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27/03/19

Working Paper

An economic assessment of the residential PV self-consumption support under cost-reflective grid tariffs

1 Introduction

In many countries worldwide, photovoltaic (PV) technology has been fostered by different policy supports such as Feed-in Tariffs or net-metering (De Boeck et al., 2016; EPIA, 2012). Globally, photovoltaic capacities went up from 1 GW in 2000 to 230 GW in 2015. This prominent development led to a fast decrease of the photovoltaic technology's costs. This trend combined with the increase of the retail rates, due to the financing of the policy supports, enabled to reach the grid parity in some European countries (Hagerman et al., 2016; Karakaya et al., 2015; Munoz et al., 2014). The grid parity refers to the situation where the cost of producing the electricity from a photovoltaic power plant is equal to the cost of buying electricity from a supplier. When the photovoltaic generation cost decreases further, it becomes profitable to invest in a PV power plant to self-consume a part of the consumption. People who produce their own consumption are called "Prosumers" because there are both **pro**ducers and con**sumers**. Prosumers save on their electricity bill and make a profit by selling their excess generation. In France, a new regulation was implemented in 2016 allowing PV owners to self-consume a part or all their generation. Before this support scheme, PV owners were encouraged to sell all their generation at a feed-in tariff (FIT). At the end of 2017, the number of prosumers was low (20 000) compared to residential PV owners (340 400) but the development of self-consumption is expected to grow in the future (Yu, 2018). Indeed, 3.8 million of households in France are expected to be prosumers in 2030 according to the French transmission grid operator (RTE, 2017). Despite the grid parity was reached, the profitability of PV self-consumption still relies on subsidies. In Europe, the production is not well synchronized with the consumption leading to low self-consumption rate (the ratio of the production that is consumed). For instance, in countries such as Germany or France, a feed-in tariff above the market price is guarantied for the excess generation injected into the grid. Prosumers could shift their consumption in order to improve their self-consumption rates but some consumption are difficult to shift such as TV or cooking appliances. For these electric appliances, the elasticity is very low (Oberst et al., 2019). Stationary batteries could improve the self-consumption rate by storing PV generation during afternoon to consume it at night. Prosumers could reach high self-consumption rates without changing their habits. To this end, Germany implemented a subsidy to decrease the battery investment cost.

However, the development of self-consumption raises a lot of concern for the grid management (Council of European Energy Regulators (CEER), 2017; Tobnaghi, 2016). A lot of grid operators want to charge their consumers with demand charges or Time-of-Use tariffs in order to better reflect the grid operator's costs. For instance, the French energy regulator introduced a four-part tariff for residential consumers. These tariffs could have an impact on the profitability of self-consumption (La Monaca and Ryan, 2017). Indeed, peak prices occur during night while PV generation occurs during afternoon. In this context, batteries could improve the prosumers' savings by storing PV generation when the price is low and release it during peak prices. On top of that, stationary batteries could bring benefits for the grid by decreasing bottlenecks and so deferring or avoiding grid investments (Li et al., 2016; Rowe et al., 2014, 2013).

In order to examine the consistency of the current French PV self-consumption support, we compare this policy by an alternative policy which subsidizes PV and battery investment. We focus on the impact of these policies on the PV-battery investment profitability under different tariffs. Two different households in a city with high solar irradiance are considered. A simulation model is performed to compute the Net Present Value of the PV-Battery investment for each policy support under a flat and two Time-of-Use tariffs (TOU). Then, we compare the cost of each policy in order to evaluate which one is efficient.

The remainder of this paper is structured as follow. In section 2, we describe some features regarding self-consumption in France and present some literature background. In section 3, we present our model and give an overview of the data. In section 4, we show the Net Present Value with the current policy and without subsidy. In section 5, we define the alternative policy and compare with the current one in section 6. In section 7, we conclude and propose some policy recommendations.

2 Self-consumption in France and related literature

France had encouraged residential PV adoption by implementing a Feed-in tariff scheme. The cumulated PV setup grew from 140 000 at the end of 2010 to 385 000 at the end of 2018 (Figure 1 – left graph). In July the 27th 2016, the French government implemented a regulation which allowed people to invest in a PV power plant in order to self-consume a part of their generation. With this new regulation, a new subsidy scheme was introduced for residential prosumers. They receive an upfront purchase subsidy on the PV investment and have a free connection to the grid. Capacities up to 3 kW benefit from a reduced VAT on the PV investment. They also receive a feed-in tariff for each kilowatt-hour (kWh) injected into the grid. For capacities up to 3 kW, there are two possibilities to sell the excess generation. Prosumers can sell their excess generation with a FIT or inject it freely into the grid. In the last case, prosumers benefit from reduced administrative costs. This subsidy scheme can be an alternative to the previous one which consists of applying a feed-in tariff on the whole generation. The feed-in tariffs allowed a prominent development of the PV capacities in France. However, the share of self-consumption capacities is now higher than capacities under feed-in tariffs scheme (Figure 1 – right graph).

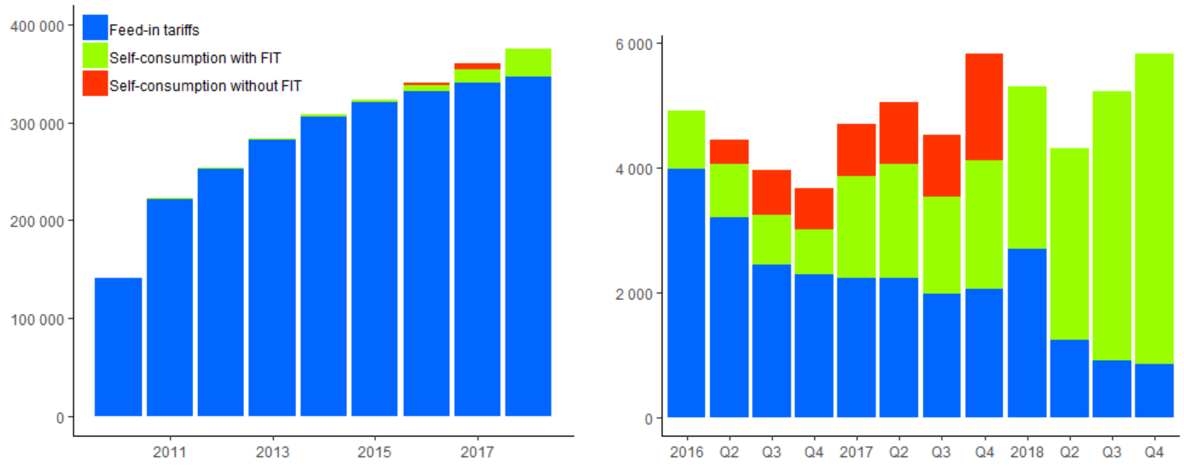

Figure 1: Cumulated PV setup (left) and quarterly evolution of PV setup (right) in France – Source : Enedis (2018)

Even if PV technology costs have decreased over many years, subsidies are still needed to ensure profitability. Indeed, because of the mismatch between the production and the consumption, the self-consumption rates are low in France and in many European countries (Luthander et al., 2015; PV-Net, 2016). FIT applied on the excess generation allows a stable income for prosumers. Stationary batteries can increase the self-consumption rate and so, the investment profitability. Since the grid parity was reached in many countries worldwide and with the quick decrease of the battery costs, many research articles focused on the profitability of PV coupled with battery investments (Kazhamiaka et al., 2017). Such investments in the German residential sector were already profitable in 2013 for lead-acid batteries without subsidy (Hoppmann et al., 2014). Others have confirmed this result for lithium batteries but only in the case where retail rate increases significantly (Kaschub et al., 2016; Truong et al., 2016). According to Bertsch and al. (2017), the internal rate of return for such investments is about 3.7% in Germany with subsidies. However, some authors found a negative profitability for an investment made in 2015 (Quoilin et al., 2016). Others focused on the drivers of the profitability such as the evolution of the technology costs, of the retail rates and the level of the subsidies (Dietrich and Weber, 2018). They stated that PV-battery will be profitable in 2020 in Germany for large capacity batteries. Tervo et al. (2018) emphasized the upfront purchase subsidies as a prominent factor of profitability. In France, PV coupled with battery investments are far from reaching profitability (Yu, 2018). Subsidies are needed to prompt battery investments because PV investment alone is more profitable than a PV coupled with a battery (Hesse et al., 2017).

Some studies focused on the impact of the tariff scheme on the profitability. A time-of-Use tariff (TOU) decreases the PV investment’s profitability (O’Shaughnessy et al., 2018). Installing a battery with the PV improves the profitability under a TOU or a demand charge (Kaschub et al., 2016). However, it’s not profitable under the current scheme in Switzerland (Schopfer et al., 2018) or in the United Kingdom (Davis and Hiralal, 2016). Nevertheless, changing the charge operation can decrease the power subscribed and so, improve the profitability under a demand charge (Solano et al., 2018) or a TOU (Sani Hassan et al., 2017). So, it is important to subsidize batteries to encouraged prosumers to invest in them, but an ill-designed subsidy scheme can hinder the adoption of the battery technology. The regulator scheme on the excess generation has an important impact on the adoption of batteries. Indeed, high Feed-in tariffs hinder battery adoption (Barbour and González, 2018; Kazhamiaka et al., 2017; Pena-Bello et al., 2017). If the prosumers sell their excess generation at the market price, they could be encouraged to invest in a battery to optimize their profit according to the time at which they self-consume or not.

New regulations such as network pricing could decrease the need of subsidies. To limit cross-subsidies, many grid operators and regulators want to implement demand charges or Time-of-Use tariffs. By optimizing the battery schedule to maximize self-consumption during peak rates or to decrease the peak load, PV-batteries’ profitability can be improved (O’Shaughnessy et al., 2018). In France, the current subsidy scheme is inappropriate to challenge the future development of Time-of-Use tariffs. The evaluation of public supports for the PV technology was largely studied in the literature (Avril et al., 2012; Leepa and Unfried, 2013; Lüthi, 2010; Mir-Artigues and del Río, 2016; Pyrgou et al., 2016) but they focused only on feed-in tariffs or net-metering. To the best of my knowledge, there isn’t evaluation of public supports for PV self-consumption under different tariffs.

3 Model and data

The investments of PV coupled with batteries are analyzed by computing the Net Present Value (NPV). An investment is profitable when the total incomes are higher than total costs. We do not consider payback time and focus only on whether the investment is profitable or not under different subsidy schemes and retail pricing. To compute the NPV, a simulation of the electric flows between household appliances, PV, battery and the grid is performed.

3.1. Economic metrics

The NPV compares the discounted costs of an investments with the discounted incomes. For prosumers, incomes represent the bill savings and the sell of the excess generation injected into the grid. The profitability of the PV-Batteries investment for the household *i* is represented by equation 1:

$$NPV_i = \frac{\sum_{y=1}^{Y} CF_y}{(1+d)^y} - [(PV * Cost_{PV}) - Prime_{PV}] - \frac{(PV * Cost_{inverter})}{(1+d)^{12}} - \left[Batt * \left(Cost_{Batt} + \frac{Cost_{Batt}}{(1+d)^{n_{Batt}}}\right) - \sum Prime_{Batt}\right] + \left[\left(\frac{Batt_{25} - Batt_{min}}{Bat_{max} - Bat_{min}}\right) * \left(\frac{Batt * Cost_{Batt}}{(1+i)^{25}}\right)\right] \quad (1)$$

With:

$$CF_y = \sum_{t=1}^{8760} \left(P_{SC_t} * \left(Cost_{En} + Cost_{grid_t} + taxes\right)\right) + (P_{Ex} * Price_{Ex}(y)) \quad (2)$$

PV investment is made once and PV lifetime is assumed to be 25 years. Cash flows (CF_y) represent the avoided cost by self-consuming (P_{SC_t}) and the income from the selling of the excess generation (P_{Ex}). The price $Price_{Ex}$ depends on the subsidy scheme. The current policy support guarantees a FIT until 20 years. After this period, the excess generation is supposed to be sold at the current average spot price. An upfront purchase subsidy of the PV ($Prime_{PV}$) and the batteries ($Prime_{Batt}$) can decrease the investment cost depending on the subsidy scheme. The inverter is assumed to be replaced on the 12th year. When the battery ($Batt$) has reached the end of its life, it is replaced. The last term represents the remaining value of the last battery set up when the PV is obsolete (Bertsch et al., 2017; Kaschub et al., 2016). It can represent a saving if the household wants to invest in a new PV power plant. In this case, they could use his last battery.

3.2. Electric flow simulation

An electric flow simulation is performed to computed the quantity of electricity self-consumed and injected into the grid in an hourly time resolution (Figure 2).

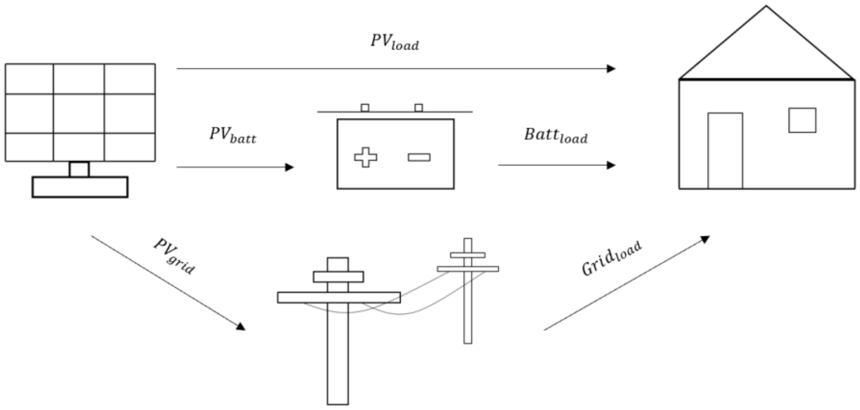

Figure 2: Electric flow chart of electricity of the PV-battery installation

The model is constrained by several technical features. First, the household's demand ($Load_t$) can be served only by the PV power plant (PV_{load}), the battery ($Batt_{load}$) and the grid ($Grid_{load}$) :

$$Load_t = PV_{load} + Batt_{load} + Grid_{load} \quad (3)$$

The state of charge depends on the following equations:

$$SOC_t = \eta . PV_{batt} - \frac{1}{\eta} . Batt_{load} \tag{4}$$

$$SOC_1 = Batt_{min} \tag{5}$$

Where η is the battery round-trip efficiency. The state of charge at the first period is assumed to be at the minimum. The battery's charge and discharge cannot exceed the battery capacity:

$$PV_{batt} \leq SOC_{max} \tag{6}$$

$$Batt_{load} \leq SOC_{max} \tag{7}$$

Two simulations are performed in this study. In both cases, PV generation supplies household's appliances or battery first. The battery stores solely electricity from the PV power plant. We do not consider the possibility to store electricity from the grid. This strategy can decrease the quantity of self-consumption and the investment's profitability (Pena-Bello et al., 2017). The purpose of the first strategy is to maximise the PV self-consumption. The PV power plant supplies first the household's appliances. If the PV production is higher than the load, the excess generation charges the battery. If the battery is charged at the maximum if its capacity, the excess generation is injected into the grid. An illustration of this strategy can be seen with the Figure 3.

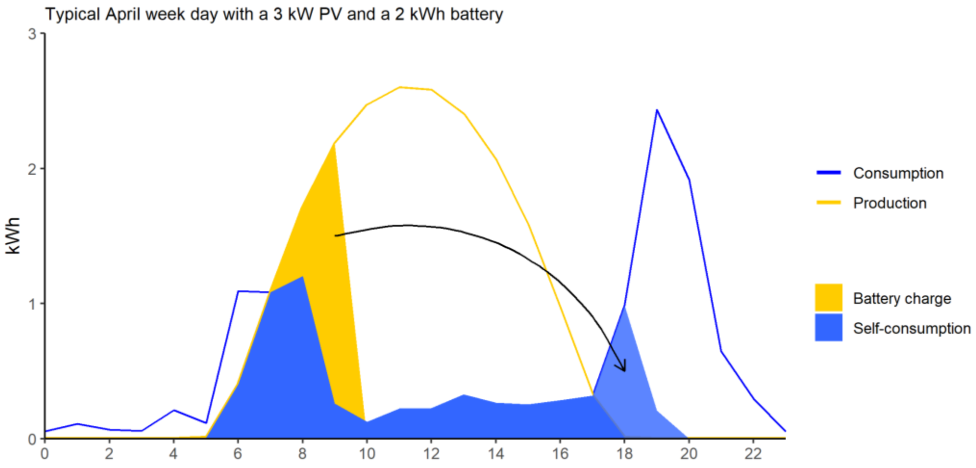

Figure 3: Charge strategy which maximizes the PV self-consumption

The purpose of the second strategy called "Peak charge" is to maximize the PV self-consumption during peak prices in order to maximize bill savings. During peak prices, the charge is the same as the first strategy charge which maximizes the self-consumption. During off-peak prices, the PV generation supplies the battery first. When the maximum capacity of the battery is reached, the generation supplies the household's electric appliances. When the PV is weaker than the consumption, the battery doesn't supply the load (Annexe).

3.3. PV and battery

PV load profiles are generated with the software "Renewable Ninja"[1]. This software provides PV generation power at an hourly time step for any location in Europe. The data used corresponds to a PV power plant of 1 kW and it is multiplied according to the PV capacity. The efficient rate of the PV is set to 94%. The PV lifetime is assumed to be 25 years and 12 years for the inverter. We consider a lithium-ion technology for the battery as it's the main technology used in the current market

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[1] https://www.renewables.ninja/

(Anuphappharadorn et al., 2014; IRENA, 2017; Stan et al., 2014). The quantity of electricity charged by the battery depends on several parameters. The depth of discharge (DOD) represents the battery's capacity which can be used. There are electric losses during the charges and the discharges which depend on the round-trip efficiency of the battery (η_{Batt}). All the parameters are set in Table 1 and correspond of the reference case of the IRENA's review. Battery cost is expressed in dollars so an exchange rate is applied to express the cost on euro. The current average rate of 0.88 is applied. Unlike all the other parameters, battery cost corresponds to the worst case because installation costs are not taken into account. By applying these assumptions, battery cost is equal to 680€/kWh in 2020. Performances of lithium-ion batteries will be improved with the growth of battery market (Zubi et al., 2018). These performances are related to the lifetime, the number of cycles and the investment costs. When the battery is obsolete, it is replaced by a new battery with improved performances depending on the year of replacement (Table 1).

Table 1: Battery parameters (IRENA, 2017)

Parameters	Unités	NMC		
		2020	2025	2030
Depth of discharge (DOD)	%	90	90	90
Round-trip efficiency (η_{Batt})	%	95	96	96,8
Self-discharge (φ)	%/jour	0,01	0,01	0,01
Calendar lifetime (N_{Batt})	Années	13	16	18
Cycle life indicator (NB_{cycles})		2 400	3030	3820
Battery cost (VAT excluded)	$/kWh	645	465	335

The aging storage is difficult to predict but it can be express as the charge throughput the battery. The same expression is used from Hesse et al. (2017) to express the capacity degradation:

$$V_{cycles} = \frac{0{,}5 * \int |P_{batt}| dt}{NB_{cycles} * E_{batt}^{nom}} \tag{8}$$

Where $\int |P_{batt}| dt$ represents the power flow via the battery, NB_{cycles} is the number of cycles before the battery is obsolete and E_{batt}^{nom} corresponds to the nominal capacity of the battery. The factor 0.5 corresponds to the conversion of a full cycle from the charge and the discharge process.

3.4. Load profiles

Load profiles are generated by a software "LoadProfileGenerator" (Pflugradt, 2016). This software provides the power of each electric appliances for default households in a second time frame. Here, we apply an hourly time frame in order to be consistent with the generation time frame. Two default households are simulated and based in the city of Carpentras with a high solar irradiance compared to the other French cities. The first one is a household with one child called "CH03" and the second has 3 children and called "CH05" (Bertsch et al., 2017; Mateo et al., 2018). The annual consumption is respectively 3.1 MWh and 4.6 MWh.

4 Case study

Households who invest in a PV power plan to consume a part of their production benefit from an upfront purchase subsidy and a reduced VAT for capacities up to 3 kW. The also benefit of a free connection charge to the grid. A feed-in tariff is applied on the excess generation for 20 years. After which, the excess generation is assumed to be sold at the current average market price equal to 40€/MWh. For capacities above 3 kW, the incomes from the sale of the generation is subject to a levy. Subsidies are described in the following table:

Table 2: Current subsidy scheme in France for residential self-consumption

1st T - 2019	[0 – 3] kW	]3 – 9] kW
Upfront purchase subsidy	0,39 €/W	0,29 €/W
VAT	10%	20%
Tax system	Non	15,5% of the excess generation revenue
Grid connection	0€	
FIT	0,10€/kWh	

The NPV is computed regarding 3 different retail pricings: a flat tariff, a two-part tariff (TOU_2P) and a two-part tariff with a seasonal differentiation (TOU_4P). The first two rates are widely used in France. The two-part tariff corresponds to a peak and off-peak prices during the day. The corresponding hours are one of these applied by the grid operator in Carpentras (Table 3).

Table 3: Retail rates for a residential consumer with a subscribed capacity of 6 kW (CRE)

	Flat	Peak price	Off-peak price
Tariffs (€/kWh)	0,1452	0,1580	0,1230
Periodes		[7h à 14[[17h à 2h[	[2h à 7h[[14h à 17h[

The French regulator introduced in July 2017 a new grid pricing with four part-tariff. There is still a peak and an off-peak price during the day but also a peak season (winter) and an off-peak season (summer). No seller has yet proposed such a pricing scheme. However, with the implementation of smart meters', a four-part tariff is likely to be proposed by suppliers (Grünewald et al., 2015; Layer et al., 2017; Levin, 2019). In this context, we simulated the profitability of an PV-battery installation with this tariff. To compute the price of each period, we took the same supply and tax part from the two-part tariff. Then, we apply the grid part from the French regulator. By doing so, peak price in winter is higher than the peak price from the two-part tariff and conversely for the off-peak price in summer (Table 4).

Table 4: Four-part tariff based on the regulated tariff and the grid rate calculated by the French regulator

TOU_4P (€/kWh)	December to April		April to december	
	Winter Peak	Winter Off-peak	Summer Peak	Summer Off-peak
Energy	0,0715	0,0519	0,0715	0,0519
Taxes	0,0482	0,0453	0,0482	0, 0453
Grid	0,0560	0,0320	0,0130	0,0100
Retail rate	0,1757	0,1292	0,1327	0,1072

The housholds' bills are quiet similar according to the tariff applied (Table 5). It allows us to compare with the NPV generated with the PV-battery investment under these tariffs.

Table 5: Households' bills under different tariffs

Tariffs	Flat	TOU_2P	TOU_4P
CH03	460€	476€	475€
CH05	670€	694€	697€

5 PV profitability without subsidy and under the current policy support

In this section, the profitability of PV investments under different pricing are presented. Batteries are not simulated in this section. We first, show the profitability without subsidies and with the current subsidy scheme. Then, results are described by analysing the profitability drivers of PV investments.

5.1. NPV without subsidy and with the current subsidies

Without subsidy, photovoltaic self-consumption is not profitable for both households (Figure 4). The pricing scheme doesn't have an important impact on the investment profitability. However, the sizing of the PV highly affects the profitability. Indeed, the NPV is about -1,150€ with a 1 kW PV for the household CH03 and -860€ for CH05. The more the capacity increases, the lesser the NPV is: -6,000€ for both households with a 4 kW PV. With the current subsidy, PV investment is profitable for the household CH05 with a PV sizing from 1 kW to 3 kW and the optimal sizing is 1.5 kW. For CH03, the increase of the PV capacity entails a decrease of the NPV. Above 3 kW, the decrease of the PV upfront purchase subsidy with the levy applied on the incomes from the selling of the excess generation highly affect the profitability. The impact of the pricing scheme on the NPV is higher in the case with the current subsidies and the NPV is higher under the TOU_2P tariff for both households.

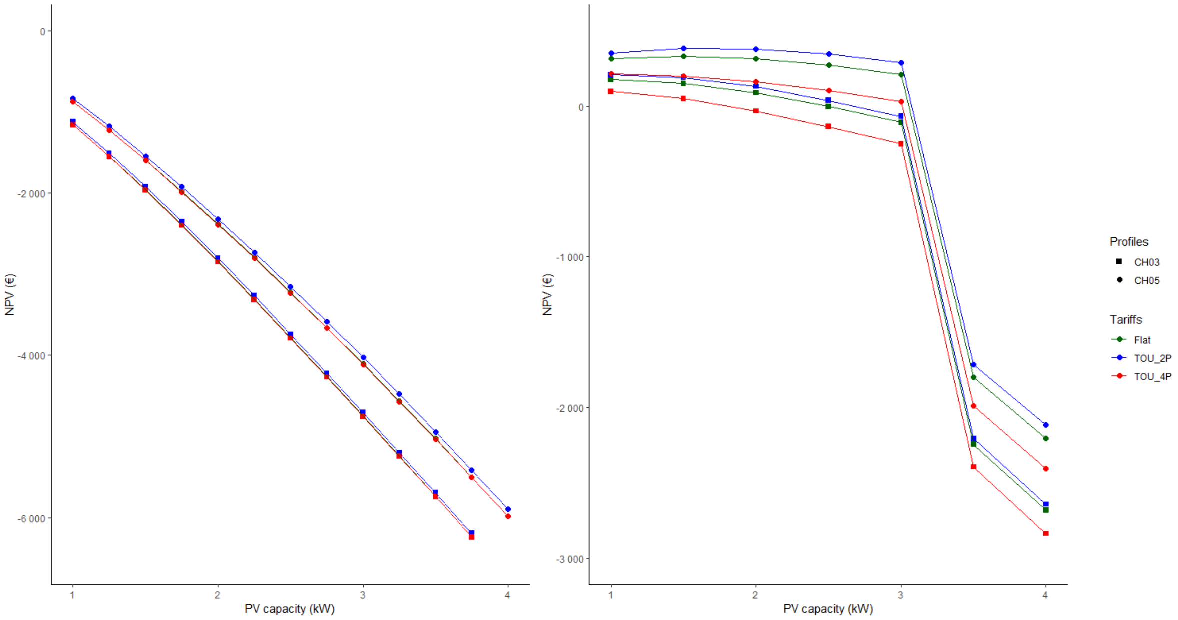

Figure 4: NPV of PV installations without subsidy (left) and with the current subsidy scheme (right)

Without subsidy, PV investments costs are prominent compared to the savings from self-consumption for both households (Figure 5). Feed-in tariffs enable them to strongly increase the incomes even for low PV capacities. Indeed, incomes from FIT represent 50% of the total incomes for CH03 and 40% for CH05. Regarding the savings from self-consumption, the most important savings occur during peak periods for both TOU_2P and TOU_4P tariffs. For the last tariff, savings are more important during summer.

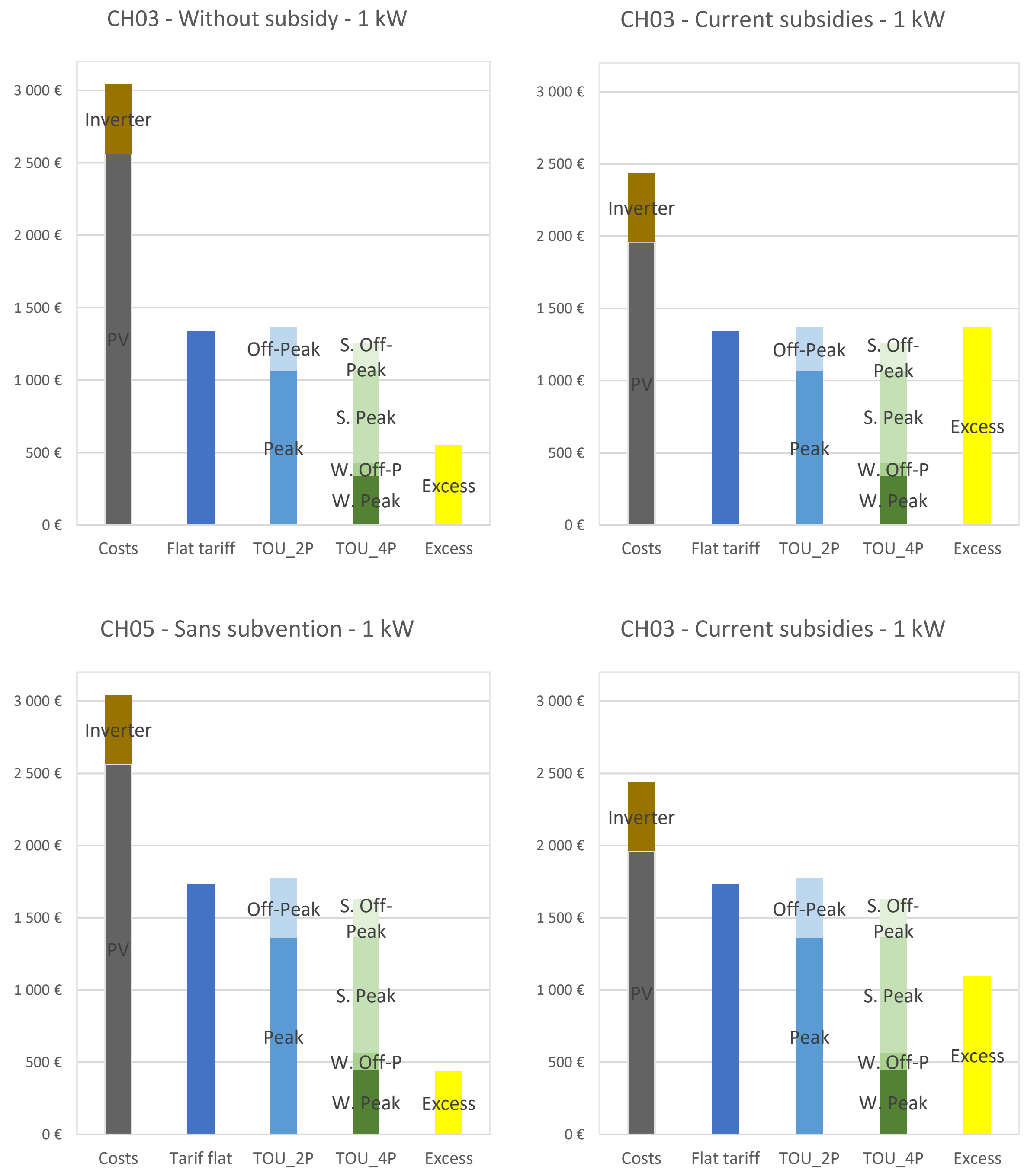

Figure 5: Share of the incomes and costs for a PV investment of 1 kW

5.2. Economics of PV systems

We have seen that the PV investments without subsidy are not profitable for both households. The calculation of the levelized cost of electricity (LCOE) enables us to determine whether it is profitable or not. The $LCOE_{PV}$ is define as:

$$LCOE_{PV} = \frac{\sum_{n=1}^{N} \frac{Cost(n)}{(1+r)^n}}{\sum_{n=1}^{N} \frac{Prod(n)}{(1+r)^n}} \tag{9}$$

By comparing the $LCOE_{PV}$ with the retail rate, we can define if the grid parity is reached. Without subsidy, the $LCOE_{PV}$ is equal to $0{,}1327€/kWh$, so the $LCOE_{PV}$ is lower than the retail rate $(0{,}1452€/\text{kWh})$. If the prosumer invests in PV power plant to self-consume his generation, he would save $0{,}1452 - 0{,}1327 = 0{,}0125€$ for each kWh self-consumed. Why the NPV is negative for both households? The profitability depends on the self-consumption rates and on the value of the excess generation. When the $LCOE_{PV}$ is lower than the retail rate, the prosumers must have a minimum self-consumption rate (α) of:

$$LCOE_{PV} = \alpha . Price_{RT} + (1 - \alpha) Price_{Ex} \tag{10}$$

With $Price_{RT}$ as the retail rate and $Price_{Ex}$ the selling price of the excess generation. In our case study, the PV investment profitability without subsidy is reached with a self-consumption rate of:

$$0{,}1327 = \alpha 0{,}1452 + (1 - \alpha) 0{,}04$$

$$0{,}1327 = \alpha 0{,}1452 + 0{,}04 - 0{,}04\alpha$$

$$0{,}0927 = \alpha 0{,}1052$$

$$\frac{0{,}0927}{0{,}1052} \approx 0{,}88 = \alpha$$

If the households self-consumed more than 88% of their PV generation, the PV investment would be profitable under the flat rate. However, both households are far from reaching this self-consumption rate level.

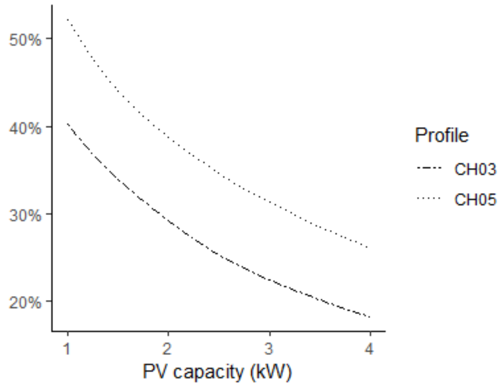

Figure 6: Self-consumption for different PV capacities

Stationary batteries are a solution to reach a high self-consumption rate. However, the costs of battery investments are high compared to the retail prices in France (Yu, 2018). A more suitable policy to improve profitability under TOU tariffs could be an upfront purchase subsidy for battery investment and phasing out the FIT on the excess generation. With a stationary battery, prosumers could increase their self-consumption rates and improve their profitability by shifting consumption from off-peak price to peak price.

6 Alternative policy

To define the level of subsidy for the battery investment, the economic features of the batteries is described in the next section. Then, we present the results of the PV-battery investment profitability under the alternative policy.

6.1. Battery investment premium

The incentivizing to invest in batteries depends on the levelized cost of storage (LCOS) and the gap between the retail rate and the $Price_{Ex}$ (Figure 7). The income from storing electricity is equal to the difference between the retail rate and the LCOS. If this difference is lower than the difference between the retail rate and the price for the excess generation, prosumers are prompted to invest in a battery.

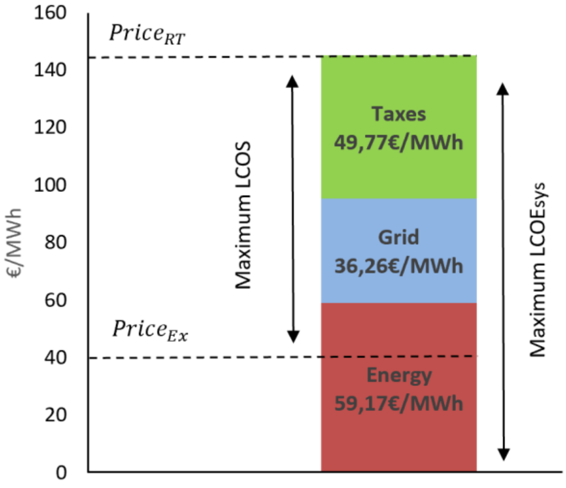

Figure 7: Breakdown of flat retail rate for a household with a power subscribed of 6 kW and maximum LCOS according to the retail rate and the price of the excess generation (the grid part represents the variable part and does not include the fixed part)

The LCOS is defined as:

$$LCOS = \frac{\sum_{n=1}^{N} \frac{cost(n)}{(1+r)^n}}{\sum_{n=1}^{N} \frac{E_{out}(n)}{(1+r)^n}} = \frac{cost_{Batt}(1) + \sum_{n=1}^{N} \frac{cost_{Batt}(n)}{(1+i)^n}}{\sum_{n}^{N} \frac{cycles * DOD * C_{rated} * \eta_{Batt}}{(1+r)^n}} \tag{11}$$

The cost depends on the first battery investment ($cost_{Batt}(1)$) and on the replacement of it at year n. The total costs are divided by the electricity discharged by the battery. The upfront purchase subsidy is set to get the following result:

$$LCOS = Price_{RT} - Price_{Ex} \tag{12}$$

In this situation, a prosumer is indifferent between investing in a battery to store excess generation and to sell excess generation at $Price_{Ex}$. We assumed that the price for the excess generation is the current average market price equal to 40€/MWh. So, the LCOS must be equal to:

$$LCOS = 0{,}145 - 0{,}04 = 0{,}1052$$

$$0{,}1052 = \frac{cost_{Batt}(n)}{\sum_{n=1}^{N} \frac{E_{out}(n)}{(1+r)^n}}$$

$$cost_{Batt}(n) = 0{,}1052 * 1480 = 155€/kWh$$

The cost of the battery in 2020 is 680€/kWh, so the upfront purchase subsidy is set as $680 - 155 = 525€/kWh$. The upfront purchase subsidy is calculated for each battery replaced based on the evolution of battery performances.

6.2. NPV of PV-battery systems with the alternative policy

PV-battery investments are not profitable in any case with the alternative policy (Figure 8). In some cases, PV-battery investments are more profitable than PV investments alone. The TOU_2P tariff is more attractive than the others for both households. So, this tariff is attractive whether there are subsidies are not. The pricing scheme has a higher effect compared to the current subsidies. For both households, the gap between the TOU_2P and the TOU_4P is about 100€ and 300€. The PV sizing has a strong impact on the profitability. Indeed, the NPV decreases by about 1,500€ from a 1 kW PV to a 2 kW PV. So, they are encouraged to invest in a small PV capacity. The optimal peak power for the PV system is 1 kW for both households with a battery capacity of 4 kWh for CH03 and 3 kWh for CH05.

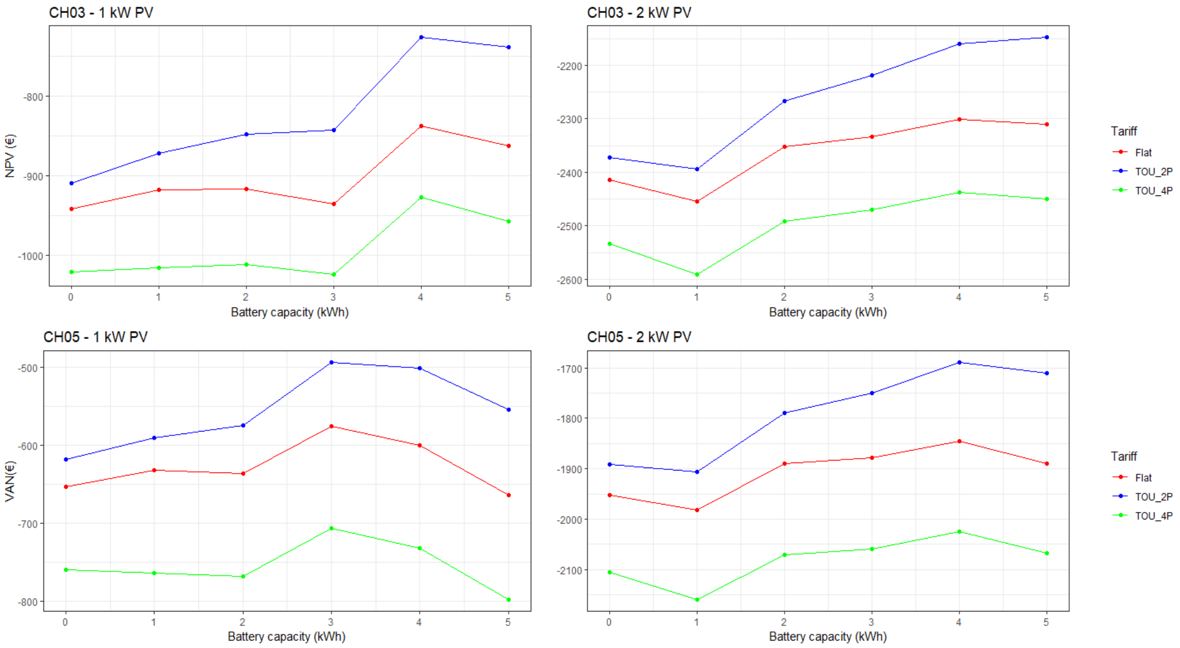

Figure 8: NPV with the alternative policy

The results reveal some variations for PV sizing of 1 kW. In some cases, the battery is replaced once or twice. These features have an important impact on the NPV because it costs less to invest in two batteries instead of three even by taking into account the value of the last battery. It turns out that the number of battery replacements depends highly on the relationship between the PV and the battery sizing. If the PV capacity is higher than the battery capacity, the battery aging will be accelerated. Indeed, the amount of electricity which throughput the battery will be higher leading to a higher aging process. For instance, if CH03 installs a 1 kW PV with a 3 kWh battery, he will need to replace the battery twice whereas once if he installs a 4 kWh battery. Self-consumers must take this into account in their decisions. The sizing of the two technologies has to be optimal in order to decrease the investment costs related to the battery replacements. According to Solano and al. (2018), optimal sizing corresponds to a relation of 2 kWh/kW installed. Our simulations show an optimal relation of 3 kWh/kW for CH03 and 4 kWh/kW for CH05 confirmed by the results of Dietrich and Weber (2018).

Regarding pricing scheme, the TOU_2P tariff maximizes the profitability of PV-battery investments as for PV investments alone. Batteries increase self-consumption mainly during peak prices. The TOU_2P has a higher peak price than the flat rate and occurs mainly during sunny hours, so the TOU_2P is more attractive than the flat rate. Nevertheless, the NPV gap between these tariffs is low compared to the investment amounts. The worst NPVs are reached with the TOU_4P because PV produce less in winter while the higher price corresponds to this period. By increasing the battery capacity, the self-consumption increases mostly in summer where the tariff is less costly than the flat rate and the TOU_2P. Despite that peak price in winter is higher by 4 c€/kWh than the flat rate, the volume effect is higher than the price effect.

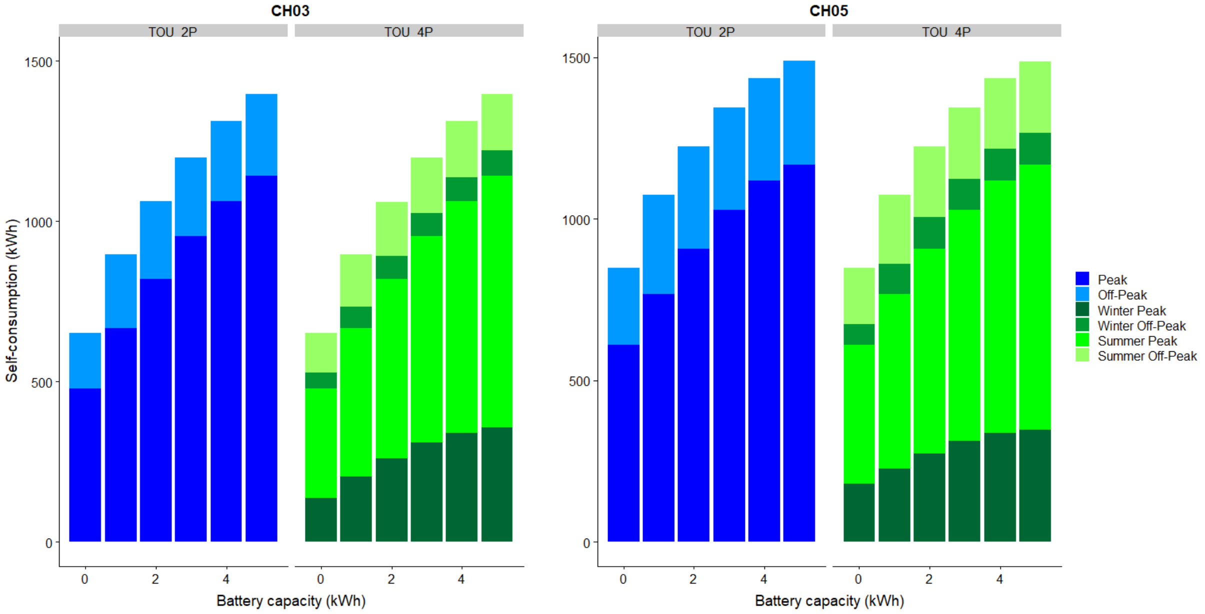

Figure 9: Self-consumption by period

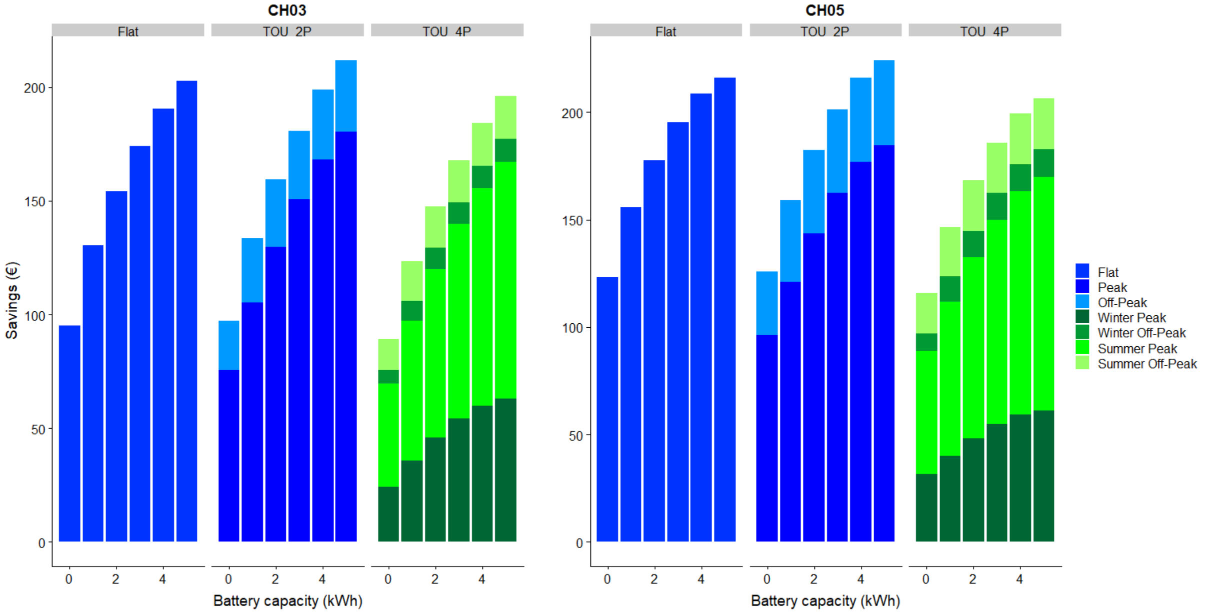

Figure 10: Savings from self-consumption by period

Even if the PV-battery investments are not profitable with the alternative policy for both households, they could be profitable for others. The self-consumption needed to reach a 0€ profitability and the observed self-consumption for both households are depicted on the (Figure 11). We can notice that the households are far from reaching a 0€ NPV. Moreover, with 1 kW PV, battery capacities above 2 kWh is not profitable even if the prosumers self-consume all their generation. Indeed, they have to reach a self-consumption above 100% which is not possible albeit CH03 maximizes its investment profitability with a capacity of 3 kWh/kW and 4 kWh/kW for CH05. If these households decide to invest, they have to setup lower capacities and to increase their self-consumption rates. Regarding dynamic rates such as TOU_2P and TOU_4P, prosumers can improve the investment profitability by changing the battery charge operation. If we consider an installation of 2 kWh/kW which maximizes the NPV, the "Peak strategy" strategy enables to increase the self-consumption during peak rates (Figure 13).

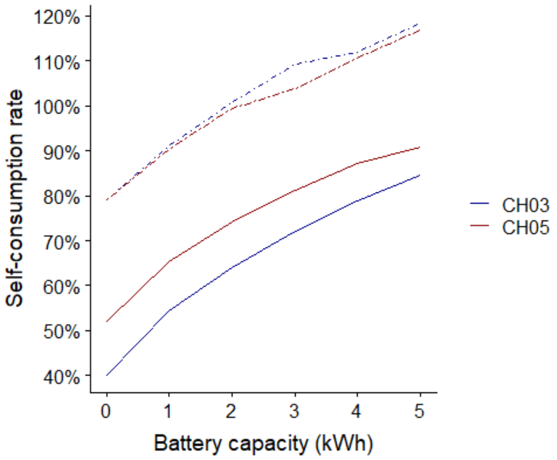

Figure 11: Self-consumption reached by houseĥolds (solid lines) and self-consumption rates to reached a 0€ NPV (dashed lines)

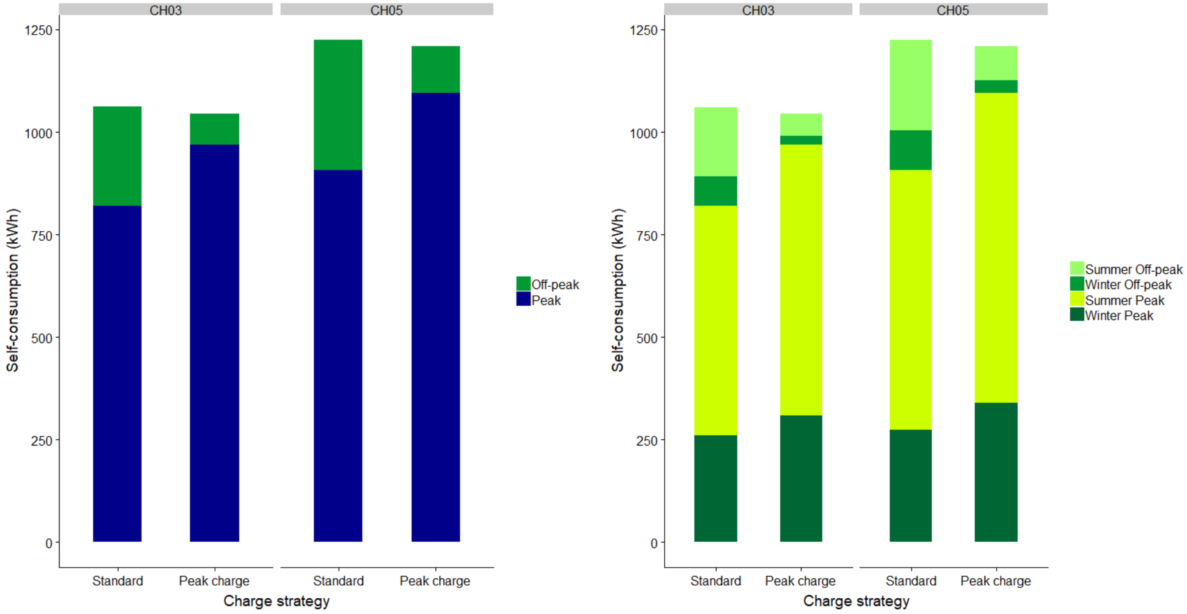

Figure 12: Self-consumption with different strategies for a 1 kW PV and a 2 kWh battery

For TOU_2P rate, there is an increase of 10% of self-consumption during peak rates for CH03 and 20% for CH05. However, the total self-consumption decreases compared to the strategy that maximizes self-consumption because the battery doesn't release the electricity stored during off-peak prices. In this case, the likelihood of having excess generation during off-peak prices is higher because the battery is more often empty during off-peak prices with the strategy that maximizes self-consumption. Even if the self-consumption increases during peak rates, the NPV is still negative for both households but it increases by about 200€ for TOU_2P and TOU_4P rates (Table 6).

Table 6 : NPV with "Peak strategy" strategy and the one which maximizes self-consumption

	CH03		CH05	
	TOU_2P	TOU_4P	TOU_2P	TOU_4P
Maximize SC	-850€	-1 010€	-575€	-770€
"Peak strategy"	-633€	-800€	-370€	-570€

6.3. Cost comparison of the policy supports

We have seen that the PV-battery investment is not profitable with the alternative policy but, if it costs less than the current one, the upfront purchase subsidy could be higher. The comparison of the policy costs is made with the optimal sizing. For the current one, the optimal sizing is 1 kW for CH03 and 1.5 kW for the CH05. Regarding the alternative policy, the optimal sizing is 3 kWh/kW for CH03 and 4 kWh/kW for CH05. The alternative policy's costs are three times higher than the current one (Table 7).

Table 7: Policy supports cost comparison

	CH03		CH05	
	PV 1 kW	PV 1 kW Batt 4 kWh	PV 1,5 kW	PV 1 kW Bat 3 kWh
FIT costs	730€	0€	580€	0€
PV upfront purchase subsidy	390€	390€	585€	390€
Reduced VAT	215€	215€	320€	215€
Battery upfront purchase subsidy	0€	3 820€	0€	2 870€
Total	1 330 €	4 425€	1 485 €	3 475€

7 Conclusion

The simulations performed have shown that the grid parity is reached in France, but prosumers have to self-consume at least 88% of their production. The current subsidy scheme encourages households to invest in a PV power plan to self-consume a part of their generation even if the generation doesn't often match the consumption because FIT guarantees stable incomes. The profitability of a PV-battery investment is not profitable even with the implementation of an upfront purchase subsidy which represents 77% of the battery costs. It is the case for all pricing schemes. If time of use rates will be applied in the future such as TOU_4P, the PV generation and the storage during peak hours will not be sufficient to generate enough profitability. Without subsidy, the pricing scheme has not an important impact on the NPV because the investment costs are high compared to the incomes. Regarding the current subsidy scheme, the impact of the pricing scheme is also low because the incomes from FIT represent an important share of the total incomes. However, the pricing scheme is important to take into account in the case of the alternative subsidy because the battery can increase the self-consumption during peak rates. So, the phase out of the current subsidies with the development of Time of Use Tariffs can highly affect PV self-consumption development. The NPV increases by modifying the battery operation but it is not sufficient to encourage households to invest in batteries. In this study, we have assumed that prices are constant over time which is probably a conservative assumption. By releasing this hypothesis, the break-even point for PV-battery investments is reached with an annual increase of the retail rate of 2% for CH05 and 3.3% for CH03. This study has revealed that, in countries where retail rates are low, the investment costs are the key driver of PV self-consumption investment.

Indeed, the savings are to low compared to the investment costs. We have also pointed out that the sizing is an important driver of the profitability. If households decide to invest, they have to take into account the aging process related to the sizing of the two technologies. A relation from 3 kWh/kW to 4 kWh/kW enables to maximize the profitability.

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9 Annexe

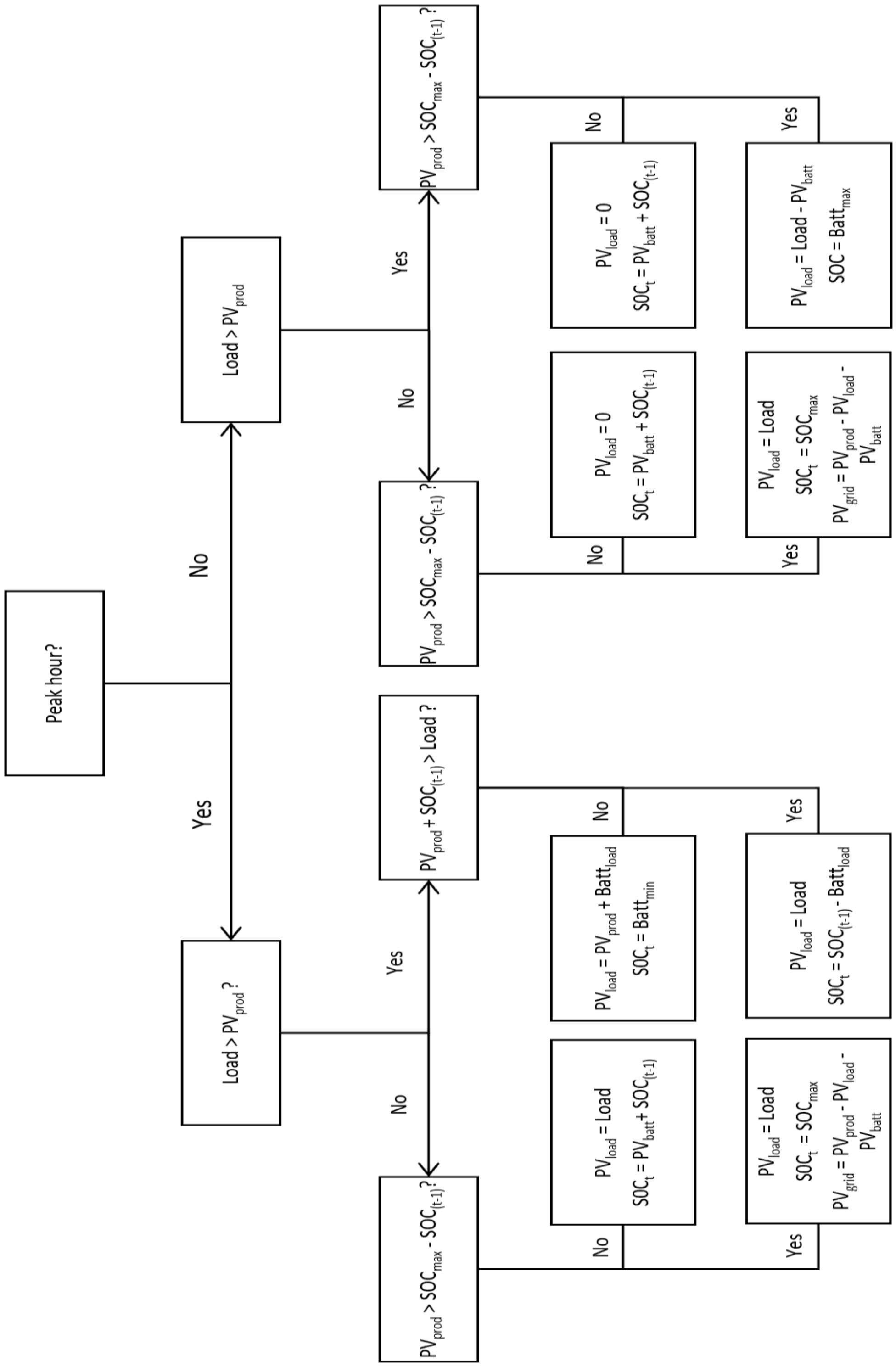

Figure 13: "Peak strategy" strategy derived from Young and al. (2019)