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WORKING PAPER

CROSS SUBSIDIES ACROSS NETWORK USERS: RENEWABLE SELF-CONSUMPTION

Cédric CLASTRES [1], Jacques PERCEBOIS [2, 3*],*
Olivier REBENAQUE [1,2] and Boris SOLIER [2, 3*]*

The deployment of renewable energies relies upon incentive policies to make their use profitable for owner. However, their development needs adjustments of network to manage intermittency and additional energy fed into the grid. Moreover, the Public Service Obligation Tariffs (PSOT) are increasing to fund policies that support renewable energy deployment. Therefore, some decisions are taken to promote self-consumption by owners of renewable energy power plants, as photovoltaic prosumers. This behavior is encouraged by payment exemptions of PSOT, special tariffs dedicated to remunerate each self-consumed energy unit or savings on the variable part of the network tariff. Thus, some cross-subsidies appear between self-consumers and other users of the network to compensate all these previous self-consumers' gains. We show that these cross-subsidies occur but they strongly rely on self-consumption rate and on renewable energy share in the total produced or consumed energy. So, currently, the levels of cross-subsidies are not significant for consumers. We also show that regulator could fund these cross-subsidies increasing the fixed part of the network tariff for prosumers.

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[1]GAEL (UMR 5313), university of Grenoble-Alpes, CNRS, INRA, Grenoble-INP CS 40700, 38058 Grenoble Cedex, France
[2] Climate Economics Chair, Palais Brongniart, 28 Place de la Bourse, 75002 Paris
[3] University of Montpellier, Avenue Raymond Dugrand CS 79606, 34960 Montpellier Cedex 2

***** Corresponding authors E-mail addresses:
cedric.clastres@univ-grenoble-alpes.fr
jacques.percebois@umontpellier.fr
olivier.rebenaque@chaireeconomieduclimat.org
boris.solier@chaireeconomieduclimat.org

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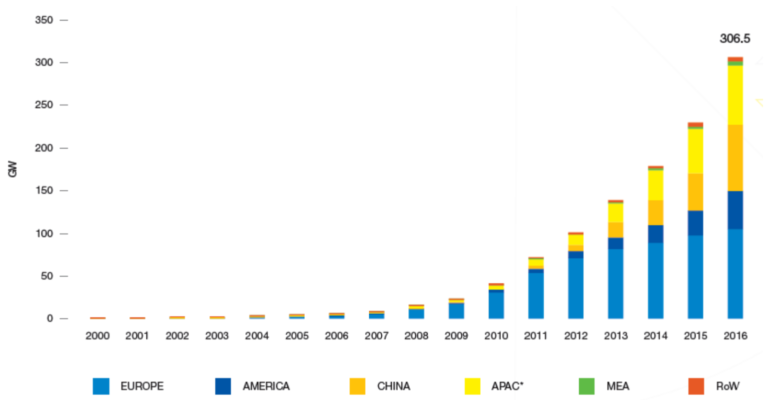
Introduction

Public and environmental policies have launched the deployment of renewable Energies, as photovoltaic (PV) capacities. We do not come back on environmental policies and the obligation for all countries to develop renewable energies to achieve the 3*20 goals of the third Energy Package. Regarding public policies, we could classify them into two categories (Zachmann et al., 2015). The first one is the financial support for Research and Development (R&D) in a specific technology. The second one is based on subsidies to develop investments in selective generation processes, in our case in clean technologies as for example PV generation capacities. These later incentive policies are decided by public authorities to internalize high investment costs in renewable energies and to lower electricity prices (IEA PVPS, 2016). In the sector of renewables, we could cite the Feed In Tariffs, the Feed in Premium or the Net metering as public incentive policies which have improved the increase in renewable energy capacities. The PV sector will benefit from these policies and we could observe that PV capacities have increased since 2007 at a great rate in the world, from 1 GW in 2000 to 230 GW in 2015 (Figure 1). This increase in PV installed capacities has dropped the cost of PV panels. Between 1975 and 2008, their costs have decreased at a 2% rate (from 65$/W to 4$/W). Since 2008, we observe an accelerate decreasing rate to achieve 1$/W today, so a decrease in cost of 80% in this period of time (Mir-Artigues and del Río, 2016). According to Bloomberg New Energy Finance (2016), when PV installed capacities increase twofold, the cost of panels is reduced by 23.4%. However, PV energy has not reached the grid parity in all country. The grid parity is achieved when energy prices are equal than the Levelized Cost of Electricity (LCOE) for PV technology. This could be the case in areas where solar radiations are important or in countries with high electricity prices. According to SOLAR POWER EUROPE (2016), only 1.3% of PV capacities have been developed without incentive policies. For these installations, subsidies are not useful and, because they are not included in the public budget (Couture et al., 2010; Mendonça et al., 2010), weight of Public Service Obligation Tariffs could be reduced for consumers. Thus, in most of studied cases, public incentive policies are always needed to develop renewable energy capacities (IEA PVPS, 2016).

Figure 1 : PV installed capacities in the world (Solar Power Europe, 2017)



*Asian-Pacific excluded China

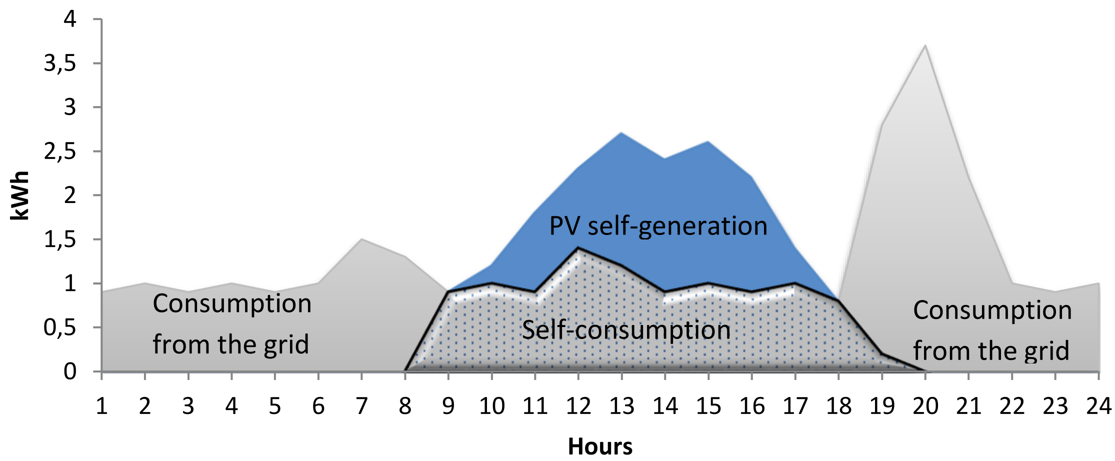
Large renewable energy capacities go with grid and financing difficulties. Network operators, mainly Distribution System Operator (DSO)[1], must invest in new capacities to manage the surplus of

[1] The distributed generation is mainly connected to distribution network. For example, in France, 93% of distributed generation is connected to distribution network.

distributed energy fed into the grid and its intermittency. Incentive policies must be compensated with revenues coming from consumption or network uses. Thus, we often observe an increase in Public Service Obligation Tariff (PSOT). For example, in France, the PSOT, called the CSPE (Compensation for Electricity Public Services) and paid by all consumers of electricity, has increased between 2010 and 2015 from 120 million € to 2.2 billion €. This increase mainly comes from the obligation for suppliers to buy renewable energies at regulated prices (Feed In Tariffs). Thus, we observe two kinds of transfers between electricity consumers. The first one is a transfer based on the PSOT. Indeed, the PSOT increases for all consumers but part of it is redistributed towards PV producers, which could also be consumers (usually called prosumers). The second one is a transfer based on network tariffs. Grid costs are increasing because of distributed energy management. This increase must be compensated by the regulated tariff which is the unique network operator's revenue. As this regulated tariff is paid by all consumers of electricity, we observe another transfer towards prosumers.

In recent years, and to internalize increasing network and intermittency costs, the deployment of self-consumption for renewable energies has been studied and implemented in several countries. Self-consumption situation is defined as the opportunity for a prosumer to consume part or the entire amount of its own generation (Figure 2).

Figure 2 : Consumption and PV generation daily profiles for a household "prosumer"



Two kinds of values are usually used to evaluate the Self-Consumption (SC) for a prosumer (Table 1). The first one is the SC rate (τ_{SC}) which is defined as the share of PV production that is consumed in the generation area. The second one is the Self-Generation (SG) rate (τ_{SG}) which is defined as the share of consumed electricity that is not withdrawn from the grid.

Table 1: Self-consumption and self-generation rates

Self-consumption rate	Self-generation rate
$\tau_{SC} = \frac{\text{Total PV electricity consumed for a day on site}}{\text{Total PV generation for a day on site}}$	$\tau_{SG} = \frac{\text{Total PV electricity consumed for the day on site}}{\text{Total Electricity consumed for a day on site}}$

These two rates are different and do not refer to the same objectives. If the objective is to maximize the SC rate τ_{SC}, then prosumers must decrease their PV generation (and their PV installed capacity) or must shift part of their demand in hours when PV generation occurs. In this case, demand could stay at the same level; prosumers do not have incentive to reduce it. Otherwise, if the objective is to maximize the SG rate τ_{SC}, then prosumer could have incentives to reduce their demand.

According to JÄGER-WALDAU (2013), the SC rate is around 30% in Europe. In some implementations, as for example in France for consumers with smart-meters, this rate was around 45% for households and 70% for industries (PV-NET, 2016). In Italy, the 2015 SC rate was 48% in the tertiary sector, 58% for the industry and 42% in the agricultural sector (GSE, 2015). In Germany, this rate is 27% for households that benefit from an incentive policy to promote self-consumption. The rate is more often below 50% for households (Luthander et al., 2015), except for Sweden (Thygesen and Karlsson, 2014; Widén, 2014). The self-consumption rate is different in Europe because it depends on solar radiation but it also depends on the self-consumption regulatory framework. For instance, in Italy, the incentive to self-consume is based on a net-metering scheme which doesn't encourage a high self-consumption rate. However, industrial sector could have greater SC rates because of their level of consumption when PV generation occurs (Ong et al., 2012). So, some industrial prosumers could have a SC rate between 95 and 100% (cf section 3.5). There exist some innovations that could increase this rate. If prosumers use batteries to store their produced energy to consume it at low solar radiation periods, self-consumption could increase from 10 to 24 percentage points. If some technologies, as smart technologies, are used to manage prosumers' demand, for example shifting some uses when the sun shines, self-consumption could increase from 2 to 15 percentage points (Luthander et al., 2015).

Thus, self-consumption could improve the management of the PV intermittency. However, it creates some cross-subsidies between consumers because of the incentive policies that could be applied to favor SC. In this paper, we propose to study these cross-subsidies from standard electricity consumers to prosumers that consume their own energy production. In a second section, we begin with the analysis of SC deployment and on incentive policies that could be applied to foster it. In a third section, we present some empirical illustrations of SC deployment, as several countries have decided to favor it to internalize renewable energies impacts on the electricity sector. In the fourth section, we focus on cross-subsidies between categories of consumers. We show with some implementations that cross-subsidies occur but the amount is currently low. In the fifth section, we propose two methodologies to recover the financial losses for the system operator (Distribution System Operator). We show that an increase in fixed part of the network tariff paid by self-consumers could internalize cross-subsidies.

2. Incentive policies and self-consumption deployment

2.1. Main features in favor of self-consumption

Investing or not in renewable energies and consuming its own production rely on several features. Firstly, the initial cost of investment in renewable installations impacts consumers' decision to realize the project. Secondly, the electricity price paid by the consumers, the solar radiations and demand curve act upon the profitability of the project. Thirdly, the network tariff components reinforce the reduction in costs for investors but create concerns on network costs recovery. Indeed, network tariffs are often based on two parts: a fixed part based on the contractual power (in MW) and a variable part based on consumed energy (in MWh). The more this later part is, the more self-consumption should be attractive because of savings on variable costs, as the electricity withdrawn from the grid is reduced (Schittekatte et al., 2018). Finally, the exemption on the taxes for the electricity self-consumed creates an incentive to invest in a PV power plant.

These features could be influenced by public decisions. The cost barriers could be overcome with low rates for loan or with tax fees exemptions. Electricity price levels are often influenced by taxes set by public authorities. Network recovery costs are set by the regulation scheme that could be adapt to favor self-consumption if included in the energy policy goals of the country.

Besides these economic factors, adding behavioral analyses are relevant because they also influence the decision of investment. They are based for examples on environmental concerns, consumed energy management, the origin of power (renewables or not), security and reliability, etc.… (Boughen et al., 2013; Bremdal, 2011; Farhar and Buhrmann, 1998).

Table 2 summarizes the main features to favor self-consumption.

Table 2: Main factors impacting self-consumption deployment

Economical features	Technological features	Behavioral features
• Investment costs in renewables • Solar radiations • Electricity prices • Network tariff components	• Energy management tools • Storage	• Market maturity • Long term visibility • Environmental concerns • Security and reliability

2.2. Incentive policies and self-consumption

As the deployment of renewable energies shows it, the role of public policies is often essential to foster the adoption of new energy technologies or new behavior. Thus, we observe several decisions in favor of SC. Each of them has been implemented and, today, some are eliminated because of their low impact on the improvement of the system.

In several countries, net-metering or net-billing are used to manage SC (Dufo-Lopez and Bernal-Agustin, 2015). Net-metering consists in the calculation of the net prosumers' consumption as the total consumption of the site minus the renewable energy volumes fed into the grid (DGEC, 2014). Prosumers only pay the net consumption of their site. In this case, the network acts as a back-up power plant, i.e it supplies the residual demand of the site and offers security and reliability services. This mechanism assumes that the value of the energy fed into the grid is the same that the energy consumed from the grid. Net-billing is different from net-metering on this feature. Indeed, the exported energy to the grid and the imported energy from the grid have different monetary values. The exported energy is valued at market price or at the "avoided cost price", rather than the imported value is valued at a greater price, the retail price (Dufo-Lopez and Bernal-Agustin, 2015). So, prosumers' revenues could be:

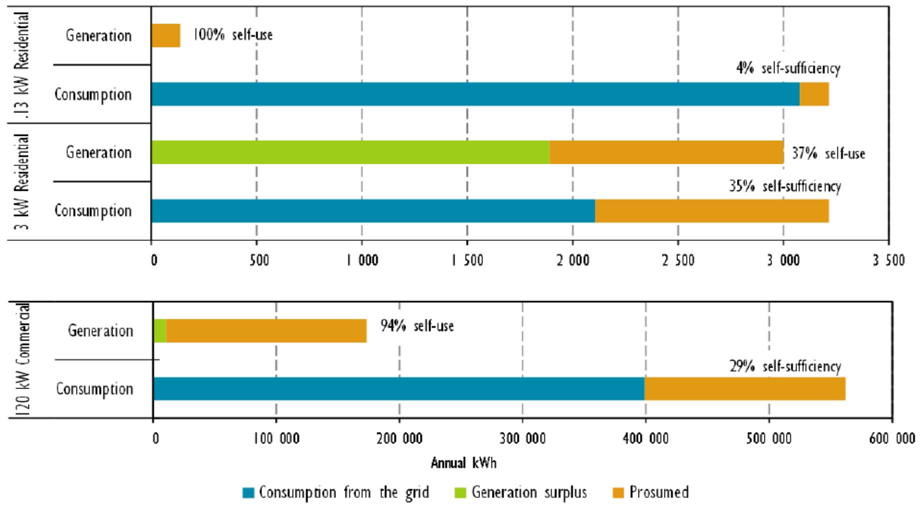
- In the case of net-metering, revenues are only reductions on their bill because of the payment of the net consumption. In case of exported energy greater than consumed energy from the grid, they could receive certificates that could be used to increase the energy fed into the grid for a period in which consumed energy is greater than renewable energy production. In other words, renewable energy surpluses in one period could be used to compensate a reduction in renewable energy production in another period of consumption.
- In the case of net-billing, their revenues are the monetary difference between the renewable energy fed into the grid and valued at a feed-in-tariff (market price or other valuation) and the

consumed energy paid at retail price. Public authorities must set the feed-in-tariff at an incentive level to improve self-consumption.

Net-metering and net-billing stand for 16% of the incentive policies that foster the deployment of PV installation, the main driver staying the feed-in-tariff scheme (IEA PVPS, 2016c). The cost of PV generation is also an important driver of the PV deployment. In case of net-metering, as savings are the unique revenue for prosumers, costs of PV generation must be lower than retail price to develop self-consumption. In case of net-billing, we have the same conclusion on PV costs adding the impact of the exported tariff. This one must not be too high to restore the incentive to self-consumption. Otherwise, prosumers earn more gains to feed all their production into the grid. The net-metering system has been criticized by several authors (Gauthier et al., 2017). These appreciations are mainly based on its inefficiency to induce good economic signal to the deployment of renewable energies[2] and because it creates numerous transfers between prosumers and other consumers (transfers of the network costs). The European Union has recently prohibited the use of net-metering to foster the deployment of self-consumption.

Thus, self-consumption is profitable if the grid parity is achieved for the PV generation, i.e if the levelized cost of PV electricity is lower than the retail price. In that case, PSOT should be reduced, self-consumption being economically profitable. Some countries, as Germany or Denmark, have increased their retail prices (respectively around 0.26€ and 0.29€ per kWh) to reduce the costs of the renewable policies. Since 2009, the levelized costs of PV electricity have decreased from $0.40 per kWh to $0.06 per kWh (Solar Power Europe, 2017). Projects in some world areas have achieved lower costs, as in Argentina ($0.33 per kWh), in Mexico ($0.29 per kWh), in Chile ($0.29 per kWh), in USA ($0.27 per kWh) or in Abu Dhabi ($0.24 per kWh). Other PV projects, mainly in the south of Europe, have also significantly reduced their costs to achieve a range of 0.035 to 0.06€ per kWh. Then, self-consumption could stand for a relevant percentage of the renewable energy production (Figure 3).

Figure 3 : Share of self-consumption for some representative prosumers (IEA PVPS, 2016c)

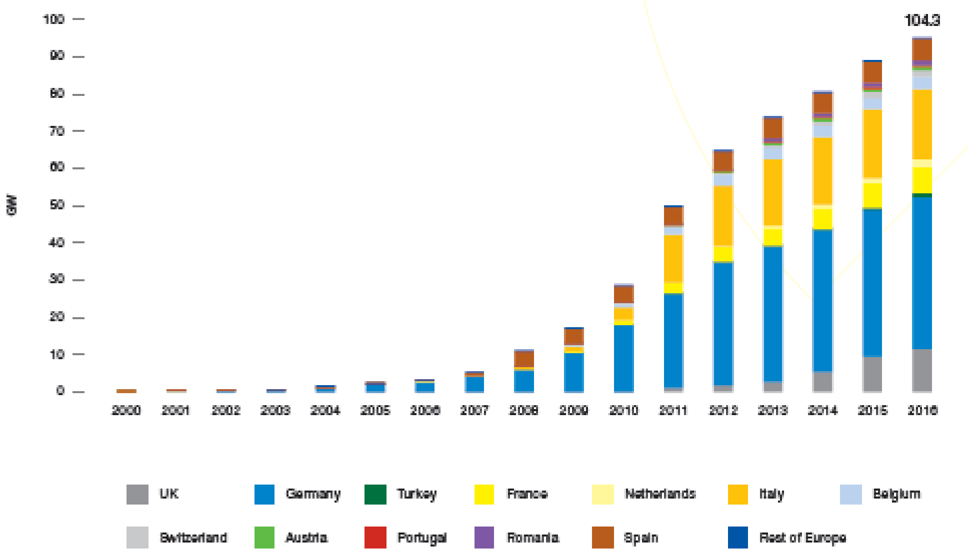


[2] The imported and exported energy from and to the grid are valued at the same price, the retail price that is higher than the wholesale price.

3. Empirical experiences in Europe on self-consumption deployment

In Europe, PV capacities have grown significantly since 2006 (Figure 4). This growth is widely due to incentive policies, as Feed-In-tariffs (FIT) schemes.

Figure 4 : Growth in installed PV capacities in Europe (Solar Power Europe, 2017).



3.1. Germany

Germany is the European country with the stronger increase in PV generation. Its FIT policy is the main driver of this growth. So, it has earlier known discussions on the costs of the FIT policy, which reached near than 1.2 billion euros in 2006 (BMU, 2007). Moreover, the exemption of PSOT for several firms has increased the small end-users' charges (of an amount of 420 million euros in 2006). So, since 2009, Germany has set premiums to favor self-consumption. Each self-consumed kWh was paid at this premium (Table 2). Besides this premium, FIT have decreased of about 10% to reduce the profitability of renewable energy fed into the grid. An exemption on the payment of fixed part of network tariffs and taxes was also decided for prosumers.

Table 2 : Premiums for self-consumption in Germany (c€/kWh)

Capacities	100 to 500 kW		30 to 100 kW		Lower than or equal to 30 kW	
Self-consumption rate	< 30%	> 30%	< 30%	> 30%	< 30%	> 30%
2009	0	0	0	0	25,01	25,01
January 2010	0	0	0	0	22,76	22,76
July 2010	14,27	18,65	16,01	20,39	17,67	22,05
October 2010	13,35	17,73	15,04	19,42	16,65	21,03
January 2011	9,48	13,86	10,95	15,33	12,36	16,74
January 2012	8,63	12,61	9,96	13,95	11,25	15,23
January 2013	7,85	11,48	9,06	12,69	10,24	13,86
January 2014	7,14	10,44	8,25	11,55	9,31	12,61

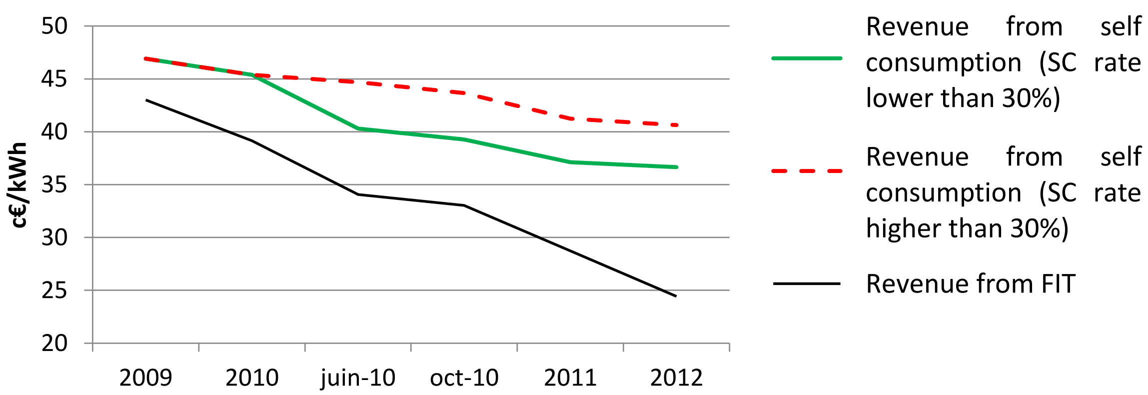
Source: Sarasa-Maestro C, 2013

These incentive policies have achieved their goals. Between 2009 and 2014, the percentage of sites that self-consumed their own generation has grown to achieve in 2014 a range of 70 to 95% for installations with a capacity between 0 to 1000 kW (BUNDESNETZAGENTUR, 2015). A simple comparison between revenue from FIT and self-consumption could resume this growth. Self-consumption is profitable if the revenues from premiums and savings from retail price are greater than the revenue of FIT, as we could see in Equation 1

$$\underbrace{\underbrace{\sum_{t=1}^{n} \mathbf{p}^*_{\mathbf{AC_t}} * \mathbf{q}_{\mathbf{AC_t}}}_{\text{Revenue from self-consumption premium}} + \underbrace{\sum_{t=1}^{n} (\mathbf{p_t} - \mathbf{b}) * \mathbf{q}_{\mathbf{AC_t}}}_{\text{Revenue from savings in purchases at retail price}}}_{\text{Revenue from self-consumption}} - \underbrace{\sum_{t=1}^{n} \mathbf{q}_{\mathbf{x_t}} * p_{FIT}}_{\text{Revenue from FIT}} \geq \mathbf{0} \qquad (1)$$

Where $p^*_{AC_t}$ is the premium for self-consumption (Table 2), q_{AC_t} the self-consumed energy, p_t the energy price, b the fixed part of the network tariff (paid by the self-consumers), q_{x_t} the amount of energy fed into the grid and p_{FIT} the FIT. Some figures from Bundesnetzagentur (2015) could be used to compute the revenue from one self-consumed kWh or sold at the FIT (Figure 5). Each year, self-consumption is more profitable rather than FIT.

Figure 5: Revenue from one kWh under self-consumption or FIT



Source: data from Bundesnetzagentur (2015).

Self-consumption rates have increased to achieve a range of 20% to 40% in 2014. During the period 2009-2013, Germany has known a significant increase in self consumption volumes, increasing the costs of incentives policies (Table 3) and their part in the PSOT to stands 44% of the Erneuerbare Energien Gesetz[3] (EEG) contribution in 2012 (BMU, 2016)

[3] "Act on Granting Priority to Renewable Energy Sources (Renewable Energy Sources Act, EEG)" (FRAUNHOFER ISE, 2017).

Table 3 : Volumes and costs of the German self-consumption program

	2009	2010	2011	2012	2013	2014	2015
Self-consumed volumes (GWh)	5	46	259	734	821		
Costs of self-consumption premium (millions €)	1	11	45	102	111		
PSOT (EEG) to PV generation (c€/kWh)	0.67	1.1	1.66	2.03			
Total of PSOT (EEG) for PV generation (Billions €)	3,2	5	7,8	9,2	9,5	10,4	10,8

Source: BMU

As the costs of the policy are always important, the government of Germany has decided in 2012 several changes. Firstly, the FIT is again reduced (of 20 to 26%). Secondly, only part of PV capacities could benefit from FIT. Thirdly, the potential energy fed into the grid from PV installations is lowered (with a maximum of 70% of PV generation, reduced to 50% in 2016). If a producer found economically profitable to continue to value its production at the FIT, it had to contract with the Network System Operator (NSO) a "feed-in management" clause, i.e the NSO could cut the PV generation if necessary. In this case, the PV producer could receive a fee. Fourthly, self-consumption premiums were stopped because of the achievement of the grid parity for PV generation (Fraunhofer ISE, 2017; Fulton and Capalino, 2012). This was due to a huge increase in retail price of electricity, the EEG amount was the main driver of this increase (from 5% of the household's retail rate in 2009 from 14% in 2012[4]). All these measures created incentives for all prosumers to increase their self-consumption. For example, in 2014, 95% of residential prosumers are under self-consumption (BMU). In the same period, self-consumption is extended to a group of consumers in the same area. Then, they benefit from EEG or network tariff exemptions (they ended up in 2016). Government also wants to develop the storage of renewable energies to improve self-consumption during all the hours of the day (and not only when PV generation occurs). It has invested between 2013 and 2015 about 50 million € per year for this policy to cover at least 30% of the costs for one installation[5].

Despite the improvement in self-consumption rate, the charges of the incentive policies have increased (Table 3). This is mainly due to the higher gap between FIT and spot price because of great renewable energy volumes in the spot market, reducing spot prices (FRAUNHOFER ISE, 2017). Thus, this difference has raised charges paid by end-consumers. They also have suffered from cross-subsidies. Their appearance is due to the exemptions in EEG or network tariffs payments for the prosumers. All network and EEG costs are passed on to users of the network or consumers of electricity from the grid. So, they subsidize self-consumers. According to l'OFAEnR, self-consumption has involved losses in EEG revenues of 100 million € in 2012 and could achieve 300 million € for the 2013-2018 period. To reduce these inequalities, self-consumers had to pay 30% of the EEG fees on self-consumed kWh in 2014. This percentage had increased to achieve 35% in 2016 and 40% in 2017 (EEG law, 2014). However, some are always excluded from taxes, as small generation sites or industrial and large consumers. These losses in EEG revenues have stood for 5.1 billion € in 2014 (Fraunhofer ISE, 2017). As costs of distribution network have known a huge increase, from 14.6 billion € in 2011 to 17.7 billion € in 2016 (OFAEnR), Distribution Network Operator could now apply a reduction in annual renewable generation (EEG law 2012, §6, 1, 2).

[4] At the same period, the retail rate evolved from 22.75 c€/kWh in 2009 to 26.06 c€/kWh in 2012.

[5] This proportion has decreased to 22% in 2016, to 19% in 2017 and will be at 10% in 2018.

The implementation in Germany of self-consumption is certainly those we have the more information. We could conclude that the deployment of self-consumption goes with an increase in retail prices and a decrease in FIT. To foster this development, some incentive policies have been added, as feed-in-premium or exemptions on taxes and network tariffs. These policies have increased PSOT (EEG costs) and cross-subsidies between consumers of electricity withdrawn from the grid and prosumers. Public authorities came back with the tax on the self-consumed volumes to partially restore the equality between consumers.

3.2. The United Kingdom

The United Kingdom set Feed-in-Tariffs in April 2010 to improve the deployment of PV generation lower than 5 MW (Table 4). These tariffs are applied on the total PV generation of the site. They could be increased by an export tariff for all PV energy fed into the grid. On the period 2010 to 2016, this tariff involves in a range of 3 pence/kWh in 2010 to 4.85 pence/kWh in 2016 (OFGEM).

Table 4 : Feed-in-Tariffs and installed capacities for PV generation (OFGEM)

Size of equipments	FIT (Pence/kWh) in 2010	Installed capacities (MW)[6]					
		2010	2011	2012	2013	2014	2015
<= 4 kW	44,19[7]/50,67	86	729	273	312	214	443
4 < kW <= 10	44,19	6	46	14	19	18	29
10 < kW <= 100	38,50	8	178	81	115	99	180
100 < kW <= 5 000	35,95	6	206	92	117	168	470

Source: OFGEM

According to this incentive policy, revenues of self-producers are divided into three components, as we could see it in Equation 2:

$$\boldsymbol{R_t = \sum_{t=1}^{n}[(p_t - b) * q_{AC_t}] + \sum_{t=1}^{n} q_t * p_{FIT} + \sum_{t=1}^{n} q_{x_t} * p^*_{x_t}} \quad (2)$$

With $p_t, b, q_{AC_t}, p_{FIT}, q_{x_t}$ the same parameters as in Equation 1, q_t the total PV generation with $q_t = q_{AC_t} + q_{x_t}$ and $p^*_{x_t}$the export tariff.

The first component, $[(p_t - b) * q_{AC_t}]$, is the savings on electricity bills because they don't withdraw q_{AC_t} from the grid. The second one, $(q_t * p_{FIT})$, is the revenue from the FIT incentives, applied on all PV generation. The third component, $(q_{x_t} * p^*_{x_t})$, is the revenue from PV energy exported to the grid. So, prosumers have an incentive to consume their own production if exported prices, $p^*_{x_t}$, are lower than retail price minus the fixed part of network tariff they have to pay, $(p_t - b)$. This is often verified as exported prices are lower than 4.65 pence per kWh and as the fixed parts of network tariffs are respectively around 3.2% and 0.8% of the retail price for households and small industries (COMMISSION EUROPÉENNE, 2015). For example, in 2011, retail prices were, respectively for households and small firms, 13.74 pence/kWh, with 0.44 pence/kWh for fixed network fee, and 10.87 pence/kWh, with 0.085

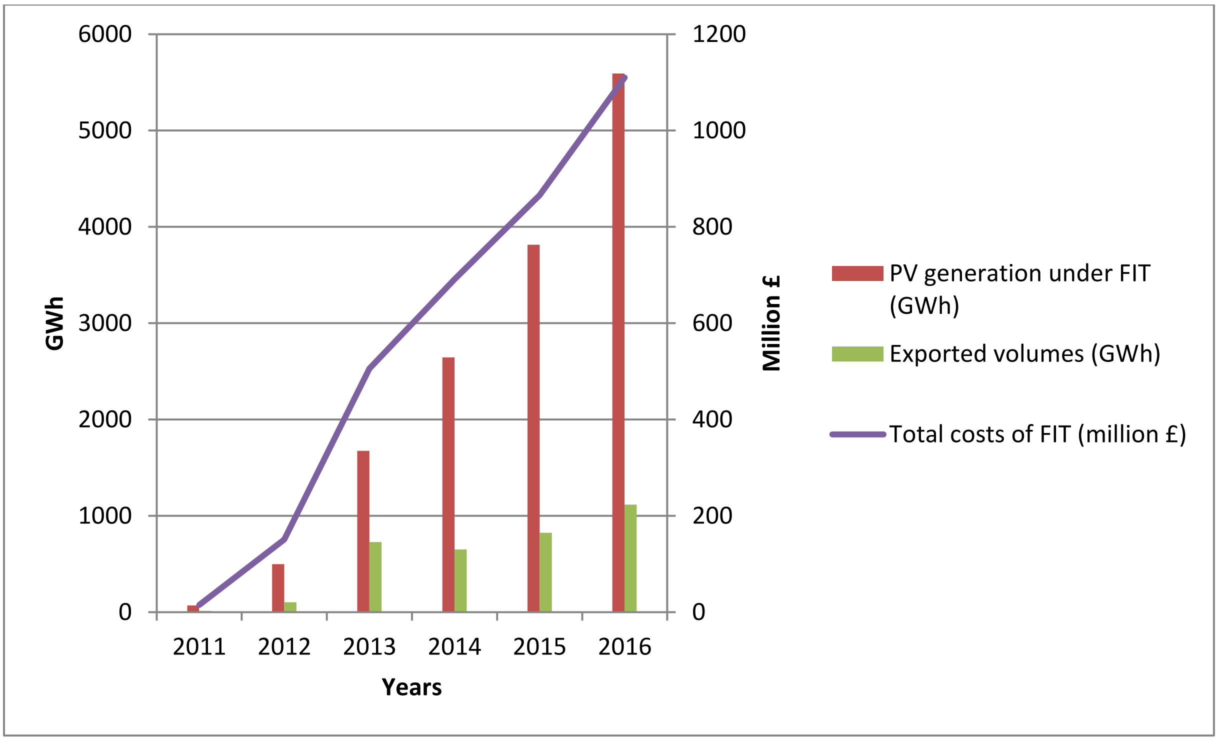
[6] These figures on installed capacities are for the period April of year "n" to April year "n+1".
[7] The FIT is lower if the PV capacity is setup on a house under construction.

pence/kWh for fixed network fee (Eurostat). As the exported tariff was 3.1 pence/kWh, it is easy to conclude that self-consumption was and remains profitable.

As expected, a huge increase in PV capacities has followed the FIT policy (Table 4). To avoid transferring a significant part of the FIT costs onto consumers, producers are paying their connecting costs to the network. The government has also reduced the level of FIT, the total costs being 18% above the forecasted implementation FIT costs (£94 million instead of the forecasted £80 million, [DECC, 2015]). The predictions of the Department of Energy & Climate Change (DECC) has increased to achieve a cost of £9.1 billion for the incentive policy on the 2010-2021 period (its first forecast was $8.6 billion in 2030). In the same way, the initial 2010-2030 predictions of a £8.5 increase in households' energy bill have been revised. The DECC has observed an increase of £9 in 2014, that could be of £14 in 2020 (DECC, 2015). Thus, in 2016, FIT were divided by a factor 2 with the objective to maintain these costs under £100 million per year. Beside this decision, some experimentations (with dynamic retail pricing) to increase self-consumption, or to shift loads to optimize the use of PV generation, are implemented.

To conclude, incentive policies of FIT and export tariffs have significantly contributed to the increase in PV capacities (Figure 6). However, this increase has been done at a high cost for consumers. This policy has also increases the self-consumption. We could note that there was no exemption of taxes and fees for self-consumers or prosumers. Nevertheless, cross-subsidies always exist when network costs are considered. Self-consumers do not pay a fee to compensate their decrease in consumption withdrawn from the grid. These cross-subsidies could create an increase in network costs for others consumers.

Figure 6 : Total PV generation, exported volumes and costs of FIT policy



Source: data from Ofgem

3.3. Spain

As in previous countries we have presented, Spain has known a substantial increase in costs of incentive policies to develop renewable energies. For instance in PV technology, this cost was around 194 million € in 2007, 991 million € in 2008 and it has raised to 2600 million € per year on the 2009-2012 period (del Río and Mir-Artigues, 2014). These costs are linked with a FIT policy followed by a premium scheme. Renewable producers must sell their generation at the spot price and then, they received a premium determined as the difference between renewable costs and the spot prices.

In October 2015, public authorities regulated the administrative, technique and economic conditions for self-consumption plants. Indeed, the electricity sector known a large deficit as government wanted to minimize the impact of renewable energies deployment costs on consumers' bills (del Río and Mir-Artigues, 2014). Then, to reduce this deficit, the decision for a deployment of self-consumption programs is adopted. This decision followed the implementation of a net-metering policy, decided in 2011 to increase capacities in distributed generation.

Since October 2015, all PV producers or prosumers must pay a fee for self-consumption. This fee, called backtop toll, is a two part tariff with a fixed fee for the subscribed capacity and a variable fee correlated with the produced energy. These fees are self-consumers' contributions to network costs' recovery. Only PV plants with a capacity lower than 10 kW and with a self-consumption rate of 100% were exempted of these charges.

Despite great solar radiations and some incentives to self-consume, its deployment is not a success. The development of small PV power plants remains low because of charges and a fixed part standing for 84% in the network tariff (COMMISSION EUROPÉENNE, 2015).

3.4. Denmark

Since 2006, Denmark has decided to use the net-metering policy to support the deployment of renewable energies. In 2011, the decision to increase the retail price of electricity has been taken to achieve 30c€/kWh in 2013; taxes stand for 58% of this price. Therefore, self-production and self-consumption were increasingly profitable. Investment in PV power plants has grown from around 15 MW in 2011 to 450 MW mid-2013 (EnergiNet). The cost of net-metering was fairly high, around 65 million € in 2012 (Kjaer et al, 2013). Indeed, 99% of PV capacities were under net-metering. Then, revenues from taxes were reduced because of lower volumes of energy withdrawn from the grid. To reduce this counter-productive effect, and as the grid parity was achieve for PV energy, the period of compensation in the net-metering program was reduced from one year to one hour. The residual PV generation, i,e PV generation which is not self-consumed along one hour, is valued through a premium as in Spain. The premium was in a range of 5 to 8 c€/kWh to maintain the price for PV energy fed into the grid. This reinforce the idea of the main goal: to favor the self-consumption. Small PV power plants (lower than 50 kW) are exempted from the PSOT[8] for each self-consumed kWh. Others are only exempted from the renewable energy subsidies on such kWh. Currently, government is working on a network fee option paid by the self-consumers to compensate the network losses in self-consumption models (IEA PVPS, 2016).

[8] It includes all network costs linked with renewable energy deployment, as renewable energies subsidies, environmental and R&D costs.

3.5. France

As several of its neighbors, France has used FIT to foster the deployment of renewable energies. At the end of 2016, the installed PV capacities were 7 134 MW and have known an exponential growth since 2007. Despite a decrease in FIT following the reduction in costs of PV energy, PSOT has increased from 7.5 €/MWh in 2011 to 22.5€/MWh in 2016. Thus, in 2016, French government has decided to introduce a support for the self-consumption, both individual and collective. The regulator published a call for tenders standing for 50 MW for PV installations (with a capacity for each PV power plant between 100 and 500 kW, so industrial, tertiary and agricultural sectors could be interested in)[9]. Bidders must indicate in their bid the forecasted rate of self-consumption and the premium they want to receive for each self-consumed MWh. A mark-up until 5€/MWh could be added to their premium. First results have shown that answers were on projects with a self-consumption rate of at least 97%.

As firstly the grid parity is not yet achieved in France and secondly the retail price is lower than in other countries, incentive policies must be adopted to favor self-consumption. To obtain the subsidies, self-consumption rates must be higher than 50%. The revenue for self-consumption is set as in Equation 3:

$$\boldsymbol{CR_t} = \left[(\boldsymbol{P^*} + \mathbf{10}) * \boldsymbol{q_{AC_t}}\right] + \left[\boldsymbol{P^*} * \mathbf{q_{x_t}}\right] - \left[\mathbf{12} * \boldsymbol{q_t} * \left(\frac{\mathbf{Power_{max_t}}}{\boldsymbol{K_t}}\right)\right] \qquad (\mathbf{3})$$

With q_{AC_t}, $\mathrm{q}_{\mathrm{x_t}}$ and q_t the same parameters as in Equation 2, P^* the premium of the bid, $\mathrm{Power_{max_t}}$ the maximum of the PV generation fed into the grid and K_t the PV installed capacities. The two first terms of Equation 3 stand for revenues from self-consumption and PV energy fed into the grid. Incentives are clearly in favor of self-consumption because of the mark-up added to the premium. The third term of Equation 3 represents losses for bidders if they fed electricity into the grid.

4. Self-consumption and cross-subsidies to recover network costs

The different implementations have shown that to internalize the costs of renewable energies deployment, several countries have decided to promote self-consumption. They have used net-metering or net-billing to remunerate prosumers that consume their own renewable production. Nevertheless, the positive impact of self-consumption is not obvious without the achievement of the grid parity for renewable energies.

Indeed, self-consumption has positive effects on the welfare. Public authorities could reduce policy supports for renewables. Thus, the evolution of PSOT could be reduced. This advancement is nevertheless linked with incentive policies to develop self-consumption. Then, households and industries increase their energy autonomy and could manage their consumption to increase their self-consumption rate. The Distribution System Operator (DSO) decreases its costs of network management, the energy fed into the grid being lower under self-consumption, and of reinforcing networks. As the renewable energy is consumed near its production area, network losses are also improved (Cohen and Callaway, 2016; Mendez Quezada et al., 2006)

However, self-consumption negatively impacts the volume of energy withdrawn from the grid. Network tariffs are usually two-part tariffs. A simple explanation is that the fixed part is paid for the capital expenditures (CAPEX) in €/MW and the variable part for operational expenditures (OPEX) in €/MWh. This allocation of costs could be modified (Commission Européenne, 2015; Schwartz et co, 2016) and some CAPEX could be recovered with the variable part. As implementations have shown it, self-consumers pay the fixed part but only a small variable part. In some cases, they could be exempted from

[9] Another call for tenders has been made in march 2017 to develop self-consumption. It applies on 450 MW until 2020.

taxes, so they benefit from incentives policy but they do not contribute to the recovering of costs of network use or PSOT. Thus, revenues from network tariffs could be reduced, and the DSO could know difficulties to recover its costs, financial flows and prices becoming unstable (Picciariello et al, 2015; Kubli, 2015; Simshauser, 2015). When the financial deficit is recovered by a increase of the variable component, the system comes in a "death spiral" (Costello et al., 2014; Felder et al., 2014). For instance, network tariffs are increasing because variable costs must be recovered on smaller electricity volumes withdrawn from the grid. This increase could become an incentive for others consumers to invest in self-consumption, reducing their demand to the grid. The demand is again reduced, then network costs increase and so on.

4.1. Data and assumptions

In this section, we describe the set of assumptions and data used to forecast the volume of photovoltaic capacities installed by 2021 as well as the consumption and PV generation load curves for different consumer profiles

a. Assumptions on forecasted PV capacities in 2021

In October 2017, 7.7 GW of photovoltaic (PV) capacities were connected to the grid in France (Ministère de la transition écologique et solidaire[10]), representing 7% of the total electricity generating capacity. Enedis, the historical DSO which manages 95% of the grid in France, published the breakdown of PV capacities for each capacity level in its network (table 6). The ADEME (Agence pour l'Environnement et de la Maitrise de l'Energie) uses a similar breakdown capacity by sector. Residential, industrial and commercial segments represent 52% of total capacities connected to Enedis' grid. This percentage might not be similar for the PV capacities in France because PV power plants above 12 MW are connected to the transmission grid. Moreover, on January 1st 2018, 2.6 GW were commissioned but not connected yet, including approximately 74% of utility-scale PV installations.

Table 6: Cumulative capacities by sector in 01/2018

kW	Sector	Total plants	Cumulative capacities (MW)
] 0 – 9]	Residential	339 378	1 167
] 9 – 250[11]]	Firms – buildings	31 379	2 237
] 250 – 12 000]	Ground-mounted	1 082	2 237
Total		371 839	6 528

Source: Enedis

The development of photovoltaic cpacities in France was triggered by the government who decided to extend policy supports until 2023. Indeed, France's government is hoping to reach about 10.2 GW in 2019, and 18.2 GW in the case of a "low scenario" and 20.2 GW in the case of a "high scenario" in 2023. From 2016 to the first quarter of 2019, the government has published a calendar of PV tenders in order to reach those goals. Over this period, 3 GW will be allocated to ground-mounted power plants (between 500 kW and 17 MW) and 1.35 GW to rooftop power plants (between 100 kW and 8 MW). Other tenders regarding self-consumption installations are planned. However, those calls for tenders

[10] Available at: http://www.statistiques.developpement-durable.gouv.fr/publicationweb/61

[11] Some firms have photovoltaic power plants above 250 kW but they are only a few of them and we assume that firms will not invest beyond 500 kW. Indeed, they will prefer to participate at a call for tenders for PV power plants between 100 kW and 500 kW.

will also deal with all categories of renewable power plants that have a capacity between 100 kW and 500 kW. The first call for tenders was launched in 2016 and, currently, 40 MW were essentially allocated to PV projects. In order to develop self-consumption in a regulative way, the government decided to renew this type of tenders until 2019, for a capacity of 150 MW per year.

The development of small and medium PV power plants was mainly driven by a feed-in tariff scheme. But willingness to self-consume increased since last year. Indeed, self-consumers represent 36% of total photovoltaic investments in 2016 (8 000 setups) and 70% of the first semester in 2017 (6 000 setups[12]). Moreover, France's energy transition law, which has been passed on February 24th, 2017 sets specific supports for self-consumers. Now, it has become a reality and all plants with a capacity lower than 100 kW connected after August 2017 are assumed to self-consume a part of their own PV production. In the following study, only these installations and self-consumption tenders are considered to estimate cross-subsidies between standard consumers and self-consumers. Self-consumption tenders are assumed to be allocated for photovoltaic projects and we assume that they will be renewed until 2021. For capacities lower than 100 kW, the government sets a goal of 350 MW a year. The same target is used until 2021 in the present article and photovoltaic deployment will be the same for households and firms, i,e 175 MW for each sector (table 7). Regarding self-consumption tenders, the selected firms aren't connected to their installations yet. We assume that it will be the case in 2018 and the selected firms for future tenders will have connected their PV installation one year after their designation. According to the calendar of tenders[13], PV capacities from tenders are following the trend in the table below. In August 2021, 1.89 GW of self-consumption PV capacities are expected.

Table 7: Evolution of PV self-consumption until 08/2021 (MW)

MW	08/18	08/19	08/20	08/21	Total
Residential	175	175	175	175	700
Firms	175	175	175	175	700
Tenders	90	150	150	100	490

b. Consumer characteristics

As the consumer profiles are heterogeneous, several assumptions are made to characterize them. Consumer profiles are based on Enedis' typology which are used by the French regulator to set network tariffs. The consumer profiles are characterized according to their load consumption and the voltage level which they are connected to. Households are split in two categories according to their load profiles. The first one represents consumers with a single flat tariff who have usually a low electric load and no electric heater. The second one corresponds to consumers with a Time-Of-Use (TOU) tariff. These households have a flatter load curve than the first category because most of them have a hot water tank which turns on during off-peak hours. According to the sample provided by the French regulator, the first profile called "RES1" represents 60% of the household consumers and the other one called "RES2" represents 40% of them. Both of them have a contractual power of 6 kVa. Firms with PV panels under 100 kW are assumed to be connected at a voltage level between 36 kVa and 250 kVa which corresponds to a specific interval between low and medium voltage. For this specific voltage interval, Enedis has made two different profiles which differ according to the gap between the average

[12] Available at: https://www.ecologique-solidaire.gouv.fr/nicolas-hulot-presente-grands-axes-accelerer-deploiement-des-energies-renouvelables-electriques
[13] Available at: http://www.cre.fr/documents/appels-d-offres

consumption and the contractual power. When the gap is high, firms have a short use and conversely, a long use. We apply the short use profile for the firms (called ENT1) because they represent 87% of the total firms in this voltage interval. For firms elected to tenders, we assume that they are connected to the medium voltage (called ENT3). This assumption is based on the fact that the first laureates of tenders announced an average self-consumption rate of about 95%. Given that, firms have to have a big amount of electricity consumption in order to absorb the PV generation. Based on the sample provided by the French regulator, average consumption and contractual power by period of time for each profile are depicted in table 8.

Table 8: Average consumption and contractual power for each consumer profile based on the sample provided by the CRE

	Profiles	RES1	RES2	ENT1	ENT3
Withdrawals (kWh)	High rate winter	1 405	2 039	55 143	468 729
	Low rate winter	-	1 400	16 966	339 689
	High rate summer	1 602	1 220	67 504	665 045
	Low rate summer	-	1 032	20 966	540 477
Contractual power (kW)	High rate winter	6	6	61	496
	Low rate winter			40	434
	High rate summer			62	503
	Low rate summer			41	446

Source: CRE

c. PV size

We assume that households install a PV capacity of 3 kW. It corresponds to the median of cumulative PV panels connected in France to low voltage (Rebenaque O, 2017). The average consumption peak for firms connected to a voltage level between 36 kVa and 250 kVa is 74 kW. We assume that firms won't install a PV installation with a capacity above their peak consumption, so we applied a PV capacity of about 70 kW for a representative firm which allows an average self-consumption rate of 74%. As it has been said in the previous section, self-consumption tenders concern PV capacities between 100 et 500 kW, so we assume that these firms will install a PV capacity of 300 kW on average.

4.2. Load curves

Enedis provides coefficient of profiles for different categories of customers. A profile represents the average behavior for a customer group according to the consumption variation of every week, day and half-hour. The coefficients are computed by calculating the weighted average of a load curve for every customer from a sample taken by the DSO. So, it represents the average load curve for an average customer. By dividing every half-hour point with the average power of the annual load curve, half-hour coefficients are computed. The coefficients of profiles are normalized by one and the deviation around one corresponds to consumption deviation around the annual average consumption (Réseau de transport d'électricité, 2015). Load curves are computed by multiplying the average annual consumption of each profile by a specific coefficient for each half-hour. Annual average consumption for a profile i (AC_i) is computed by dividing the annual consumption (TC_i) with the number of half-hours in a year:

$$AC_i = \frac{TC_i}{\sum HH} \tag{4}$$

Then, consumption for each half-hour $C_{i,HH}$ is computed by multiplying the average consumption with each half-hour coefficient (and n corresponds to the total of half-hours in a year):

$$C_{i,HH} = \sum_{HH=1}^{n} Coefficient_{i,HH} * AC_i \tag{5}$$

In order to compute the volume of PV generation for each profile per half-hour, we estimate first the annual average load factor. We rely on data provided by Enedis regarding the volume of photovoltaic generating capacities on a yearly basis from 2012 to 2017. Based on the data, we deduce the average load factor of solar capacities $(\mathrm{L}F)$ using the following relation:

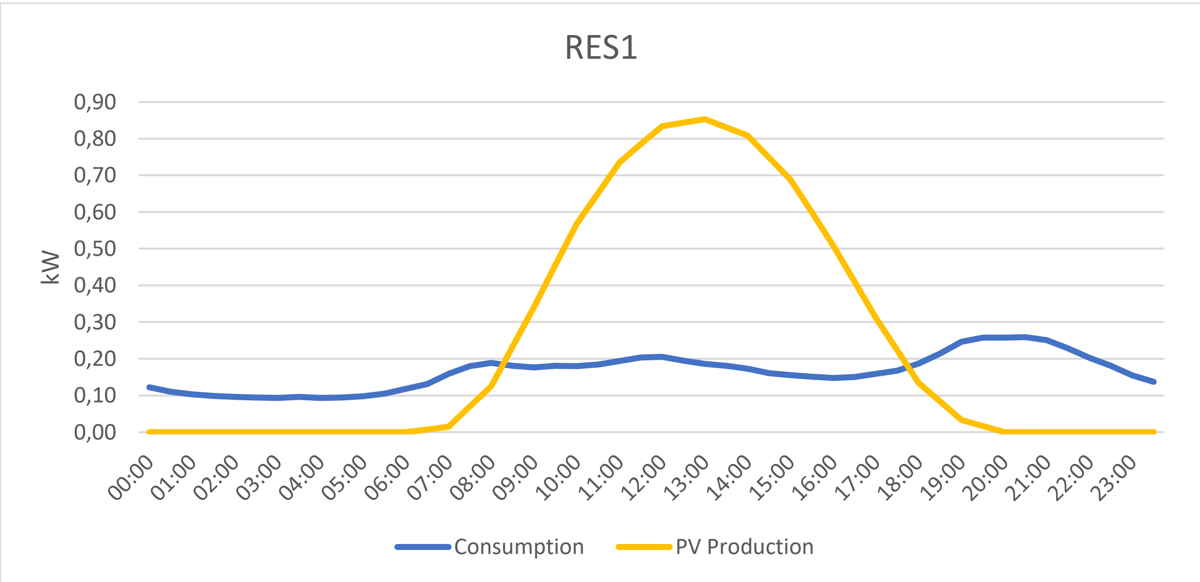
$$\mathrm{L}F = \frac{G_{PV}}{C_{PV} * \sum HH} \tag{6}$$

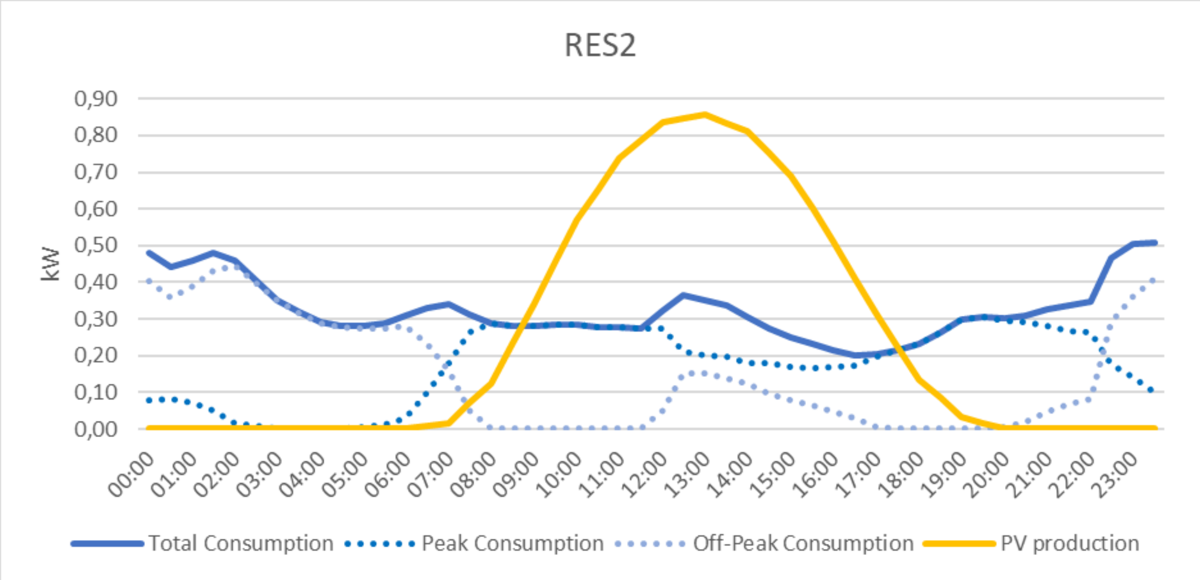
Then, annual photovoltaic generation for the profile i (G_{PV_i}) is computed from equation 3 :

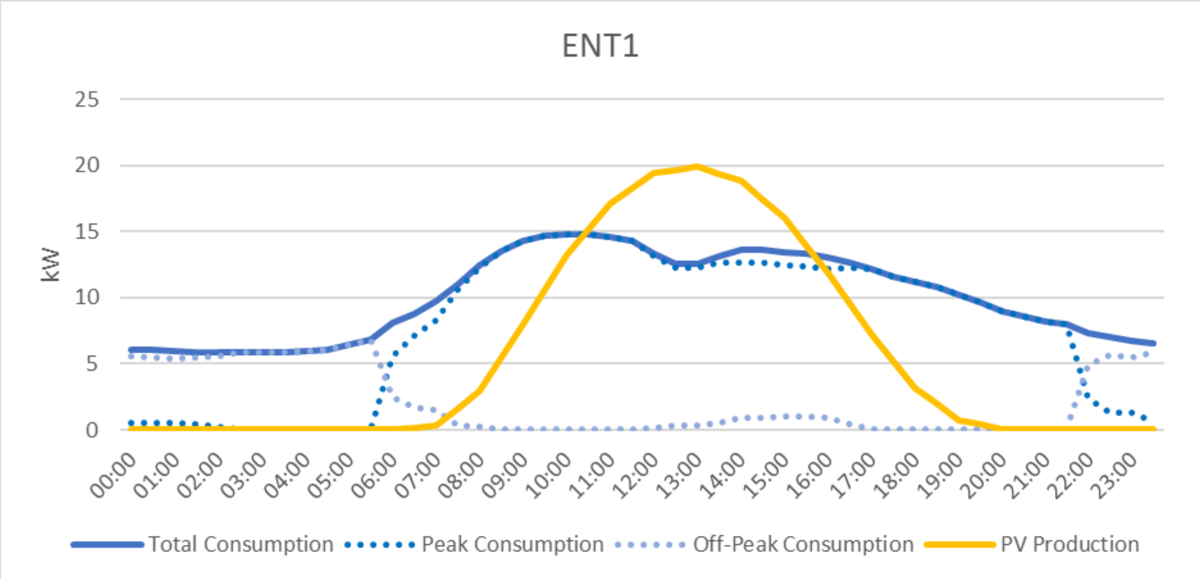
$$G_{PV_i} = K_{PV_i} * LF * \sum HH \tag{7}$$

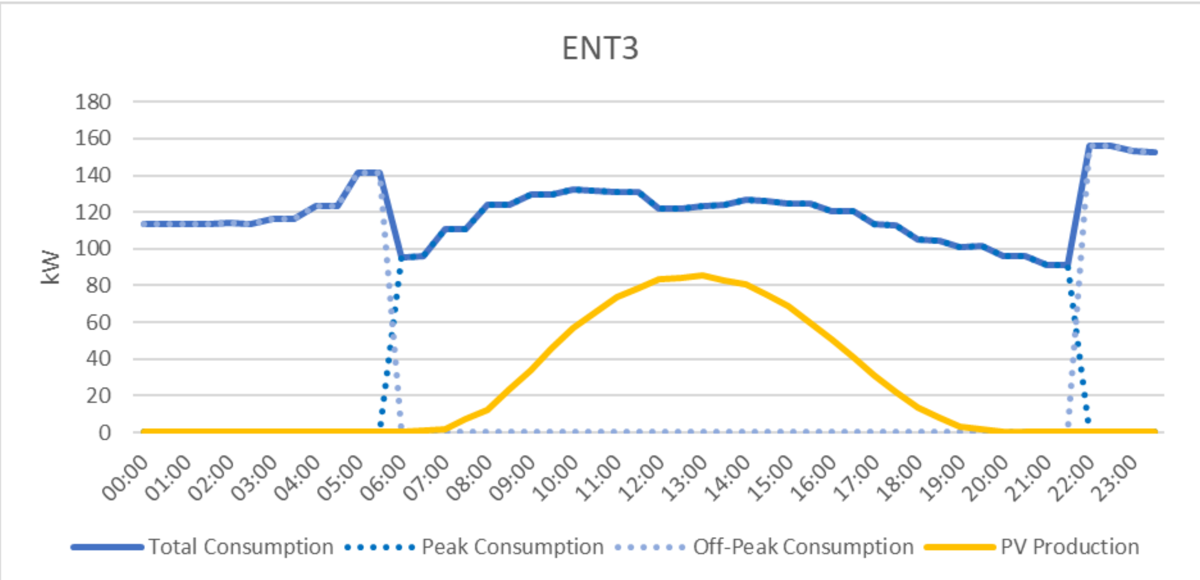
Where, K_{PV} is the total capacity, LF is the load factor as expressed in relation (3) and $\sum HH$ is the number of half-hours in a year. By comparing the volume of generation and consumption for each half-hour, we can assess the volume of self-consumption and generation injected into the grid. Typical daily load curves are depicted in figure 7. For some hours, we can observe both consumption during a peak and an off-peak tariff because the peak hours are set locally by the DSO. So, in average, for a same hour, we can observe a certain percentage of peak and off-peak consumption.

Figure 7: Typical consumption and PV Load curves for each profile (Monday April 3rd)









Source: Data from Enedis and CRE

4.3. Network tariff

The network tariff presents two different components: a fixed charge, representing both metering and administrative management costs and also the contractual capacity subscribed by the consumer (fixed network costs), and a variable charge depending on the volume of electricity withdrawals. As we have seen it before, self-consumers save money only on the variable charge. In august 2017, the French energy regulatory authority has issued new network tariff. The evolution of these rates is set until 2020 and they have known several changes from the previous one. Specific tariffs by season (winter and summer) are introduced for consumers fitted of a smart meter (Linky). As this smart meter will be deployed for all consumers in 2021, all of them will have this specific tariff[14]. Variable daily rate is still applied for some consumer types (short and medium uses). Self-consumers have a specific metering and administrative management charge which is above normal consumer's one. Every year, network tariffs are slightly adjusted, in order to account for inflation and a clearance rate. The regulator (CRE) published expectations of network rates until 2020 for residential consumers. However, concerning firms, these figures are only available for the years 2017 to 2018. For our representative consumers, network tariffs are done in table 9.

Table 9: Variable part of network tariff for end users

Consumers profiles	Households/Residential consumers			Firms/Industrial consumers		
	Periods	**RES1**	**RES2**	**Periods**	**ENT1**	**ENT2**
Variable part of the network tariffs (€/kWh)	**High rate winter**	0.0367	0.0563	**High rate winter**	0.0481	0.0192
	Low rate winter		0.0325	**Low rate winter**	0.0295	0.0120
	High rate summer		0.0131	**High rate summer**	0.0218	0.0088
	Low rate summer		0.0098	**Low rate summer**	0.0179	0.0077
Fixed part of the network tariffs (€/kW)	**2017-2018**	4.36	5.89	**High rate winter**	9.99	14.91
	2018-2019	4.8	6.33	**Low rate winter**	5.13	
	2019-2020	5.24	6.77	**High rate summer**	3.74	
	2020-2021	5.68	7.21	**Low rate summer**	1.13	

Source: Enedis and CRE

The network tariffs for the year 2017 are illustrated in table 10. Variable part of the tariff stands for between 80-85% except for large users (45%). Fixed part of the tariff change between 20-25% except for large users (55%).

[14] Moreover, this smart meter is installed when someone invests in a photovoltaic power plant.

Table 10: Variable and fixed part of network tariff for end users (2017)

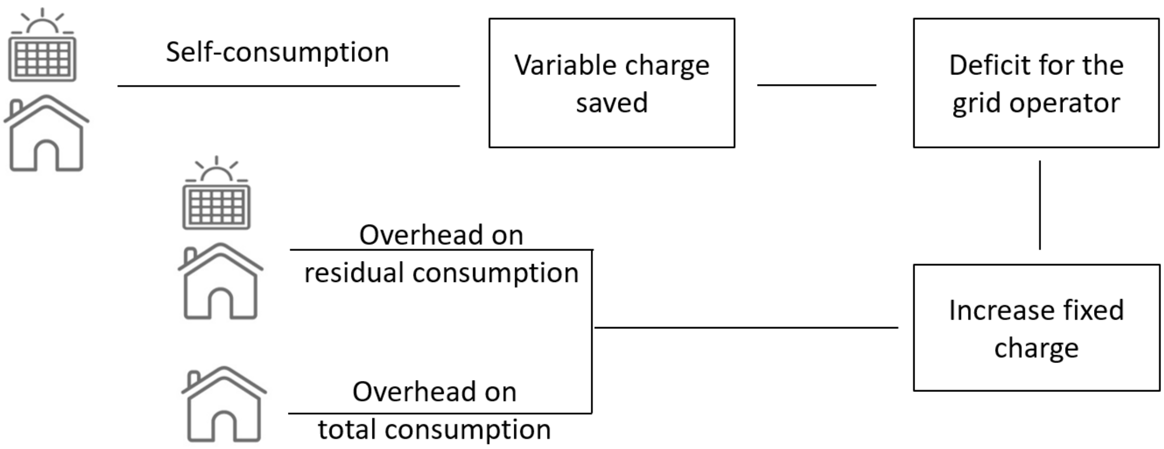
End users	Variable part	Fixed part	Network tariff
RES1	110 €	26 €	136 €
RES2	187 €	35 €	222 €
ENT1	5 002 €	1 095 €	6 097 €
ENT2	23122 €	28 007 €	51 129 €

Source: Authors (data from Enedis and CRE)

5. The simulation model to estimate cross-subsidies

Here, we present the model framework used to estimate the impact of self-consumption of electricity on the revenue losses for the distribution network operator and the corresponding increase in network tariff applied to all consumers. This methodology is based on the one set up by Athawale and Felder (2016). Consumers pay the variable part of network tariff on electricity withdrawals. Self-generators save money on the volume of self-consumed electricity. However, it creates a deficit for the network operator. In this case, feed-in generation is assumed to have no impact on network costs. However, in order to balance their financial accounts, network operators increase the fixed part of the rate. This pathway induces cross-subsidies from standard consumers to self-consumers.

Figure 8: Scheme of cross-subsidies



5.1. Network operator deficit

To estimate cross-subsidies across years, we estimate the number of self-consumers first. We set different self-consumer profiles which install a specific PV size as explained in the previous section. By dividing the cumulative capacities for each profile by the average PV size for the self-consumer profile, we computed the number of self-consumers for each year (table 11).

Table 11: Evolution of the number of self-consumers

Profiles	2017-18	2018-19	2019-20	2020-21
RES1	35 000	70 000	105 000	140 000
RES2	23 333	46 667	70 000	93 333
ENT1	2 500	5 000	7 500	10 000
ENT3	300	800	1 300	1 633
Total	61 133	122 467	183 800	244 967

Then, we estimate the volume of PV self-consumption by each time period (SC_p) by multiplying the volume of self-consumption for each consumer profile ($SC_{i,p}$) by the corresponding number of self-consumers (PV_{SC_i}).

$$SC_p = \sum_{i=1}^{4} SC_{i,p} * PV_{SC_i} \quad (8)$$

Network financial losses are computed by multiplying the volume of self-consumption by the corresponding network tariff for each period and consumer profile. Network operators face a deficit with the decrease of the electricity withdrawal but self-consumption decreases the electric losses on the grid. Indeed, electric losses are due to the resistance of the line. When electricity pass through the lines, a fraction of the electricity is transformed into heat. This process depends on the specificity of the lines, the current flowing and also the length of the electric lines. Between 2012 et 2017, the average of electric losses in Enedis' grid was about 6.8%. The electric losses (L_p) on the French grid are given by:

$$L = aP^2 + bP + c \quad (9)$$

With P as the amount of power, a a parameter applied to the weeks, b a parameter applied to the week-ends and c a non-technical parameter which depends on counting error and fraud. The estimated load curves allow us to compute the volume of self-consumption for all weeks and week-ends. So, we multiplied the parameter a and b respectively by the total amount of self-consumption during weeks and week-ends. The parameter c is independent of the volume of self-consumption because it depends on counting error and fraud. So, we don't take into account this parameter to compute the volume of electric losses avoided. To estimate the benefit from the self-consumption on the electric losses, the average future prices[15] for each year is multiplied by the volume of electric losses avoided.

5.2. Cross-subsidies estimation

To cover its financial deficit, the DSO might increase the network tariff for all consumers. In order to limit the death spiral phenomenon induced by the increase of the variable charge (Eid, 2014; Picciariello, 2015, Simshauser, 2016), we assume that the DSO will increase the fixed charge for every consumer:

$$CS = \frac{FD}{CP} \quad (10)$$

Where CS is the amount of cross-subsidies per kilowatt, FD is the DSO's financial deficit and CP the total contractual power. The last one is provided by the French regulator until 2021 (CRE, 2016). Then, we assess the impact of the development of self-consumption by multiplying the amount of cross-subsidies with the contractual power for each representative consumer.

Finally, we compare these results with the recovery of DSO's financial losses by the increase in the fixed charge only for the self-consumers.

6. The results: small values of cross-subsidies between consumers (CC)

For each representative consumer, self-consumption rates are presented in table 12 below. Obviously, they rely on the consumption levels for each consumer, the consumers RES 1 being the lower consumers, so with lower self-consumption rates (31 and 55% respectively for winter and summer periods). Large

[15] Available at: http://www.eex.com/en/market-data/power/futures/french-futures#!/2017/10/24

firms could consume the major part of their PV generation (around 98 to 100% respectively for low rate summer period and high rate winter period). These results are consistent with profiles of each consumer we presented before (figures 7). They are also consistent with the intuition that self-consumption rates are higher for firms rather than for residential consumers, the activity of firms being more often in accordance with hours where the PV generation occurs.

Table 12: Self-consumption rates for each representative consumer

Periods of consumption	Consumer with fixed retail rate (RES 1)	Consumer with Time of Use pricing (RES 2)	Small firms (ENT 1)	Large firms (ENT 3)
High rate winter	55%	84%	91%	100%
Low rate winter	-	80%	90%	99%
High rate summer	31%	34%	69%	98%
Low rate summer	-	30%	64%	98%
Overall self-consumption rate	37%	45%	74%	98%

Source: Authors (data from Enedis and CRE)

Using self-consumption volumes and network tariffs presented in table 9, we could easily compute the variable network charges self-consumers saved. They are presented in table 13.

Table 13: Savings (€) in network charges for self-consumers 2018-2021

Periods of consumption[16] / Consumer's profiles	2018	2019	2020	2021	Savings per self-consumers
RES 1	1 683 194 €	3 366 387 €	5 049 581 €	6 732 775 €	48 €
RES 2	1 130 852 €	2 261 704 €	3 392 556 €	4 523 408 €	48 €
ENT 1	4 531 478 €	9 062 957 €	13 594 435 €	18 125 913 €	1 813 €
ENT 3	1 145 848 €	3 055 595 €	4 965 343 €	6 238 507 €	3 819 €
Total	8 491 372 €	17 746 644 €	27 001 915 €	35 620 604 €	

Sources: Authors (data from Enedis and CRE)

The gain per consumer is higher for large industries, according to the self-consumed volumes and the smaller number of self-consumers. Indeed, according to consumption profiles, each residential consumer could save 48€ per year and firms between 1813€ or 3819€ per year respectively for small and large industries[17]. The global amount of savings is increasing from one period of time to another

[16] Consumption periods run from September year Y-1 to august year Y.

[17] As consumers' profiles are constant along periods of time, savings per consumers are the same ones for each period.

because of an increase in the number of self-consumers and PV generation capacities. As these increases are linear ones, savings are also increasing linearly. As we have seen it before, these savings are also losses for the DSO. Self-consumers do not pay the variable part of the network tariffs which create imbalances in DSO's revenues. However, self-consumption also leads to cost savings for the DSO in the management of network losses. Using an average price in electricity future markets of 40,87 €/MWh for 2018, 40,24 €/MWh for 2019, 40,5 €/MWh for 2020 and 2021, and the equation 9, we could compute avoided network losses per year. They are presented in table 14.

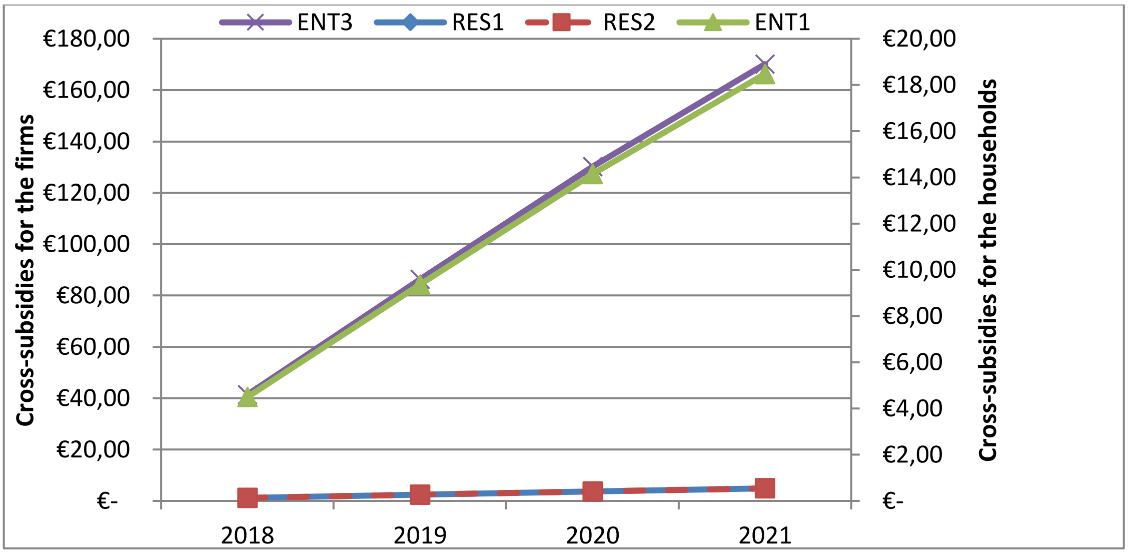
Table 14: Savings in network losses for the DSO 2018-2021

Periods of consumption	2018	2019	2020	2021
Savings in network losses in MWh	16312 MWh	35992 MWh	55672 MWh	72546 MWh
Savings in network losses in €	754 995 €	1 487 638 €	2 244 203 €	2 992 271 €

Sources: Authors (data from Enedis and CRE)

Savings in network losses could stand for 8,4% of DSO's revenue losses in 2021. They reduce financial losses that the DSO must recover through its network charge when self-consumption occurs. As we have seen before, self-consumption creates cross-subsidies between consumers. Indeed, regulator could decide to increase the fixed or variable part of the network tariff paid by each consumer to fund DSO losses in revenue. The increase in the variable part of the tariff will be very low, because of the lower self-consumption volumes compared to the overall consumption (self-consumption stands for 0,07% in 2018 to 0,35% in 2021 of the total forecasted consumption). Thus cross-subsidies will represent between 0,02€/MWh in 2018 to 0,07€/MWh in 2021. The increase in the fixed part should be higher because of the less volumes contracted in MW or kW but they remain very low if we consider the fixed part paid by consumers (Table 8). Cross-subsidies are between 0,022€/kW in 2018 to 0,09€/kW in 2021. The increase in the fixed part of the network tariff for each consumer is presented in Figure 9. For each consumer, cross-subsidies only marginally increase its fixed part of network costs with a maximum of a 2% for consumers RES 1 in 2021. This increase remains below 1% for large consumers and below 1.7% for consumers with Time of Use pricing or small firms on the four studied periods.

Figure 9: Increase in fixed part of network tariffs for each consumer 2018-2021



Sources: Authors (data from Enedis and CRE)

7. The impact of self-consumption on network access pricing: a way to reform the network tariff

The promotion of self-generation / self-consumption of renewable electricity is done in France thanks to two strong incentives: a partial exemption (40%) of the costs of connection to the distribution network, on the one hand, an exemption from the CSPE for the self-produced and self-consumed part of electricity, on the other. In the latter case, the balance sheet is neutral for the self-producer since what the producer saves by not paying the CSPE is largely compensated by the loss of profit that would be obtained if he sold his production instead of consuming it and thereby benefiting from the guaranteed purchase price (FIT for feed-in tariffs). The CSPE essentially covers the difference between the guaranteed price (FIT) and the market price, which is assumed not to be very far from the production cost of self-produced kWh when one approaches the market parity.

But the self-producer remains connected to the network because it has to withdraw a part of its consumption when its demand for electricity is not covered by its production due to intermittence of solar. It therefore has to pay the network access tariff for the kWh withdrawn from the network.

As mentioned in the previous section, the tariff for access to electricity network is generally a two-part tariff which includes a share proportional to the capacity subscribed by the final consumer in kW and a share proportional to the amount of electricity withdrawn in kWh. There is also sometimes an injection rate, at least for high voltage levels. In countries like France which maintain the principle of spatial equalization of tariffs in the name of equal treatment of all consumers, this tariff is the same independently of the location of the consumer, ie its distance from the network. The regulatory commission generally authorizes a horo-seasonal differentiation of tariffs to take account of the period and time during which the kWh is withdrawn. Because this differentiation is the standard adopted by the supplier, it is normal to apply it to the distributor due to the observation that the networks are congested at the busiest times of the year at the demand peaks.

The important issue for the network operator is that of sharing between fixed and variable tariff parts. In Europe, and in particular in France, the fixed share for households is in the order of 20 to 30% of the all taxes included tariff (TURPE) compared with 70 to 80% for the variable part. Only a few countries, such as the Netherlands, have a 100% based on the subscribed power. The choice between the fixed and the variable parts is not neutral: a high fixed share penalizes consumers who consume little kWh and therefore have a low utilization of the subscribed power. A low fixed share penalizes large consumers since the fixed costs of the network are largely recovered according to the number of kWh withdrawn.

The large-scale development of self-consumption of electricity (by households as well as small and medium-sized enterprises) puts the question of the optimal structure of the tariff on the agenda. With the current structure, which relies on a low fixed component, a large producer of photovoltaic or wind power that consumes almost all of its production and only uses the network on a marginal basis will pay the variable costs associated with which is fair, but will only marginally contribute to the coverage of fixed network costs, which will lead to "cross-subsidization" to the detriment of other customers who rely heavily on the network since the coverage of fixed costs is mainly on a pro rata basis. For reasons of equity, the structure of the tariff for access to the transmission and distribution networks must therefore be reviewed by increasing the fixed part of the tariff. Indeed, regulator, defining network regulated tariffs, could use several tools to compensate losses for DSO:

- An increase in the variable part of the network tariff for all consumers or only self-consumers. Each kWh withdrawn from the network compensates the DSO’s revenue losses.

Cross-subsidies always exist in the first case and incentives for self-consumption increase in the second case, with the risk of "death spiral". According to these difficulties, this solution is not consistent with the internalization of cross-subsidies.

- An increase in the fixed part of the network tariff for all consumers (but we keep the existence of cross-subsidies and the "free-riding" behavior) or only for self-consumers (but the incentive to self-consume and to invest in own generation could be reduced). As the incentive to invest in PV generation does not only rely on self-consumption gains, this decision could improve the payment of network costs by self-consumers[18]. Moreover, all consumers connected to the grid must pay a fee to DSO to avoid shortfalls. In fact, the self-producer who remains connected to the distribution network considers this network as a back-up and must therefore be given a pricing that takes account of this specific behavior.

The interest of the network operator, supported by the regulator, is to recover its costs while guaranteeing the fairness of the tariff between consumers. Self-consumers have to support the increase in costs they create, but also they must benefit for savings linked with the decrease in consumption from the grid, as we saw with the improvement in physical network losses.

In other words, with self-consumption, networks must be able to cope with the same power but with a lower utilization rate and with a part of the users that de facto behave like a « free rider ». It is therefore necessary to restore equity by charging the self-consumer for this guarantee of access to the network.
Two approaches are possible to determine the fair price of access to the network of a self-consumer: either one sets the tariff according to the willingness to pay, or it is fixed by taking account of the network operator's shortfall and charging that customer with what would have been its fixed-cost bill if it had not been a self-consumer.

7.1. A tariff established according to the willingness to pay of the self-consumer.

In this case, recourse to the network can be considered as a relief which makes it possible to avoid a loss of well-being for the customer at the time of the intermittent occurrence of his wind or photovoltaic production. Thus, the "cost of failure" approach can be used. From the point of view of a mesh network, it is generally considered that the failure cost of one kWh (Value Of Lost Load - VOLL) is a parabolic function of the "depth of failure" defined as the share of energy not supplied as a percentage of the electricity demand (Hansen & Percebois) i.e.:

$$\boldsymbol{Y = af^2 + bf + c} \qquad (11)$$

where c represents the marginal cost of the last plant called just before the failure, f the depth of the failure, and a and b of the parameters to be estimated through a survey of consumers who have suffered losses as a result of the interruption of the supply. It is often estimates of insurance companies that are used nationally for these estimates. As an example, RTE carried out a survey of 1600 customers in France during 2010-2011 (households and companies). The economic cost of a power outage of more than 3 minutes, according to this survey, is 26 euros per kWh, which is very high (recall that the price inclusive of one kWh purchased by a household is of the order of 0.17 euro). The cost is higher for

[18] Incentives to invest in PV generation and to self-consumption are also in the decrease of energy purchases at the retail price, the FIT that remunerates PV surplus fed into the grid, the exemption of PSOT, the fee that remunerates each self-consumed kWh, etc. The study of these incentives policies is out of the scope of this research.

businesses than for households. But this is a macroeconomic cost that takes into account the economic losses of various kinds that will have an impact on the evolution of the GDP in case of blackout.

For a household, the survey reveals that the average cost of a 1-hour cut is 25 euros, but households would be willing to pay only 17 euros to avoid it and they would ask 49 euros for the network operators in return of a voluntary load-shedding (source: RTE survey). These figures include both the cost of production, the cost of transmission and distribution of the kWh and the corresponding taxes. As self-consumers also save expenditures in energy purchases and in PSOT, it could pay a fixed fee to the network operator to avoid shortfall. Which fee consumers are willing to pay to maintain this service? It all depends on their aversion to the risk and the alternative solutions available to them in case of unavailability of their production (electricity storage for example). So, consumers have to manage between the maximization of savings with self-consumption and the probability to be cut if the DSO does not cover all its network costs, yet facing to VOLL for each shedded kWh. According to its overall savings with self-consumption, and its WTP to avoid shortfall (between 17€/kWh and 25€/kWh), consumer would be willing to pay the DSO's revenue losses. Thus, RES 1 and RES 2 could agree to pay a maximum fixed fee of 48€, ENT 1 and ENT 3 respectively fees of 1813€ and 3819€. These fees are consistent with a shortfall of few kWh compared to the consumption of end users (a shortfall between 0.32 and 2.8 kWh for residential consumers, 72.5 and 106.6 kWh for small firms, 152.6 and 224.6kWh for large firms). According to these fees, the DSO could recover its costs to continue to serve consumers. We may think that the more the share of self-production increases, the more the consumers' willingness to pay decreases. Indeed, consumers reduce the use of network so they could have fewer concerns on the reliability and security of the network they marginally use.

Obviously, the consumer will waive this guarantee if the cost of an individual storage allows him to no longer connect to the network. The cost of storage therefore constitutes the ceiling price of the emergency tariff. As the cost of battery storage is downward, it is likely that self-producers will be less and less willing to pay to maintain a guarantee of network access.

7.2. A tariff established on revenue losses of the network operator

This time, we are talking about the "damage" suffered in terms of revenue by the network operator as a result of self-consumption and we are trying to see how to recover this shortfall by modifying the structure of the network access tariff.

As we have seen before, an increase in variable part of the network tariff does not reduce cross-subsidies and could maintain or make the "death spiral phenomenon" worse. Therefore, changes in fixed part of the network tariff seem to be preferred. DSO must recover the financial amount of self-consumers' savings from the variable part of the network tariff. Indeed, the network tariff paid without and with self-consumption is presented in Table 15.
As expected, the network tariffs paid by consumers are lower with self-consumption as withdrawals from the grid are lower. The decrease in network tariffs is lower for greater firms, variable network tariffs being smaller rather than for other consumers. Moreover, residual consumption staying large as the self-consumption stands for 17,6% of their overall consumption (against 43,6% and 28.6% of respectively RES1 and RES2 overall consumption, 38.7% of small firm overall consumption).

As we seen before, for each profile of consumers, DSO must recover 48€ on each residential self-consumer, 1813€ and 3819€ respectively on each small or large firms self-consumer. Each year, the fixed part of the network tariff for self-consumers must increase of these amounts to anticipate and internalize losses in DSO's revenues. Simple calculations lead to new tariffs for subscribed power (Table 16)[19].

Table 15: Network tariffs with and without self-consumption

Consumer's profile	Network tariffs without self-consumption in €			Network tariffs with self-consumption in €			Variations in network tariffs (%)
	Variable part	Fixed Part	Overall network tariff	Variable part	Fixed Part	Overall network tariff	
RES1	110	26	136	62	26	88	35
RES2	186	35	222	138	35	173	22
ENT1	5 002	1 095	6 097	3 189	1 095	4 285	30
ENT3	23 122	28 007	51 129	19 303	28 007	47 310	7,5

Sources: Authors (data from Enedis and CRE)

Table 16: Increases in fixed part of network tariffs

Consumer's profile	Average subscribed power (kW)	Tariffs increase in € per kW	New fixed part in network tariff (€)	Increase of the fixed part (%)
RES1	6	8,02	74	184
RES2	6	8,08	84	137
ENT1	51	35,54	2 908	165
ENT3	470	8,13	31 826	14

Sources: Authors (data from Enedis and CRE)

The increase in fixed part must be significant for households and small firm to internalize the negative effect of self-consumption on DSO's revenues. The intuition relies on their network contracts features, as they pay lower fees for subscribed power and greater variable tariffs, and on lower residual demand. Using this new fixed part, network tariffs paid by self-consumers are the following (Table 17).

The overall network tariff is the same as the one without self-consumption but its structure differs, the weight of the fixed part has increased. Indeed, fixed part of the tariff stands for 38 to 62% of the costs recovery whereas it stood for 16 to 55% in the initial structure of network tariff. A large part of network costs is now recovered on the fixed part. Moreover, the overall network tariff for self-consumers has also increase to compensate losses in DSO's revenue. It has increased from 8% for large firms (from 47 310€ to 51 129€), from 42% for small firms (from 4 285€ to 6 097€), and from 54% and 28% respectively for consumers with fixed retail rate or Time of Use contracts (from 88€ to 136€ and from 173€ to 222€).

[19] For another empirical example on modifications of the structure of network tariffs, see CREDEN / OSE study, WP 2017. They found that the fixed part must increase of 75% for a firm with a subscribe power of 110 kW.

Table 17: New structure of network tariffs for self-consumers

Consumer's profile	Network tariffs with self-consumption and increasing fixed part in €				
	Variable part		Fixed part		Overall network tariff
RES1	62 €	46%	74 €	54%	136
RES2	138 €	62%	84 €	38%	222
ENT1	3 189 €	52%	2 908 €	48%	6 097
ENT3	19 303 €	38%	31 826 €	62%	51 129

Conclusion

The deployment of self-consumption is used to reduce network costs and PSOT. Public authorities have decided to use net billing or net-metering to foster this deployment. Some of them have also exempted from taxes and PSOT self-consumers to increase their gains when they do not feed into the grid own PV production. This system has achieved its goals. Self-consumption rates are between 35 and 45% for households and between 70 and 100% for industrials. The success of these policies is also linked with an increase in energy prices and a decrease in FIT; thus, the profitability of self-consumption rises. According to these exemptions and the reduction in energy withdrawn from the grid, the recovery of network costs and the funding of public services obligations are not guaranteed. Indeed, cross-subsidies exist between standard energy consumers and self-consumers. To avoid these cross-subsidies, exemptions are reduced and self-consumers will pay a share of PSOT or of network tariff. These changes usually come after a period of profitable incentive policies for self-consumers. Thus, the large-scale development of self-consumption (and self- production) therefore requires thinking about a redesign of network access tariffs if existing networks are to be financed other than by cross-subsidies, i,e deferring charges to consumers who do not opt for self-consumption. The fixed share of the network tariff must be increased for self-consumer, as they wish to continue to benefit from access to the interconnected network to serve their residual demand.

As the model shows it, cross-subsidies are very low for the next 5 years in France. Forecasted PV capacities and the share of PV production in total electricity generation or consumption are very low. So, the increase in network costs or in PSOT exist but the annual increase for consumers are not significant, only few euros on their annual bill. However, losses for Distribution System Operator should be 7.7 million € in 2018, rising until 32,6 million € in 2021. The DSO is responsible for security, public service obligations and network deployment. Thus, these costs must be recovered. As its revenue comes only from the regulated network tariff, losses in this revenue could induce lower services or shortages. Several economic tools could be used to recover theses costs, reducing cross-subsidies. Using the consumers' willingness to pay for security could lead to high costs self-consumers have to support. The self-consumption could be reduced. Regulator could also modify the share of fixed costs in the network tariff, reducing the weight of the variable part that is not paid by self-consumers. A significant increase in fixed part paid by self-consumers reduces network system operator's losses. This increase must be of 14% for large firms, in a range of 135% to 184 % for others consumers. Nevertheless, this increase must keep incentives to self-consumption. Thus, an injection tariff could be decided to complete the policy.

This new tariff is additional revenue for the network operator and further incentives for prosumers, an opportunity cost, to consume their own production to minimize injection costs.

The important point is to introduce a special access tariff for the self-consumer, which obliges the distributor to maintain the same installed power, regardless the amount of self-consumption or the use of the PV generation. This policy could also internalize the intermittence of renewable energy, the network being used as a back-up technology to serve goods as reliability and security of supply.

As the risk on network withdrawals is increasing, with self-consumption behavior or demand side management objectives, regulators have to deal with the recovering of a greater part of network costs on the fixed part of the network tariff. This study shows that a first step could be a special network tariff for self-consumers, modifying the share of variable and fixed parts of the tariff to recover all network costs. Internalizing the risk on volumes could lead to network tariff only based on subscribed power, as in Netherlands. However, some concerns remain in the allocation of costs between consumers.

Let us recall that we only take into account the cost of access to the network. Further researches on this field could complement these findings. Obviously thanks to its photovoltaic installation the consumer will save on the invoice sent by his supplier since he will buy less electricity. We do not also take into consideration the surplus of electricity that could be sold on the market or injected into the network with a FIT. It is also necessary to raise the question of the introduction or not of an injection tariff on the network, because the distributor is entitled to request compensation for the use of its network. This could be analyzed in another research as it must impact the incentive to increase self-consumption, the surplus of energy fed into the grid being taxed. It should also be noted that the self-producer may have an interest in subscribing to a lower draw-off capacity than would be the case if he did not self-consume part of its PV generation; these are fixed costs saved. So, a network tariff heavily based on the subscribed power must not be efficient or costly to implement.

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