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 has two types of exchanges with the grid: energy import when the local production is insufficient to match the local consumption and energy exports when local production exceeds local consumption. There are two systems to measure the exchanges with the grid: 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 both exports and imports. We build a model to compare the two systems in terms of deployment of DPU, redistribution, and incentives to synchronize production and consumption.

Keywords: Decentralized production unit, solar panel, grid tariff.

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[*]HEC Liege, University of Liege, LCII and CORE. E-mail: agautier@ulg.ac.be The author thanks the FNRS for its financial support.

[†]HEC Liege, University of Liege. E-mail: Julien.Jacqmin@ulg.ac.be

[‡]LAMETA, University of Montpellier and LabEx "Entreprendre", Montpellier, France. E-mail: jean-christophe.poudou@umontpellier.fr

1 Introduction

Prosumers are households that are both *producers* and *Consumers* of electricity. A prosumer has a decentralized production unit (DPU) –photovoltaic panels (PV) or a small wind turbine– to produce electricity at home and the DPU is grid-connected. Part of the electricity produced by a prosumer is consumed at home when production and consumption are simultaneous. But, when the local production does not match the consumption, the prosumer uses the grid for the balance. If consumption exceeds production then the prosumer draw 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 the grid and exports to the grid.

Decentralized production is a substitute to traditional generation units (from coal, gas or nuclear plants). An increased penetration of decentralized production technologies changes the total cost of electricity generation (including the environmental cost). In addition, power exchanges between prosumers and the grid generate costs for the grid operator as it requires 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. These 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 tariff. One key element of this interaction is the grid tariff as it affects the cost and benefits of decentralized production and thereby the rate of technology adoption.

To measures exchanges with the grid, prosumers are equipped with meter(s). There are two alternative metering technologies: the net metering and the net purchasing systems. With the net metering system, there is a unique meter that runs backward when production exceeds demand. The meter only registers the difference between imports from and exports to the grid i.e. net imports. With the net purchasing system[1], 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. Currently, the two technologies

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

are being used (see Poullikkas (2013) and IEA-RETD (2014) for detailed reviews).

Net metering is a tool to finance decentralize 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 aspects. As the registered consumption decreases, to cover the fixed network cost the grid tariff has to increase. 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 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.

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. Second, the two technologies are not equivalent in terms of income redistribution between the different categories of consumers. Last, they induce different behavior with respect to auto-consumption. There exists complementarity technologies (e.g. storage) or behavioral changes (e.g load displacement, orientation of the solar panels) that can increase the synchronization between decentralized production and consumption. Due to the different prices received for the energy produced, the attitude of prosumers towards these changes is different in the two metering systems. Due to the lower price received for the energy produced the net purchasing system creates more incentives for synchronization. The objective of this paper is to compare the two systems along these three dimensions.

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. The robustness of our results with respect to different policies set to encourage investments in renewable energies, to environmental concerns and different pricing policies are discussed in Section 6. Section 7 concludes.

2 Model

We consider an electricity system where there are 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 it is currently the case in Europe. Electricity production is considered to be a competitive activity and the price charged by producer p 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 incentive issues related to the regulation of the DSO.

2.1 Consumers and prosumers

Consumers have the opportunity to instal a DPU and become prosumers. A DPU producing k MWh has an installation cost of zk. This cost depends on many factors. For example, for solar panels, it depends on the solar irradiation level, roof orientation/size, technological costs, if the person own the place he lives in, etc. Consumers are heterogeneous with respect to the installation cost z. The population size is normalized to one but 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 it may appear an (endogenous) proportion α of prosumers in the population and a residual proportion $(1-\alpha)$ of traditional consumers. Indeed, depending on the market or institutional conditions, only a fraction of agents will be able to be eligible to prosuming so we can write that $\alpha = F(z)$.

Both types of consumers have the same energy consumption of q MWh and the energy demand is supposed to be totally inelastic. Electricity is sold by retailers at price p which is assumed to be equal to the marginal cost of centralized generation. 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 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 for also limit the DPU capacity to the actual consumption ($k \leq q$). Hence, we will assume that the DPU production is fixed and lower than actual consumption.

Production and consumption of a prosumer are not synchronized at any point in time. We will denote by $\varphi \leq 1$ the synchronization factor of a prosumer[2], 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 auto production while the other part $(q - \varphi k)$ comes from 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 exceed 0.5.[3] This is confirmed in EIA-RETD (2014) that, however, acknowledges a forthcoming rise due to technological advances in home storage facilities. 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. $\varphi \geq 0.5$).

2.2 Grid

Grid cost The DSO is in charge of managing the distribution grid. The costs of electricity distribution are at least partially linked to electricity drawn from and supplied to the network.[4] We will denote by θ the cost per MWh of importing/exporting power to/from the grid to the consumer. For simplicity, we suppose that export costs are equal to import costs per MWh while casual evidences suggest that power injections are more costly to manage.

With a proportion α of prosumers injecting $(k - \varphi k)$ on the grid, the total import

[2]Prosumers are obviously heterogeneous with respect to the synchronization factor φ. This parameter should be interpreted as a mean value.

[3]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.

[4]See Coelli *et al.* (2013) for analysis of the cost drivers in electricity distribution.

and export volumes, V^i and V^o are given by:

$$V^i = \alpha(q-\varphi k)+(1-\alpha)q = q-\alpha\varphi k, \tag{1}$$

$$V^o = \alpha(1-\varphi)k. \tag{2}$$

The total cost of the DSO is:

$$C_d(\alpha) = c^i(\alpha)+c^o(\alpha) = (V^i+V^o)\theta = (q+\alpha(1-2\varphi)k)\theta, \tag{3}$$

with $c^i(\alpha) = (q-\alpha\varphi k)\theta$ being the costs of imports and $c^o(\alpha) = \alpha(1-\varphi)k\theta$ 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. Fixed costs are supposed to be compensated by a fixed fee passed through the consumers.

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. Notice that measuring production k in addition is insufficient to recovered the full information about exports and imports unless φ is known. With *net purchasing,* the meters record both imports and exports separately.

Grid regulation The grid is regulated and the regulator sets a grid tariff per MWh denoted by r. The tariff must be such that the DSO breaks even i.e. the tariff r solves $\pi^{DSO} = 0$. With dual-metering, the regulator can distinguish a tariff for imports r^i and a tariff for exports r^o. From a very general point of view grid tariffs are set as $R = C_d(\alpha)$ where R are the access receipts for the DSO. With net metering, $R = r(V^i - V^o)$ and with net purchasing $R = r^iV^i + r^oV^o$.

2.3 First best level of prosumers

The total cost of producing and distributing electricity for the system[5] is given by sum of the cost of generation $C_g(z) = (1 - F(z))\, pq + F(z)(q-k)\, p + E(z)\, k$, where $E(z) = \int_{\underline{z}}^{z} f(x) x dx$, and the cost of network distribution, $C_d(z)$ given above, and letting $\alpha = F(z)$. Hence

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

The benevolent social planner minimizes $TC(z)$ w.r.t z. The first-order condition[6] writes

$$f(z^*)\, k \{-p + z^* + (1-2\varphi)\theta\} = 0 \tag{4}$$

$$\Rightarrow \quad z^* = p + (2\varphi - 1)\,\theta \tag{5}$$

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 imports perfectly balance the exports. If $\varphi < 0.5$, DPU generates more cost than centralized production, while for it is the reverse for $\varphi > 0.5$. Therefore, $z^* < p$ when $\varphi < 0.5$. When there are additional network cost of DPU, the cost of DPU must be strictly lower than the cost of centralized production.

The characterization of z^* in Equation (5) is similar to Brown and Sappington (2015) for which 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

[5]Indeed, only costs matter as surpluses are constants.

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

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 registered consumption with the meter running backwards declines more than network costs.

3 Net metering

Suppose that the individual has only one meter. The net utility of installing PV for a prosumer who has an PV installation of capacity $k \leq q$ 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 S is the gross (invariant) surplus derived from consuming the energy flow q, and r is grid tariff per MWh. The indifferent consumer between consuming only and installing the DPU bears a marginal installation cost $\tilde{z}$ such that:

$$\tilde{z} = p + r. \tag{6}$$

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 opportunity 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 (3). With net metering and for any bound z, the measured electricity flows are given by:

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

With the meter running backwards for prosumers, registered consumption is the difference between imports and exports i.e. $\tilde{V} = V^i - V^o$.

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

$$\tilde{r}(z) = \frac{q - F(z)\varphi k + F(z)(1-\varphi)k}{q - F(z)k}\theta = \left\{1 + 2\frac{F(z)(1-\varphi)k}{q-F(z)k}\right\}\theta. \tag{7}$$

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

From (6) and (7), one can derive the equilibrium $\tilde{z}$ with net metering such that $r = \tilde{r}(\tilde{z})$ and

$$\tilde{z} = z^* + 2(1-\varphi)\frac{q}{q - F(\tilde{z})k}\theta. \tag{8}$$

Proposition 1 *Net metering induces too much prosumerism compared to the first best i.e.* $\tilde{z} > z^*$

This inefficiency is created by two distinct mechanism. First, the opportunity cost of decentralized production does not correspond to its true cost (compare Equation (5) and Equation (6)). This effect is enlighted in Brown and Sappington (2015). 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.

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. In fact, it is quite the opposite if $\varphi \leq \frac{1}{2}$, there are more registered exchanges. When a prosumer exports power to the grid, it is bought back at the retail price p. With two meters, the the DSO can charge a different rate for the imports (r^i) and the exports (r^o) but we will consider that the rate for imports is the the same for all consumers. The net cost of a prosumer with an installation of size k is given by

$$U(z) = \begin{cases} S - (q-k)p - r^i(q - \varphi k) - (1-\varphi)kr^o - zk & \text{if} \quad k > 0 \\ S - (p + r^i)q & \qquad\quad k = 0 \end{cases}$$

The indifferent consumer between consuming only and installing the DPU bears a marginal installation cost $\hat{z}$ such that

$$\hat{z} = p + \varphi r^i - (1-\varphi) r^o \tag{9}$$

For this prosumer $\hat{z}$, the marginal installation cost must reflect again to the opportunity cost of purchasing the electricity which is now impacted by grid tariff structure (r^i, r^o) and by the share of self-consumption.

The total cost for the DSO is given by Equation (3) 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^i equal to $V^i = q - F(z)\varphi k$ and an export volume V^o equal to $V^o = F(z)(1-\varphi)k$. The break-even constraint for the DSO states that

$$TR \equiv r^i V^i + r^o V^o = C_d(F(z)) \equiv \theta\left(V^i + V^o\right)$$

This equation defines a locus of tariff (r^i, r^o) that guarantees that the DSO breaks-even:

$$\hat{r}^o\left(r^i, z\right) = \theta + \left(\theta - r^i\right)\frac{q - F(z)\varphi k}{F(z)(1-\varphi)k} \tag{10}$$

Three remarks: (1) setting the network fees r^i and r^o equal to the induced costs: $r^i = r^o = \theta$ belongs to the locus. (2) The slope of the locus is (in absolute value) higher than one. This means that if r^i decreases by 1, r^o increases by a factor > 1. The extreme values where all the burden of the network cost is charged either on exports or on imports correspond to $\left(r^i = 0,\, \bar{r}^o(z) = \theta\left(\frac{q+(1-2\varphi)F(z)k}{F(z)(1-\varphi)k}\right)\right)$ and $\left(\bar{r}^i(z) = \theta\left(\frac{F(z)(1-\varphi)k}{q-F(z)k}\right),\, r^o = 0\right)$. For a given z, we have $\tilde{r}(z) > \bar{r}^i(z)$ as with net purchasing, the import meter records true imports and not net imports. (3) A priori, there is no reason to exclude exports subsidies with $r^o < 0$ which is then a premium paid by the grid for energy exports financed by higher import prices. Figure 1 represents the locus.

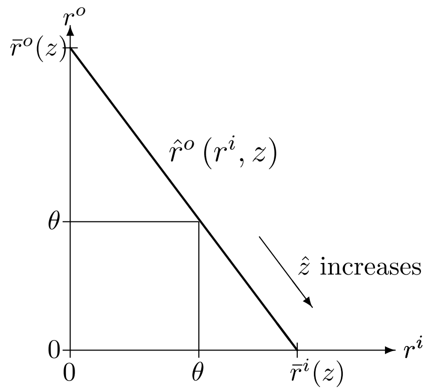

Figure 1: Break-even grid tariff with net purchasing

Solving (9) and (10), 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^i:

$$\hat{z} = z^* + \frac{q}{F(\hat{z})\,k}\left(r^i - \theta\right)$$

One can see that whenever $r^i \leq \theta$ then $\hat{z} \leq z^*$, while whenever $\theta < r^i < \tilde{r}$ then $z^* < \hat{z} \leq \tilde{z}$. Finally when $r^i \geq \tilde{r}$ 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 prosumerism when tariffs are set to cost.*

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 since at the break-even grid tariff, there is too much DPU compared to the first best.[7] With net purchasing, it is possible to construct a tariff that is fully cost reflective and that induce the efficient deployment of DPU.

It is clear that DPU penetration depends on the tariff structure and that a lower r^o stimulates DPU expansion. With the dual metering systems, there is an additional

[7]Relaxing the constraint to $\pi^{DSO} \geq 0$ would not lead to the first best either.

flexibility as there are many solutions to the equation $\pi^{DSO} = 0$, including $r^i = r^o = \theta$ leading to $\hat{z} = z^*$. Hence, depending on the objective of the regulator (cost minimization, DPU deployment, redistribution among agents, etc.) the rate structure can be adapted.

5 Comparisons

In this section, we compare the two metering technologies with respect to (1) redistribution issue between consumers and prosumers and (2) incentives to synchronize production and consumption.

5.1 Redistributional concerns

The metering technology and the tariff structure have an influence on the deployment of distributed generation. But technology adoption may not be the only concern of the regulator. In this section, we analyze the redistributive impact of the grid tariff. To analyze this, let us compare net metering and net purchasing and suppose that in the latter case, the grid tariff is cost reflective: $r^i = r^o = \theta$. This solution leads to the efficient deployment of DPU: $\hat{z} = z^*$. With net purchasing, the network bill (R) of a consumer and a prosumer are respectively equal to:

$$\hat{R}^C = r^i q = \theta q \tag{11}$$

$$\hat{R}^P = r^i(q - \varphi k) + r^o(1 - \varphi)k = \theta\left(q + k(1 - 2\varphi)\right) \tag{12}$$

With dual metering, prosumers who are making more power exchange with the grid (if $\varphi < 0.5$) contribute more to the grid financing: $\hat{R}^P > \hat{R}^C$. 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:

$$\tilde{R}^C = \tilde{r} q \tag{13}$$

$$\tilde{R}^P = \tilde{r}(q - k) \tag{14}$$

where $\tilde{r} = \tilde{r}(\tilde{z})$. Compared to that benchmark, net metering increases the bill for the traditional consumers $\tilde{R}^C > \hat{R}^C$. Reasons 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 ($\tilde{z} > z^*$). Moreover, traditional consumers contribute more to the grid financing than prosumers, quite the opposite of the net metering case: $\tilde{R}^C > \tilde{R}^P$. For prosumers, the registered consumption decreases to $(q - k)$ but the bill does not decrease in the same proportion as the rate r increases.

The metering system has important redistributive effects between the two types of consumers. To quantify these effects, we use the following parameters for a numerical simulation. Suppose that the solar panel production covers 80% of the home consumption ($k = 0.8q$) and the synchronization parameter is set to $\varphi = 0.3$. With net purchasing the grid rate is set to θ independently of z. For our simulations, we consider two values for $\alpha = F(z)$: 2.5% and 12.5%

Results are reported in tables 1 and 2. In the first, we report the change in the grid tariff Δr measured as the rate increase $\tilde{r}$ compared to the induced cost, expressed in percentage:

$$\Delta r = \frac{\tilde{r} - \theta}{\theta}$$

The second table reports the impact on the consumer's and prosumer's bill using as a reference point a consumers' bill under net purchasing with

$$\Delta R^C = \frac{\tilde{R}^C - \hat{R}^C}{\hat{R}^C} \text{ and } \Delta R^P = \frac{\tilde{R}^P - \hat{R}^P}{\hat{R}^C}$$

	$\alpha = 2.5\%$	$\alpha = 12.5\%$
Δr	2.85 %	15.55 %

Table 1: Rate increase

For prosumers, the registered consumption decreases by 80% but the impact on their bill is slightly lower due to the rate increase. This table illustrates that the development

	$\alpha = 2.5\%$	$\alpha = 12.5\%$
ΔR^C	2.85 %	15.55 %
ΔR^P	-79.43 %	-76.89%

Table 2: Bill change

of DPU has a significant impact on the payments to the DSO for traditional consumers who see a quite important increase and for prosumers who enjoy a substantial decrease. With the single-metering system, the grid costs are mostly financed by traditional consumers while the contribution of prosumers is extremely limited. Notice that this is at odd with the induced grid cost as prosumers generates more cost than traditional users.

5.2 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 thereby the grid costs. For this reason, it is efficient to have a higher deployment of DPU when synchronization increases i.e. $\frac{\partial z^*}{\partial \varphi} > 0$. Or differently, $\frac{\partial C_d}{\partial \varphi} < 0$. There are many technologies that prosumers can use to synchronize local production and consumption, the most obvious being energy storage at home. Residential batteries will in the future be able to do that. But beside storage, there are different techniques that prosumers can use to control the load and to better synchronize production and consumption such as displaced consumption, storage (water heating for instance) or the orientation of solar panels.[8]

Suppose that a prosumer can at some cost increases synchronization between consumption and local production. The cost of synchronization must be increasing and convex (at the margin, it is more and more costly to match consumption and production) and we will represent this cost by the function $\frac{\varphi^2}{2}$. 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 $\frac{\partial r}{\partial \varphi}$ captures the impact on the grid tariff of an increase in

[8]Smart grids and smart meters can also be used *at the grid level* to better synchronize production and consumption.

the synchronization parameter of *all* prosumers. In our analysis focused on individual incentives, we will focus 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.

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

$$\tilde{U}(z) = S - (p + \tilde{r}(\tilde{z}))(q - k) - zk. \tag{15}$$

This utility is independent of the synchronization level and net metering does not provide incentives for synchronization.

With net purchasing, the grid applies a tariff $(\hat{r}^i, \hat{r}^o)$ defined by Equation (10). At this tariff, the utility of a prosumer is

$$\hat{U}(z) = S - (q - k)p - \hat{r}^i\,(q - \varphi k) - (1 - \varphi)\,k\hat{r}^o - zk. \tag{16}$$

With *net purchasing*, 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: $\frac{\partial \hat{U}(z)}{\partial \varphi} > 0$. The optimal synchronization is characterized by:

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

Incentives to synchronize are linked to the network fee ($\hat{r}^i$ and $\hat{r}^o$) and the size of the installation. As the locus defined in Equation (10) has a slope > 1, the tariff structure has an impact on the synchronization level $\bar{\varphi}$. Indeed, moving along the locus and decreasing r^i, and increasing more proportionally r^o, increases the synchronization level. Therefore, given that synchronization is important and socially desirable as it reduces the grid cost, the regulator may depart from cost-based grid tariff in order to stimulate individual incentives for self-consumption.

6 Discussions

The analysis above may be extended to encompass some simplifying assumptions of the model or to incorporate some features in conformity with situations observed in energy markets.

6.1 No autoconsumption

In France, prosumers have the possibility to sell all the electricity produced by the DPU to the grid (at a premium price). In this case, registered exports are equal to k and registered imports to q. Self consumption in this model is not registered. However, for our analysis, we will suppose that when consumption and production are simultaneous, there is no associated network cost i.e. network costs are still defined in Equation 3. Exports are bought back at a price p and the prosumers pays an injection fee r^o. Decentralized production is then valued at $p + r^o$ i.e. the market price plus a grid cost (r^0) that can be positive (injection fee) or negative (feed-in premium). The utility of consumers and prosumers are defined by:

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

The indifferent consumer is characterized by:

$$\dot{z} = p - r^o \tag{17}$$

To induce the first best level of DPU, the regulator must set:

$$\dot{z} = z^* \Rightarrow \dot{r}^o = (1 - 2\varphi)\theta \, 0 < \dot{r}^i < \theta.$$

Without registered self-consumption, the prosumer should pay an export fee smaller than the induced cost: $\dot{r}^o < \theta$. The reason is that the export meters register exports that will not be associated with a cost, therefore, the price should be adjusted downward. As a consequence, the import fee should raise and it is defined by solving $\hat{r}^o(z^*, r^i) = \dot{r}^o$. Accordingly, the import fee will be set above cost $r^i > \theta$.

6.2 Environmental impact of DPU

In the model we used so far, the DPU have no positive environmental impact. This is clearly not the case for photovoltaic panels or small wind turbines that generate less greenhouse gas emission than centralized energy production based on gas or coal. To take that 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 evaluated in terms of MWh produced. For instance, if we assume that linear approximation for the damage function $D(E) = \delta E$ with $\delta > 0$,the the total cost writes now:

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

Then 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 install specific supporting scheme. We analyze the two options in turn.

6.2.1 Grid support to DPU

With net metering, if $z^e \geq \tilde{z}$, then to increase the DPU penetration further, the grid tariff must increase which then leaves a positive profit to the grid operator. On the contrary, if $z^e \leq \tilde{z}$, then net metering provides too much support to DPU. In both cases, the lack of flexibility associated with net metering makes environmental targets costly to reach.

With net purchasing, the grid tariff can be used more easily to reach environmental targets. By increasing r^i and decreasing r^o along the locus given in Equation 3, $\hat{z}$ increases. More specifically, the following tariff leads to $\hat{z} = z^e$: $(r^i, r^o) = (\theta + \frac{F(z)k}{q}\delta,\ \theta - \frac{q - F(z)\varphi k}{q(1-\varphi)}\delta)$. Notice that for sufficiently large value of δ, the export fee may become negative $r^o < 0$. In this case, it might be optimal to compensate prosumers for their exports as it is a mean to subsidize decentralized production. Note also that such a subsidy reduces the incentives to synchronize local production and consumption.

6.2.2 Effect of FIT-FIP-RPS

Decentralized energy production is often subsidized, sometimes heavily (Schmalensee, 2012). Supporting schemes for renewables ressources is motivated by their positive environmental impact that the market fails to take into account. Therefore, to support the deployment of renewable energy sources, many countries have installed support mechanisms, like feed-in tariffs (FIT), feed-in premium (FIP) or renewable portfolio standards (RPS).[9]

Feed-in tariffs (FIT) are fixed electricity prices that are paid to renewable energy producers for each unit of energy produced and injected into the electricity grid. The payment of the FIT is guaranteed for a certain period of time that is often related to the economic lifetime of the respective RE project (usually between 15-25 years). FIT are usually paid by electricity grid, system or market operators, often in the context of Power purchasing agreements (PPA).

In the model, this implies that when supplied to the grid by prosumers, the electricity is purchased by the grid at the regulated price π. Of course, in absence of any externality in the model currently, $\pi = p$. However, one might consider that $\pi > p$ if there are externalities.

Under a feed-in premium (FIP) scheme, electricity from renewable energy sources is typically sold on the electricity spot market and RES producers receive a premium on top of the market price of their electricity production. FIP can either be fixed (i.e. at a constant level independent of market prices) or sliding (i.e. with variable levels depending on the evolution of market prices). In the model, this implies that when supplied to the grid by prosumers, the electricity is purchased by the grid at the price $p + \rho$, where $\rho > 0$ is the premium.

Renewable energy quotas, renewable obligations or renewable portfolio standards (RPS) refer to the definition of minimum shares of renewable energy sources in the energy mix of power utilities, electricity suppliers or sometimes also large electricity consumers. In the model, this implies that a minimum level Q of RES produced by prosumers is targeted such that $F(z)k \geq Q$ or equivalently $z \geq F^{-1}(Q/k)$.

With FIT and FIP, prosumers receive a premium price for the electricity they pro-

[9] see Ringel (2006) for a comparison.

duce.[10] With a premium ρ, the total cost of the supporting scheme is equal to $F(z)\rho k$. One way to finance this subsidy is to raise the network fee. FIP in our model can be seen as an increase in the total cost of the grid which becomes $C_d(z) + F(z)\rho k$. The regulatory problem is then to the set the grid fee (r or r^i and r^o) and the premium ρ to reach the first best level of DPU (z^e) while guaranteeing a zero profit for the grid. In principle, with the additional flexibility provided by the premium ρ, it is possible to reach z^e with both net metering and net purchasing. However as we explain above, the two systems are not equivalent from a redistributive point of view.

7 Conclusion

The main findings of the model can be summarized as follows. On the one hand, we find that, under a net metering system, there tends to be too much energy users who switch in order to become prosumers compared with the first best. On the other hand, under a net purchasing system, the first best level of prosumers can be achieved if the tariff is set at the cost level. In addition, we find that the net metering system leads to no incentive to synchronize while it is so under a net purchasing system. This is explained by the fact that exports are not priced differently than net exports under a net metering system while it is so under a net purchasing system. We also argue that some of these conclusions can be put into reconsideration depending on the way the environmental externality created by the decentralized production is valued.

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