Optimal grid tariffs with heterogeneous prosumers

Axel Gautier, Julien Jacqmin, Jean-Christophe Poudou

To cite this version:

Axel Gautier, Julien Jacqmin, Jean-Christophe Poudou. Optimal grid tariffs with heterogeneous prosumers. Utilities Policy, Elsevier, 2021, 68, pp.101140. 10.1016/j.jup.2020.101140 . hal-02988150

Optimal grid tariffs with heterogeneous prosumers *

Axel Gautier[†], Julien Jacqmin[‡] and Jean-Christophe Poudou[§]

November 3, 2020

Energy consumers can invest in photovoltaic (PV) panels and become prosumers. The benefit of such an investment depends on the regulatory framework. We consider a population of heterogenous consumers, with respect to both the cost of decentralized production and their degree of self-consumption.it is efficient to have investment by low-cost and high self-consumption profiles. We determine the optimal tariff in the presence of heterogenous prosumers. Net metering fails to screen consumers on the self-consumption dimension. Net purchasing can lead to the efficient investment if the tariffs are non-Coasian that is fixed fees exceed the grid operator's fixed costs.

Keywords: Decentralized production unit; grid regulation; solar panels; grid tariffs.

JEL Codes: D13, L51, L94, Q42

1 Introduction

Motivations. The electricity sector is transforming worldwide. The liberalization of upstream and downstream markets and the emergence of renewable energy sources such as photovoltaics (PVs) and windmills are creating new ways to consume and produce electricity. The affordability of PV devices makes it feasible for households to self-consume electricity, and could eventually lead to peer-to-peer exchanges of self-produced energy. This new trend of households being both producers and consumers of energy, called "prosumption", is facilitated by technical developments such as battery systems, smart meters and advanced business models that promote self-consumption through the technical design of electricity systems. However, the success of these developments depends on regulatory and administrative frameworks for energy policy, grid financing, taxation and legal relationships, and it requires innovative solutions coupled

---

[*] The authors thank the Walloon Region (grant TECR) for its financial support and the online audience of the 7th FAERE Annual Conference.

[†] University of Liège, HEC Liege, LCII; CORE (UCL) and CESifo. E-mail: `agautier@uliege.be`.

[‡] NEOMA Business School E-mail: `julien.jacqmin@neoma-bs.fr`.

[§] University of Montpellier, MRE, MUSE, and LabEx "Entreprendre", Montpellier, France. E-mail: `jean-christophe.poudou@umontpellier.fr`.

with suitable business and management models to achieve a sustainable integrated system.

Households that purchase PV panels tend to stay connected to the energy grid so they can purchase electricity when weather conditions are not favorable for self-production. According to McKenna *et al.* (2018), such households on average consume 45% of the electricity they produce, with the rest sold to the grid to satisfy the demand of other consumers. However, this behavior varies significantly across households. Since production largely depends on the level of solar radiation, differences in self-consumption rates are for the most part due to differences in consumption profiles. For example, a household whose members stay at home during the day will self-consume much more energy than a household whose members are away during the day.

From a grid management perspective, self-consumption is relevant because it reduces the amount of energy flows. By decreasing the aggregate peak demand from the grid and injection to the grid, it can further impact the costs associated with grid reinforcement investments or energy losses related to congestion. Unfortunately, smart meters have not yet been widely adopted[1] and precise information about the self-consumption rate of households is limited. In a near future, new technological developments for smart metering as described for instance in Sanchez-Sutil *et al.* (2019), and Cano-Ortega *et al.* (2019), may allow grid operators to use such precise information.

Methodology and results. The originality of this research is to study how *heterogeneous* prosumer profiles for self-consumption interact with the way tariffs are chosen. The key point is to introduce a synchronization factor as an heterogeneous variable. As a first approximation, this aspect has been neglected in the previous microeconomic literature analyzing the interactions between prosumers and the energy system. This synchronization factor represents the individual degree of self-consumption for consumers when they invest in PV to become prosumers. It provides a measure of the degree of correlation between the timing of consumption and the timing of production of PV panel, depending on the individual variety of behaviors and situations. This factor is of importance as prosumers with a higher self-consumption profile are preferable for the grid operator in order to save costs related to grid exchanges. We then study both net metering and net purchasing systems, which are two common approaches used to integrate decentralized production units (DPUs) into the energy system. Net metering prices energy imports and exports the same, whereas net purchasing sets different prices for each. We analyze how different tariff schemes affect consumers' decisions to become prosumers and we search for the most efficient tariffs when the grid operator lacks information about households' self-consumption profiles.

Our main results are as follows. First, we show that consumers who are relatively more inclined to self-consume are more likely to invest in PV installations to become

---

[1] According to European Commission (JRC-SESI, (2020)), by 2020 it is expected that almost 72% of European consumers will have a smart meter for electricity. However, in many national laws, a complete rollout is required before it is possible to take advantage of some of its features.

prosumers when a net purchasing system is in place. Under net metering, investment decisions are independent of self-consumption profiles. The reason is that under net purchasing, energy sold to the grid is priced lower than energy drawn from the grid. Hence, we show that net metering not only encourages too much investment in DPUs but also attracts the wrong types of consumers to invest in production from a grid management perspective. Our second key result is that even if the grid operator has no information regarding self-consumption profiles of prosumers, efficient tariffs can be achieved through net purchasing. However, to be the case, tariffs should not be Coasian, i.e. fixed fees paid by consumers and prosumers should exceed the grid operator's fixed costs. Overall, our analysis highlights that net purchasing without Coasian tariffs provides a better way to integrate prosumers in the energy system.

The economic literature. Our study belongs to a broader economic literature addressing electricity grid tariff regulation in the presence of decentralized energy sources.[2] More precisely, we analyze the financial interactions between DPUs and network operators, primarily via the grid tariff. The key idea of our analysis is to study how tariffs, constrained by the available metering technology, are structured to cover the (mostly fixed) network costs and how they will influence the consumers' decision to invest in PV's. The main novelty in our contribution is that we drop the representative consumer/prosumer assumption to introduce heterogeneous agents, with respect to both the cost of PV installation (related to their income, location and house orientation) and the self-consumption profile (related to their consumption habits). Grid tariff regulation is hardly able to catch this last dimension, which potentially creates socially undesirable inefficiencies. However, depending on the available metering technology, the social cost of these inefficiencies can be mitigated or eliminated by using judiciously adapted grid tariffs. In this sense, we extend the literature and mainly Brown and Sappington (2017), Gautier *et al.* (2018) and Cambini and Soroush (2019). These studies assumed that the choice of electricity meter and the network tariff design could impact the decision to become a prosumer. We build on these analyses by allowing consumers to differ in their self-consumption rate. This novel feature allows us to examine the types of households that decide to become prosumers by investing in PVs and compare it with a centrally planned allocation.

Our analysis shows the influence of the tariff structure on the decision to invest in DPUs and on grid financing. Eid *et al.* (2014) and La Monaca *et al.* (2017) have analyzed these two dimensions separately. The former estimate the impact of different grid tariffs on the grid financing and the latter show that the tariff structure influences the profitability of investment and, hence, the level of investment. Finally, Wagner (2019) develops a spatial economics model to show that, in a decentralized setting, the locational choice of renewable production units is not always optimal and that the inefficiencies depend on the tariff structure.

We also contribute to the literature on public utility regulation, which is concerned

---

[2] A survey of this strand of literature can be found in Burger *et al.* (2019)

with tariff structures. According to the classical result of Coase (1946), two-part tariffs with volumetric charges set to marginal costs and a fixed fee that recoups a monopoly's fixed costs lead to efficient outcomes. However, one of our key results is that, due to agent heterogeneity, the optimal tariffs diverge from the Coasian tariffs because of the heterogeneity in self-consumption profiles. To be optimal (i.e. to attract the efficient number and type of prosumers), the fixed fee needs to generate more revenue than the network operator's fixed costs. This fixed fee can also differ for prosumers and ordinary consumers.

There is also a large and growing empirical literature that analyzes the design of retail tariffs in the presence of distributed solar PV using numerical simulations (see for example Schittekatte *et al.* (2018), Solano *et al.* (2018), Clastres *et al.* (2019), Gunther *et al.* (2019) and Young *et al.* (2019)). Most of these works focus on the incentives to invest in solar PV and batteries to increase self-consumption in a population of heterogeneous households and the influence of the grid tariff on those investments. To our knowledge, none of these works highlights that investing in PV will differ depending on the rate of self-consumption, at the exception of Solano *et al.* (2018). However, this approach abstracts from how this self-selection problem can further impact the choice of tariffs but instead focuses on the heterogeneity of the bill savings.

Outline. The article is organized as follows. Section 2 presents the model, and Section 3 discusses the first-best outcome. Section 4 highlights the two key policies chosen by the grid operator. Then, Section 5 presents the net metering case, and Section 6 presents the net purchasing case. Section 7 describes partial-netting, a hybrid system between net metering and net purchasing. Section 8 concludes. A nomenclature of variables and an appendix are provided in Sections 9 and 10 respectively.

2 Model

Our model builds on Gautier *et al.* (2018), where a separated and regulated distribution system operator (DSO) operates a power grid as a monopoly. There are two other key groups in the energy system: centralized electricity producers and consumers who can also become producers by investing in a DPU. By choosing the way DPUs are integrated into the energy system and the prices that consumers pay for exchanges with the grid, the DSO can encourage different numbers and profiles of consumers to invest in DPUs.

Consumers Our model contains a population of consumers of size 1. All consumers have a fixed level of consumption q, giving them a surplus S. Consumers can install a DPU of capacity $\tilde{k}$ that produces an energy flow $k = \beta\tilde{k}$, where β is the average load factor of a consumer. The cost of an installation of size $\tilde{k}$ is equal to $\tilde{z}\tilde{k}$. The prosumer cost to produce k is equal to zk, with $z = \tilde{z}/\beta$. We assume that all prosumers produce the same quantity[3] $k < q$. Prosumers differ in their installation cost z, and we consider an independent and log-concave distribution $f(z)$ on a closed interval, $[\underline{z}, \bar{z}]$. Without loss of generality, we normalize $\underline{z} = 0$ and $\bar{z} = 1$. Hence, the installation cost is the first source of heterogeneity in our model.

We extend Gautier *et al.* (2018) by introducing a second source of heterogeneity among consumers: a synchronization factor, φ, which represents the degree of self-consumption. Prosumers only consume a fraction φk of the k units they produce; the remaining $(1-\varphi)k$ is exported to the grid. The variable $\varphi \in [0,1]$, independently distributed by $g(\varphi)$ between these two extreme self-consumption profiles. It measures the degree of correlation between the timing of consumption and the timing of DPU production.[4] When perfectly correlated, everything that is produced by the PV installation is consumed at the place of production. On the other hand, when $\varphi = 0$, all the decentralized production is exported to the grid. In between these two extremes, this variable tends to be very heterogeneous according to the literature on self-consumption (see McLaren *et al.* (2015), Luthander *et al.* (2015) and Lang *et al.* (2016)). Focusing on different contexts and using different methods, McKenna *et al.* (2018) and Gautier et al. (2019) find the heterogeneity results from daytime electricity usage at home. For example, someone working from home will have a much higher self-consumption rate than someone working away from home. Likewise, there is more self-consumption in office buildings than in residences. In the model, we represent self-consumption by this synchronization factor.

We assume that the two parameters z and φ are distributed independently of each other.[5] Each consumer is identified by two variables (z, φ), and consumers are distributed on a square of size 1, where the vertical axis represents the cost of installing a DPU (z) and the horizontal axis represents the synchronization factor (φ). We represent the decision to become a prosumer by a binary variable $x(z,\varphi) \in \{0,1\}$. If $x(z,\varphi) = 1$, the household is a prosumer and produces k; if $x(z,\varphi) = 0$, the household only consumes electricity and does not produce any.

Cost of generation Since the population size is 1, total consumption is equal to q, which includes electricity that is produced by both the centralized production unit (CPU) and DPUs. The CPU produces energy at a unit cost c, which we assume lies between $\underline{z} = 0$ and $\overline{z} = 1$. Without prosumers, the total generation cost would be $C_g = cq$.

The total production of DPUs is equal to $k \int_0^1 \int_0^1 x(z,\varphi) f(z)\, g(\varphi)\, d\varphi dz$ and the

---

[3] As a result, we consider that none of the prosumer is self-sufficient

[4] Note that behind this simplified parameter, we have the minute-to-minute matching between the demand and the decentralized production of energy. Using unidimensional parameter allows us to keep the model analytically tractable.

[5] This independence assumption allows for a simplified presentation of results, but our results hold if we impose a more general bivariate law $f(z,\varphi)$.

corresponding cost of decentralized production is

$$C_g^{DPU} = k\int_0^1\int_0^1 x(z,\varphi)zd\varphi dz.$$

We suppose that centralized and decentralized production are perfect substitutes[6]. The total generation cost is equal to:

$$\begin{aligned} C_g &= \int_0^1\int_0^1 \left\{(1-x(z,\varphi))\,cq + x(z,\varphi)\left[zk + c(q-k)\right]\right\} f\left(z\right) g\left(\varphi\right) d\varphi dz \\ &= cq + k\int_0^1\int_0^1 x(z,\varphi)\left(z-c\right) f\left(z\right) g\left(\varphi\right) d\varphi dz. \end{aligned}$$

Notice that the generation costs are independent of prosumers' synchronization factors.

Grid costs There are two types of costs for the grids: fixed costs associated with user and variable costs linked to the MWh of energy distributed. We denote by K_c the cost of connecting one user to the grid and, as all users are connected, the sum of these costs is equal to K_c. For prosumers, there is an additional cost of connecting their DPU to the grid (such as change of meter and panel connection costs) and this cost is denoted by K_l.

We use θ_i to denote the variable costs per MWh of power distributed by centralized $(i = c)$ and local exchanges $(i = l)$.[7] To simplify the analysis, we assume that centralized and local energy exchanges have the same variable costs per MWh: $\theta_l = \theta_c = \theta$.

Each prosumer consumes a fraction φ of their DPU's production, with the remaining amount exported and consumed by other consumers through a local exchange, so the total local distribution volume (V_l) is:

$$V_l = \left(\int_0^1\int_0^1 x(z,\varphi)(1-\varphi)f\left(z\right) g\left(\varphi\right) d\varphi dz\right) k. \tag{1}$$

The total volume of centralized distribution (V_c) is equal to the CPU's production:

$$V_c = q - \left(\int_0^1\int_0^1 x(z,\varphi)f\left(z\right) g\left(\varphi\right) d\varphi dz\right) k. \tag{2}$$

Denoting the fixed cost associated with prosumers as

$$\bar{K}_l = \left(\int_0^1\int_0^1 x(z,\varphi)f\left(z\right) g\left(\varphi\right) d\varphi dz\right) K_l,$$

---

[6] At first sight, this seems to be an extreme assumption. However we take a capacity-based approach rather than a generation-based approach. As a consequence, as noted before we do not explicitly model intermittency to make things tractable. An additional argument is that that intermittency is a problem at the production stage but not at the distribution stage which is the focus of the analysis.

[7] Local exchanges refer to power exchanges between a DPU and other consumers, and centralized exchanges refer to power exchanges between the CPU and consumers/prosumers.

the total cost of the DSO is equal to:

$$\begin{aligned} C_d &= \theta\left(V_c+V_l\right)+\bar{K}_l+K_c \\ &= \theta q+\int_0^1\int_0^1 x(z,\varphi)\left(K_l-\varphi k\theta\right)f\left(z\right)g\left(\varphi\right)d\varphi dz+K_c. \end{aligned} \tag{3}$$

We also denote $c_d = C_d - K_c$.

3 First-best outcome

The total cost of producing and distributing electricity for the entire grid is given by the sum of generation costs C_g and distribution costs C_d given above. The total cost is:

$$\begin{aligned} C &= C_g+C_d \\ &= \left(c+\theta\right)q+\int_0^1\int_0^1 x(z,\varphi)\left[\left(z-c\right)k-\varphi\theta k+K_l\right]f\left(z\right)g\left(\varphi\right)d\varphi dz+K_c. \end{aligned} \tag{4}$$

A benevolent social planner must determine whether an agent with the characteristics (z,φ) should purchase a DPU to become a prosumer or should remain a consumer. Given that consumption is fixed, the first-best outcome minimizes the total cost of the energy system, which is accomplished by minimizing C with respect $x\left(z,\varphi\right)\in\{0,1\}$ and it entails the following:[8]

Proposition 1 *At the first-best outcome,* $x^*(z,\varphi)=1$ *if* $z\leq z^*\left(\varphi\right)=c+\varphi\theta-\frac{K_l}{k}$ *and* $x^*(z,\varphi)=0$ *otherwise.*

The expression for the first-best outcome is similar to Brown and Sappington (2017) and Gautier *et al.* (2018). The idea is that DPUs should be valued at the marginal cost of the centralized generation unit net of the additional network costs created by the DPU. A DPU results in additional connection costs but saves on distribution costs because self-consumption reduces power exchanges with the grid.

The first-best outcome identifies a frontier $z^*(\varphi)$.[9] Interestingly, the frontier increases in φ, meaning that consumers with a higher installation cost z will become prosumers only if they have a higher level of consumption. Self-consumption reduces exchanges with the grid and the variable cost of operating the grid. Hence, a higher

---

[8] All proofs are provided in the appendix.

[9] One additional side-product of DPU is that they are substitutes of the production carbon-intensive energy sources. The positive impact of the deployment of renewables can also be considered by assuming a linear environmental cost/damage function $C_e = \delta V_c$. Doing so would just push up the first best frontier to $z^*\left(\varphi\right)+\delta$. Considering this aspect would not change our key result as the self-selection problem would remain an issue under net metering due to the inability of this technology to encourage comparatively more types with a high degree of self-consumption to invest in DPU.

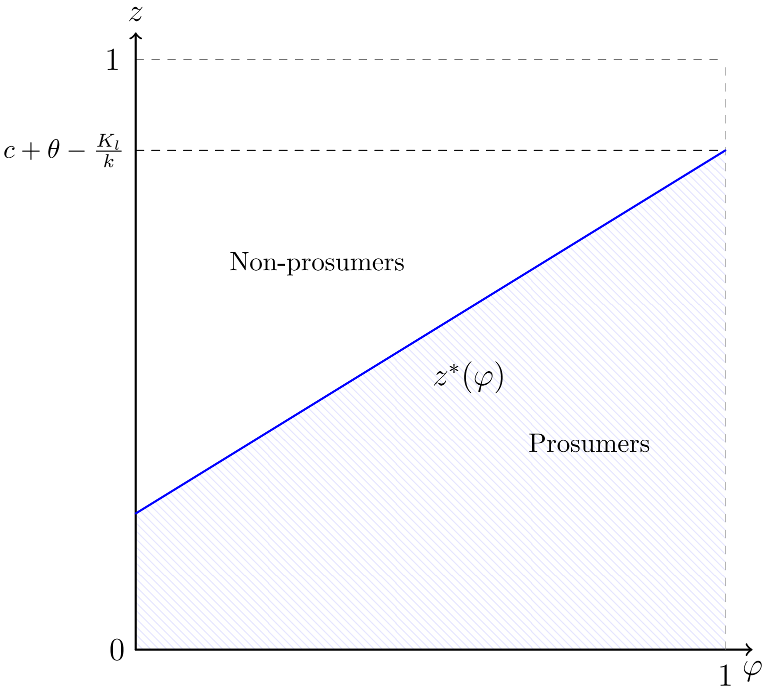

Figure 1: First-best prosumption (if $c-\frac{K_l}{k}>0$)

installation cost can be recouped if there is a high degree of self-consumption. This important consideration is often neglected in the design of policies to encourage the installation of DPUs. Figure 1 represents the first-best frontier $z^*(\varphi)$.

At the first-best outcome, the optimal mass of prosumers is $M^*=\int_0^1\int_0^{z^*(\varphi)} f(z)\,g(\varphi)\,dzd\varphi=\int_0^1 F(z^*(\varphi))\,g(\varphi)\,d\varphi$, and the total cost of the electricity grid is

$$C^*=(c+\theta)\,q+k\int_0^1\int_0^{z^*(\varphi)}\left[z-z^*(\varphi)\right]f(z)\,g(\varphi)\,dzd\varphi+K_c.$$

In the following sections, we examine how the number and profile of consumers who become prosumers changes when this decision is decentralized, depending on the regulations in place.

4 Metering technologies and grid regulation

We now consider the outcome when consumers decide whether to purchase a DPU. We consider an energy system where production and distribution are separated. Production is a competitive activity, and the energy price p is equal to the marginal cost of CPUs: $p=c$. Distribution is a monopolistic activity, and an energy regulator fixes the tariff of the DSO and organizes power exchanges between prosumers and the grid.

4.1 Metering technologies

Prosumers make two types of exchange with the grid. First, prosumers supply power to the grid when their DPUs produce more electricity than prosumers can instantaneously consume. Second, a prosumer draws power from the grid when their DPU's production is insufficient to meet their instantaneous consumption needs. A prosumer with a synchronization factor φ supplies $(1-\varphi)k$ to the grid and draws $q-\varphi k$ from the grid.

Smart meters can record these two power flows separately. Alternatively, customers may have either two mechanical meters (one for recording imports and another recording exports) or a single meter that runs backwards when energy is exported to the grid (net metering). In the latter case, the single meter records the net imports $q-k$.

The synchronization factor φ and total consumption q are not reported on meter readings. A prosumer needs an additional meter to record production, k,[10] which allows q and φ to be recovered *ex-post* from the meter readings.[11]

4.2 Net metering and net purchasing

A consumer who purchases electricity from the grid pays the commodity price p and a network fee $r_m > 0$, which we refer to as the "import fee". A prosumer who provides electricity to the grid is paid the commodity price p; however, the prosumer must pay an injection fee r_x that we call the "export fee". This export fee can be positive, negative (in which case exports are subsidized by the DSO) or nil.

Net metering is a commonly used system in which imports and exports have the same price (that is, $r_m = -r_x$). As discussed in Moura and Brito (2019), net metering is used in most U.S. states, Mexico, Brazil, Finland, India and Belgium, among other countries. Net metering is the only possible system where prosumers have a single mechanical meter to record their exchanges with the grid.

Under net purchasing, imports and exports are priced separately (i.e. $r_m \neq -r_x$).

4.3 Tariff structure

The tariff structure is regulated and must be set such that the DSO can recover its total cost, C_d.

We consider different tariff structures:

- A Coasian two-part tariff where each consumer pays a fixed fee equal to the grid's

---

[10] In the case of solar PVs, a meter or an app installed on the inverter can be used to measure a DPU's production.

[11] The export meter records $(1-\varphi)k$, from which the synchronization factor φ can be computed. Total consumption q can be calculated from the import meter that records $q-\varphi k$.

fixed cost $\rho = K_c$, and variable fees that are designed to cover the variable costs, c_d.

- A Coasian tariff where prosumers pay a supplementary fixed fee to cover the specific fixed cost related with their DPU. In this tariff structure, traditional consumers pay $\rho = K_c$ and prosumers pay $\rho = K_c + K_p$.[12]
- A non-Coasian two-part tariff where the tariff is designed to minimize the total cost of the system $(C_d + C_g)$.

We consider the effect of each tariff for both a net metering and net purchasing system. Finally, we assume that the regulator cannot observe φ, that is, the regulator has no access to prosumers' production meters (if they exist as a smart metering system would be required). Therefore, it cannot make the network tariff structure contingent on a prosumer's synchronization factor and use this variable to screen prospective prosumers. Furthermore, we will prove that a menu of contract where prosumers select their preferred option add no value in this context.

5 Net metering

5.1 Prosumer's investment decision

Consider net metering with a unique variable fee $r = r^m = -r^x$ and a fixed fee of ρ per consumer. As in Gautier *et al.* (2018), the net utility of a consumer who installs a DPU that produces $k \leq q$ and who consumes that power at a rate φ is given by:

$$U(z,\varphi) = \left\{ \begin{array}{ll} S - (c+r)(q-k) - \rho - zk & \\ S - (c+r)q - \rho & \end{array} \right. \text{if} \begin{array}{l} x(z,\varphi) = 1 \\ x(z,\varphi) = 0. \end{array}$$

The consumer is indifferent between investing or not investing in a DPU if

$$\tilde{z} = c + r. \tag{5}$$

Hence, we have

$$\begin{aligned} \tilde{x}(z,\varphi) &= 1 \text{ if } z \leq c + r \\ \tilde{x}(z,\varphi) &= 0 \text{ if } z > c + r. \end{aligned}$$

---

[12] Cambini and Soroush (2019) discuss and compare different tariff structures under net metering. In particular, they focus on recovering fixed connection costs linked to DPUs. The Coasian tariff corresponds to what they call the "shallow connection cost", where fixed connection costs are recovered by the variable part of the tariff. The Coasian tariff with a prosumer's fixed fee corresponds to the "deep connection cost". They show that charges associated with deep connection costs achieve better results than charges associated with shallow connection costs from a welfare point of view.

With net metering, the synchronization factor does not affect a consumer's investment decision. The reason is that net metering does not differentiate between the price of the two energy flows, so the prosumer's electricity bill and resulting utility depend only on net imports $q-k$, independent of the synchronization level.

Therefore, as we rule out tariffs contingent on φ, we can see that:

Proposition 2 *It is impossible to achieve the first-best outcome with net metering.*

5.2 Coasian tariff

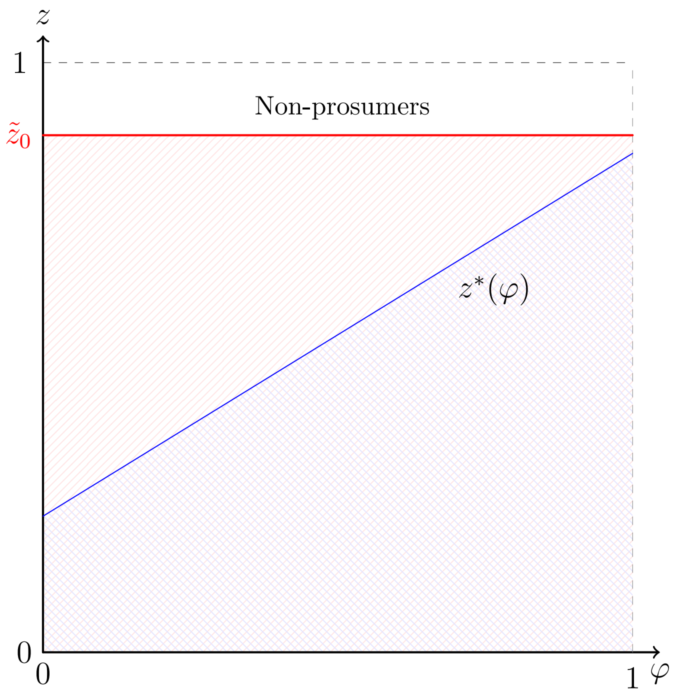

Figure 2: Prosumers under net metering (Coasian tariff)

With a Coasian tariff ($\rho = K_c$), the recorded consumption volume is V_c, and the break-even distribution tariff $\tilde{r}_0$ satisfies:

$$\tilde{r}_0 = \frac{c_d}{V_c}.$$

Given that $\tilde{z}_0 = c + \tilde{r}_0$, the proportion of prosumers in the population is $F(\tilde{z}_0) = F(c+\tilde{r}_0)$. Replacing the cost c_d and the recorded consumption volume V_c by their values evaluated at $\tilde{z}$, the break-even grid fee is given by:

$$\tilde{r}_0 = \frac{\theta q + F\left(\tilde{z}_0\right)\left(K_l - \theta\bar{\varphi}k\right)}{q - F\left(\tilde{z}_0\right)k} \tag{6}$$

where $\bar{\varphi} = \int_0^1 \varphi g(\varphi)\, d\varphi$ is the mean value of φ, i.e. the average self-consumption level for the society. The resulting cut-off value $\tilde{z}_0 = c + \tilde{r}_0$ is represented in Figure 2. We observe that the cut-off value is higher than the first-best $\tilde{z}_0 > z^*$ for all $\varphi \in [0, 1]$ and is independent of φ.

Proposition 3 *Compared to the first-best outcome, net metering with a Coasian tariff induces too many consumers to become prosumers.*

This result is similar to the "death spiral" described in Brown and Sappington (2017) and Gautier *et al.* (2018). The idea is that tariffs do not send the right signal to consumers when they make investment decisions. Consumers place too much value on installing a DPU because the price at which they sell their energy to the network is the same as the price at which they buy electricity from the network, even though the variable costs faced by the DSO are higher for energy exported by prosumers than for energy imported by prosumers. Since prosumption is over-encouraged, the uniform tariff rate has to increase to ensure that the DSO will break even, and this further encourages households to become prosumers.

5.3 Coasian tariff with a higher fixed fee for prosumers

To limit the number of prosumers, the regulator can rebalance the tariff structure by charging prosumers a higher fixed fee than consumers, or by increasing the fixed fee charged to everyone (see Subsection 5.4).

In the first case, the regulator imposes a fixed fee $\rho_p = K_c + K_l$ to prosumers and $\rho = K_c$ to consumers. With such a fee, the cut-off investment level is now:

$$\tilde{z}_1 = c + r - \frac{K_l}{k}$$

and the corresponding break-even grid fee is:

$$\tilde{r}_1 = \theta \frac{q - F(\tilde{z}_1)\, k\bar{\varphi}}{q - F(\tilde{z}_1)\, k}.$$

Combining the two equations, we have:

$$\tilde{z}_1 = z^*(\varphi) + \theta \frac{(1-\varphi)\, q - F(\tilde{z}_1)\, k\, (\bar{\varphi} - \varphi)}{q - F(\tilde{z}_1)\, k}.$$

And we can straightforwardly show that there exists

$$\tilde{\varphi}_1 = \frac{q - F(\tilde{z}_1)\, k\bar{\varphi}}{q - F(\tilde{z}_1)\, k} > \bar{\varphi}$$

such that

$$\begin{array}{lll} \tilde{z}_1 & \geq & z^*(\varphi) \text{ if } \varphi \leq \tilde{\varphi}_1 \\ \tilde{z}_1 & < & z^*(\varphi) \text{ if } \varphi > \tilde{\varphi}_1. \end{array}$$

Under this tariff, prosumers pay for the fixed connection cost of the DPU. Consequently, the variable fee can be reduced ($\tilde{r}_1 < \tilde{r}_0$) and the death spiral is avoided. The tariff is now based on the variable cost for an average prosumer who has a self-consumption rate of $\bar{\varphi}$. This tariff structure limits the number of prosumers by discouraging consumers with higher self-consumption rates from becoming prosumers.

5.4 Optimal two-part tariff

Instead of charging prosumers an additional fixed fee, the regulator can decrease the variable fee r and increase the universal fixed fee ρ to decrease investments in DPUs, while guaranteeing that the DSO breaks even or earns a profit. The optimal two-part tariff under net metering is the solution of:

$$\min_{r,\rho} C \text{ subject to } z = c + r \text{ and } \rho + r(q - F(c+r)k) = C_d.$$

The solution to this problem is to set the following unit tariff

$$\tilde{r}_2 = \bar{\varphi}\theta - \frac{K_l}{k} - H(c + \tilde{r}_2) < \bar{\varphi}\theta - \frac{K_l}{k},$$

where $H(z) = \frac{F(z)}{f(z)} \geq 0$ which is increasing in z,[13] and to cover the remaining costs of the DSO with the fixed fee

$$\tilde{\rho}_2 = \left((1 - \bar{\varphi})\theta + \frac{K_l}{k}\right) q + K_c + H(c + \tilde{r}_2)(q - F(c + \tilde{r}_2)k)$$

so that $\tilde{\rho}_2 > \left((1 - \bar{\varphi})\theta + \frac{K_l}{k}\right) q + K_c$. We can show easily that there exists

$$\tilde{\varphi}_2 = \bar{\varphi} - \frac{H(\tilde{z}_2)}{\theta} < \bar{\varphi}$$

with $\tilde{z}_2 = c + \tilde{r}_2$ and such that

$$\begin{array}{lll} \tilde{z}_2 & \geq & z^*(\varphi) \text{ if } \varphi \leq \tilde{\varphi}_2 \\ \tilde{z}_2 & < & z^*(\varphi) \text{ if } \varphi > \tilde{\varphi}_2. \end{array}$$

Under this tariff, the total fixed fees paid by consumers and prosumers exceed the fixed connection costs associated with DPUs. As a result, the variable fee can be reduced

---

[13] This is due to the log concavity of $f(z)$.

($\tilde{r}_2 < \tilde{r}_0$) and the death spiral is avoided. The tariff is now set *below* the variable costs for an average prosumer who exhibits a self-consumption rate of $\bar{\varphi}$, which takes into account the total effect of the prosumer's level. As was the case for the Coasian tariff with a higher fixed fee for prosumers, this tariff structure also discourages consumers with higher self-consumption rates from becoming prosumers, resulting in fewer prosumers than under a Coasian tariff.

5.5 Menu pricing

It is ineffective to offer prosumers a menu of contracts $(r(\varphi), \rho(\varphi))$ from which to choose from. Indeed, as a prosumer's utility is independent of φ, all prosumers will pick the same tariff and it is impossible to screen prosumers according to their synchronization factor. This is because the DSO has no mechanism to observe the synchronization factor, and prosumers have no incentive to reveal this information.

5.6 Comparisons

Comparing the three tariffs above, we establish:

Lemma 1 $\tilde{r}_2 < \tilde{r}_1 < \tilde{r}_0$ *and* $\tilde{z}_2 < \tilde{z}_1 < \tilde{z}_0$.

With a given net metering tariff, the total cost is:

$$C(r,z) := (c+\theta)\,q + \int_0^1 \int_0^z \left[rk - \varphi\theta k + K_l\right] f(y)\, g(\varphi)\, dy d\varphi + K_c,$$

which increases with both (r,z). Then, given Lemma 1, we have $C^* < \tilde{C}_2 < \tilde{C}_1 < \tilde{C}_0$.

Therefore, under net metering, the optimal tariff consists of charging a high fixed fee independent of consumption. This fee should cover the fixed grid cost and part of the variable costs. Increasing the fixed fee above the Coasian level limits incentives to become a prosumer and reduces grid costs. Indeed, from Lemma 1, we have that $\tilde{M}_2 < \tilde{M}_1 < \tilde{M}_0$ where $\tilde{M}_i = F(\tilde{z}_i)$ is the mass of active prosumers for $i = 0, 1, 2$.[14] Finally, the first-best outcome can never be achieved under net metering as the regulator cannot make the tariff (and subsequent investment decisions by consumers) contingent on the level of self-consumption.

6 Net purchasing

We now consider the case where the DSO can implement a net purchasing system, which requires that prosumers be equipped with smart meters or mechanical meters

---

[14] However, one cannot compare these masses to the one in the first-best M^*, as it depends on the particular distribution of z.

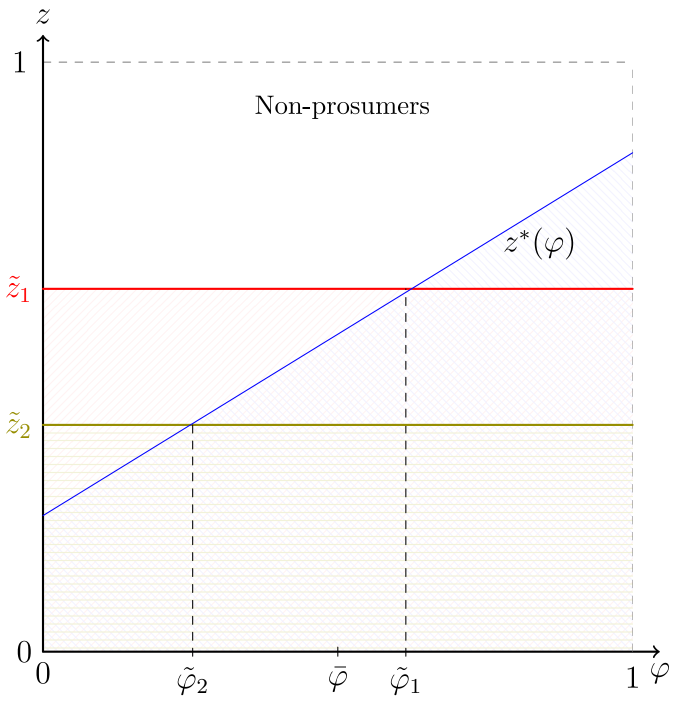

Figure 3: Comparisons

with two separate lines to measure imports and exports.

6.1 The prosumer's investment decision

Under a net purchasing scheme, the net utility of a prosumer who can install a DPU producing k and with a self-consumption level φ is given by

$$U(z) = \begin{cases} S - c(q-k) - r_m\left(q - \varphi k\right) - r_x\left(1-\varphi\right)k - \rho - zk \\ S - \left(c + r_m\right)q - \rho \end{cases} \text{if} \begin{array}{c} x(z,\varphi) = 1 \\ x(z,\varphi) = 0. \end{array}$$

For a consumer who is indifferent between becoming a prosumer or remaining a consumer, we have:

$$\hat{z}\left(\varphi\right) = c + \varphi r_m - \left(1-\varphi\right)r_x. \tag{7}$$

Therefore, only agents with preferences (z,φ) such that $z \leq \hat{z}\left(\varphi\right)$ will become prosumers.

6.2 Coasian tariff

Let us first consider a Coasian tariff such that $\rho = K_c$. It is now clear that net purchasing can only lead to the first-best quantity of prosumers if for all agents $\varphi \leq 1$:

$$\varphi \left(r_m + r_x\right) - r_x = \varphi\theta - \frac{K_l}{k}.$$

That is, if

$$r_m = \theta - \frac{K_l}{k} \quad \text{and} \quad r_x = \frac{K_l}{k}. \tag{8}$$

However this tariff structure is not profitable for the DSO, as it leads to a loss of $K_l q/k$.

Proposition 4 *Under a net purchasing system, Coasian tariffs cannot achieve the first-best outcome.*

This result contrasts with Gautier *et al.* (2018), where a net purchasing system with a uniform tariff is shown to lead to an efficient outcome. We have that the import rate must be set below the marginal cost θ and the export rate is used to fully charge prosumers the fixed distribution cost of a DPU installation. This makes it impossible to construct a tariff that is fully cost-reflective and that induces an efficient deployment of DPUs. The source of heterogeneity in the society is also coming from the different synchronization factors between a DPU owner's consumption and production. Moreover, net purchasing with a Coasian tariff generates distortions differently than Coasian tariffs under net metering. Indeed, with net purchasing the first best would be achievable but at the social cost of a profit loss for the DSO. Consequently, it is not implementable due to a productive distortion. With net metering the first best is unachievable but the DSO breaks even, it is not implementable due to an allocative distortion. As a result, the Coasian tariff distortions are not comparable with respect to the metering regime.

Since an efficiency-inducing uniform tariff is not feasible, let us consider a second-best uniform Coasian tariff under a net purchasing scheme that ensures the DSO can recoup its costs and minimizes the total cost calculated in (4). In other words, we look for (r_m, r_x) that solves the problem:

$$\begin{cases} \min_{r_m, r_x} \ C \\ \text{s.t. } \Pi = r_m \left(V_c + V_l\right) + r_x V_l - c_d \geq 0 \\ \text{with } x\left(z, \varphi\right) = 1 \text{ if } z \leq \hat{z}\left(\varphi\right) = c + \varphi r_m - \left(1 - \varphi\right) r_x, \text{ for all } \varphi \in [0, 1]. \end{cases} \tag{9}$$

We solve this problem in the appendix. The solution gives us the following result, using the following notations $\hat{M} = \int_0^1 F\left(\hat{z}\left(\varphi\right)\right) g\left(\varphi\right) d\varphi$ and $\hat{\Phi} = \int_0^1 \varphi F\left(\hat{z}\left(\varphi\right)\right) g\left(\varphi\right) d\varphi$:

Proposition 5 *The second-best uniform tariff structure with net purchasing is*

$$\hat{r}_m^* = \theta - \hat{\Gamma}\frac{K_l}{k} \text{ and } \hat{r}_x\left(\hat{r}_m^*\right) = \frac{\left(\theta - \hat{r}_m^*\right)\left(q - k\hat{\Phi}\right) + K_l\hat{M}}{k\left(\hat{M} - \hat{\Phi}\right)}$$

where $\hat{\Gamma} < 1$.

The second-best uniform tariff allows us to define the prosumption locus $\hat{z}^*\left(\varphi\right) = c + \varphi\hat{r}_m^* - \left(1-\varphi\right)\hat{r}_x\left(\hat{r}_m^*\right)$, which is steeper than the optimal locus.

So there may exist $\hat{z}\left(\hat{\varphi}\right) = z^*\left(\hat{\varphi}\right)$ with $\hat{z}\left(\varphi\right) \leq z^*\left(\varphi\right)$ for $\varphi \leq \hat{\varphi}$ and conversely. Hence, the second-best uniform tariff under a net purchasing scheme favors highly synchronized agents, as they are more likely to invest in a DPU compared with the first-best outcome.

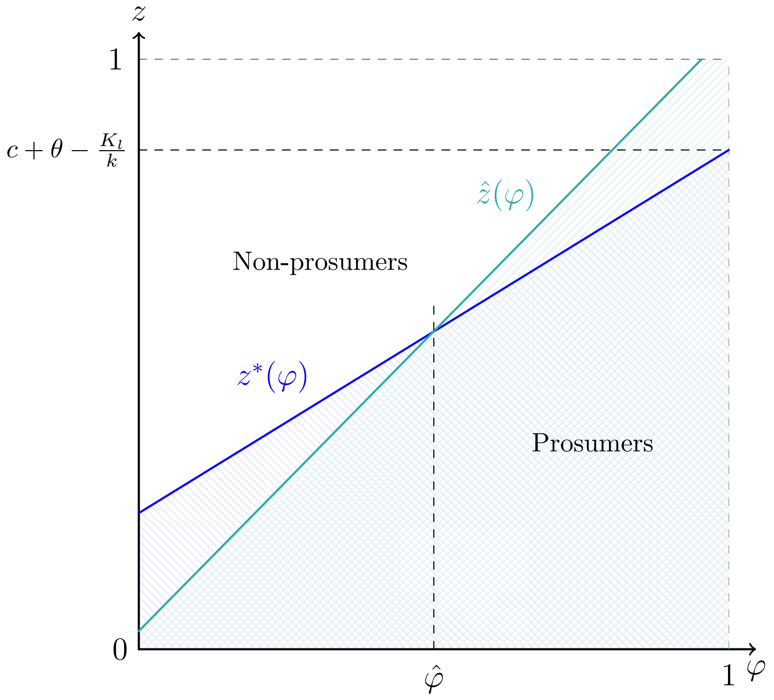

Figure 4: The second-best quantity of prosumption under a net purchasing scheme is in green. The first-best level is in blue.

6.3 Optimal tariffs

Although a Coasian tariff cannot achieve the first-best quantity of prosumption, it can still be achieved under net purchasing. The regulator can either relax the Coasian constraint and increase the fixed fee, or it can charge different tariffs for prosumers and consumers. By doing so, it can better allocate the specific costs linked to DPUs to prosumers, as proposed by Cambini and Soroush (2019), among others. We now show that the first-best quantity of prosumption can be achieved with simple tariff structures.

First, the regulator can depart from Coasian tariffs and increase the fixed fee paid by consumers. With $\rho > K_c$, it is possible to recover the grid costs and use the grid tariff given by Equation (8) to achieve the first-best outcome. The following tariff accomplishes this:

$$r_m = \theta - \frac{K_l}{k},\ r_x = \frac{K_l}{k},\ \rho = K_c + \frac{K_l}{k} q.$$

Second, the regulator can impose a discriminatory tariff that charges prosumers and consumers different rates for their energy imports. Let us denote prosumers' import and export fees by r_m and r_x, respectively, and use r_c to denote consumers' import fees. The following Coasian tariff (r_m, r_x, r_c, ρ) achieves the first-best outcome:

$$r_m = \theta + \frac{K_l}{q-k},\ r_x = \frac{K_l}{q-k},\ r_c = \theta,\ \rho = K_c.$$

Third, the regulator can charge an additional fixed fee to prosumers to recover the additional costs they impose on the DSO. If we denote this fee by ρ_p, the following tariff (r_m, r_x, ρ_p, ρ) achieves the first-best outcome:

$$r_m = \theta,\ r_x = 0, \rho_p = K_l + K_c,\ \rho = K_c.$$

6.4 Menu pricing

We previously showed that it is not possible to use menu pricing under a net metering scheme to identify different types of prosumers. Under a net purchasing regime, screening consumers by proposing menus of tariffs is not relevant. As explained in Section 4, when agents are equipped with smart meters or two mechanical meters, synchronization is technically observable and net purchasing tariffs can be implemented with full information about self-consumption. However, this information is not required for the DSO to construct an efficiency-inducing two-part tariff, as it can be done through cost parameters alone.

7 Partial-netting

The partial-netting (PN) described by Koumparou *et al.* (2017) is a variant of net metering. They show that this does not systematically lead to over-returns on investments by prosumers as illustrated by the experience in Greece. Under partial-netting, if over a billing period, the imported energy $(q-\varphi k)$ is larger than the exported energy $((1-\varphi)k)$, that is if $q>k$, the prosumer pays the retail rate $(c+r_m)$ on the net imports[15]; that is, the prosumer pays $(c+r_m)(q-k)$ as under net metering. The prosumer also pays a specific fee (r_x) on energy exports. Partial-netting is a hybrid system where energy net imports are priced as under net metering and energy exports are priced as under net purchasing.

The Partial-netting system can be implemented either with a net purchasing or net metering scheme. In the former case, the export fee is based on the actual export level; in the latter, it is based on an estimation $\bar{\varphi}$ of the self-consumption level.

7.1 Partial-netting with bi-directional metering

Under a PN scheme and bi-directional meters, the net utility of a prosumer who can install a DPU producing k and with a self-consumption level φ is given by

$$U(z)=\left\{\begin{array}{l} S-(c+r_m)(q-k)-r_x\,(1-\varphi)\,k-\rho-zk \\ S-(c+r_m)\,q-\rho \end{array}\right. \text{if} \begin{array}{r} x(z,\varphi)=1 \\ x(z,\varphi)=0. \end{array}$$

The consumer is indifferent between investing or not in a DPU if

$$\tilde{z}_p=c+r_m-(1-\varphi)r_x.$$

The first best can be achieved with $r_m=\theta-\frac{K_l}{k}$ and $r_x=\theta$ and an appropriate fixed fee allowing the DSO breaks even such that $\rho=\frac{K_l}{k}q+K_c>K_c$, that is with non-Coasian tariff structure. The partial-netting system is closely comparable to the net-purchasing regime we described in Section 6.

7.2 Partial-netting with single metering

With a single meter, the export fee in the above equation should be replaced by the estimated average value $r_x\,(1-\bar{\varphi})\,k$. The decision to become prosumer is then independent of the actual value of φ and it is given by: $\tilde{z}_p=c+r_m-(1-\bar{\varphi})r_x$. As for the net metering case, the first best cannot be reached; that is. consumers turn to prosumers if their installation cost is lower than a given threshold that is independent of the actual self-consumption level.

Compared to the Coasian tariff we analyzed above, the export fee gives an additional degree of freedom to the regulator who can use it to adjust downward the incentives to become prosumer. The export fee under partial-netting plays the same role as the fixed prosumer fee in the net metering case. One key issue with partial-netting is the assessment of self-consumption and actual PV production which cannot be measured without bi-directional meters. As a result, the billing needs to be contractually based on *ex-ante* estimations or expectations of self-consumption profiles for typical prosumers.

---

[15] In this system, there is a renewable energy credit (REC) to store the excess production from one billing to another.

8 Conclusion

Investments in PV panels by households are intended to tackle climate change by decreasing our reliance on fossil fuels and it is a key element of the energy transition. The increase in installed distributed renewable generation capacities has been backed by both a significant decline in the cost of solar power technology and the introduction of compensation mechanisms in many countries. However these policies have often been blamed for not being cost reflective, resulting in inadequate incentives to invest for the prosumers and the grid operators. This paper discusses how to integrate distributed generation into the energy grid with different pricing and metering systems.

The key point of this paper is to provide a theoretical analysis of how heterogeneous prosumer profiles for self-consumption, i.e. with different synchronization factors, can be correctly incentivized to invest efficiently in solar PV, depending on the tariff structure and the metering technology available. Our main results are as follows. We show that in an efficient outcome, only consumers who are relatively more inclined to self-consume should invest in PV installations and become prosumers. This selection can only be made under net purchasing when the energy sold to the grid is priced lower than energy drawn from the grid. Under net metering, the two flows have the same price, self-consumption does not pay, and the investment decision is made irrespective of the self-consumption level, resulting in inefficiencies. Hence, we show that net metering not only encourages too much investment in DPUs, but also attracts the wrong types of consumers to invest in production from a grid management perspective.

Another key result is that even if the grid operator has no information regarding self-consumption profiles of prosumers, efficient tariffs can be achieved through net purchasing. However, to be the case, tariffs should not be Coasian, i.e. fixed fees paid by consumers and prosumers should exceed the grid operator's fixed costs. Overall, our paper highlights that net purchasing without Coasian tariffs provide a better way to integrate prosumers in the energy system. As the question is highly relevant in policy debates, we believe that these conclusions can be of interest for regulators dealing with the integration of prosumers in the energy system.

The analysis provided in this paper is based on several assumptions that partly influence the conclusions and some model limitations that deserve discussion. First, in our analysis, we use a simplified and unidimensional parameter to represent the degree of correlation between of consumption and production of DPUs. This assumption allows us to ensure a fair tractability and readability of the results. However, it can be easily removed using a more general framework with a minute-to-minute matching between the demand and the decentralized production of energy. Indeed, let us consider that all consumers have a fixed path of consumption $q(t, \gamma)$ where t is time and γ is a parameter capturing the heterogeneity in energy consumption in the population. Synchronization is a consequence of the adequacy between $k\left(t\right)$ the energy flow produced by the DPU at time t, and consumption $q\left(t, \gamma\right)$. Heterogeneity in consumption or production (if consumers are located at different places with different levels of solar irradiation) leads to heterogeneity in self-consumption. Indeed, self-consumption levels at time t are given by $\min\{q\left(t,\gamma\right),k(t)\}$ so the degree of self-consumption at time t is time-dependent and writes $\varphi(t,\gamma)=\frac{\min\{q(t,\gamma),k(t)\}}{k(t)}$. In our model, the self-consumption rate φ is equal to the weighted average of $\varphi(t,\gamma)$ over the billing period. At period t, a prosumer is a net exporter of energy when $q\left(t,\gamma\right)<k(t)$ and net importer when $q\left(t,\gamma\right)>k(t)$. As a result, these assumptions would allow for temporary self-sufficiency for some prosumers, specifically when at a given time $t, q\left(t,\gamma\right)<k(t)$. Using such a framework, one can establish the dynamic foundations for our model and prove that our results still hold.[16].

Second time-varying tariffs, capacity tariffs and tariffs conditioned on the synchronization rate are not considered in our model and merit further analysis. However, these tariffs require individual smart meters and, to remain non-discriminatory, most legislations require a complete rollout of the technology. According to the latest figures, this rollout has not yet been achieved in most European countries (ACER/CEEM (2019)); in some exceptional cases, an extra decade or longer will even be needed to reach the 80% coverage goal initially set for 2020 by the EU Commission. This concern is also observed elsewhere (Draugelis *et al.* (2018)). For example, in the U.S., as of 2018, only around 50% of the population had a smart meter at home.

Third, we do not consider the intermittent dimension of DPU for prosumers as we assumed a simplified calibrated load factor for any DPU installed. The effects of intermittency have been already analyzed in the economic literature together with the role of storage and batteries (see. for instance Dato *et al.* (2020)). Introducing intermittency for distributed renewable generation units in the analysis calls for a dynamic and stochastic version of the model we analyzed. Nevertheless, as the uncertainty about the load factor of the DPU can be anticipated *ex ante* anticipated by prosumers and the DSO, all results we present still hold at their expected levels. However, due to potential risk aversion behaviors of agents involved in the market relations at stake, some standard deviations of the optimal tariffs should be considered as a track for future research.

Fourth, the recent appearance of energy communities as well as the local exchanges between prosumers leads to imagine that grid pricing issues may now be related to the need of coordination between these agents at a local level (see. Abada *et al.* (2020)). Energy communities can facilitate the coordination of investments at the local level, but their implementation could be complex. These aspects have been neglected in our analysis and are left for further research.[17]

Finally, we emphasize the role of tariff design but some further challenges are also on the table, especially for net purchasing systems. Following the IRENA (2019, p. 11) "*to enable the adoption of net billing schemes, a method must be developed to send the right price signals to prosumers*", identifying four key factors that are *(i)* the

---

[16] An addendum for this case can be requested to the authors.

[17] Cortade and Poudou (2020) analyze the noncooperative inner incentives to install DPU for prosumers able to exchange their energy in excess through peer-to-peer platforms.

determination of appropriate mechanisms to recover network costs, *(ii)* methods for valuing the electricity supplied by distributed generation according to system needs, *(iii)* deployment of advanced metering infrastructure and *(iv)* prosumer awareness, empowerment and engagement via automation. We mainly addressed the first one in this paper and the three others may constitute tracks for future works.

References

[1] Abada, I., A. Ehrenmann and X. Lambin, (2020a). On the viability of energy communities, *Energy Journal*, 41(1), 113150.

[2] ACER/CEEM (2019). Annual Report on the Results of Monitoring the Internal Electricity and Natural Gas Markets in 2018, Agency for the Cooperation of Energy Regulators (ACER) and Council of European Energy Regulators (CEER), Annual report.

[3] Brown, D. P. and D. Sappington (2017). Designing compensation for Distributed solar generation: Is net metering ever optimal? *The Energy Journal*, 38 (3), 1-32.

[4] Burger, S. P., J. D. Jenkins, C. Batlle and I. J. Pérez-Arriaga (2019). Restructuring Revisited Part 2: Coordination in Electricity Distribution Systems. *The Energy Journal* , 40(3), 55-76.

[5] Cambini, C., and G. Soroush (2020). Designing grid tariffs in the presence of distributed generation, *Utilities Policy*, 61, 100979

[6] Cano Ortega, A., F. Sánchez Sutil and J. De la Casa Hernández (2019). Power Factor Compensation Using Teaching Learning Based Optimization and Monitoring System by Cloud Data Logger. *Sensors* , 19(9) 21-72.

[7] Clastres, C., Percebois, J., Rebenaque, O. and Solier, B. (2019), Cross subsidies across electricity network users from renewable self-consumption, *Utilities Policy*, 59, 100925.

[8] Coase, R. H. (1956). The marginal cost controversy. *Economica*, 13, 169-182.

[9] Cortade, T. and J.-C. Poudou (2020). Peer-to-Peer Energy Platforms: Incentives for Prosuming, *mimeo.*

[10] Dato P., T. Durmaz and A. Pommeret (2019). Smart Grids and Renewable Electricity Generation by Households, *Energy Policy*, 86, 104511.

[11] Draugelis, G., R. Mittal, A. Gupta, P. M. Hannam, N. Sharda (2018). Survey of International Experience in Advanced Metering Infrastructure and its Implementation. Washington, D.C. : World Bank Group.

[12] Eid, C., J. R. Guilln, P. F. Marn and R. Hakvoort (2014). The economic effect of electricity net-metering with solar PV: Consequences for network cost recovery, cross subsidies and policy objectives. *Energy Policy*, 75, 244-254.

[13] Gautier, A., J. Jacqmin and J.-C. Poudou (2018). The prosumers and the grid. *Journal of Regulatory Economics*, 53(1), 100-126.

[14] Gautier, A., B. Hoet, J. Jacqmin and S. Van Driessche (2019). Self-consumption choice of residential PV owners under net-metering. *Energy policy*, 128, 648-653.

[15] Gunther, C., Schill, W. P., and A. Zerrahn (2019). Prosumage of solar electricity: tariff design, capacity investments, and power system effects. Working paper.

[16] International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) (2016), A Methodology for the Analysis of PV Self-consumption Policies, Report IEA-PVPS T1-28:2016.

[17] IRENA (2019), Innovation landscape brief: Net billing schemes, Report, International Renewable Energy Agency, Abu Dhabi.

[18] JRE-SESI (Joint Research Centre, Smart Electricity Systems and Interoperability) (2020). Smart Metering deployment in the European Union. Accessed October 7th, 2020. `https://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union`.

[19] Koumparou I., G. C. Christoforidis, V. Efthymiou, G. K. Papagiannis, and G. E. Georghiou (2017). Configuring residential PV net-metering policies – A focus on the Mediterranean region, *Renewable Energy*, 113, 795-812.

[20] La Monaca, S. and L. Ryan (2017). Solar PV where the sun doesn't shine: Estimating the economic impacts of support schemes for residential PV with detailed net demand profiling. *Energy Policy*, 108, 731-741.

[21] Lang, T., D. Ammann and B. Girod (2016). Profitability in absence of subsidies: A techno-economic analysis of rooftop photovoltaic self-consumption in residential and commercial buildings. *Renewable Energy*, Vol. 87, Part 1, p. 77-87.

[22] Luthander, R., J. Widen, D. Nilsson and J. Palm (2015). Photovoltaic self-consumption in buildings: A review. *Applied Energy*, 142, p. 80–94.

[23] McKenna, E., J. Pless and S. Darby (2018). Solar photovoltaic self-consumption in the UK residential sector: New estimates from a smart grid demonstration project. *Energy Policy*, 118, 482-491.

[24] McLaren, J., C. Davidson, J. Miller and L. Bird, L. (2015). Impact of rate design alternatives on residential solar customer bills: Increased fixed charges, minimum bills and demand-based rates. *The Electricity Journal*, 28(8), 43–58.

[25] Moura, R. and M. C. Brito (2019). Prosumer aggregation policies, country experience and business models. *Energy Policy*, 132, 820-830.

[26] Sanchez-Sutil, F., A. Cano-Ortega , J. Hernandez and C. Rus-Casas (2019). Development and Calibration of an Open Source, Low-Cost Power Smart Meter Prototype for PV Household-Prosumers. *Electronics*, 8, 878, 2-29.

[27] Schittekatte, T., I. Momber and L. Meeus (2018). Future-proof tariff design: Recovering sunk grid costs in a world where consumers are pushing back. *Energy economics*, 70, 484-498.

[28] Solano, J., M. Brito and E. Caamano-Martin (2018). Impact of fixed charges on the viability of self-consumption photovoltaics. *Energy Policy*, 122, 322-331.

[29] Wagner, J. (2019). Grid investment and support schemes for renewable electricity generation. *The Energy Journal*, 40(2).

[30] Young, S., Bruce, A., and MacGill, I. (2019). Potential impacts of residential PV and battery storage on Australia's electricity networks under different tariffs. *Energy Policy*, 128, 616-627.

9 Nomenclature of variables

We provide a nomenclature of variables used in our model. Depending on the regimes studied all of them can be stared, tilded or hatted and adorned with a subscript or superscript letter/number.

Index	Description
c	CPU energy production unit cost
c_d	Total net distribution cost
C	Total cost
C_d and C_g	Total distribution costs and generation cost
$f(\cdot), F(\cdot)$	Distribution, cumulative functions for DPU installation cost
$g(\cdot), G(\cdot)$	Distribution, cumulative functions for synchronization factor
k and $\tilde{k}$	DPU flow of energy and capacity
K_l and K_c	Additional fixed grid cost of connecting a prosumer and a standard user
$\bar{K}_l$	Total fixed grid cost associated with prosumers
$H(\cdot)$	(Inverse) hazard rate function based on f
M	Mass of prosumers is M
p	Energy price
q	Fixed level of electric consumption
r	Network fee with net metering
r_m and r_x	Network export and import fees with net purchasing
S	Fixed gross surplus level derived from consumption
U	Net surplus/utility level for a consumer
V_c and V_l	Total volume of centralized and local distribution
x	Prosumption decision binary variable
z and $\tilde{z}$	Unit costs of installation of DPU (flow and capacity)
$\underline{z}$ and $\bar{z}$	Bounds for the unit costs of installation of DPU
β	Average load factor of a consumer
δ	Unit environmental cost/damage
φ	Degree of self-consumption
θ	Variable grid costs of power distribution
θ_l and θ_c	Variable grid costs of power distributed by local exchanges and centralized
ρ	Consumer fixed fee

Table 1: Nomenclature of variables

10 Appendix

Proof of Proposition 1. Straightforwardly, by pointwise optimization and from the linearity of the integrand of (4) with respect to z.

Proof of Proposition 3. From expression (6) in the text, we can derive $\tilde{z}_0 = c + \tilde{r}_0$ and rewrite it as:

$$\begin{aligned} \tilde{z} &= z^*(\varphi) + (1-\varphi)\theta + (1-\bar{\varphi})\frac{F(\tilde{z})k}{q - F(\tilde{z})k}\theta + \frac{q}{q - F(\tilde{z})k}\frac{K_l}{k} \\ &> z^*(\varphi). \end{aligned}$$

Net metering: Optimal two-part tariff. The problem is now:

$$\begin{aligned} \min_r C(r) &= (c+\theta)q + (rk - \theta k\bar{\varphi} + K_l)F(r+c) + K_c \\ \rho + r(q - F(r+c)k) &= \theta q + (K_l - \bar{\varphi}k\theta)F(r+c) + K_c. \end{aligned}$$

The solution is

$$\begin{aligned} C'(r) &= (rk - \theta k\bar{\varphi} + K_l) f(r+c) + F(r+c)k = 0 \\ &\Leftrightarrow \tilde{r}_2 + H(\tilde{r}_2 + c) = \bar{\varphi}\theta - \frac{K_l}{k} \end{aligned}$$

where $H(z) = \frac{F(z)}{f(z)} \geq 0$ and is increasing in z. If $F(z)$ is logconcave this implies

$$\tilde{r}_2 < \bar{\varphi}\theta - \frac{K_l}{k}$$

and $\tilde{\rho}_2 = \left((1-\bar{\varphi})\theta + \frac{K_l}{k}\right)q + K_c + H(\tilde{r}_2 + c)\left[q - F(\tilde{r}_2 + c)k\right]$ which yields:

$$\tilde{\rho}_2 > \left((1-\bar{\varphi})\theta + \frac{K_l}{k}\right)q + K_c$$

.

Proof of Lemma 1. *(a)* Comparing $(\tilde{z}_0, \tilde{r}_0)$ and $(\tilde{z}_1, \tilde{r}_1)$ implies that

$$\begin{aligned} \tilde{r}_0 &= \tilde{z}_0 - c \text{ and } \tilde{r}_1 = \tilde{z}_1 - c + \frac{K_l}{k} \\ \tilde{z}_0 &= \theta Y(\tilde{z}_0) + c + \frac{F(\tilde{z}_0)}{q - F(\tilde{z}_0)k}K_l \quad \text{and} \quad \tilde{z}_1 = \theta Y(\tilde{z}_1) + c - \frac{K_l}{k} \end{aligned}$$

where we denote $Y(z) = \frac{q - F(z)\bar{\varphi}k}{q - F(z)k}$, a strictly increasing positive function of z with $Y(0) = 1$. Then, for all $z \in [0,1]$:

$$\theta Y(z) + c + \frac{F(z)}{q - F(z)k}K_l > \theta Y(z) + c - \frac{K_l}{k},$$

and since $\theta Y\left(z\right)+c+\frac{F(z)}{q-F(z)k}K_l$ is also a strictly increasing positive function of z, this clearly shows that

$$\tilde{z}_1<\tilde{z}_0 \quad \text{and} \quad \tilde{r}_1<\tilde{r}_0.$$

(b) Comparing $\left(\tilde{z}_2,\tilde{r}_2\right)$ and $\left(\tilde{z}_1,\tilde{r}_1\right)$ implies that

$$\begin{aligned}\tilde{r}_1-\tilde{r}_2 &= \theta\frac{q-F\left(\tilde{z}_1\right)k\bar{\varphi}}{q-F\left(\tilde{z}_1\right)k}-\left(\bar{\varphi}\theta-\frac{K_l}{k}-H\left(\tilde{r}_2+c\right)\right)\\ &= \theta\frac{\left(1-\bar{\varphi}\right)q}{q-F\left(\tilde{z}_1\right)k}+\frac{K_l}{k}+H\left(\tilde{r}_2+c\right)>0\end{aligned}$$

so $\tilde{r}_2<\tilde{r}_1<\tilde{r}_0$. For the level of prosumption

$$\tilde{z}_1-\tilde{z}_2=\tilde{r}_1-\frac{K_l}{k}-\tilde{r}_2=\theta\left(\frac{q\left(1-\bar{\varphi}\right)}{q-F\left(\tilde{z}_1\right)k}\right)+H\left(\tilde{r}_2+c\right)>0$$

so $\tilde{z}_2<\tilde{z}_1<\tilde{z}_0$.

These relationships are represented in Figure 5.

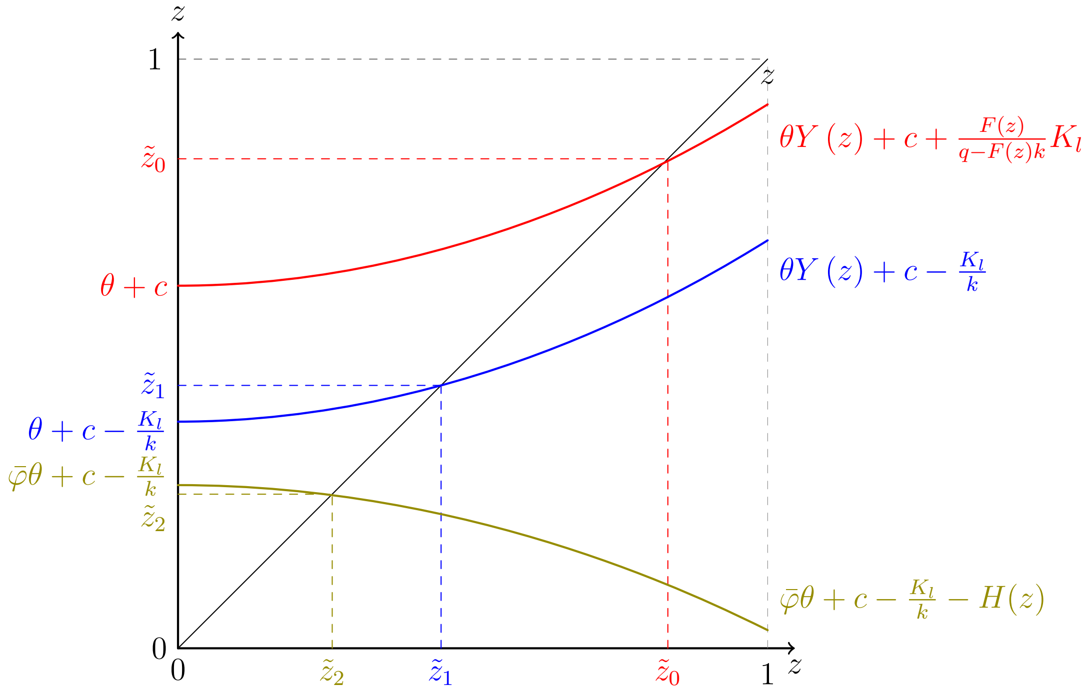

Figure 5: Comparisons of $\tilde{z}_0$, $\tilde{z}_1$ and $\tilde{z}_2$.

Proof of Proposition 4. With the tariff structure proposed in (8) and $\hat{\rho}=K_c$, the DSO break-even constraint is:

$$\Pi=r_m\left(\hat{V}_c+\hat{V}_l\right)+r_x\hat{V}_l-c_d=\left(\theta-\frac{K_l}{k}\right)\hat{V}_c+\theta\hat{V}_l-c_d$$

where from (1) and (2), the distribution volumes are:

$$\hat{V}_l = k\int_0^1 (1-\varphi)F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi \text{ and } \hat{V}_c = q - \left(\int_0^1 F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi\right)k$$

and

$$\hat{c}_d = \theta q - k\int_0^1 \left(z^*\left(\varphi\right)-c\right)F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi.$$

At the first-best outcome, we have that $\hat{z}\left(\varphi\right) = z^*\left(\varphi\right)$. Rearranging the terms, the DSO's profit is

$$\hat{\Pi} = -\frac{K_l}{k}q < 0$$

so the DSO cannot break even and the first-best outcome cannot be achieved.

Proof of Proposition 5. Again, $\hat{\rho} = K_c$. With net purchasing, the total cost and the DSO's profit are functions of (r_m, r_x), so we have:

$$\begin{aligned}\hat{C}\left(r_m,r_x\right) &= \left(c+\theta\right)q + \int_0^1\int_0^{\hat{z}(\varphi)}\left[\left(z-c\right)k - \varphi k\theta + K_l\right]f\left(z\right)g\left(\varphi\right)d\varphi dz \\ \hat{\Pi}\left(r_m,r_x\right) &= \left(r_m-\theta\right)q - \left(\int_0^1\left[\hat{z}\left(\varphi\right)-z^*\left(\varphi\right)\right]F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi\right)k\end{aligned}$$

Indeed at this optimum, it cannot be the case that the DSO break-even constraint is slack, as we have seen in Proposition 4 that the cost-minimizing tariff scheme is not feasible for the DSO. So the solution will necessarily imply that $\hat{\Pi}\left(r_m,r_x\right) = 0$. The tariff structure that guarantees that the DSO breaks even is implicitly given by:

$$\hat{r}_x\left(r_m\right) = \frac{\left(\theta-r_m\right)\left(q-k\hat{\Phi}\right)+K_l\hat{M}}{k\left(\hat{M}-\hat{\Phi}\right)} \tag{10}$$

where $\hat{M}$ is the mass of prosumers under a tariff structure:

$$\hat{M} = \int_0^1 F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi \text{ and } \hat{\Phi} = \int_0^1 \varphi F\left(\hat{z}\left(\varphi\right)\right)g\left(\varphi\right)d\varphi$$

where $\hat{\Phi}$ is the mean value for the synchronization factor for prosumers only, where $\hat{\Phi} \leq \hat{M}$.

Differentiating (10) yields

$$\hat{r}_x'\left(r_m\right) = \frac{-\frac{\left(q-k\hat{\Phi}\right)}{k}+\left(r_m-\theta\right)\hat{A}-\hat{r}_x\left(r_m\right)\hat{B}+\frac{K_l}{k}\hat{E}}{\hat{M}-\hat{\Phi}+\left(r_m-\theta\right)\hat{B}-\hat{r}_x\left(r_m\right)\hat{D}+\frac{K_l}{k}\hat{C}} \tag{11}$$

with positive constants defined as

$$\begin{aligned}
\hat{A} &= \int_0^1 \varphi^2 f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0 \;;\; \hat{B} = \int_0^1 \varphi (1-\varphi) f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0; \\
\hat{C} &= \int_0^1 (1-\varphi) f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0, \;\; \hat{D} = \hat{C} - \hat{B} = \int_0^1 (1-\varphi)^2 f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0; \text{ and} \\
\hat{E} &= \hat{A} + \hat{B} = \int_0^1 \varphi f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0 \;;\; \hat{F} = \int_0^1 f(\hat{z}(\varphi)) g(\varphi)\, d\varphi > 0
\end{aligned}$$

with $\hat{C} > \hat{B}$. Note that:

$$\frac{\partial \hat{M}}{\partial r_m} = \hat{E} - \hat{r}_x'(r_m)\, \hat{C} \;\text{ and }\; \frac{\partial \hat{\Phi}}{\partial r_m} = \hat{A} - \hat{r}_x'(r_m)\, \hat{B}.$$

Now let $\hat{C}(r_m) = \hat{C}(r_m, \hat{r}_x(r_m))$. We can write the first-order condition as:

$$\hat{C}'(r_m) = 0 \Leftrightarrow k \int_0^1 (\hat{z}(\varphi) - z^*(\varphi)) (\varphi - (1-\varphi)\, \hat{r}_x'(r_m)) f(\hat{z}(\varphi)) g(\varphi)\, d\varphi = 0.$$

From Proposition 4**,** there is no r_m such that $\hat{z}(\varphi) = z^*(\varphi)$ when the $\hat{\Pi}(r_m, r_x) = 0$. Then, $\hat{C}'(r_m) = 0$ if and only if

$$\int_0^1 (\hat{z}(\varphi) - z^*(\varphi))\, \varphi f(\hat{z}(\varphi)) g(\varphi)\, d\varphi = \hat{r}_x'(r_m) \int_0^1 (\hat{z}(\varphi) - z^*(\varphi)) (1-\varphi) f(\hat{z}(\varphi)) g(\varphi)\, d\varphi,$$

which can also be rewritten as a differential equation in $\hat{r}_x'(r_m)$:

$$\hat{r}_x'(r_m) = \frac{(r_m - \theta)\, \hat{A} - \hat{r}_x(r_m)\, \hat{B} + \frac{K_l}{k} \hat{E}}{(r_m - \theta)\, \hat{B} - \hat{r}_x(r_m)\, \hat{D} + \frac{K_l}{k} \hat{C}}. \tag{12}$$

Equating (11) and (12) and substituting (10) leads to

$$\hat{r}_m^* = \theta - \hat{\Gamma} \frac{K_l}{k}$$

where

$$\hat{\Gamma} = \left[1 + \frac{q}{k} \frac{\left(q - \hat{\Phi} k\right) \hat{C} - \left(q - k\hat{M}\right) \hat{B}}{k\hat{\Phi}\left(\hat{\Phi} + 2\hat{M}(\hat{C} - 1)\right) + k\left(\hat{B} + \hat{C} - 1\right) \hat{M}^2 + q\hat{B}\hat{M} - \hat{\Phi} q \hat{C}} \right]^{-1} < 1.$$