdot \frac{C_N \cdot (1-e)}{\sum_n L} \quad \textbf{(4)}$$

Energy share (e), and load share (1-e) respectively, are determined by the network operator or the regulator and add up to 100%. These parameters divide total network cost (C_N) into a proportion assigned via the user's yearly energy (q_u) and contribution to network peak load (L_u). Total energy in the network (Q) and respectively network peak load are summed over all users (n).

$$\sum_n L = n \cdot L_u \quad \textbf{(5)}$$

$$Q(\alpha) = \sum q_H + \sum q_P = n \cdot q_H \cdot (1 - \alpha + d \cdot \alpha) \quad \textbf{(6)}$$

We assume that regular households as well as prosumers have their peak load in the evening when no coincident PV generation reduces consumption. Hence peak load is the same for regular households and prosumers. In a model network populated only with identical households and prosumers the network peak is the sum of all users' evening peaks (formula (5)). Overall energy is the sum of individual energy of all users. To adjust for the share of prosumers (α) in the model network and for the extent of their energy reduction (d) we include the latter term in formula (6).

$$q_P = d \cdot q_H \quad \textbf{(7)}$$

Prosumers' energy reduces compared to regular households by the factor d. The reduction depends on the netting concept applied for billing as depicted in Figure 2. With coincident metering d accounts for the fraction of consumption withdrawn from the network when no coincident PV generation is available. The factor decreases when net metering is applied. Thus, potential savings from becoming a prosumer are highest with net metering. The reduction factor (d), and respectively the potential savings are lowest when billing occurs irrespective of generation, meaning no rebate even for coincident generation. In theory the fraction of consumption is decided 'freely' by the network operator or regulator, in practice however, coincident and net metering are the most common concepts.

Saved network charges are the difference in network charges for a regular household and for a prosumer. Using the above we determine them as follows in formula (8).

$$s_N(\alpha) = P_{N,H} - P_{N,P} = \frac{C_N \cdot e \cdot (1-d)}{n(1-\alpha+d\cdot\alpha)} \text{ with } \mathrm{C_N}, \mathrm{e}, d, n > 0 \text{ and } \frac{\partial s_N}{\partial \alpha} > 0 \quad \textbf{(8)}$$

Besides network charges, self-suppliers also save energy cost and energy-based surcharges. In formula (9) saved energy cost is the product of energy prices (p_E) and the share of a household's energy demand (q) reduced via self-supply (d). For the model we assume energy prices to remain constant with increasing shares of self-supply[4]. Subsidies for renewable energies and other efficient and innovative technologies, energy taxes and other price components (σ) are often added to end users' bills per consumed energy. For surcharges that redistribute given cost, e.g. for the support of renewable energies, in principle the same dynamic described for network charges in figure Figure 1 applies. While the amount to be redistributed is at best unaffected by self-supply, energy volumes decline. Thus, specific surcharges rise. However, the boundary for redistribution may not be limited to a network area only. Hence the effect is somewhat mitigated as compared to network areas with a steep increase in self-supply. Also, not all surcharges are redistributive, some are fixed or by percentage. Consequently, we model energy-based surcharges as exponentially increasing with prosumer shares (α) from a basis (β) with an intensity of v (see formula (10)).

$$s_E = q \cdot d \cdot p_E \text{ with } \frac{\partial s_E}{\partial \alpha} = 1 \tag{9}$$

$$s_S(\alpha) = q \cdot d \cdot \sigma \cdot \beta^{(v \cdot \alpha)} \text{ with } q, \sigma, v > 0, \beta > 1 \text{ and } \frac{\partial s_S}{\partial \alpha} < \frac{\partial s_N}{\partial \alpha} \tag{10}$$

For the case of PV self-supply, the cost side is limited to investment cost. In formula (11), we consider that the initial investment (I_{PV}) increases in view of increasing prosumer shares due to the deterioration of sites available for new PV plants. As self-supply becomes more profitable, an increasing number of households invest whose preconditions are not perfectly suited for PV generation. With panels facing east or west instead of south, partially shaded panels or even PV facades, yield declines. Hence, the investment cost to achieve the same electricity output increase. The second term of the sum in formula (11) describes an exponential cost increase from an initial availability (b) with an intensity of z, again proportional to the prosumer share (α).

$$C_I(\alpha) = I_{PV} + b^{(\alpha \cdot z)} \text{ with } z > 0, b > 1 \text{ and } \frac{\partial C}{\partial \alpha} > 0 \tag{11}$$

In the following we analyse the influence of changes in network tariffs on self-supply dynamics. Hence, we focus on saved network charges, as defined in (8) and sum up all other savings and cost (formulas (9), (10) and (11)) as residual net benefit (r) in formula (12). Taking formula (1) into account, profitability (π) is simplified in (13) to the sum of saved network charges (s_N) and residual net benefit.

[4] The assumption is arbitrary to some extent. One might as well assume decreasing average cost with increasing excess PV-supply from prosumers. The assumption of increasing average energy cost, due to lower utilization of flexible peak load plants seems valid.

$$r(\alpha) = s_S(\alpha) + s_E - c_I(\alpha) \quad \textbf{(12)}$$

$$\pi(\alpha) = s_N(\alpha) + r(\alpha) \text{ with } \frac{\partial s_N}{\partial \alpha} > 0 \text{ and } \frac{\partial r}{\partial \alpha} < 0 \quad \textbf{(13)}$$

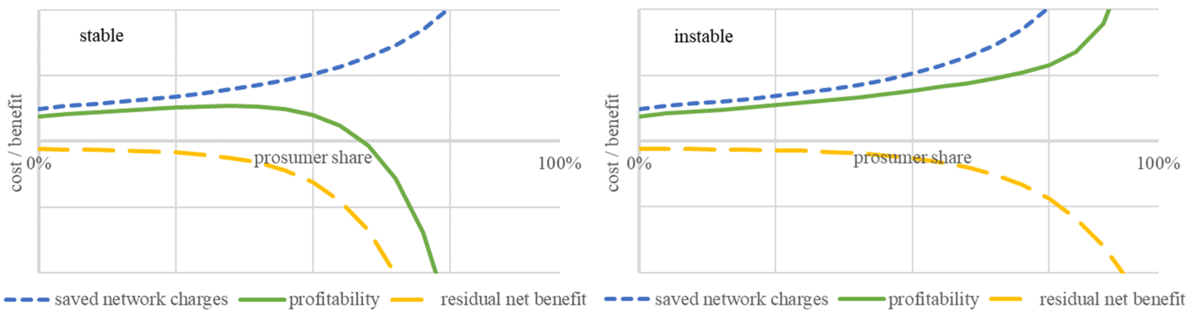
4 General analysis

Modelling investment into self-supply in electricity networks as presented in section 3 enables a general understanding of the dynamics. The following presents the main insights from a general analysis. Distributed generation and self-supply are generally positively connotated. Thus, there are often subsidy schemes to promote them. Yet, the concept of a 'utility death spiral' following the self-reinforcing dynamic described in section 2 has brought about a new perspective. Too much self-supply could render network-based supply and the efficiency that comes with it obsolete. As a starting point for our analysis we replicate this effect in our model.

4.1 Stability and efficiency

Figures 3 a and b depict profitability as the sum of saved network charges and residual net benefit (formula (13)). In both figures the savings to be obtained from network charges by investing into self-supply rise with the share of network users that are prosumers. On the left, in 3a, residual net benefit is characterized by a steep, exponential decrease. At a certain prosumer share this decrease outweighs the increase in saved network charges. Hence, profitability starts out positive for low prosumer shares but becomes negative as more and more network users invest into self-supply. With zero or negative profitability no further investment occurs, and the system stabilizes at said prosumer share. On the right, in 3b, however, the decrease of residual net benefit is assumed more moderate. In this scenario, possible savings from investing into self-supply dominate and profitability increases even for very high prosumer shares. As long as profitability increases, network users continue to invest into self-supply and the trend to invest into self-supply reinforces itself. Eventually, with 100% prosumer the networks' utilization becomes so low, that network supply is rendered economically unfeasible.[5] Hence, in this scenario the finance of the system destabilizes once the increase in self-supply has started.

[5] In our analysis we refer to prosumer share and not self-supply share. Since PV generation does not fully coincide with demand and as we do not consider the use of batteries, these parameters are not identical. Hence, even at 100% prosumer share there is still some energy consumed from the network. We assume, however, that this proportion is not sufficient to sustain the existing network or that depending on the rebate for self-supply (4.2) this network usage is not paid for.



Figures 3 a & b:dynamics of self-supply in a stable (a) and an instable (b) scenario

Under the assumption of steep exponential decrease in residual net benefit, as depicted in figure 3a, the self-reinforcing effect is mitigated by market dynamics. At some point profitability drops below zero and the number of prosumers in the system stabilizes. It is in the second scenario, depicted in figure 3b, that we can observe a spiral effect of self-reinforcing self-supply. Prosumers will switch to self-supply with positive profitability. Therefore, in this second scenario investments continue until all network users are prosumers. There is no stable level with a moderate number of prosumers as in the first scenario.

As profitability is comprised of saved network charges and residual net benefit, the course of those two terms define whether the system is stable or not. In the first scenario the effect of the other drivers summed up in residual net benefit outweighs the impact of savings in network charges, i.e. in this scenario the deterioration of sites with larger prosumer shares dominates over increasing savings. As a result, the system is stable. In the second scenario, however, saved network charges dominate and the finance of the system destabilizes once self-supply has started.

We point out that an instability as such is not necessarily economically inefficient. In a setting where self-supply becomes cheaper than the cost of interconnecting users for collective supply, instability is the logical and efficient consequence. If network charges however, assign a too large proportion of overall cost to an elastic demand, the incentive to defect from the network is inefficiently high. We assume network cost as entirely fixed and unaffected by daytime demand reductions via self-supply. Under these assumptions, efficient charges should render daytime use cheaper to boost utilization and the social welfare that comes with it.[6] Thus, the observed excessive incentive for self-supply, and the resulting financing instability, is caused by the volumetric charging approach. In practice, there are many reasons to implement partially volumetric charges and they are fairly common.

[6] To understand this in more detail see Brandstätt (2021).

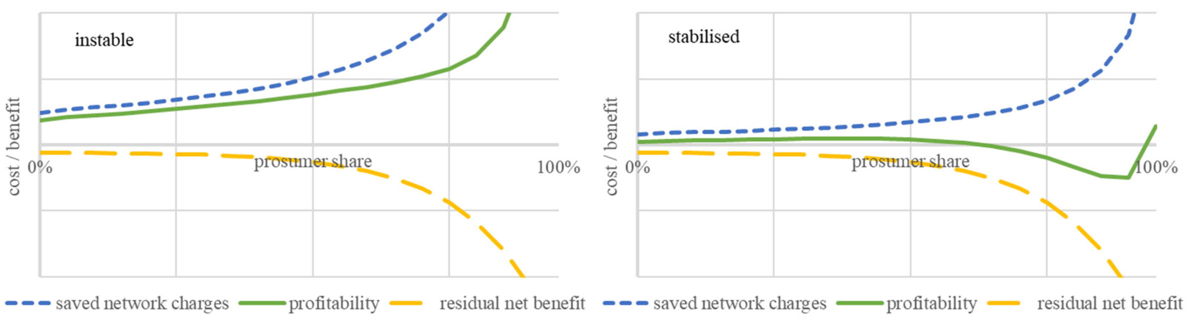
Therefore, we propose changes within a partially volumetric charging scheme to stabilize a system with self-supply and prevent a spiral effect.

4.2 Remedies for instability

In the following we analyse options to counteract this self-enforcing dynamic by modifying the network charging scheme and hence changing the savings from and consequently the incentives for self-supply. We focus on three main aspects of the charges: (1) energy/load-split, (2) rebate for prosumers' energy reductions and (3) cost split between parallel network areas. We find that all three aspects serve to a certain extent to tune network charges to prevent self-reinforcing dynamics.

Option 1: Energy / load split

The first countermeasure to be discussed is a modification of the energy/load-split in network charges. In formulas 4 and 8 the parameter *e* denotes to which extent total network cost is distributed to network users based on their energy volume. The reverse (1-*e*) is passed on according to users' peak load respectively. Investment into self-supply decreases a users' energy volume but is assumed not to affect its peak load. Hence the larger the cost share distributed via energy the higher the savings for prosumers. A higher load share, on the other hand, reduces potential savings for prosumers and consequently reduces profitability of investments into self-supply. Hence, higher values for *e* steepen the upward slope of saved network charges. Correspondingly, as depicted in figure 4, low values for *e* slow down the slope of the saved network charges curve. All else equal, this affects the course of profitability and promotes its intersection with the horizontal axis. Bringing profitability of investment into self-supply down to zero eventually stabilizes the system.

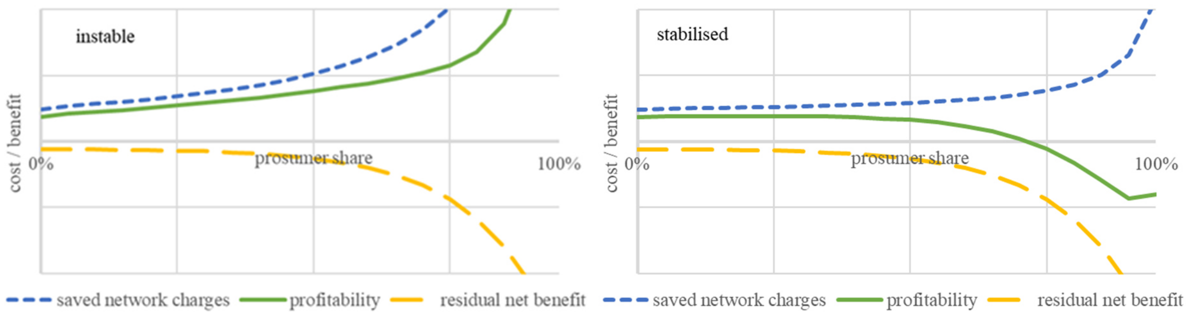


Figures 4 a & b: mitigating a self-reinforcing dynamic by modifying the energy/load-split

Figures 5a depicts the instable scenario from figure 3b and one possible stabilization via a increasing energy share. In figure 4b the graph of saved network charges has moved downwards compared to Figures 3 as a result of an increased load fraction in network charges. Consequently, also profitability is shifted vertically and now intersects the horizontal axis. Once profitability becomes zero, no further investment into self-supply occurs. Hence the self-reinforcing dynamic is mitigated by altering the energy/load-split in network charges.

This measure is often considered in view of self-supply as it is deemed more cost-reflective and therefore more efficient. We note that efficient pricing distinguishes between the users demand during network peak and off-peak times. Yet, the parameter modelled here (and often implemented in practice), is individual peak load. Therefore, the assumption that shifting to load-based pricing is more efficient is not necessarily true. The same holds for pricing based on users connected capacity. However, we consider only two types of users in the network and assume they have the same peak load. Thus, in our framework shifting the pricing approach more towards individual peak load coincides with network peak load and is therefore more cost-reflective and gains efficiency.

We have shown, that increasing the load share can stabilize a system with increasing self-supply. Yet, the determination of an adequate energy/load-split is not trivial. For a network with low prosumer share and low propensity for self-supply the energy share can remain high as it is in many countries today. With increasing prosumer shares on the other hand, a higher load share is beneficial as described above. Consequently, an interesting design option may be to link the energy/load-split to the prosumer share in the network. This automates the price discrimination between regular and prosumer households. The latter of which cannot escape the charges further, as opposed to the former for whom the charges are an incentive to invest into self-supply. Figures 5 show the effect of a simple correlation, where the load part ($1-e$) equals the prosumer share (α). Other, more complex correlations between load- and energy-split and prosumer share are possible as well. It becomes clear in the figure that the self-reinforcing dynamic is mitigated with this tariff alternative as well.



Figures 5 a & b: mitigating a spiral effect via variable energy/load-split

Option 2: Reducing the rebate for self-supply

A second important parameter in self-reinforcing dynamics is the rebate for self-supply. There is no explicit rebate but self-supply implicitly causes a reduction in billed energy. The size of the rebate depends on the principle of netting as sketched in figure 2. Depending on the concept applied billed energy may be total consumption, withdrawal from the grid, i.e. consumption adjusted for coincident local generation, net-metered withdrawal, i.e. consumption netted for local generation during a set period – or any other delineation in between. In practice we observe that a plausible narrative, i.e. one of the three mentioned concepts discussed, is usually preferred and considered more acceptable for network users. However, in theory, a sliding scale can be applied.

In our model the reduction of billed energy via self-supply is denoted as d. Low values for d, i.e. between 0 and 0,5, mean large rebates for self-supply and thus increase the upward slope of saved network charges. Correspondingly, high values for d, i.e. between 0,5 and 1, bring the slope of saved network charges down as depicted in figure 6. A lesser slope in saved network charges translates into the course of the profitability curve, making it more likely to intersect with the horizontal axis. If profitability is brought down to zero, investment into self-supply stalls and prevents the spiral effect.

However, d also affects the term of residual net benefit. If the same billing concept applies to network charges as well as energy cost and surcharges, reductions in saved network charges go along with less savings.[7] Consequently residual net benefit is shifted upwards. The resulting profitability still intersects the horizontal axis at some point. With profitability below zero investment into self-supply stalls and the system stabilizes at the respective prosumer

[7] This may not be completely intuitive. For savings from energy and surcharges the rebate simply reduces the quantity charged for. Thus, a reduction increases savings. Yet, for network charges the rebate also reduces the individual quantity but at the same time reduces overall demand, meaning that cost is split among less overall withdrawal. This increases individual network charges and reduces savings. Technically, the same dynamic applies to surcharges, but we assume that the effect is small within one network area (see section 3).

level. Thus, reducing the rebate for self-supply serves to prevent the self-reinforcing dynamics of self-supply.

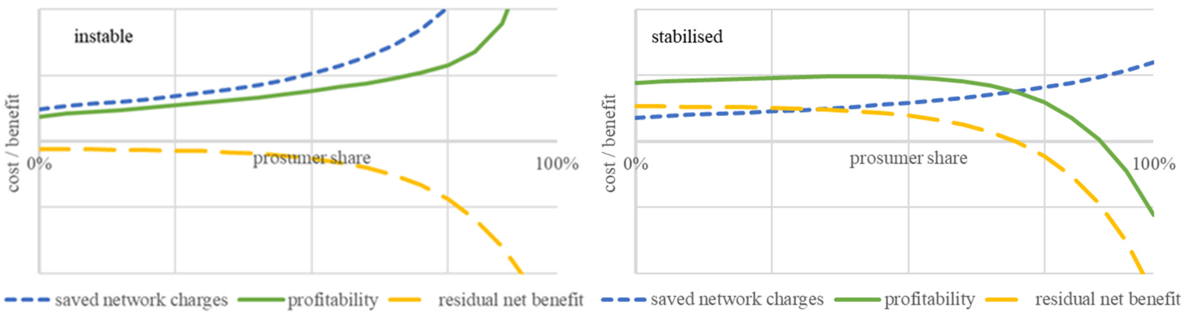


Figure 6a & 6b: mitigating a spiral effect by altering the rebate for self-supply

Billing network charges for total consumption, regardless of whether the energy is generated on site or withdrawn from the network, corresponds to $d = 1$, meaning no rebate for self-supply at all. On the other extreme, net metering, i.e. netting energy withdrawn from the grid for local generation during a set period, results in d up to zero, eliminating the volumetric part of network charges for self-suppliers[8]. Generous rebate concepts for self-supply are often implemented in practice to promote self-supply and distributed generation. It is then consistent to reverse the support, i.e increase d, when a desired self-supply level is reached. In theory, tying the rebate to the share of self-suppliers in the network can be considered. However, a sliding scale for determining the energy reduction is not intuitive and hence maybe not be accepted by network users.

In terms of acceptance and transparency, it seems desirable in practice to apply a consistent concept of determining billed energy for network charges, energy cost and surcharges. Yet this countertrades the effect on saved network charges with effects in the realm of saved energy cost and surcharges. Also, reducing the rebate entails a negative distributive effect for existing prosumers. While this could be prevented via grandfathering, preserving the benefits for existing self-suppliers also limits the effect on saved network charges for further self-suppliers.

Option 3: Allocation of network cost from upper network levels between parallel grids

The last alternative discussed in this paper is to change the cost pass-through of network cost from upper levels to parallel, lower grids. This concerns how cost is passed down between network levels. We assume that the cost of upper network levels is at least

[8] Importantly, and opposed to option 1, this eliminates the volumetric part of network charges for self-suppliers only. If charges overall more load-based, the investment incentive is reduced. Yet, if only self-suppliers save on the volumetric part, the incentive becomes even stronger.

partially passed down to subsequent levels and split between several parallel lower levels as depicted in figure 7.

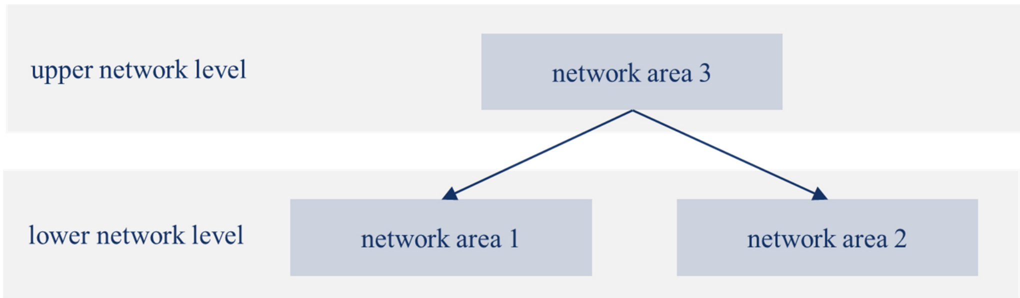
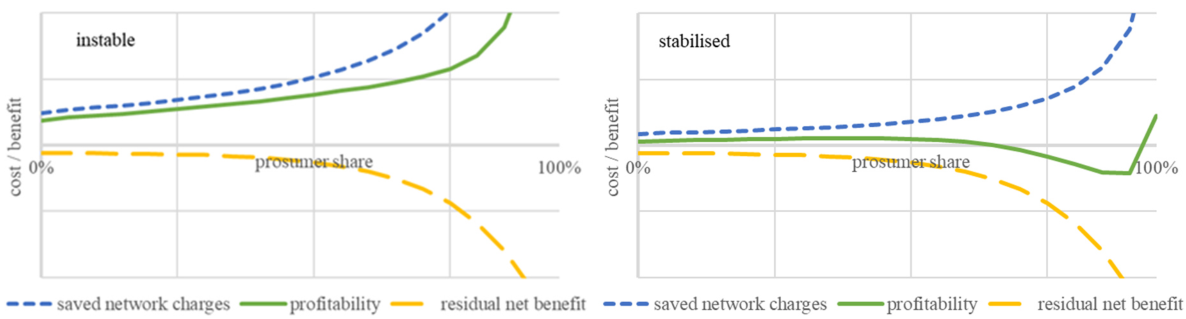


Figure 7: cost allocation between network levels

To prevent excessive incentives for self-supply, network cost may be partially shifted from a network area with a lot of potential self-supply to a parallel one. For example, in figure 7 level 1 would bear less cost from the upper level which is made up for by increasing cost for level 2. In formula 4 this means a reduction of C_N in one network and an increase in the other. With high network cost there is a lot to be saved via self-supply. Hence, high values for C_N push the curve of saved network charges up and away from the horizontal axis. Correspondingly, low values for C_N keep the curve low and close to the axis as depicted in figure 8. This effect translates to the resulting term of profitability. Hence, low values for C_N make it more likely for profitability to intersect with the horizontal axis, i.e. become zero and hence stall further investment. Therefore, in the instable scenario of self-reinforcing self-supply, a reduction of network cost in the concerned network stabilizes the finance of the system. This is shown in figure 8.



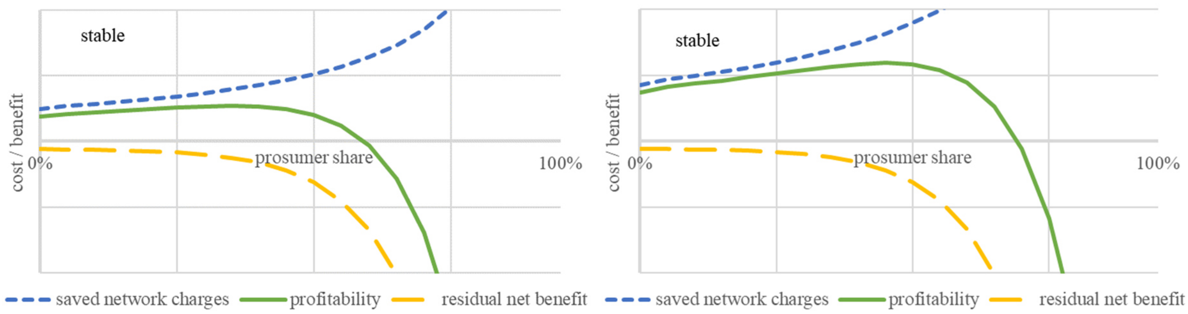
Figures 8a & 8b: mitigating a spiral effect by a shifting network cost away

Figure 8a, on the left, reminds the instable scenario, which serves as the basis for this analysis. If cost is reduced in the respective network level, this decreases possible savings from network charges. Consequently, saved network charges and thus also profitability decrease. In figure 8b, on the right, the curves are shifted downwards. In result, profitability and with it the incentive to invest in self-supply becomes zero (and eventually) negative before the prosumer share hits 100% percent. Hence, the system has a new, stable level of self-supply.

The cost reduction in one network area, however, brings about an increase in network cost in a parallel network area. We assume that in the status quo network cost is normally cascaded downwards from higher to lower network levels. Hence, two identical parallel network areas bear the same cost fraction of their upstream level. With bi-directional allocation, cost is shifted from one network level to the other.[9] In effect, network cost decreases in networks with high propensity for self-reinforcing self-supply and increases in networks less likely to develop a spiral effect. This is achieved by changing the charging scheme between network levels. The shift of cost from networks with high propensity for self-reinforcing dynamics towards networks with lower propensity can be linked to a kind of Ramsey pricing approach, where fixed cost is allocated to distort demand the least, i.e. is incurred by those with the least flexibility to avoid cost. The propensity to shift to self-supply then exhibits an elasticity to network prices between network areas. In some network areas consumers can shift to self-supply if network-based supply becomes expensive. In other network areas this option is less available. Hence, it can be efficient for the network operator to shift cost towards customers with lesser elasticity, i.e. into network areas with a lower propensity for self-supply.

The cost increase may actually create financing instability in the other network area, which was originally less prone to self-supply. In effect, we would have shifted the instability of one network into another and nothing would be gained. Now, particularly if the slope of residual net benefit differs substantially between two parallel network levels, it is possible to avoid this problem and to achieve stability in both networks. Figure 8 depicts a network level with high propensity for self-reinforcing self-supply. In contrast, figure 9 shows the effect of increased cost on another network with less propensity for self-reinforcing dynamics.

[9] In fact, the details of the alternative allocation approach are irrelevant so long as it reduces cost in the self-supply intensive network area. One can think of a bi-directional allocation in analogy to the netting approaches for network users. It is common to allocate cost to lower network levels according to their withdrawal from upper levels, i.e. to apply coincident metering. A switch to a net metering approach between network levels would take upward feed-in into account. This lowers the cost allocated to network levels with higher self-supply shares and produces the desired effect of stalling the self-reinforcing investments.



Figures 9 a&b: effect of a shift of network cost on the parallel grid

Figure 9a, on the left, depicts the stable scenario of a network with an exponential term for residual net benefit (see figure 3a). Increasing the cost in this network increases saved network cost and profitability and shifts the respective curves upwards in figure 9b. However, due to the exponential term of residual net benefit the system does not become instable. Even with the cost increase there is a stable share of prosumers, albeit somewhat higher than before. Hence, by shifting cost from the network in figure 8 to the one in figure 9 self-reinforcing dynamics do not destabilize the system in both networks.

The proportion of the cost-shift can be a fixed share but may also be determined by a function. In theory the assignment of cost between network levels can differ from the charging rule for end users. Hence for example a load-based approach can be applied between network levels even if end-user charging continues to follow volumes. Just like it is difficult to assess the elasticities for Ramsey prices, also the course of residual net benefit, i.e. the propensity for self-supply, is difficult to assess for a certain network. And just like with Ramsey prices, the shift of cost may fall short of what the public perceives as fair. While it seems efficient to push the cost towards a network less likely to switch to supply alternatives, the scheme is not necessarily cost reflective. Consequently, it may distort signals for flexibility and thus forego efficiency.

5 Case-study results

In the following, we apply the model and the findings from the general analysis to a case-study based on the German framework. We analyse a scenario with moderate evolution of investment cost for self-supply and one with a steep exponential increase. This setup allows us to explore the three options to counteract self-reinforcing dynamics discussed above in a more practice-oriented setting. The results hint at the relevance of the effects observed in the theoretical setting. Formulas (14) and (15) expand the basic model for the practical application in the case-study.

$$d = 1 - \frac{k_{PV} \cdot \tau_{PV} \cdot \varphi}{q_H} \tag{14}$$

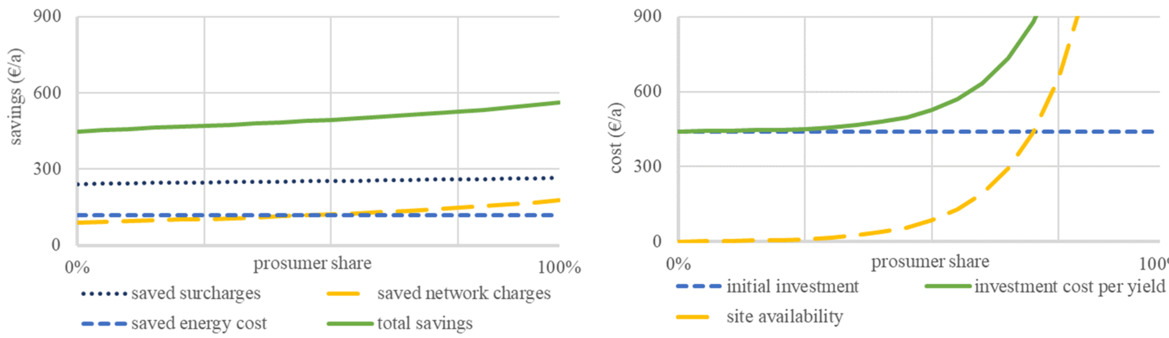
$$I_{PV} = \frac{p_{PV} \cdot k_{PV}}{t} \tag{15}$$

Formula(14) specifies the reduction factor for billed energy (*d*). The energy volume is reduced corresponding to installed PV-capacity (k_{PV}) multiplied by a yield factor (τ_{PV}), adjusted for the coincidence of self-supply (φ). When netting not only coincident but any generation and consumption of a billing period (net metering) the coincidence factor (φ) amounts to 1. Thus, the amount of energy billed to prosumers is lower with net metering than with coincident metering. Formula (15) specifies the initial investment (I_{PV}) as the product of price per peak capacity (p_{PV}) and PV capacity (k_{PV}) discounted over its the lifespan (*t*). Table 1 sums up parameters for a low voltage grid and on-roof PV in Germany.

Parameter	symbol	Unit	Value	reference
prosumer share of network users	α	%	0 – 100	assumption
total annual network cost	C_N	€/a	200.000.000	assumption
number of network users	n	-	8.500.000	assumption
energy share	e	%	75	assumption
energy reduction factor	d	-	0,5	assumption
household yearly energy demand	q_H	€/a	3.000	assumption
energy price	p_E	€/kWh	0,0794	BNetzA 2020
energy-based surcharges and taxes	σ	€/kWh	0,1603	BNetzA 2020
PV installation cost	p_{PV}	€/kW$_p$	1100	Fh ISE 2020
PV lifespan	t	A	20	Fh ISE 2020
PV yield	τ y_{PV}	kWh/kW$_p$	900	Fh ISE 2020
consumption coincidence factor PV	φ	%	20	Fh ISE 2020
installed PV capacity	k_{PV}	kW$_p$	8	assumption
basis for surcharge evolution	β	-	1,01	assumption
intensity of surcharge evolution	v	-	2	assumption
basis for deterioration of sites	b	-	1,4 & 1,25	assumption
intensity of deterioration of sites	z	-	20	assumption

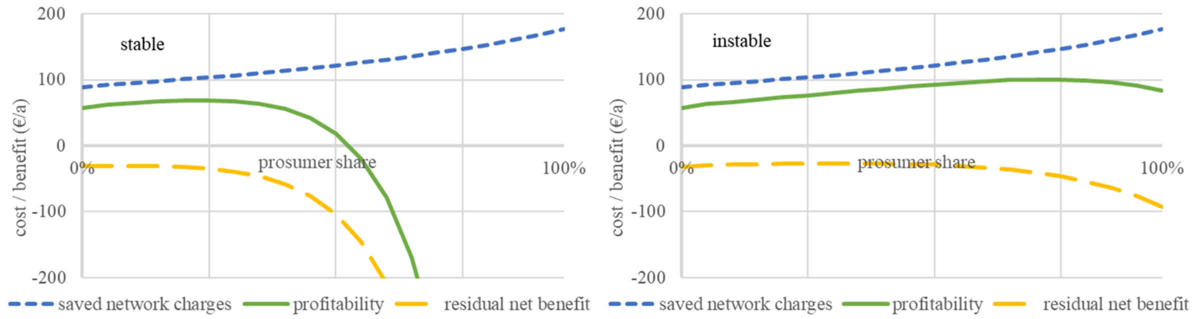
Table 1: parameters for the case-study

The share of prosumers is varied between 0 and 100 %, reflecting the bandwidth from no prosumers at all up to a rather hypothetical all prosumer network. Total cost and number of network users are assumed such that network charges amount to around 7 ct/kWh for 30% share of prosumers. In 2019 17,6% of overall consumption were supplied on-site, including commercial and industrial self-supply (BNetzA 2020). Further we assume a rather energy-based pricing that assigns 75% of total cost according to energy volumes, as it is in place in Germany, and an average demand of 3000 kWh per household. The reduction of energy demand down to 40% for prosumers corresponds to a conservative estimate for an 8 kWp PV-plant with an average production of 900 kWh per kWp (FhISE 2020) and a consumption coincidence of 25% (FhISE 2020). Energy retail as well as surcharges and taxes are the average values published by the regulator for 2019 (BNetzA 2020). The remaining factors are set for the evolution of parameters to match intuition. Figures 10 a and b depict the evolution of cost and savings according to the model and the values in table 1, with intensive deterioration of PV sites on the left and modest deterioration on the righthand side.



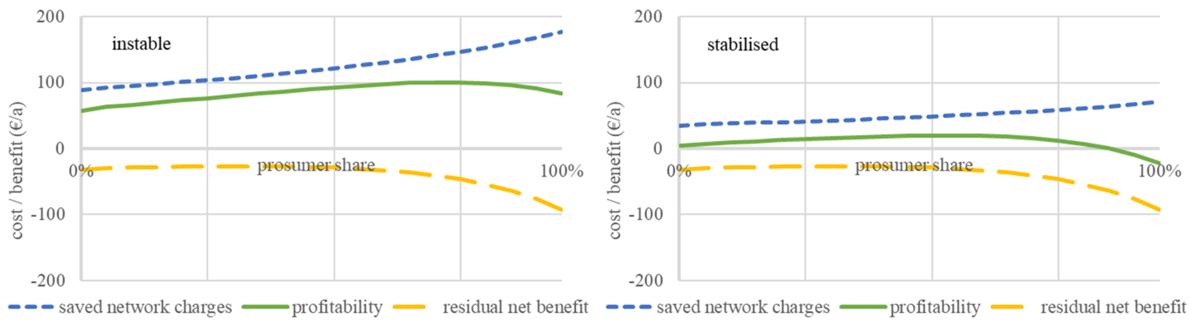
Figures 10 a & b: evolution of cost and savings in the case-study

Savings, particularly saved network charges rise with increasing prosumer shares. Saved energy cost is assumed as a constant. Savings from surcharges increase somewhat slower than saved network charges. Their effect evens out over the entire energy system and does not correlate strongly with prosumer shares in just one network. The overall cost of investment into self-supply rises relatively steeply with prosumer shares. This stems mainly from the exponential term for the deterioration of available sites. From these parameters and assumptions, we obtain two scenarios. One for a system leaning towards self-reinforcing dynamics and another where self-reinforcing dynamics are mitigated by exponential cost. Both are depicted in figures 11 a and b.



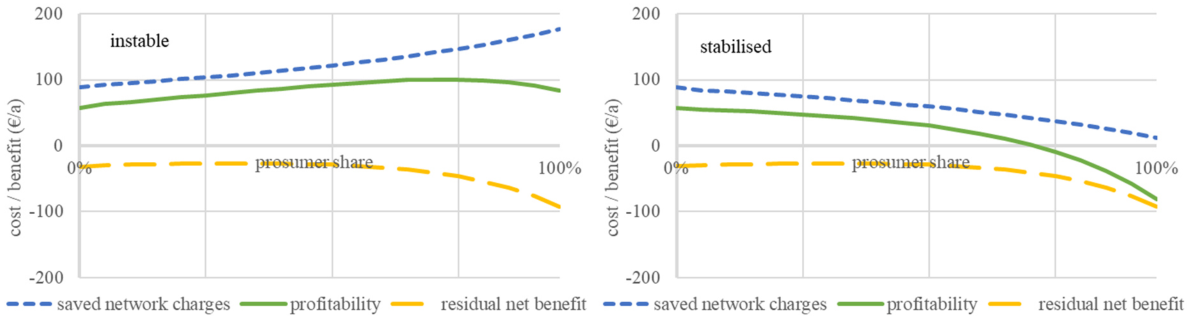
Figures 11a & b: stable system and spiral effect in the case-study

In the left-hand scenario, profitability and thus the self-reinforcing dynamic is prevented by the exponential course of residual net benefit. Contrarily on the right, profitability remains positive no matter how high the shares of prosumers. Hence, a self-reinforcing dynamic of more and more self-supply unfolds. The two scenarios can be interpreted as two extremes in a bandwidth of networks with varying propensity for self-supply. In the context of our analysis, they may be considered representative of different network types, e.g. an urban network where available sites use up relatively quickly and a rural network with plenty of adequate surfaces. In the following we will explore the options to prevent the self-enforcing dynamic in the left-hand scenario by changing the network tariff scheme as suggested before. Figures 12 a and b illustrate the potential and limits of altering the load- and energy split.



Figures 12 a & b: mitigating the spiral effect via load- and energy split

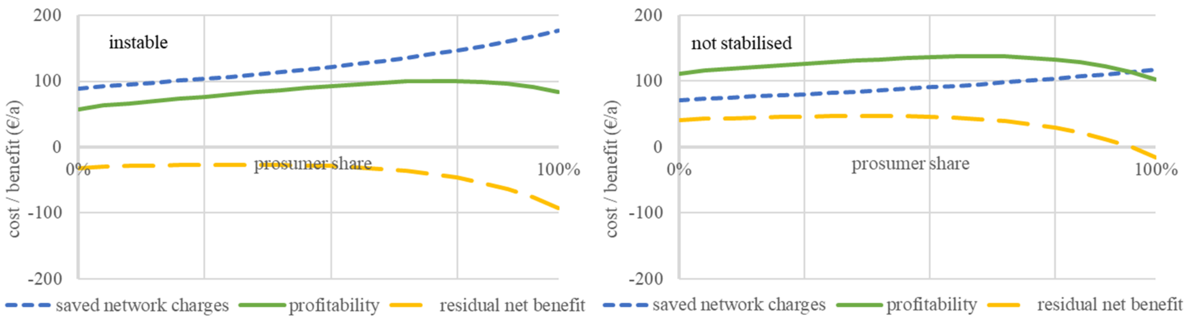
In figure 12 the load- and energy split is reduced to 30 % energy-based cost share in the graph on the righthand side (12b) as compared to the reference on the left (12a). With this charging option profitability becomes zero and eventually negative for very high prosumer shares. As a result, the self-reinforcing dynamic is mitigated.



Figures 13 a & b: correlating the load-energy split to self-supply

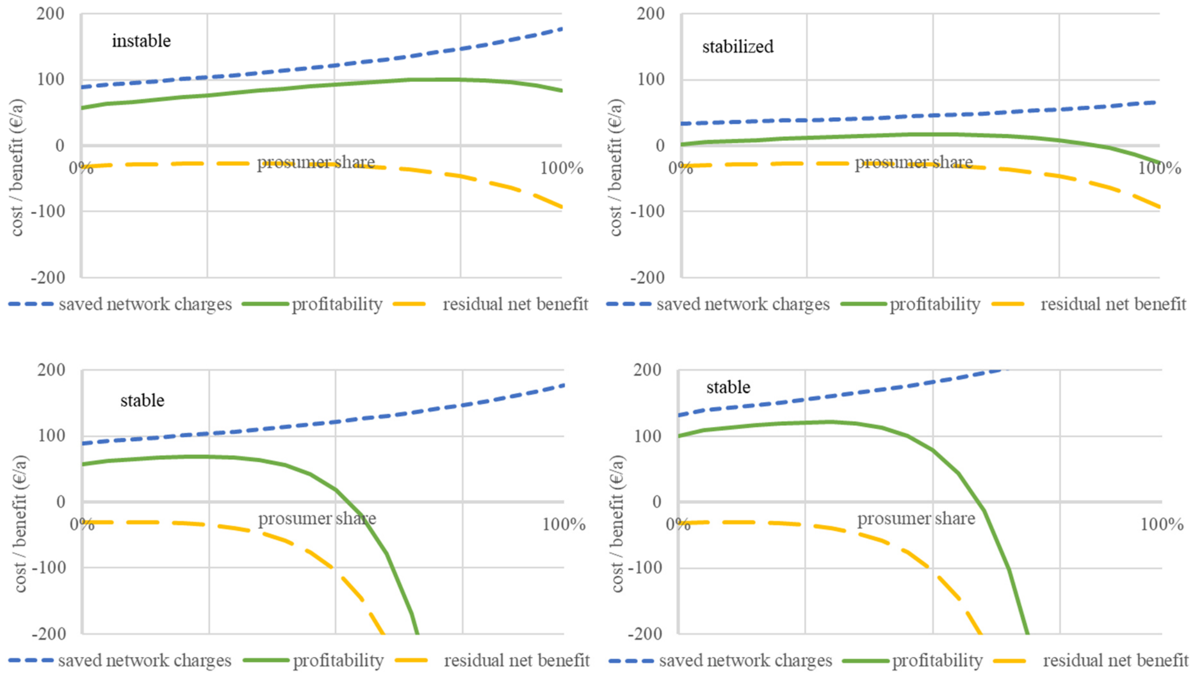
Correlating the load-energy split with the prosumer share as depicted in figures 13 a and b achieves the same. Yet the stabilization occurs already at lower self-supply shares. A more intense correlation leads to even earlier stabilization.

Next, adjusting the rebate for self-supply does not produce the desired effect in the case-study. Initially we assume that with coincident metering in place in Germany a prosumer reduces consumption from the grid by 50%. In figures 14 we show the effects of reducing the rebate, so that prosumers are billed for 60 instead of 40 % of their consumption (14a). This lowers the possible savings from network charges but at the same increases the other savings as described in section 4.2. This second effect dominates, and as a result profitability is increased instead of reduced by the measure. However, the measure could be effective, if the rebate is defined independently for network charges and does not apply in the same way for saved energy and other surcharges.



Figures 14 a & b: altering the rebate for self-supply

The third option, shifting cost from one network to another, successfully mitigates self-reinforcing effects for the case-study. Figures 15 a and b show the effect of shifting 1.250.000 €, more than half of the network cost, away from a parallel network prone to self-reinforcing dynamic. The shift brings down profitability below zero in the network with only moderate deterioration of sights which is instable without the measure. The cost is shifted to another network area less inclined to self-supply. This increases saved network charges and consequently profitability in this other network. Yet due to the more exponential correlation between cost and prosumer share profitability still drops below zero and self-reinforcing dynamics are mitigated as shown in figures 15 c and d.



Figures 15 a, b, c & d: mitigating the spiral effect by shifting cost between parallel networks

In sum, self-reinforcing dynamics can be mitigated via altered network charges in the case-study. However, all practical solutions may be considered somewhat extreme. The load-energy split required to stabilize the finance of the system even at a very high prosumer level is found at 60 vs 40%. It is likely that an even lower level of self-supply is considered desirable and hence an even stronger load-based charging would be needed. Hence, coupling the shift to the network's prosumer share seems promising. The same holds for shifting cost between parallel networks. In our case-study, shifting as much as 50% of the total cost to another level, stabilizes the system at a rather high prosumer share. To obtain a lower, possibly more reasonable prosumer share, a substantial amount of cost would have to be shifted. In practice, a combination of several approaches may produce a desirable result.

6 Conclusions

In this paper, we analyse the circumstances under which self-supply leads to a self-reinforcing dynamic. We present three options for network charging which are suitable to prevent a spiral effect. Based on a model of the profitability of investments into self-supply, we analyse possible self-reinforcing dynamics both theoretically and in a case-study based on the German framework. The model captures the effect that with volumetric network charges, incentives for investments into self-supply rise with increasing prosumer shares. An unsustainable network setting with self-reinforcing self-supply results from the combination of favourable conditions for PV and savings from self-supply which evolve with rising prosumer shares. To address such unsustainable network settings, we present three network charging options to mitigate self-reinforcing dynamics. These approaches are modifications of

1) the load- and energy-split,
2) the rebate for self-supply and of
3) the allocation of network cost from upper network levels.

The paper describes the basic principles of preventing self-reinforcing dynamics with these charging options. It serves as a basis for designing network charges in practice and as a point of departure to explore specific charging aspects in greater detail. With our model setup we show that the approaches contain self-reinforcing dynamics in theory.

In practice, modifications of the load- and energy split and variations in the cost pass-through from upper network levels between parallel grids seem most promising. Determining these tariff parameters endogenously, coupled to prosumer shares observed in the network opens up the possibility to calibrate a new, stable level of self-supply and to incorporate uncertainties in the tariff design. Tuning the rebate for self-supply to prevent a spiral effect is difficult, particularly if it applies to network tariffs in the same way as to energy cost and surcharges. As a further step, a combination of several approaches may be required.

The analysis explicitly focuses on a self-reinforcing dynamic initiated by PV-based self-supply. It is for further research to consider flexibility options, such as batteries to store self-generated energy or shift withdrawal within a certain time interval. Technologies that substitute not only away from network use but also between peak and off-peak use likely require different incentives. Eventually, new users, such as electric vehicles and heat pumps, may help to prevent financing instabilities as they increase the overall electricity volume in the grid.

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