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The Prosumers and the Grid*

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

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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 insufficient 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.

Keywords: Decentralized production unit, grid regulation, solar panel, grid tariff, storage. **JEL Codes**: D13, L51, L94, Q42

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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 residential consumers – the 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.

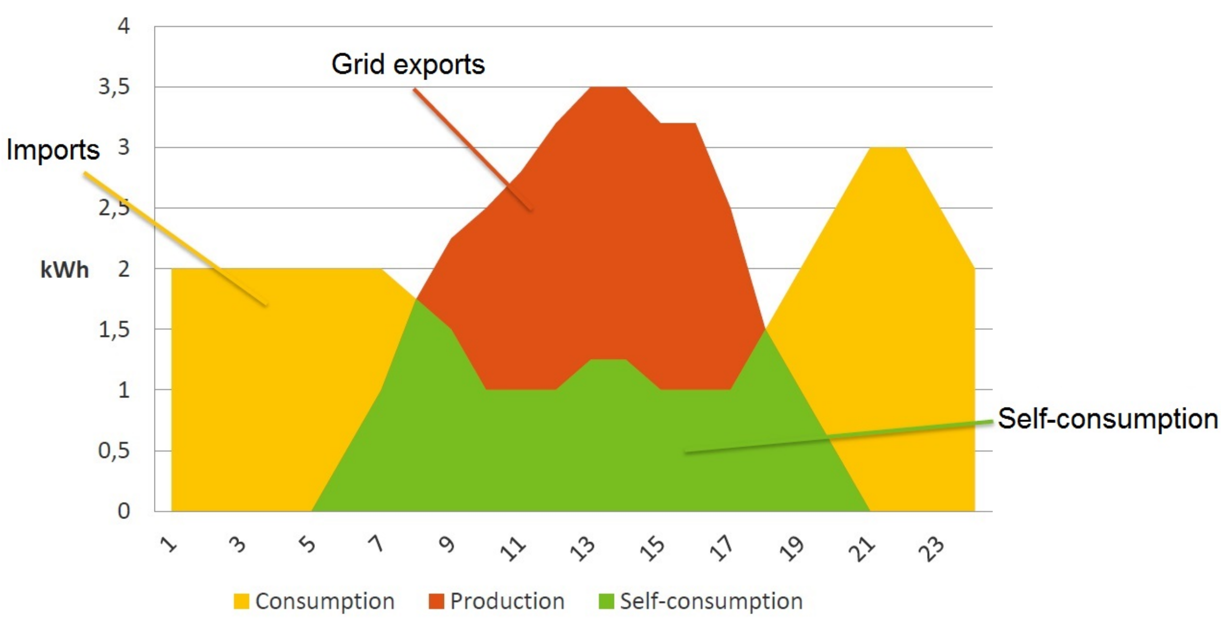

Figure 1: Autoconsumption Profile (Source IEA-PVPS (2014))

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 (2016), 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.

[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-billing in Europe (Source res-legal.eu)

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 (2016)). This rate increase makes decentralized 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 grid tariffs 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 grid tariff 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. Electricity production is considered to be a competitive activity and the price p charged by producers is equal to the marginal cost of centralized production. 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]

2.1 Consumers and prosumers

We consider a population of residential consumers of size 1. These consumers have the opportunity to install a DPU and become prosumers. We denote by $\tilde{k}$ the capacity (in MW) of the DPU and by $\tilde{t}$ the utilization time. For solar panels, $\tilde{t}$ 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 $k = \tilde{k}.\tilde{t}$. For a given production k, the consumer must instal a capacity of $\tilde{k} = k/\tilde{t}$. We then write that the cost of producing k MWh is equal to $z(k)$. This cost depends on the utilization time $\tilde{t}$ and the technological costs. We will suppose that $z(k) = zk$ and that consumers are heterogeneous with respect to the cost z. 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 instal a DPU. We thus write $\alpha = F(z)$.

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.

Electricity is sold by retailers at price p. Traditional consumers buy their whole consumption on the market so that they pay pq to their electricity retailer. The decentralized production unit of prosumers is connected to the grid. The size of the DPU (k) may be limited by legal or regulatory constraints or by technical constraints such

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

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.

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, meaning that a prosumer consumes φk from its own production; the remaining $(1-\varphi)k$ being supplied to the grid. For a prosumer, a part φk of the total consumption q comes from self-production while the other part $(q - \varphi k)$ comes from the grid. The total exchanges with the grid of consumers and prosumers are represented on Figure 3.

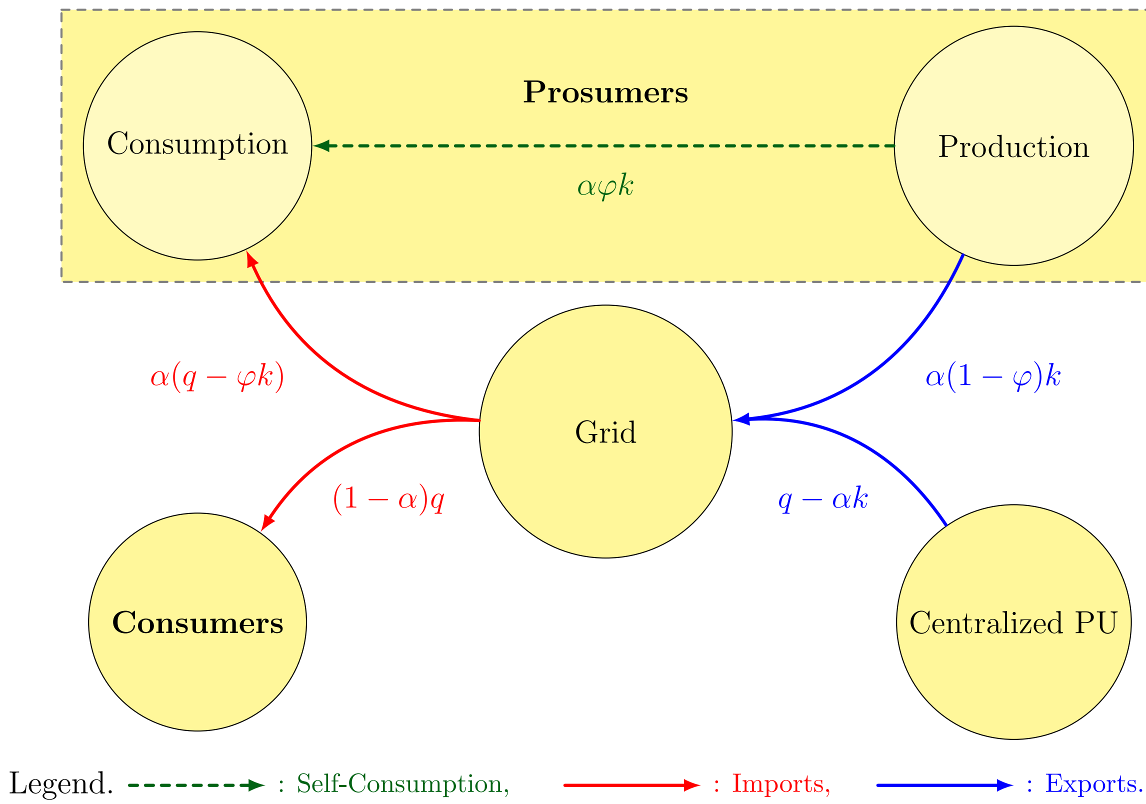

Figure 3: Exchanges with the grid

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.[5]

[5]For households, Bost et al. (2011) report a share of self-consumption ranging from 11.8% to 32.1%.

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. The total power exchanges (imports+exports) of a prosumer are equal to $q + (1 - 2\varphi)k$ implying that there are more (resp. less) exchanges with the grid than for traditional consumer if $\varphi \leq 0.5$ (resp. $\varphi \geq 0.5$). As our focus is on residential consumption, we consider that $\varphi < 0.5$.

2.2 The grid

Grid costs The DSO is in charge of managing the distribution grid. The grid has both fixed and variable costs. These variable costs are linked to electricity drawn from and supplied to the network.[6] We will denote by θ the cost per MWh of importing/exporting power to/from the grid to/from the consumer. For simplicity's sake, we suppose that export costs are equal to import costs per MWh while casual evidences suggest that power injections are more costly to manage.[7] We also normalize to zero the export costs from the centralized production units to the grid.[8]

With a proportion α of prosumers injecting $(k - \varphi k)$ on the grid, the total import and export volumes, V_m and V_x are given by:

$$\begin{aligned} V_m &= \alpha(q - \varphi k) + (1 - \alpha)q = q - \alpha\varphi k, \\ V_x &= \alpha(1 - \varphi)k. \end{aligned}$$

The variable cost of the DSO is:

$$C_d(\alpha) = c_m(\alpha) + c_x(\alpha) = (V_m + V_x)\theta = (q + \alpha(1 - 2\varphi)k)\theta, \tag{1}$$

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).

[6]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.

[7]When exports are too important, DSO have to disconnect some DPU. In this case, the cost of exports is the opportunity cost of lost energy.

[8]This assumption is made without loss of generality as large power plants and the grid have usually been highly entwined from both a historical and a technical point of view.

with $c_m(\alpha) = (q - \alpha\varphi k)\,\theta$ being the costs of imports and $c_x(\alpha) = \alpha(1-\varphi)k\theta$ the costs of exports. If $\varphi < 0.5$ (resp. $\varphi > 0.5$), the total cost of the grid increases (resp. decreases) with the proportion of prosumers α. In addition, it should be noted that self-consumption is a cost reducing activity for the grid as the cost decreases with the parameter φ. The total cost of the grid is the sum of the variable cost C_d and the fixed cost K.

Metering technology Consumers with a DPU are connected to the grid and their exchange with the grid are measured by one or two meters. With *net metering*, the meter measures the difference between imports $q - \varphi k$ and exports $(1-\varphi)k$. The meter 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,* the meters 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 $R = C_d(\alpha) + K$ 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 fixed cost and the variable part set to cover the variable costs. 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 grid 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 registered consumption is $(V_m - V_x)$ and the unit tariff r must be such that $R = r(V_m - V_x) = C_d(\alpha)$. In the case of net purchasing, the regulator can distinguish a tariff for imports r_m and a tariff for exports r_x. With net purchasing, the tariff must be such that $R = r_m V_m + r_x V_x = C_d(\alpha)$.

2.3 First best level of prosumers

The total cost of producing and distributing electricity for the system[9] is given by the sum of the cost of generation $C_g(z) = (1 - F(z))\,pq + F(z)\,(q-k)\,p + H(z)\,k$, where $H(z) = \int_{\underline{z}}^{z} f(x)x dx$, and the cost of network distribution, $C_d(z)$ given above. Letting $\alpha = F(z)$, the total cost is:

$$C(z) = C_g(z) + C_d(z) = (p+\theta)\,q - F(z)\,kp + H(z)\,k + F(z)\,(1-2\varphi)k\theta$$

The benevolent social planner minimizes $C(z)$ with respect to z. The first-order condition[10] can be rewritten as:

$$\begin{aligned} f(z^*)\,k\,\{-p + z^* + (1-2\varphi)\theta\} &= 0 \\ &\Rightarrow \; z^* = p + (2\varphi - 1)\,\theta \end{aligned} \tag{2}$$

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 (p) corrected for the additional network cost of decentralized production. This cost is zero, when $\varphi = 0.5$ i.e. when the imports perfectly balance the exports. If $\varphi < 0.5$, DPU generates more costs than centralized production, while for $\varphi > 0.5$ it is the reverse. Therefore, $z^* < p$ when $\varphi < 0.5$. When there are additional power exchanges, the installation cost of DPU must be strictly lower than the cost of centralized production.

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

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

The characterization of z^* in Equation (2) is similar to Brown and Sappington (2017) 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 (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 while network costs increase.

3 Net metering

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

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

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, $p+r$. 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. If not, electricity is exported at unit cost θ. However, 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 $p+r$. Hence, there is a discrepancy between the opportunity cost perceived by the prosumer and the true cost of decentralized production. In other words, even if exchanges with the grid are charged at marginal cost ($r = \theta$), there will be more prosumers than in the first best for $\varphi < 0.5$.

The total cost of the grid is given by (1). With net metering and for any bound z, as the meter running backwards for prosumers, registered consumption is the difference between imports and exports i.e. $\tilde{V} = V_m - V_x$ and is given by:

$$\tilde{V}(z) = (1 - F(z))q + F(z)(q - k) = q - F(z)k.$$

The break-even network rate is equal to the ratio between the total cost and the total measured flow: $\tilde{r}(z) = C_d(z)/\tilde{V}(z) = \frac{V_m+V_x}{V_m-V_x}\theta$.

$$\tilde{r}(z) = \frac{q - F(z)\varphi k + F(z)(1-\varphi)k}{q - F(z)k}\theta = \left\{1 + 2\frac{F(z)(1-\varphi)k}{q - F(z)k}\right\}\theta. \tag{4}$$

Notice that, for $F(z) > 0$, the registered consumption $\tilde{V}$ is inferior to the total power exchanges with the network $V_m + V_x$ and therefore the network rate is higher than the cost θ. In addition, the break-even network fee increases with the proportion of prosumers: $\partial\tilde{r}(z)/\partial z > 0$ and the size of DPU: $\partial\tilde{r}(z)/\partial k > 0$.

From (3) and (4), one can derive the equilibrium[11] $\tilde{z}$ with net metering such that $\tilde{r} = \tilde{r}(\tilde{z})$ and

$$\tilde{z} = z^* + 2(1-\varphi)\frac{q}{q - F(\tilde{z})k}\theta. \tag{5}$$

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 (2017). Second, the network rate r increases, which further increases the benefit of "prosuming". This rate increases results from the combination of higher grid costs (exports more than compensated reduced imports for $\varphi < 0.5$) and decreased registered consumption. Consequently, the network fee is increased above the marginal cost thus reinforcing the benefit of "prosuming".

[11] Its existence is ensured if $\bar{z} > p + \frac{q-(2\varphi-1)k}{q-k}\theta$.

4 Net purchasing

With two meters, one to measure the imports $q - \varphi k$ and another to measure the exports $k - \varphi k$, there is no decrease in the registered consumption as all the exchanges are recorded. And, if $\varphi \leq \frac{1}{2}$, there are more registered 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 retail price p. With two meters, the DSO can charge a different rate for the imports (r_m) and the exports (r_x) but there is no need to discriminate between prosumers and consumers. The net cost of a prosumer with an installation producing k is given by

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

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.

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 V_m equal to $V_m = q - F\left(z\right)\varphi k$ and an export volume V_x equal to $V_x = F\left(z\right)(1-\varphi)k$. The break-even constraint for the DSO states that:

$$R \equiv r_m V_m + r_x V_x = C_d\left(z\right) \equiv \theta\left(V_m + V_x\right)$$

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

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

The locus (r_m, r_x), represented on Figure 4, has two interesting properties. First, setting the network fees r_m and r_x equal to the induced costs: $r_m = r_x = \theta$ belongs to the locus. Second, 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[12] correspond to $\left(r_m = 0,\, \bar{r}_x(z) = \theta\left(\frac{q+(1-2\varphi)F(z)k}{F(z)(1-\varphi)k}\right)\right)$ and $\left(\bar{r}_m(z) = \theta\left(\frac{F(z)(1-\varphi)k}{q-F(z)k}\right),\, r_x = 0\right)$.

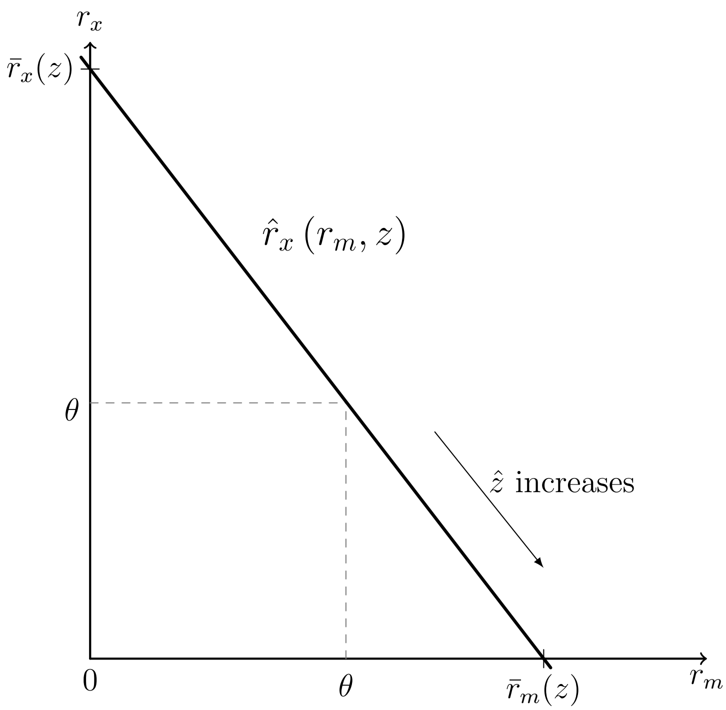

Figure 4: Break-even grid tariff with net purchasing

Solving (6) and (7), we can 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:

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

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,

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

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:* $r_m = r_x = \theta$.

The net purchasing system is able to induce the first best – i.e. cost-minimizing – level of DPU by setting import and export tariffs equal to cost. This was not the case in the metering system associated with an excessive deployment of DPU. 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 the locus defined in Equation (7) and decreasing r_x below θ stimulates the deployment of DPU. 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 import fee is also lower. To replicate $\tilde{z}$ with the net purchasing system, the regulator should set negative export fees.

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: $r_m = r_x = \theta$. 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:

$$
\begin{aligned}
\hat{R}^c &= r_m q = \theta q \\
\hat{R}^p &= r_m(q - \varphi k) + r_x(1-\varphi)k = \theta\left(q + k(1-2\varphi)\right)
\end{aligned}
$$

With net purchasing, prosumers who are making more power exchanges with the grid (if $\varphi < 0.5$) contribute more to the grid financing: $\hat{R}^p > \hat{R}^c$ and the contribution of consumers and prosumers corresponds to their induced cost. Notice that 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 the benchmark, net metering increases the bill for the traditional consumers $\tilde{R}^c > \hat{R}^c$. Reasons for this are multiple. Firstly, only net imports are recorded for prosumers meaning that the registered consumption declines leading to an increase in the grid tariff. Secondly, this effect is further exacerbated by the fact that grid costs increase as prosumers are making more power exchanges with the grid ($\varphi < 0.5$) and the deployment of DPU is above the first best level ($\tilde{z} > z^*$).

For prosumers, the rate is increased compared to the benchmark but the recorded consumption is reduced. As $\hat{R}^p - \tilde{R}^p = 2\theta k(1-\varphi)q\frac{1-F(\tilde{z})}{q-F(\tilde{z})k} > 0$, the later effect dominates the former. We thus have:

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.[13] 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 $(r_m, r_x) = (\bar{r}_m, 0)$. With such a tariff, we have a deployment of DPU above the first best level:

$$\hat{z}(\bar{r}_m, 0) = z^* + \frac{q}{F(\hat{z})k}(\bar{r}_m - \theta) < \tilde{z}. \tag{9}$$

The corresponding consumer's payments are given by:

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

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.

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

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 both electricity exports and imports of prosumers 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: $\partial C(z)/\partial\varphi = -2F(z)k\theta < 0$. There are many technologies 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 that can be stored through a heat pump, before the final usage, 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 match 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:

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

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 incentives for synchronization while it is socially desirable. Net purchasing can lead to first best levels of “prosumption”and synchronization jointly with cost-oriented grid tariffs.*

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

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

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

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

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:

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

Cost-oriented grid tariffs lead to the first best level of DPU installation and provide adequate incentives for prosumers to synchronize their production and their consumption. With $r^m = r^x = \theta$, we have both $\tilde{\varphi} = \varphi^*$ and $\tilde{z} = z^*_{\varphi}$.

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 strong case *against* net metering.

6 Extensions

In this section we discuss the robustness of our results with respect to different grid tariff 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.[14] Differentiating tarifs can be used to align network fees with induced costs which is a major concern with net metering.

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

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

[14] 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 indifferent consumer bears a marginal installation cost $\tilde{z}'$ such that:

$$\tilde{z}' = p - r_p \frac{q-k}{k} + r_c \frac{q}{k}. \tag{10}$$

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:

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

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

$$\tilde{r}_p(z) = \frac{C_d(z)}{F(z)(q-k)} - \tilde{r}_c(z) \frac{1-F(z)}{F(z)} \frac{q}{q-k}. \tag{11}$$

From Equations (10) and (11), 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* $\tilde{r}_p = \frac{\theta}{q-k}(q + (1-2\varphi)k)$.

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:

$$\begin{aligned} \tilde{r}_p - \tilde{r}_c &= 2\theta \frac{k}{q-k}(1-\varphi) \geq 0 \\ \tilde{r}_p - \tilde{r} &= 2kq\theta \frac{(1-\varphi)(1-F(\tilde{z}))}{(q-k)(q-F(\tilde{z})k)} \geq 0 \end{aligned}$$

Discriminatory net-metering tariffs restore efficiency of net-metering when the consumer's rate is reduced to marginal cost and the prosumer's rate is above the uniform net metering rate. The discriminatory tariff is such that the contribution of each category of consumer to the network financing is equal to the induced cost. Traditional consumers are charged at marginal cost θ. The rate for prosumers is adjusted to take into account the increased exchanges with the grid and the decreased registered consumption. 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 Ramse-like tariff

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

With net metering, the regulator must inflate the grid fee by $\frac{K}{V_m - V_x}$ to cover the fixed cost, so that:

$$\tilde{\tilde{r}}(z) = \tilde{r} + \frac{K}{q - \varphi k}.$$

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 $\frac{K}{V_x}$ and writes now:

$$\hat{\hat{r}}_x\left(r_m, z\right) = \theta + (\theta - r_m)\,\frac{q - F\left(z\right)\varphi k}{F\left(z\right)\left(1-\varphi\right)k} + \frac{K}{F(z)(1-\varphi)k}. \tag{12}$$

Solving (6) and (12), we find that:

$$\hat{\hat{z}} = \hat{z} - \frac{K}{F(\hat{\hat{z}})k} = z^* + \frac{q}{F(\hat{\hat{z}})k}(r_m - \theta) - \frac{K}{F(\hat{\hat{z}})k} \tag{13}$$

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

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

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.

6.2 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 $\hat{z} = z^e$:

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

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 means 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).[15] 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 $\rho > 0$ in addition to the market price p for each MWh they produce

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

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 $F(z)\rho k$ 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 $z'\left(\rho\right) = p + r + \rho + \tau\left(\rho\right)$. Setting $z' = z^e$ and replacing r by the break-even value given in Equation (4), we have the optimal FIP:

$$\rho' = \delta\frac{q - F\left(z^* + \delta\right)k}{q} - 2\left(1 - \varphi\right)\theta$$

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 tarif. 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 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 dropping prices for rooftop PV and financial supports at the local, regional and federal levels (via subsidies and tax cuts), have led to a massive rise of PV's and subsequent increase in the grid fee, an issue that can be avoided in the 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 own and are lodging in a house. 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 it 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 limit their net metering programmes.

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.[16] 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.

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