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The Prosumers and the Grid

Abstract

Prosumers are households that are both producers and consumers of electricity. A prosumer has a grid-connected decentralized production unit (DPU) and makes two types of exchanges with the grid: energy imports when the local production is insuffcient to match the local consumption and energy exports when local production exceeds it. There exists two systems to measure the exchanges: a net metering system that uses a single meter to measure the balance between exports and imports and a net purchasing system that uses two meters to measure separately power exports and imports. Both systems are currently used for residential consumption. We build a model to compare the two metering systems. Under net metering, the price of exports paid to prosumers is implicitly set at the price of the electricity that they import. We show that net metering leads to (1) too many prosumers, (2) a decrease in the bills of prosumers, compensated via a higher bill for traditional consumers, and (3) a lack of incentives to synchronize local production and consumption.

JEL-Codes: D130, L510, L940, Q420.

Keywords: decentralized production unit, grid regulation, solar panel, grid tariff, storage.

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1 Introduction

Prosumers are households that are both *producers* and *consumers* of electricity. A prosumer has a decentralized production unit (DPU) – a rooftop photovoltaic system (PV) or a small wind turbine – to produce electricity at home and this DPU is grid-connected.

A generic auto-consumption profile of a residential DPU is provided in Figure 1. Part of the electricity produced by a prosumer is consumed at home when production and consumption are simultaneous. Production and consumption, though, are not usually synchronized. When the local production does not match the consumption, the prosumer uses the grid for the balance. If consumption exceeds production then the prosumer draws electricity from the grid, like any other consumer. Conversely, if production exceeds consumption then the excess power is supplied to the grid. There are thus two distinct power exchanges between a prosumer and the grid: imports from and exports to the grid. For a residential consumer installing solar panels on his roof – the main focus of this paper –, less than 30% of the electricity produced is self-consumed and the largest part of their production is exported to the grid.

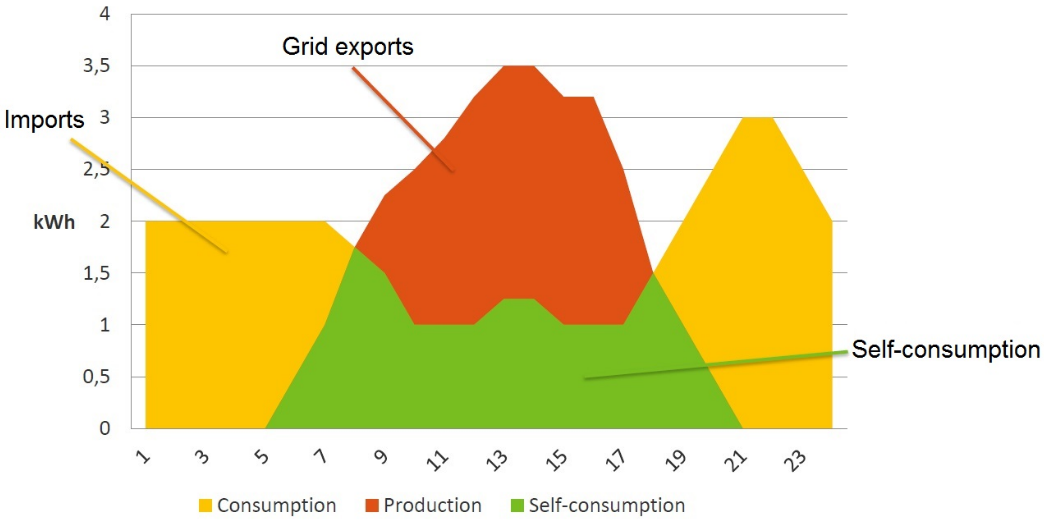

Figure 1: Auto-consumption Profile (Source IEA-PVPS (2014))

From the consumer's point of view, decentralized production units substitute traditional generation units (from coal, gas or nuclear plants). From the energy system's point of view, an increased penetration of decentralized production technologies changes both the total cost of electricity generation (including the environmental cost) and the cost of the network. Power exchanges between prosumers and the grid generate costs for the grid operator as they require additional investments in on-load tap changers to support grid stability, in booster transformers to provide voltage support or in static volt ampere reactive control to improve the reactiveness of the system (IEA-RETD (2014)). The interplay between decentralized production and the grid cost is the subject of this paper. Grid costs will be passed through consumers and prosumers via the distribution tariff i.e. the price consumers pay for using the network which accounts for about 20 to 30% of the total electricity bill. Hence, this tariff, by affecting both the costs and benefits of the DPU, will influence the rate of technology adoption.

To measure exchanges with the grid, residential prosumers are equipped with meter(s). There are two alternative metering technologies for residential service: the net metering and the net purchasing systems. With the net metering system[1], there is a unique meter that runs backwards when production exceeds consumption. The meter only registers the difference between imports from and exports to the grid i.e. net imports. With the net purchasing system[2], there are two meters: a traditional one to measure electricity drawn from the grid and an export meter to measure the power supply to the grid. Whichever the system, the registered consumption is used as a basis for billing. Currently, the two technologies are being used in Europe (see Figure 2 and Poullikkas (2013) for detailed reviews). In the U.S, the net metering system is used in 43 states (DSIRE, 2016[3]).

Net metering is a tool to support and finance decentralized energy production (Eid et al. (2014)). With net metering local electricity production is valued at a price equal to the electricity retail price plus the unit network fee which represents the avoided cost/price of electricity generated. Net metering is criticized on many grounds. For Brown and Sappington (2017a), it induces an inefficient deployment of distributed generation. Net metering has also important redistributional consequences. As the registered consumption decreases, the grid tariff has to increase so as to cover the network costs. This leads to an important redistribution of income between prosumers and traditional consumers (see Darghouth et al. (2011), Yamamoto (2012), Cai et al. (2013) or Brown and Sappington (2017a)). This rate increase makes decentralized

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[1] It is also known as the single metering system.

[2] The denomination dual or double metering and net billing are also often used in the literature.

[3] Informations collected from the DSIRE website `www.dsireusa.org`

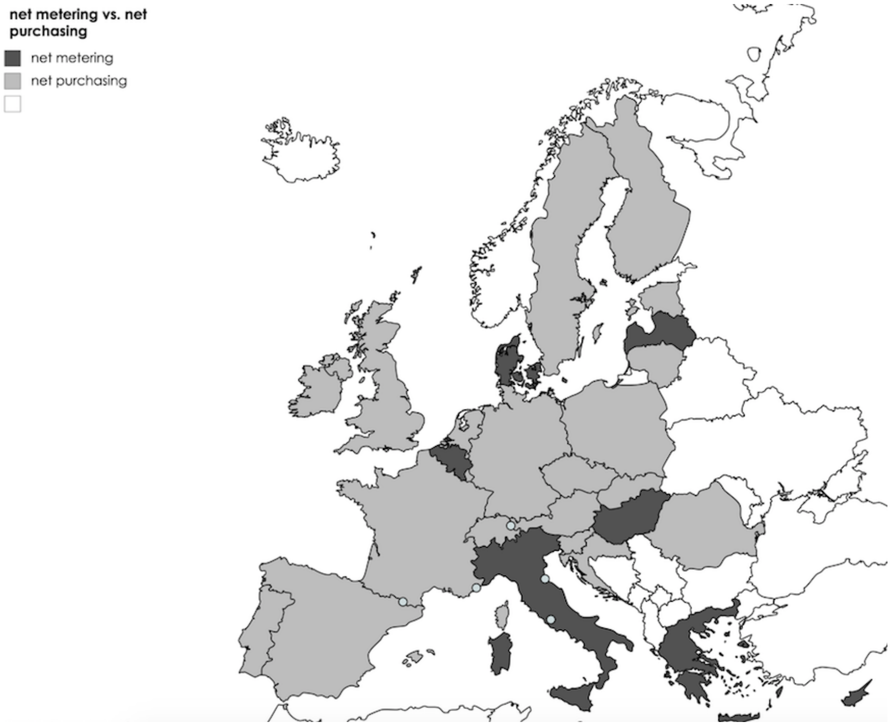

Figure 2: Net-metering vs net-purchasing in Europe (Source res-legal.eu)

production even more profitable and stimulates further the DPU expansion; a *death spiral* in the words of Borenstein and Bushnell (2015).

With net purchasing, prosumers can export electricity to the grid and they are compensated for the power injection (via a feed-in-tariff). Electricity is either valued at retail price or at a premium price. In addition, there might be specific network fees charged by the grid operator for power injection.

In this paper, we show that the two metering technologies are not equivalent from an economic point of view. There are at least three differences. First, as the costs for the prosumers may differ, the deployment of DPU is affected by the metering technology. This in turn has an impact on the total cost of both electricity generation and the grid. We will show that net metering will lead to too much "prosumption". Second, the two technologies differ in terms of income redistribution between the consumer categories. In particular, net metering transfers the burden of the network cost to traditional users. Last, they induce different behavior with respect to self-consumption, i.e. the consumption of self-generated renewable electricity. According to the European Commission (2015), self-consumption can lead to consumer empowerment and a more efficient energy system. There exists complementary technologies (e.g. storage) or demand side management practices (e.g load displacement, orientation of the solar panels) that can increase the synchronization between decentralized production and consumption. With net metering, self-consumption is not encouraged as exports and self-consumption are perfect substitutes from the prosumer's perspective but not from the system's perspective. With net purchasing, an increase in self-consumption decreases the prosumers' bill. Overall, our paper shows that net purchasing is a better way to integrate prosumers in the energy system compared to net metering on these dimensions. These conclusions are further confirmed by looking at various structures for the retail and grid prices and the positive externalities created by a green electricity production. They tend to corroborate the recent trend among regulatory agencies in Europe and the U.S towards a switch away from net metering policies.

Section 2 presents our general framework. The net metering and the net purchasing systems are, respectively, exposed in Section 3 and Section 4. Both are compared in Section 5 with respect to the deployment of decentralized production, the contribution to the network financing of consumers and prosumers and the incentives to synchronize production and consumption. The robustness of our results with respect to both different price structures and environmental concerns are discussed in Section 6. Section 7 concludes in the light of recent regulatory evolutions.

2 Model

We consider an electricity system with three categories of operators. Centralized electricity producers-retailers, a regulated Distribution System Operator (DSO) and consumers/prosumers. In our model, centralized electricity production is separated from network activities as currently in Europe. The DSO remains a monopolistic activity and regulation consists in setting a distribution tariff such that the DSO breaks even. In this paper, we set aside all the well documented incentive issues related to the regulation of the DSO.[4]

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[4] See Jamasb and Pollitt (2007) for a general overview.

2.1 Consumption and production

Consumers We consider a population of residential consumers of size 1. All consumers have the same energy consumption of q MWh and the energy demand is supposed to be totally inelastic. We denote by S, the consumer's gross (invariant) surplus derived from consuming the energy flow q.

Centralized production units Electricity is produced either by centralized production units (CPU) or by decentralized production units (DPU). CPU produce energy at a cost of c per MWh and they sell their energy to the consumers. We suppose that CPU operate in a perfectly competitive market and that the retail price of energy p is equal to the production cost c. With marginal cost pricing at the centralized level, we leave aside any distortion created by imperfect competition at the retail level.

Decentralized production units The consumers have the opportunity to install a DPU and become prosumers. We denote by $\tilde{k}$ the capacity (in MW) of the DPU and the installation cost is equal to $\tilde{z}$ per unit of capacity. An installation of capacity $\tilde{k}$ has an installation cost of $\tilde{z} \cdot \tilde{k}$.

The efficiency parameter of the DPU is denoted by τ. For solar panels, τ depends on the solar irradiation level and the housing characteristics (roof orientation/size, etc.). The production k of the DPU (in MWh) is equal to $k = \tilde{k} \cdot \tau$. In other words, to produce 1 MWh of energy, the consumer needs a DPU of capacity $1/\tau$. The production cost with a DPU is then equal to $\tilde{z}/\tau$ per MWh. Let us call this unit cost by z, with $z = \tilde{z}/\tau$.[5] We will suppose that consumers are heterogeneous with respect to the cost z, due for instance to different efficiency of their installation or to different technologies for decentralized production (wind vs. solar). We suppose further that z is distributed on an interval $[\underline{z}, \bar{z}]$ according to a given continuous distribution $f(z)$ and cumulative $F(z)$.

As a result, an (endogenous) proportion $[\underline{z}, z]$ of the population become prosumers and a residual proportion $[z, \bar{z}]$ remains traditional consumers. Indeed, depending on the market or institutional conditions, only a fraction of agents will choose to install a DPU. We thus write $\alpha = F(z)$.

The DPU are grid-connected. Prosumers use the grid for making bidirectional

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[5] In a dynamic setting, we would interpret z as the leveraged cost of energy.

power exchanges: energy imports when production does not cover the consumption and exports when production exceeds consumption.

The size of the DPU may be limited by legal or regulatory constraints or by technical constraints such as the roof size for solar panels. For instance, in some countries the (value of) excess energy is credited to the next month and credit are set back to zero at the end of each year (Dufo-Lopez and Bernal-Agustin (2015)). Other countries also limit the DPU capacity to the actual consumption ($k \leq q$). In our model, we will assume that the DPU production is fixed, identical for all prosumers and lower than actual consumption. This simplifying assumption is done without loss of generality.

Cost of generation The total production of DPU is αk. CPU must produce enough to cover the consumption of traditional consumers $(1-\alpha)q$ and the consumption of prosumers that is not covered by the DPU $\alpha(q-k)$. The total cost of producing energy $C_g(\alpha)$ is the sum of the centralized and decentralized production cost, respectively $C_g^C(\alpha)$ and $C_g^D(\alpha)$:

$$C_g^C(\alpha) = (1-\alpha)\, cq + \alpha\,(q-k)\, c = (q-\alpha k)c \quad \text{and} \quad C_g^D(\alpha) = kH(z),$$

where $H(z) = \int_{\underline{z}}^{z} f(x)x dx$. So the total cost of generation writes

$$C_g(\alpha) = (q-\alpha k)c + kH(z).$$

Synchronization of production and consumption Production and consumption of a prosumer are not perfectly synchronized at any point in time. We will denote by $\varphi \leq 1$ the synchronization factor of a prosumer. This means that a prosumer, producing k, consumes φk from its own production and that the remaining production $(1-\varphi)k$ is injected to the grid (export). A prosumer, consuming q, self-consumes a part φk of its total production and the remaining part $(q-\varphi k)$ comes from the grid (import).

According to McLaren et al. (2015), in the U.S, on average 1/3 of the production of solar energy is consumed at home. In none of the utilities analyzed, it exceeds 0.5.[6]

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[6] For households, Bost et al. (2011) report a share of self-consumption ranging from 11.8% to 32.1%. Lang et al. (2015) estimate a share of self-consumption of 40% for small residential buildings, this share is increasing up to 80% for large residential buildings and even 90% for office buildings. This difference can be explained by consumption patterns which are the highest for residential users when the solar radiations tend to be lower (before and after average office working hours).

This is confirmed in EIA-RETD (2014), which nevertheless acknowledges a forthcoming rise due to technological advances in home storage facilities and the emergence of smart appliances.

2.2 The grid

Exchanges with the grid Consumers, prosumers and CPU are connected to the grid who facilitates power exchanges between them. In a system with both CPU and DPU, the grid organizes two types of exchanges: distribution of energy from the CPU to the consumption places and distribution of the *excessive* energy production from the DPU to the consumers. We will call these two exchanges: centralized distribution and local distribution respectively.

The total consumption is equal to q. A fraction αk of this consumption is covered by the DPU, the remaining is covered by the CPU. The volume of centralized distribution (V_c) is equal to the CPU production:

$$V_c = q - \alpha k.$$

The volume V_c is decreasing with the penetration rate of decentralized production.

A fraction φ of the production of a DPU is self-consumed, the remaining fraction being exported and consumed elsewhere. Local distribution volume (V_l) is then:

$$V_l = \alpha(1 - \varphi)k.$$

The total exchanges with the grid of consumers and prosumers are represented on Figure 3.

Grid costs The DSO is in charge of managing the distribution grid. We will distinguish the cost of centralized and local distribution. In both cases, costs are linked to the electricity volumes managed by the grid[7] and to the number of connected users, 1 for centralized distribution, α for local distribution.

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[7] In the literature on the production technology of a DSO, the electricity distributed measured either by the peak value or the total value is always a significant cost driver (see Jamasb and Pollitt (2001) for a survey). To give an example, Coelli *et al.* (2013) estimate an average cost elasticity of 0.25 for the electricity distributed with a significantly higher value in low density areas.

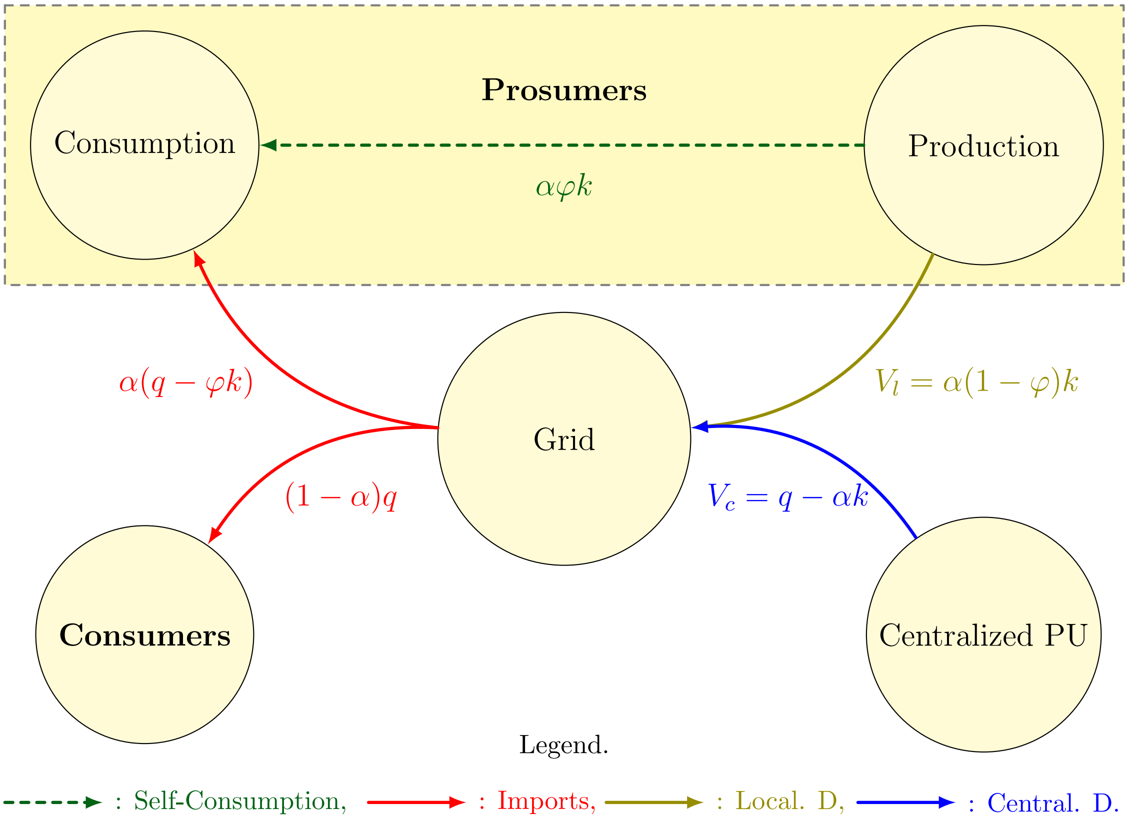

Figure 3: Exchanges with the grid

Let us denote by K_i and θ_i, the fixed cost per user and the variable cost per MWh distributed associated with centralized ($i = c$) and local distribution ($i = l$). To simplify the analysis, we will suppose that the variable costs per MWh are identical for centralized and local distribution: $\theta_l = \theta_c = \theta$. Total cost of the DSO is equal to:

$$C_d(\alpha) = K_c + V_c\theta_c + \alpha K_l + V_l\theta_l = K_c + \alpha K_l + (q - \alpha\varphi k)\,\theta. \tag{1}$$

Decentralized production has two impacts on the grid cost: an additional cost per prosumer (K_l) to integrate and to support the decentralized production capacity in the grid and a cost saving as part of the energy consumed is self-produced. A greater synchronization increases these saving. DPU penetration generates additional network costs if $K_l \geq \varphi\theta k$.

In the sequel, we will distinguish the fixed cost of centralized distribution K_c, which can be considered as the historical cost of the network from the variable costs $c_d(\alpha) = \alpha K_l + (V_c + V_l)\,\theta$. We thus have that: $C_d(\alpha) = c_d\,(\alpha) + K_c$.

Metering technology Consumers with a DPU are connected to the grid and their exchanges with the grid (imports and exports) are measured by one or two meters. With *net metering*, there is a single meter measuring the difference between imports $q - \varphi k$ and exports $(1 - \varphi)k$. The meter runs backward when the energy is exported and it measures the net electricity flow $q - k$ which is positive if the total consumption exceeds the production and negative otherwise. In this paper, we restrict our attention to the situation where $k < q$. Notice that measuring production k in addition is insufficient to recover the full information about exports and imports unless φ is known. With *net purchasing,* prosumers are equipped with two meters that record both imports and exports separately.

Grid regulation and distribution tariff The grid is regulated and the regulator sets a grid tariff such that the DSO breaks even. From a very general point of view grid tariffs are set as $R = C_d(\alpha)$ where R are the total grid fees paid by consumers and prosumers to the DSO.

In the main part of the model, we will consider a non-discriminatory two-part tariff, with the fixed part of the tariff set to cover the historical fixed cost of the network K_c and the variable part set to cover the variable costs $c_d(\alpha)$. This pricing for the utilities has been proposed by Coase (1946), with a variable fee equal to marginal cost. With such a tariff structure, the fixed cost of the centralized distribution K_c can be ignored in the analysis.

The non-discrimination constraint imposes that prosumers and traditional consumers face the same rate for energy imports. In Section 6, we will relax these two assumptions and consider both a discriminatory tariff where prosumers and consumers are charged a different rate and a Ramsey-like tariff where the fixed grid cost (or part of it) must be covered by a markup on every consumed unit. We will show that our results will not be qualitatively changed. Rather, the distortions created by net metering would be amplified as one of the driver of our results is a lower registered consumption under net metering. Therefore, the corresponding markup –and the associated inefficiencies– would be higher in the net metering case.

In the case of net metering, the total registered consumption is V_c that is the volume of centralized distribution and the unit tariff r must be such that $R = rV_c = c_d(\alpha)$. In the case of net purchasing, the regulator can distinguish a tariff for imports r_m and a tariff for exports r_x. Recorded imports are equal to $V_c + V_l$, recorded exports are equal to V_l. With net purchasing, the tariff must be such that $R = r_m(V_c + V_l) + r_x V_l = c_d(\alpha)$.

2.3 First best level of prosumers

The total cost of producing and distributing electricity for the system[8] is given by the sum of the cost of generation $C_g(z)$ and the cost of network distribution, $C_d(z)$ given above. Letting $\alpha = F(z)$, the total cost is:

$$\begin{aligned} C(z) &= C_g(F(z)) + C_d(F(z)), \\ &= (c+\theta)q - F(z)kc + H(z)k - F(z)\varphi k\theta + F(z)K_l + K_c. \end{aligned}$$

The benevolent social planner minimizes $C(z)$ with respect to z. The first-order condition[9] can be rewritten as:

$$\begin{aligned} f(z^*)k\left\{-c + z^* - \varphi\theta + \frac{K_l}{k}\right\} &= 0, \\ &\Rightarrow \quad z^* = c + \varphi\theta - \frac{K_l}{k}. \end{aligned} \tag{2}$$

Optimal "prosumption" defines an upper bound z^* for consumers in the population that become prosumers. A total of $F(z^*)k$ MWh are generated by DPU, the remaining $F(z^*)(q-k) + (1-F(z^*))q$ by centralized production. We assume that $\underline{z} \leq z^*$ which guarantees that there is a positive fraction of prosumers in the first best-case.

At the upper bound z^*, the marginal cost of 1 MWh of decentralized production (z) must be equal to the marginal cost of centralized generation (c) corrected for the additional network costs and savings of decentralized production. If DPU generates additional grid costs ($\frac{K_l}{k} > \varphi\theta$), at the first best, the generation cost of a DPU is smaller than the cost of centralized production: $z^* < c$.

The characterization of z^* in Equation (2) is similar to Brown and Sappington (2017b) for whom decentralized energy production should be valued at the marginal cost of centralized generation minus the additional network cost generated by decentralized production. Because net-metering fails to take this second component into account

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[8] Only costs matter as surpluses are constant (by assumption).

[9] It leads to characterize a local minimum $C(z)$ as $C''(z^*) = f'(z^*)\{0\} + f(z^*)k > 0$.

(energy is valued at the marginal cost of centralized generation), they conclude that net metering is not optimal. We will show further that this effect is exacerbated by the fact that the DSO charges a higher network price because grid-registered consumption with the meter running backwards declines.

3 Net metering

Suppose that the individual has only one meter. The net utility of installing a DPU producing $k \leq q$ is given by:

$$U(z) = \begin{cases} S - (p+r)(q-k) - zk & \text{if } k > 0 \\ S - (p+r)q & \phantom{\text{if }} k = 0 \end{cases}$$

where r is the grid tariff per MWh. The consumer who is indifferent between purchasing all its consumption from the grid and installing a DPU bears a marginal installation cost $\tilde{z}$ such that:

$$\tilde{z} = p + r. \tag{3}$$

At this bound $\tilde{z}$, the marginal installation cost is equal to the opportunity cost of purchasing the electricity throughout the grid, $p + r$. For a prosumer a MWh produced is either self-consumed or exported to the grid. From the prosumers' point of view, self-consumption and exports are equivalent. Self-consumed electricity replaces centralized production which costs $p + r$. Exports offset imports that cost $p + r$.

From a system point of view, self-consumption and exports are not equivalent. Self-consumption reduces costs while exports are costly. With net metering, the opportunity cost of DPU for the prosumer does not reflect its true cost for the system as a whole. Indeed, there is an avoided network cost only if the electricity produced is self-consumed. Hence, there is a discrepancy between the opportunity cost perceived by the prosumer and the true cost of decentralized production.

The total cost of the grid is given by (1). With net metering and for any bound z, as the meter runs backwards for prosumers, registered consumption is the difference between imports and exports i.e. $V_c = q - F(z)k$. The break-even network rate is equal to the ratio between the total variable cost and the total measured power flow:

$$\tilde{r}(z) = \frac{c_d(\alpha)}{V_c} = \frac{q - F(z)\varphi k}{q - F(z)k}\theta + \frac{F(z)}{q - F(z)k}K_l. \tag{4}$$

Notice that, for $F(z) > 0$ and $\varphi < 1$, the registered consumption V_c is inferior to the total power exchanges with the network $V_c + V_l$. Therefore, the ratio $\frac{q-F(z)\varphi k}{q-F(z)k} = \frac{V_c+V_l}{V_c}$ is larger than one and it is impossible to have a cost reflective tariff.

From (3) and (4) and the competitive assumption $p = c$ on the retail market, one can derive the equilibrium[10] $\tilde{z}$ with net metering such that $\tilde{r} = \tilde{r}(\tilde{z})$ and

$$\tilde{z} = z^* + \left[(1-\varphi)\theta + \frac{K_l}{k}\right]\frac{q}{q - F(\tilde{z})k}. \tag{5}$$

Proposition 1 *Net metering induces too much "prosumption"compared to the first best: $\tilde{z} > z^*$.*

This inefficiency is created by two distinct mechanisms. First, the opportunity cost of decentralized production does not correspond to its true cost (compare Equations (2) and (3)). This effect is enlightened in Brown and Sappington (2017b). Second, the network rate r increases, which further increases the benefit of "prosuming". This rate increase results from the discrepancy between power exchanges and registered consumption which leads to rates that are not cost-reflective. Consequently, the network fee is increased above cost thus reinforcing the benefit of "prosuming". Notice that this result is true even if DPU generate cost savings for the grid.

An increase in the synchronization factor decreases the distortions created by net metering. An increase in φ reduces local distribution V_l and induces cost savings for the grid. Consequently, the ratio of power exchanges on measured consumption ($\frac{V_c+V_l}{V_c}$) gets closer to one and the grid tariff is closer to the cost. At the limit if $\varphi \to 1$ and prosumers self-consume all their production, the distortions associated with net metering vanish. Indeed, if $\varphi = 1$, there are no power injections and thus no local distribution and we should suppose in this case that $K_l = 0$. This implies that $\tilde{z} = z^*$. Net metering is thus more appropriate for technologies associated with a large share of self-consumption.

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[10] Its existence is ensured as the function $g(z) = z - \left[(1-\varphi)\theta + \frac{K_l}{k}\right]\frac{q}{q-F(z)k}$ is continuous over $\mathbb{R}_+$ and varies from $-\left[(1-\varphi)\theta + \frac{K_l}{k}\right]\frac{q}{q-k} < 0$ and $+\infty$. So it necessarily exists an intermediate value $\tilde{z}$ such $g(\tilde{z}) = z^*$.

4 Net purchasing

With two meters, the import meter records both local and centralized distribution volumes, so there is no problem of unregistered power exchanges. With net purchasing, when a prosumer exports power to the grid, it is bought back at the price that we suppose to be equal to the cost based retail price $p = c$. With two meters, the DSO can charge a different rate for the imports (r_m) and the exports (r_x). The net cost of a prosumer with an installation producing k is given by

$$U(z) = \begin{cases} S - p(q-k) - r_m\left(q - \varphi k\right) - \left(1-\varphi\right) k r_x - zk & \text{if} \quad k > 0 \\ S - \left(p + r_m\right) q & \qquad\;\; k = 0 \end{cases}$$

The consumer who is indifferent between purchasing all its consumption from the grid and installing a DPU bears a marginal installation cost $\hat{z}$ such that

$$\hat{z} = p + \varphi r_m - \left(1-\varphi\right) r_x. \tag{6}$$

For this prosumer $\hat{z}$, the marginal installation cost must reflect the opportunity cost of purchasing the electricity which is now impacted by the grid tariff structure (r_m, r_x) and by the share of self-consumption. Higher self-consumption reduces power exchanges and the registered consumption.

The total cost for the DSO is given by Equation (1) and this cost is identical to the cost with net metering as long as the synchronization factor remains the same. The meters register an import volume equal to $V_c + V_l = q - F\left(z\right)\varphi k$ and an export volume equal to $V_l = F\left(z\right)(1-\varphi)k$. The break-even constraint for the DSO states that:

$$R \equiv r_m(V_c + V_l) + r_x V_l = c_d\left(F(z)\right) \equiv \theta\left(V_c + V_l\right) + F(z) K_l.$$

This equation defines a locus of tariff (r_m, r_x) that guarantees that the DSO breaks-even:

$$\hat{r}_x\left(r_m, z\right) = \left(\theta - r_m\right) \frac{q - F\left(z\right)\varphi k}{F\left(z\right)\left(1-\varphi\right)k} + \frac{K_l}{(1-\varphi)k}. \tag{7}$$

The locus (r_m, r_x) is represented on Figure 4. The slope of the locus is (in absolute value) higher than one. This means that if r_m decreases by one, r_x increases by a factor greater than one. The extreme values where all the burden of the network cost is charged either on exports or on imports[11] correspond to $\left(r_m = 0,\, \bar{r}_x(z) = \theta \frac{q-F(z)\varphi k}{F(z)(1-\varphi)k} + \frac{K_l}{(1-\varphi)k}\right)$ and $\left(\bar{r}_m(z) = \theta + \frac{F(z)}{q-F(z)\varphi k} K_l,\, r_x = 0\right)$.

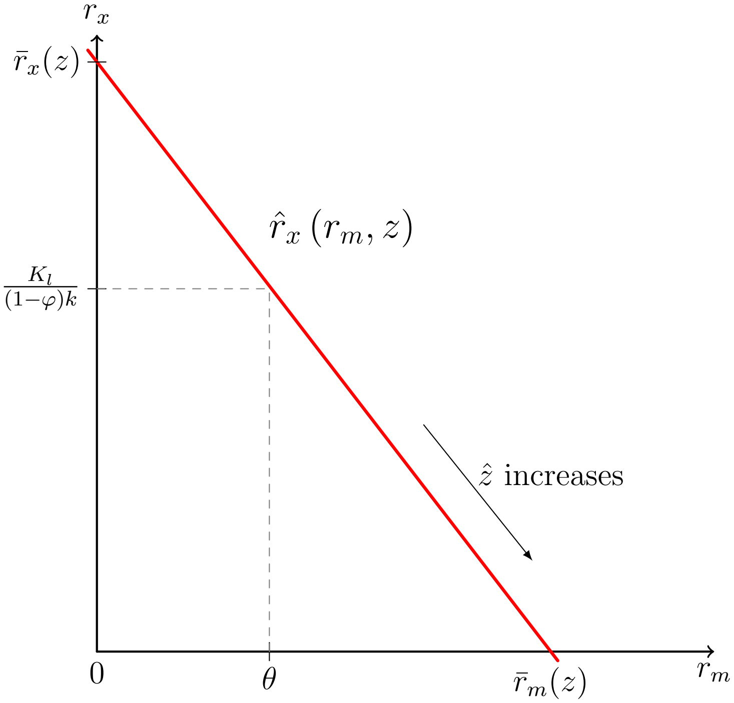

Figure 4: Break-even grid tariff with net purchasing

Solving (6) and (7), we find the equilibrium $\hat{z}$ with net purchasing compatible with the break-even constraint for the DSO. This value is expressed as a function of r_m:

$$\hat{z} = z^* + \frac{q}{F(\hat{z})\, k} (r_m - \theta) . \tag{8}$$

One can see that whenever $r_m \leq \theta$ then $\hat{z} \leq z^*$, while whenever $\theta < r_m < \tilde{r}$ then $z^* < \hat{z} \leq \tilde{z}$. Finally when $r_m \geq \tilde{r}$ we have $\hat{z} \geq \tilde{z}$. As the slope of the locus is higher than one, moving along the locus and increasing the import fee, increases the number of DPU installations.

Proposition 2 *Net purchasing leads to the first best level of "prosumption" with cost-oriented grid tariffs:* $r_m = \theta$ *and* $r_x = \frac{K_l}{(1-\varphi)k}$.

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[11] Under net purchasing, some DSO record exports but do not impose an export fee and rather set $r_x = 0$

The net purchasing system is able to induce the first best – i.e. cost-minimizing – level of DPU. For that, the import rate must be set equal to the cost θ. Costs linked to the power flows are covered by an import fee equal to the cost. This is possible as the import meter records all the power flows, i.e. local and centralized distribution volumes. The export fee is used to charge prosumers the fixed distribution cost of a DPU installation. With net purchasing, it is possible to construct a tariff that is fully cost reflective and that induces the efficient deployment of DPU.

5 Comparisons

In this section, we compare the two metering technologies with respect to (1) the deployment of decentralized production, (2) the contribution to the network financing of consumers and prosumers and (3) the incentives to synchronize production and consumption.

5.1 Deployment of DPU

Propositions 1 and 2 show that the first best level of DPU can be reached with a cost-oriented tariff in the net purchasing case while it cannot be reached with net metering.

In this section, we show more generally that net metering is associated with a larger deployment of DPU than net purchasing and that this result holds true for different rate levels under net purchasing. The driving force behind this result is the lower registered consumption under net metering.

Proposition 3 *For all the break-even tariffs* (r_m, r_x) *with* $r_m, r_x \geq 0$*, the deployment of DPU is lower with net purchasing compared to net metering and the import fee is lower:* $r_m < \tilde{r}$*.*

With net purchasing, moving along the locus defined in Equation (7) and decreasing r_x below $\frac{K_l}{(1-\varphi)k}$ stimulates the deployment of DPU and one can easily see that $\bar{r}_m(z) < \tilde{r}$. The proposition shows that even if all the grid costs is recovered with import fees, the deployment of DPU is still lower than under net metering. The higher penetration rate of DPU is not linked to the tariff structure under net purchasing. For all break-even tariffs, there are more DPU installations under net metering than under net purchasing.

5.2 Redistribution and equity

The metering technology and the tariff structure do not only have an influence on the deployment of distributed generation. The burden of the network cost is shared differently with the two technologies. In this section, we analyze the redistributive impact of the grid tariff. To analyze this, let us compare the consumers' and the prosumers' contribution to the network financing under net metering and net purchasing.

For that, we use as a reference point a cost reflective tariff under net purchasing: $r_m = \theta$ and $r_x = \frac{K_l}{(1-\varphi)k}$. This solution leads to the efficient deployment of DPU: $\hat{z} = z^*$. With net purchasing, the network bill of a consumer (R^c) and a prosumer (R^p) are respectively equal to:

$$\begin{aligned} \hat{R}^c &= r_m q = \theta q, \\ \hat{R}^p &= r_m(q - \varphi k) + r_x(1-\varphi)k = \theta(q - \varphi k) + K_l. \end{aligned}$$

The tariff is fully cost reflective under net purchasing and each category of consumer pay the induced cost of their consumption. And, with a cost-oriented tariff, the bills are independent of the DPU deployment.

With net metering, the bill of the two types of consumers are equal to:

$$\tilde{R}^c = \tilde{r} q \quad \text{and} \quad \tilde{R}^p = \tilde{r}(q-k),$$

where $\tilde{r} = \tilde{r}(\tilde{z})$. Compared to net purchasing, net metering increases the bill for the traditional consumers $\tilde{R}^c > \hat{R}^c$ and this is true even in the case where a higher deployment of DPU would decrease the grid cost. In other words, the decline in registered consumption inflates the grid tariff above cost and this effect is dominated (or is reinforced) by a possible cost saving effect (or cost increase effect) of the DPU.

For prosumers, the rate is increased compared to net purchasing but the recorded consumption is reduced. As $\hat{R}^p - \tilde{R}^p = \frac{q(1-F(z))}{q-F(z)k}\left[\theta\left(1-\varphi\right)k + K_l\right] > 0$, the latter effect dominates the former. We thus have that net metering transfers the burden of the grid costs from prosumers to consumers.

Proposition 4 *Compared to net purchasing with cost oriented tariffs, with net metering the consumers' bill increases while the prosumers' bill decreases:* $\hat{R}^c < \tilde{R}^c$ *and* $\hat{R}^p > \tilde{R}^p$.

The metering technologies not only differ with respect to DPU deployment but they have an important redistributive impact. Traditional consumers pay more with net metering while prosumers pay less and the burden of the grid cost is transferred to traditional consumers.[12] This effect could be quite important as, if $k \to q$, the prosumer's contribution to the network approaches zero and the whole burden is transferred to consumers (creating even more inadequate incentives to adopt a DPU).

Finally, notice that if the regulator departs from cost-oriented grid pricing and decreases the import fee, the result of Proposition 4 continues to hold true: with net purchasing, consumers are still paying less and prosumers are paying more. To show this, we use Proposition 3 and we compute the bill of the two types of consumers corresponding to the tariff $(r_m, r_x) = (\bar{r}_m(\hat{z}), 0)$. With such a tariff, we have a deployment of DPU above the first best level:

$$\hat{z}(\bar{r}_m(\hat{z}), 0) = z^* + \frac{q}{q - F(z)\varphi k}\frac{K_l}{k} < \tilde{z}.$$

The corresponding consumer's payments are given by:

$$\begin{aligned} \hat{R}^c &= \bar{r}_m(\hat{z})\, q, \\ \hat{R}^p &= \bar{r}_m(\hat{z})\,(q - \varphi k). \end{aligned}$$

Because $\bar{r}_m(\hat{z}) < \tilde{r}(\tilde{z})$, we have $\hat{R}^c < \tilde{R}^c$ and $\hat{R}^p > \tilde{R}^p$. Again the driving force behind this result is the decline in registered consumption with net metering and the transfer of the grid cost to the non-prosumers. The redistributive effect of net metering is qualitatively independent of the rate structure under net purchasing.

5.3 Incentives to synchronize production and consumption

An important parameter of the model is the synchronization factor φ. Synchronization of consumption and production reduces local distribution hence the grid costs. For this reason, it is efficient to have a higher deployment of DPU when synchronization increases i.e. $\partial z^*/\partial\varphi > 0$. Or differently, for a given z, the grid cost decreases when synchronization increases: $\partial C(z)/\partial\varphi = -F(z)k\theta < 0$. There are many technologies

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[12] This corroborates the empirical work of Picciariello *et al.* (2015) which shows substantial cross-subsidies from consumers toward prosumers for six U.S states.

that prosumers can use to synchronize local production and consumption (Luthander et al. (2015) and IEA PVPS (2016)), the most obvious being residential energy storage. Residential sodium-ion or lithium-ion based batteries are becoming increasingly popular. A power-to-heat system that converts the solar electricity into heat is a low-cost alternative storage technology. Besides storage, various demand side management practices also encourage self-consumption. For example, load shifting can take place manually or via a specific device that shifts on and off heating, air conditioning or other appliances, depending on production conditions. Alternatively, synchronization can be influenced when choosing the orientation of the photovoltaic panels at the installation stage in order to better align power production and consumption. In this section, we look at the grid tariff as an incentive mechanism to encourage better synchronization of production and consumption.

Suppose that a prosumer can at some cost increase synchronization between consumption and local production. The cost of synchronization is increasing and convex; at the margin, it is even more costly to synchronize consumption and production. Let us denote the initial level of synchronization by $\bar{\varphi}$ and the cost of increasing synchronization above $\bar{\varphi}$ by the function $(\varphi - \bar{\varphi})^2/2$. Our objective is to look at the individual incentives to increase synchronization. Note that we have considered that the parameter φ is identical for all prosumers. Therefore, the second order effect of an increase in φ measured by $\partial r/\partial \varphi$ captures the impact on the grid tariff of an increase in the synchronization parameter of *all* prosumers. In our analysis focused on individual incentives, we will consider exclusively on first order effects, i.e. we will consider that the impact of an individual increase in φ has a negligible impact on the grid tariff.

First let us identify the levels of z and φ that are jointly optimal. A benevolent social planner would solve the problem $\min_{\varphi,z} C(z) + F(z)\frac{(\varphi-\bar{\varphi})^2}{2}$ for which the interior solution writes:

$$\begin{aligned} \varphi^* &= \bar{\varphi} + k\theta, \\ z^*_\varphi &= z^* - \frac{(\varphi^* - \bar{\varphi})^2}{2k}. \end{aligned}$$

Synchronization is socially desirable as it reduces the grid cost and implies a lower optimal level of "prosumption" compared to z^*. When synchronization devices are properly adjusted, less "prosumption" is needed at the optimum: synchronization and "prosumption" are substitutes for reducing the total cost of the energy system. We then investigate whether the metering systems manage to implement this first best.

Proposition 5 *Net metering does not provide any incentives for synchronization while it is socially desirable. With net purchasing, there is no break even tariff that leads to the first best level of synchronization (φ^*) and DPU deployment (z^*_φ).*

With *net metering*, the gross utility of a prosumer ($z \leq \tilde{z}$) is given by:

$$\tilde{U}(z) = S - (p + \tilde{r})(q - k) - zk,$$

with $p = c$. This utility is independent of the synchronization level and net metering does not provide incentives for synchronization so the equilibrium synchronization with net metering is then $\tilde{\varphi} \equiv \text{argmax}_\varphi \tilde{U}(z) - \frac{(\varphi - \bar{\varphi})^2}{2} = \bar{\varphi}$. With net metering, prosumers will not invest to increase the synchronization between consumption and production. With net metering, the grid is seen as a storage facility by prosumers.

With *net purchasing*, the grid applies a tariff $(\hat{r}_m, \hat{r}_x)$ defined by Equation (7). At this tariff, the gross utility of a prosumer ($z \leq \hat{z}$) is

$$\hat{U}(z) = S - (q - k)p - \hat{r}_m (q - \varphi k) - (1 - \varphi) k\hat{r}_x - zk,$$

with $p = c$. Thus, the utility of a prosumer increases with the synchronization factor. A larger fraction of self-consumption decreases both imports and exports and therefore the grid bill: $\partial\hat{U}(z)/\partial\varphi > 0$. The equilibrium synchronization with net purchasing is then characterized by:

$$\hat{\varphi} \equiv \underset{\varphi}{\text{argmax}}\, \hat{U}(z) - \frac{(\varphi - \bar{\varphi})^2}{2} \Rightarrow \hat{\varphi} = \bar{\varphi} + (\hat{r}_m + \hat{r}_x)k. \tag{9}$$

The comparison of the net utility of a prosumer $\hat{U}(z) - \frac{(\varphi - \bar{\varphi})^2}{2}$ with the utility of a traditional consumer defines a new threshold $\hat{z}_\varphi$:

$$\hat{z}_\varphi = p + \varphi r_m - (1 - \varphi) r_x - \frac{(\varphi - \bar{\varphi})^2}{2k}. \tag{10}$$

We observe that the cost oriented grid tariffs $(r_m, r_x) = (\theta, \frac{K_l}{(1-\varphi)k})$ is such that $\hat{\varphi} \geq \varphi^*$

and $\hat{z}_\varphi \leq z^*_\varphi$.[13] At this tariff, prosumers invest too much in synchronization technologies and they consequently under invest in decentralized production units.

To replicate the first best, the grid tariff must be such that $\hat{\varphi} = \varphi^*$ and $\hat{z}_\varphi = z^*_\varphi$. By setting $(\hat{r}_m, \hat{r}_x) = (\theta - \frac{K_l}{k}, \frac{K_l}{k})$, the first best is achieved but the DSO does not break even. The profit of the DSO is:

$$\pi^D = (r_m - \theta)\left(q - F\left(\hat{z}_\varphi\right)\hat{\varphi}k\right) + r_x(1-\hat{\varphi})F\left(\hat{z}_\varphi\right)k - F\left(\hat{z}_\varphi\right)K_l.$$

Using the above tariff, we have that $\pi^D = -\frac{q}{k}K_l < 0$. This means that unless $K_l = 0$, it is not possible to implement the first best with net purchasing while guaranteeing a non-negative profit for the DSO.

To break even, the regulator must increase the income of the DSO. By doing so, it will increase the synchronization level and/or the deployment of DPU above the first best. To find the optimal grid tariff structure the regulator solves the following program:

$$\begin{aligned} &\min_{r_x, r_m} C(F(\hat{z}_\varphi)) + F(\hat{z}_\varphi)\frac{(\hat{\varphi}-\bar{\varphi})^2}{2} \\ \text{subject to } \pi^D &\geq 0 \text{ ; (10) and (9).} \end{aligned}$$

This leads[14] to define optimal grid tariffs such that $\hat{r}_m > \theta$ and $\hat{r}_x < \frac{K_l}{(1-\varphi)k}$ which implies in turns that $\hat{\varphi} > \varphi^*$ and $\hat{z}_\varphi > z^*_\varphi$. In that case *net purchasing* implies too much "prosumption" and too much synchronization compared to the corresponding first best. Tariffs must be departed from imputed costs in order to guarantee a non-negative profit for the DSO. And increasing the import fee above the marginal cost is more effective then using the export rate as a consequence both prosumption and synchronization are increased.

Our comparisons show that net purchasing is superior to net metering in all the three dimensions considered. With a cost oriented grid tariff, the first best deployment of DPU will be achieved with net purchasing while net metering will lead to excessive "prosumption". On top of that, net metering transfers the burden of the grid cost to the non-prosumers, which raises equity concerns and does not provide any incentives to synchronize local production and consumption. Our model, therefore, provides a

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[13] With strict inequalities for $K_l > 0$.

[14] Details are provided in the Appendix.

strong case *against* net metering.

6 Extensions

In this section we discuss the robustness of our results with respect to different grid tariff and retail pricing structures than those discussed in the main analysis. We also consider the fact that the DPU creates an externality at the system level by encouraging the production of green electricity.

6.1 Alternative tariff structures

6.1.1 Discriminatory network tariff

The inefficiency described in Proposition 1 can be potentially overcome by having a discriminatory import tariff: r_c for consumers, and r_p for prosumers.[15] Differentiating tariffs can be used to align network fees with induced costs which is a major concern with net metering.

With a discriminatory tariff, the net utility of having a DPU is defined as:

$$U(z) = \begin{cases} S - (p + r_p)(q - k) - zk & \text{if } k > 0 \\ S - (p + r_c)q & \phantom{\text{if }} k = 0 \end{cases}$$

with $p = c$. The indifferent consumer bears a marginal installation cost $\tilde{z}'$ such that:

$$\tilde{z}' = c - r_p \frac{q - k}{k} + r_c \frac{q}{k}. \tag{11}$$

With a discriminatory import tariff, a way to dampen excessive "prosuming"is to increase the prosumer's rate and/or decrease the consumer's rate. With net metering and a discriminatory tariff, the regulator sets an import tariff r_c for consumers and r_p for prosumers. Total receipts are:

$$R = r_c(1 - F(z))q + r_p F(z)(q - k).$$

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[15] This is the case in Belgium: prosumers are connected with a single meter (net metering) and some DSO apply a specific prosumer fee to compensate for network costs. This prosumer fee is linked to the power installed (approximately 80 euros per KVA).

The locus of break-even network rates (r_c, r_p) is equal to

$$\tilde{r}_p(z) = \frac{c_d(F(z))}{F(z)(q-k)} - \tilde{r}_c(z)\frac{1-F(z)}{F(z)}\frac{q}{q-k}. \tag{12}$$

From Equations (11) and (12), one can easily determine that there exists a discriminatory tariff structure $(\tilde{r}_c, \tilde{r}_p)$ such that the DSO breaks even and the first best level for DPU is achieved, i.e. $\tilde{z}' = z^*$.

Proposition 6 *Net metering with a discriminatory network tariff leads to the first best level of "prosumption"when* $\tilde{r}_c = \theta$ *and* $\tilde{r}_p = \frac{K_l}{q-k} + \frac{q-\varphi k}{q-k}\theta$.

Comparing $\tilde{r}_c$, $\tilde{r}_p$ and $\tilde{r}$ shows that $\tilde{r}_p(z^*) \geq \tilde{r}(\tilde{z}) \geq \tilde{r}_c(z^*)$ as:

$$\begin{aligned}
\tilde{r}_p - \tilde{r}_c &= \frac{K_l}{q-k} + \frac{(1-\varphi)k}{q-k}\theta > 0, \\
\tilde{r}_p - \tilde{r} &= \frac{q}{q-k}\frac{1-F(\tilde{z})}{q-F(\tilde{z})k}\left(K_l + k(1-\varphi)\theta\right) > 0.
\end{aligned}$$

Discriminatory net-metering tariffs restore efficiency of net-metering when the grid rate for each category covers the induced costs. For consumers, the import rate should be set equal to cost. For prosumers, the import rate should be inflated above to take into account the fact that registered consumption increases and that there are additional cost (K_l) per installation. This accords with the idea in Bennear and Stavins (2007) that it is easier to reach the first best with two instruments rather than one. For this reason, the first best can also be achieved with net metering if the tariff applied to the two categories of consumer is different. Efficiency is restored when net metering is combined with a discriminatory network tariff. As regards the third dimension of our comparison, however incentives for synchronization are still missing as self-generated and imported energy are seen as perfect substitutes for the prosumers under net metering, which is not the case at the system level.

6.1.2 Ramsey-like tariff

Previously in the analysis, we considered that the historical fixed cost of centralized distribution K_c is covered by a fixed connection fee paid by consumers and prosumers. In this section, we relax this hypothesis and we suppose that $R = C_d(\alpha) + K_c$.

With net metering, the regulator must inflate the grid fee by $\frac{K_c}{V_c}$ to cover the fixed cost, so that:

$$\tilde{\tilde{r}}(z) = \tilde{r} + \frac{K_c}{q - F(z)\,k}.$$

Such a mark-up obviously makes "prosuming"even more attractive and the inefficiency result of Proposition 1 is further exacerbated.

With net purchasing, the locus of break-even tariff defined in Equation (7) is shifted upwards by $\frac{K_c}{V_l}$ and writes now:

$$\hat{\hat{r}}_x\,(r_m, z) = (\theta - r_m)\,\frac{q - F(z)\,\varphi k}{F(z)\,(1-\varphi)k} + \frac{F(z)\,K_l + K_c}{F(z)\,(1-\varphi)k}. \tag{13}$$

Solving (6) and (13), we find that:

$$\hat{\hat{z}} = \hat{z} - \frac{K_c}{F(\hat{\hat{z}})k} = z^* + \frac{q}{F(\hat{\hat{z}})k}(r_m - \theta) - \frac{K_c}{F(\hat{\hat{z}})k}.$$

The first best ($\hat{\hat{z}} = z^*$) can still be achieved by setting

$$(r_m, r_x) = (\theta + \frac{K_c}{q}, \theta + \frac{\varphi K_c}{(1-\varphi)q}).$$

With net purchasing, it is possible to achieve the first best for different tariff structure, including Ramsey-like tariffs where costs are only covered by variable fees.

To sum up, we find that considering fixed costs of the grid do not alter the main results previously derived in the analysis (i.e. Propositions 1 and 2). Naturally, Ramsey-like tariffs must be substituted to marginal cost based ones when net purchasing applies.

6.1.3 Time-of-use pricing

In the baseline model, we assumed that the costs of generating electricity with conventional resources were independent of the number of prosumers. However, decentralized production removes demand from the centralized electricity system. And, with an increasing marginal cost of centralized generation, it decreases costs and wholesale market prices. The decrease in wholesale prices can be passed through consumers if retailers use time-of-use (TOU) pricing.

To capture these features, we no longer assume that all the hours of the day are the same and we distinguish two periods: a "sunny" period where DPU are producing (period 1) and a "shadow" period where they are not (period 2). We suppose that the cost of centralized generation is smaller in period 1 than in period 2: $c_1 < c_2$. All other costs remain invariant across time and we set $c_1 = c$ to simplify the exposition.

Consumption q is split between period 1 consumption q_1 and period 2 consumption q_2 with $q_1 + q_2 = q$. As we assume that a fraction φ of the prosumer's production is self-consumed, we must have that $q_1 \geq \varphi k$.

In period 1, DPU are active and the total amount of decentralized production is αk. If decentralized production is insufficient to cover consumption, CPU must produce $q_1 - \alpha k$ MWh at cost c_1. In period 2, the whole consumption must be covered by CPU at cost c_2. The total cost of centralized production is equal to

$$C_g^C(\alpha) = c_1 (q_1 - \alpha k) + c_2 q_2.$$

With $c_1 = c$, the first best level of prosumption remains defined by (6). As prosumers offset centralized production during the low cost period, there, the optimal level of prosumption is the same compared to the baseline model. Notice that this formulation does not take into account marginal effects, the fact that a larger deployment of decentralized production may decrease further the cost of centralized production.

We now aim to compare the effects of TOU retail pricing on the efficiency of metering devices considering that grid rates are time invariant.

Uniform pricing. With uniform retail pricing, electricity is traded at the retail level at the same price p_u during the two periods. To break-even, this price should be above the cost c. With $p_u > c$, the electricity produced by DPU is valued above its cost distorting the incentives to install a DPU. With *net metering*, this effect reinforces the inefficiencies identified in Proposition 1 of the baseline model. Indeed from (5), now the prosumption level is set to:

$$\tilde{z}^u = z^* + (p_u - c) + \left[(1 - \varphi)\, \theta + \frac{K_l}{k} \right] \frac{q}{q - F(\tilde{z}^u)\, k}.$$

There is an additional inefficiency term associated with uniform retail pricing.[16]

With *net purchasing* this inefficiency can still be corrected by modifying the distribution tariff. From (8), the prosumption level writes:

$$\hat{z}^u = z^* + (p_u - c) + \frac{q}{F(\hat{z}^u)\,k}(r_m - \theta).$$

The first best ($\hat{z}^u = z^*$) can be achieved by setting

$$r_m^u = \theta - (p_u - c)\,F(\hat{z}^u)\,\frac{k}{q} \text{ and } r_x^u = (p_u - c)\,\frac{q - F(\hat{z}^u)\,\varphi k}{q(1-\varphi)} + \frac{K_l}{(1-\varphi)k}.$$

Efficiency is easily restored but now grid tariffs are no longer cost-oriented: the export grid tariff must be increased to correct the inefficiencies created by a retail tariff that is not cost-reflective.

Time-of-use pricing. Instead of distorting network tariffs (under net metering), the retail pricing can be adapted to reflect the costs of centralized production with time-varying prices. With TOU, retailers charge a price $p_1 = c_1 = c$ for the electricity produced/consumed in period 1 and a price $p_2 = c_2$ for the electricity consumed in period 2. We suppose that the DSO charges a uniform invariant rate across periods. With TOU, prosumers are selling their excess production $(1-\varphi)k$ in period 1 at price p_1 and buy their consumption q_2 at price p_2 in period 2. Traditional consumers are paying their consumption q_i at price p_i, $i = 1, 2$. At the retail level, TOU changes the benefit of having a decentralized production unit to $((1-\varphi)kp_1 - p_2q_2) - (\varphi kp_1 - p_2q_2) = kp_1$. The production of a DPU is valued at the price of period 1. TOU pricing corrects the above inefficiency.

Indeed, with *net metering* when TOU prices are set, the prosumption level is unchanged relatively to the baseline model and still defined by (5). So net metering leads to the same prosuming inefficiencies but, as expected, they are reduced compared to a uniform pricing scheme. When *net purchasing* applies and with TOU prices, Proposition 2 remains valid.

Finally notice that in the case where a higher penetration of decentralized production decreases the period 1 cost of centralized generation: $c = c(\alpha)$, with $c'(\alpha) < 0$, the first

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[16] The same result would apply in the case of market-power at the retail level.

best would change to:

$$z = z^* - c'(\alpha^*)\,(q - k)\,.$$

where $\alpha^* = F\,(z)$. In this case, it is still possible to distort the distribution tariff to restore the first best as we did above when retailers choose a uniform price.

6.2 The environmental impact of DPU

An important feature of DPU is their ability to produce the so called "green electricity" and the environmental impact of renewable energies constitutes a non negligible motivation for regulators to promote the deployment of DPU. Taking the environmental impact of DPU into account, the excessive deployment with net metering should be further qualified. Environmental friendly DPU, like photovoltaic panels or small wind turbines, generate less greenhouse gas emissions than centralized energy production based on gas or coal. To take it into account, suppose that the total system cost $C(z)$ is increased by an additional environmental damage function $D(E)$ where $E = q - F\,(z)\,k$ are the carbon emissions per MWh produced by centralized generators. And let us consider that this damage function is linear$D\,(E) = \delta E$ with $\delta > 0$. The total cost is rewritten as:

$$C(z) = C_g\,(z) + C_d\,(z) + \delta\,(q - F\,(z)\,k)\,.$$

Thus, the social cost minimizing prosumer's cutoff increases now to $z^e = z^* + \delta$.

To reach this environmental goal, regulators can either manipulate the grid tariff to foster the deployment of DPU or introduce specific subsidizing schemes. We analyze these two options for both metering technologies.

6.2.1 The grid supports to DPU

With *net purchasing*, the grid tariff can be used easily to reach environmental targets. By increasing r_m and decreasing r_x along the locus given in Equation (7), $\hat{z}$ increases. More specifically, the following tariff couple (r_m, r_x) leads to $\hat{z} = z^e$:

$$r_m = \theta + \frac{F(z^e)k}{q}\delta \quad \text{and} \quad r_x = \frac{K_l}{(1-\varphi)k} - \frac{q - F(z^e)\varphi k}{q(1-\varphi)}\delta.$$

Notice that for sufficiently large value of the marginal damage δ, the export fee may become negative $r_x < 0$. In this case, it might be optimal to compensate prosumers for their exports as it is a mean of subsidizing decentralized production. But such a subsidy reduces the incentives to synchronize local production and consumption.

With *net metering*, if $z^e \leq \tilde{z}$, then net metering already provides too much support to DPU and the first best cannot be reached. On the contrary, if $z^e \geq \tilde{z}$, then to increase the DPU penetration further, the grid tariff must increase. An increase in the grid tariff either leaves a positive profit to the grid operator or it can be achieved by lowering the fixed fee charge to consumers. The two solutions are problematic. The first solution implies that the DSO is collecting rents paid by consumers. The second solution by decreasing the fixed fee would exacerbate redistribution concerns discussed above. Both solutions might be problematic to implement for a regulator. For these reasons, we conclude that net purchasing is a more effective device than net metering in order to internalize the environmental impacts of DPU, should this be done by using the grid tariff.

6.2.2 Net metering and feed-in premium

As an alternative, a specific supporting scheme for DPU can be installed independently of the grid tariff. In many countries, decentralized energy production is subsidized and sometimes heavily (Schmalensee, 2012). There are different supporting mechanisms: feed-in tariffs (FIT), feed-in premium (FIP) or renewable portfolio standards (RPS).[17] These mechanisms offer a subsidy for each MWh produced from a green source. This requires a metering system that measures the production of the DPU, the green meter.

In this subsection, we analyse the impact of combining a feed-in premium with a net metering system. We suppose that $z^e \geq \tilde{z}$ meaning that additional support should be provided to reach the first best. Under a feed-in premium (FIP) scheme, prosumers receive a premium $\rho > 0$ for each MWh they produce and the production k is measured with a green meter. Prosumers thus receive a total premium ρk. We suppose that the FIP is organized and financed by the DSO. Thus, the DSO charges a unit tax τ on each registered consumption unit. This green fund must balanced: total premium $F(z)\rho k$

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[17] See Ringel (2006) for a comparison.

should be equal to the tax receipts $\tau\left(q-F\left(z\right)k\right)$. The fund is balanced if:

$$\tau\left(\rho\right)=\rho\frac{F\left(z\right)k}{q-F\left(z\right)k}. \tag{14}$$

The regulatory problem is then to set the grid fee r, the premium ρ and the tax τ to reach the first best level of DPU (z^e) subject to the break-even constraints for the DSO (Equation 4) and the green fund (Equation 14). The indifferent consumer is characterized by $z'\left(\rho\right)=c+r+\rho+\tau\left(\rho\right)$. Setting $z'\left(\rho\right)=z^e$ and replacing r by the break-even value given in Equation (4), we have the optimal FIP:

$$\rho^*=\delta\frac{q-F\left(z^*+\delta\right)k}{q}-\left[\left(1-\varphi\right)\theta+\frac{K_l}{k}\right].$$

Interestingly, the premium is not necessarily increasing with the environmental damage. Indeed a larger damage increases the benefit of decentralized production (z^e increases in δ). With net metering, an increase in DPU reduces registered consumption (and increases the grid costs) which in turn increases the grid tariff. As a result the supporting scheme is less powerful and may be lowered when environmental damage is important.

Combined with a FIP, the first best can be achieved with net metering.

Proposition 7 *If $z^e \geq \tilde{z}$, net metering leads to the first best level of "prosumption"if combined with a FIP ρ^*.*

Proposition 7 echoes Proposition 6: Net metering should be combined with another instrument to reach the first best level of "prosumption". Still, redistribution and synchronization issues are not addressed the same way with the two technologies.

7 Conclusion

The objective of this paper was to study how residential prosumers should be integrated into the electricity grid by comparing the net metering/purchasing systems in three dimensions. These conclusions corroborate the recent claims made by various regulatory and governmental institutions.

First, we find that the net metering system tends to over-encourage investments in decentralized production units, as the price at which the electricity sold by the prosumers via the grid is implicitly set at the retail price and not at the cost. As claimed by the National Association of Regulatory Utility Commissioners (NARUC (2016)), the simplicity of the net metering system in times when PV systems were available at a high cost has made it a practical way to integrate prosumers into the energy grid. However, with an increasing fraction of prosumers, the system quickly becomes financially unsustainable for the grid operator. The concomitant drop in prices for rooftop PV and financial supports at the local and national levels (via subsidies and tax cuts), have led to a massive rise of PV's and subsequent increases in the grid fee, an issue that can be avoided in the net purchasing system. Hence, as coined by European Commission (2015), the net metering is very attractive from the point of view of prosumers but not for the energy system.

Second, the traditional residential users cross-subsidize prosumers. As the network costs are socialized via the energy tariff, traditional users will pay a higher energy bill. Recent empirical works such as De Groote et al. (2016) have shown that wealthier households far more often install solar PV's, a.o. as they tend to live in a house that they own. Hence, this issue translates in terms of wealth distribution. Rising concerns for energy poverty in times where electricity prices tend to increase and 20 to 30% of this price is made of tariffs further challenges the limits of net metering systems.

Third, as also argued by the Council of European Energy Regulators (CEER (2017)), net metering does not encourage self-consumption by the prosumers, who see electricity imports via the grid and self-consumption as perfect substitutes. In other words, net metering policies will not provide accurate price signals to synchronize consumption and production. For example, prosumers will not choose the orientation of photovoltaic panels to displace their energy consumption or to invest in storage capacities to improve synchronization. In other words, self consumption is discouraged while it is beneficial at the energy system level and prosumers will use "the grid to artificially store electricity "(European Commission (2015), p. 10).

Our message in favor of a net purchasing system is robust to the extensions related to the tariff structure and the environmental externality created by DPU. At the very least, net metering will not encourage self-consumption and it requires the costly installation of an additional green meter. These various arguments explain why many countries across the Atlantic have somehow decided to switch away from net metering programs.

Seemingly it follows a clear-cut result in favor of a net-purchasing approach that calls for an empirical validation. Unfortunately electricity "prosumption"is quite a recent phenomenon and data at the residential level are insufficiently abundant.[18] Building an empirical evidence will be a key issue for future research. An experimental approach might alleviate some of the issues faced by real-life data. We believe that developing convincing empirical evidence about the impact of the modes of integration of prosumers to the grid will be a challenge for future research.

Appendix

Let $L = C(F(\hat{z}_\varphi)) + F(\hat{z}_\varphi)\frac{(\hat{\varphi}-\bar{\varphi})^2}{2} + \lambda\pi^D$, the Lagrangian function of the problem with $\lambda \geq 0$ substituting (10) and (9). The Khun and Tucker FOC write, for $i = m, x$:

$$\frac{\partial L}{\partial r_i} = 0 \Rightarrow f(\hat{z}_\varphi)\left[C'(F(\hat{z}_\varphi)) + \frac{(\hat{\varphi}-\bar{\varphi})^2}{2}\right]\frac{d\hat{z}_\varphi}{dr_i} + \left[\frac{C(F(\hat{z}_\varphi))}{\partial\hat{\varphi}} + F(\hat{z}_\varphi)(\hat{\varphi}-\bar{\varphi})\right]k$$

$$-\lambda\left\{\frac{1}{k}\frac{\partial\pi^D}{\partial r_i} + f\left(\hat{z}_\varphi\right)k\left[-\left(r_m-\theta\right)\hat{\varphi} + r_x(1-\hat{\varphi}) - \frac{K_l}{k}\right]\frac{d\hat{z}_\varphi}{dr_i} + \left(\theta - r_m - r_x\right)F\left(\hat{z}_\varphi\right)k^2\right\} = 0,$$

$$\lambda\ \pi^D = 0$$

As $\frac{d\hat{z}_\varphi}{dr_m} = \hat{\varphi}$; $\frac{d\hat{z}_\varphi}{dr_x} = -\left(1-\hat{\varphi}\right)$, $\frac{\partial\pi^D}{\partial r_m} = q - F\left(\hat{z}_\varphi\right)\hat{\varphi}k$ and $\frac{\partial\pi^D}{\partial r_m} = (1-\hat{\varphi})F\left(\hat{z}_\varphi\right)k$, after substitutions and some manipulations this leads to

$$\begin{aligned}
\frac{\partial L}{\partial r_m} &= 0 \Rightarrow (1+\lambda)\left\{\hat{\varphi}\left(\hat{z}_\varphi - z_\varphi^*\right) + \frac{F\left(\hat{z}_\varphi\right)}{f\left(\hat{z}_\varphi\right)k}\left(\hat{\varphi}-\varphi^*\right)\right\} - \lambda\frac{q - F\left(\hat{z}_\varphi\right)\hat{\varphi}k}{f\left(\hat{z}_\varphi\right)k} = 0,\\
\frac{\partial L}{\partial r_x} &= 0 \Rightarrow (1+\lambda)\left\{-\left(1-\hat{\varphi}\right)\left(\hat{z}_\varphi - z_\varphi^*\right) + \frac{F\left(\hat{z}_\varphi\right)}{f\left(\hat{z}_\varphi\right)k}\left(\hat{\varphi}-\varphi^*\right)\right\} - \lambda\frac{F\left(\hat{z}_\varphi\right)}{f\left(\hat{z}_\varphi\right)}(1-\hat{\varphi}) = 0,\\
\lambda\ \pi^D &= 0.
\end{aligned}$$

We see that $\lambda^* = 0$ implies $\hat{\varphi} = \varphi^*$ and $\hat{z}_\varphi = z_\varphi^*$ with a grid tariff structure $(\hat{r}_m, \hat{r}_x) = (\theta - \frac{K_l}{k}, \frac{K_l}{k})$ but with such tariffs $\pi^D = -\frac{q}{k}K_l < 0$: a contradiction. So $\lambda^* > 0$ and the joint first best cannot be implemented and the break-even constraint is necessarily

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[18] Some data are available since 2015 from the Energy Information Agency, `www.eia.gov/todayinenergy/detail.cfm?id=23972`

binding. Then solving the FOC with respect to $\hat{z}_\varphi$ and $\hat{\varphi}$ leads to

$$\begin{aligned}
\hat{\varphi} - \varphi^* &= (1-\hat{\varphi}) \frac{\lambda^*}{1+\lambda^*} \frac{q}{F(\hat{z}_\varphi)} \Rightarrow \hat{\varphi} > \varphi^*, \\
\hat{z}_\varphi - z_\varphi^* &= \frac{\lambda^*}{1+\lambda^*} \left\{ \frac{q - F(\hat{z}_\varphi) k}{f(\hat{z}_\varphi) k} \right\} \Rightarrow \hat{z}_\varphi > z_\varphi^*, \\
\lambda^* &= \frac{q f(\hat{z}_\varphi)}{q - F(\hat{z}_\varphi) k} (r_m - \theta) > 0.
\end{aligned}$$

which in turns implies in order to verify the break-even constraint that:

$$\hat{r}_m > \theta \text{ and } \hat{r}_x < \frac{K_l}{(1-\varphi)k}.$$

We verify that $\lambda^* = \frac{qf(\hat{z}_\varphi)}{q-F(\hat{z}_\varphi)k} (\hat{r}_m - \theta) > 0$.

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