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WORKING PAPER

AN ECONOMIC ASSESSMENT OF THE RESIDENTIAL PV SELF-CONSUMPTION SUPPORT UNDER DIFFERENT NETWORK TARIFFS

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By generating their own electricity with photovoltaic (PV) panels, households are less dependent on the grid. However, because there is a mismatch between PV generation and consumption, the economic benefits from the bill savings are usually low compared to the economic compensation of the excess electricity fed into the grid. The economic benefits may drop by the implementation of Time-of-Use tariffs or capacity tariff because the prices and the peak load might be higher in the evening at night when PV generation does not occur. Stationary batteries might increase PV self-consumption by storing PV production when electricity prices are low and releasing it during peak prices. However, Feed-in-tariffs applied on the excess generation does not encourage prosumers to invest in a battery. In this paper, we assess the profitability of a PV investment under the current French subsidy scheme. Then, we propose an alternative policy which guarantees an upfront purchase subsidy for the PV and battery investments but without Feed-in tariffs. Based on this alternative policy, we simulate economic benefits from various PV and battery capacities with different pricings. We show that PV self-consumption investment is more profitable with Feed-in tariffs than with a battery premium under Time-of-Use and capacity tariff. Nonetheless, the current subsidy scheme is costly compared to the implementation of a battery premium. Thus, some policy recommendations are provided to improve subsidy scheme.

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Introduction

In many countries worldwide, photovoltaic (PV) technology has been fostered by different support policies such as Feed-in Tariffs (FIT) 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 (IEA PVPS, 2016). This prominent development led to a fast decrease of the photovoltaic technology costs. This trend combined with the increase of the retail rates, due to the financing of the support policies, 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 PV power plant is equal to the cost of buying electricity from a supplier. When the PV generation cost decreases further, it becomes profitable to invest in a PV power plant to self-consume a part of the production. The development of PV self-consumption has been encouraged through different incentives and regulations. Globally, the prosumers (people who are both **pro**ducers and con**sumers**) benefit from savings on the variable price of the retail rate and additional bonus or upfront purchase subsidies (Masson et al., 2016). However, there are many differences in support policies regarding the value of the excess generation injected into the grid, the time frame for the credit compensation and the additional taxes or grid charges. In some countries, the excess production is valuated with FITs or green certificates or based on the wholesale market with a bonus. In France, a new regulation was implemented in 2016 allowing PV owners to self-consume a part of their generation and the excess generation is sold at a FIT. Before this support scheme, PV owners were encouraged to sell all their generation at a FIT. On October 2019, the number of residential prosumers was low (58 000) compared to residential PV owners (405 000) but the development of self-consumption is expected to grow in the future (Yu, 2018). Indeed, 3.8 million households in France are expected to be prosumers in 2030 according to the French transmission grid operator (RTE, 2017).

Despite the PV self-consumption subsidies, the self-consumption rates (the ratio of the production that is consumed) are low in most European countries because the production is not well synchronized with the consumption. Prosumers could shift their consumption in order to improve their self-consumption rates but some consumptions are difficult to shift such as TV or cooking appliances. For these electric appliances, the elasticity is very low (Oberst et al., 2019). At the same time, the subsidy costs for PV technology raised a lot (CRE, 2014; del Río and Mir-Artigues, 2014; Fraunhofer ISE, 2018; Nolden, 2015) leading to political measures to limit the evolution costs for the ratepayers (EPIA, 2013). Moreover, the development of self-consumption raises a lot of concern for the grid management (CEER, 2017; Tobnaghi, 2016) and leads to cross-subsidies from consumers to prosumers (Clastres et al., 2019). Many grid operators want to charge their consumers based on their capacity subscribed or with Time-of-Use tariffs (TOU) in order to better reflect their costs (Masson et al., 2016). For instance, the French energy regulator introduced a four-part tariff for residential consumers. These tariffs could have a negative impact on the self-consumption profitability because peak prices occur in the evening while PV generation occurs during afternoon. Stationary batteries could improve the prosumers' savings by storing PV generation when the price is low and releasing it during peak prices. It also allows the prosumers to increase the self-consumption rate and so, to decrease the financial support applied to the excess generation. 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 this context, this paper analyses the consistency of the current French PV self-consumption policy by comparing the current policy scheme to an alternative one 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 support policy under a flat tariff, two Time-of-Use tariffs and a demand charge. A deep analysis on the relation between the self-consumption rate, the tariff and the profitability is provided. 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. The model is presented in section 3. In section 4, the data and the case study are presented. Results for the current policy and the alternative one is described in section 5. Section 6, we conclude and propose some policy recommendations.

1 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). On 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 FIT 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 in applying a FIT on the whole generation. The FIT allowed a prominent development of the PV capacities in France. However, the share of self-consumption capacities is now higher than capacities under FIT scheme (Figure 1 – right graph).

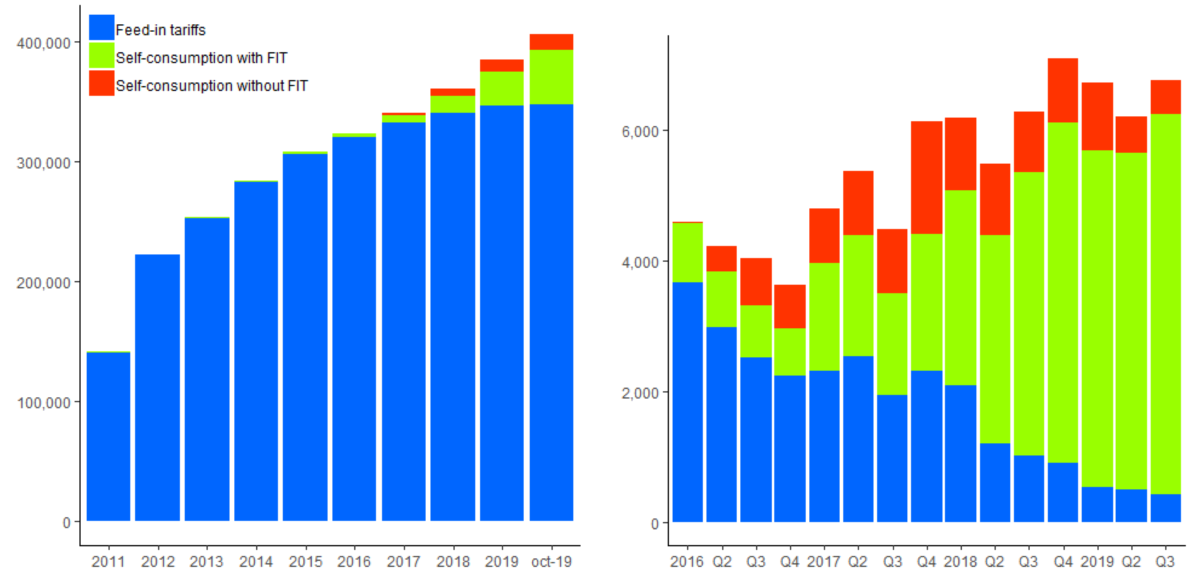

Figure 1: Cumulated PV up to 36 kW (left) and quarterly evolution (right) in France – Source : Enedis (2018)[1]

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[1] Enedis manages 95% of the French distribution grid.

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). FITs applied on the excess generation allow 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 have 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 subsidies (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 TOU decreases the PV investments profitability (O'Shaughnessy et al., 2018). Installing a battery can improve the profitability under a TOU or a demand charge (Kaschub et al., 2016). However, it is 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 encourage prosumers to invest in them, but an ill-designed subsidy scheme can hinder the adoption of the battery technology. The regulatory scheme on the excess generation has an important impact on the adoption of batteries. Indeed, high FITs 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.

To limit cross-subsidies, many grid operators and regulators want to implement demand charges or TOU tariffs. New regulations such as network pricing could decrease the need of subsidies. By optimizing the battery schedule to maximize self-consumption during peak tariffs 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 TOU 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 FITs or net-metering. To the best of my knowledge, there is no evaluation of public supports for PV self-consumption under different tariffs. Moreover, all the studies mentioned performed an optimization of the PV-Battery sizing without studying the relation between the two technologies on the profitability. This paper attempts to fill this gap by analyzing the relation between the self-consumption rate and the break-even point for each technology.

2 Model

A load flow model was performed to compute the volume of PV generation consumed by the households and also the generation injected into the grid (Section 3.1). This model allows us to assess the amount of savings and the incomes generated from the selling of the excess generation. Then, the investments of PV coupled with batteries are analyzed by computing the Net Present Value (Section 3.2). We do not consider payback time and focus only on whether the investment is profitable or not under different subsidy schemes and retail pricing. The Net Present Value is calculated according to the current subsidy scheme and an alternative one described in Section 3.3.

2.1. Electric flow simulation

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

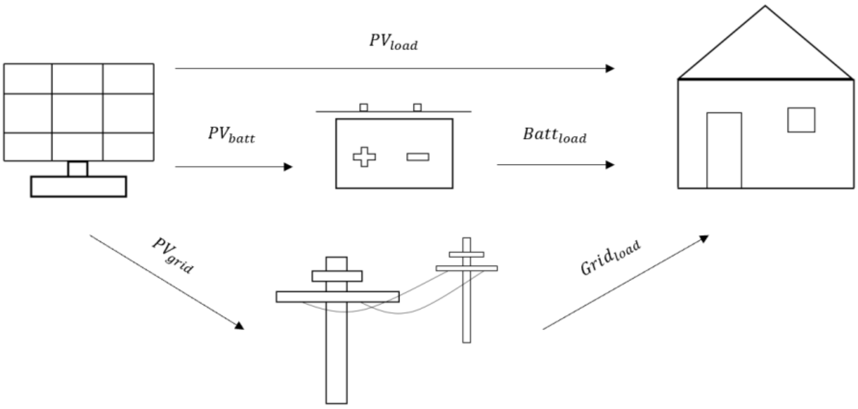

Figure 2: Electric flow chart of the PV-battery installation

Three battery charge simulations are performed in this study. The purpose of the first strategy called “Baseline strategy” is to maximize 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 goes toward charging the battery. If the battery is charged at the maximum of its capacity, the excess generation is injected into the grid. An illustration of this strategy can be seen with the Figure 3.

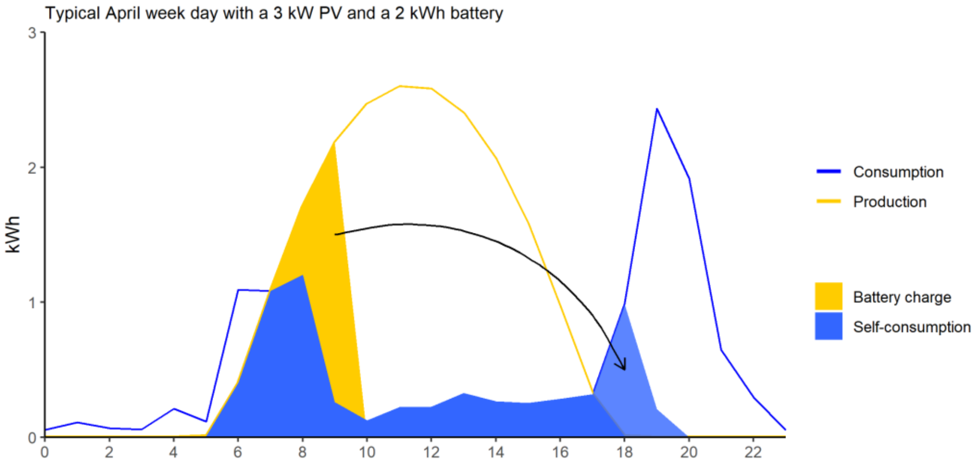

Figure 3: Baseline strategy

The purpose of the second strategy called “TOU strategy” is to maximize the PV self-consumption during peak prices in order to maximize bill savings. During peak prices, the battery operation 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 does not supply the load (Appendix 1). The purpose of the third strategy called “Peak load strategy” is to decrease the peak load in order to increase the savings from the grid charge. This strategy attempts to decrease the peak load by 1 or 2 kW when it is possible. In order to do that, the PV generation goes first towards charging the battery 24 hours before the peak load occurs. When the battery is fully charged, then the PV generation is self-consumed or injected into the grid. We do not consider the possibility to store electricity from the grid. This strategy can decrease the quantity of self-consumption and the investment profitability (Pena-Bello et al., 2017).

2.2. Economic metrics

a) LCOE and grid parity

The Levelized Cost of Electricity (LCOE) is a common metric to evaluate the generation cost for a given technology (Lai and McCulloch, 2017). The $LCOE_{PV}$ defines the generation cost per kWh over the PV panels lifetime:

$$LCOE_{PV} = \frac{\sum_{n=1}^{N} \frac{I^{PV} + I_n^{Inn} + I_n^{Batt}}{(1+r)^n}}{\sum_{n=1}^{N} \frac{q_n^{prod}}{(1+d)^n}} \tag{1}$$

Where, $I^{PV}, I_n^{Inn}, I_n^{Batt}$ is respectively the PV, inverter and battery investments, d is the discount rate, q_n^{prod} is the production and n is the period. If the $LCOE_{PV}$ is equal to the volumetric part of the retail rate, the grid parity is reached. In that case, a household is indifferent between purchasing electricity from a supplier or investing in PV panels to self-consume all the generation. If the $LCOE_{PV}$ is less than the retail rate, then the prosumer saves the retail rate minus the cost of producing the electricity ($LCOE_{PV}$) for each kWh self-consumed. The grid parity is calculated according (2) in many studies (Branker et al., 2011) but a change in the pricing scheme affects the profitability such as an increase of the fixed component of the network tariff. This is not taken into account in the LCOE formula. Furthermore, the grid parity depends on the self-consumption rate and the level of incomes from the excess generation. In fact, an investment could be nonprofitable even if the grid parity were reached because the self-consumption rate is low. If we assume that the excess generation is injected freely into the grid, the self-consumption rate (α) must at least be equal to the ratio between the $LCOE_{PV}$ and the retail rate p^{RR} (€/kWh):

$$LCOE_{PV} = \alpha \cdot p^{RR} \xrightarrow{\qquad} \frac{LCOE_{PV}}{p^{RR}} = \alpha \tag{2}$$

For instance, if the left side of (2) is 0.8, the prosumer must self-consume at least 80% of the PV generation. When the excess generation is remunerated (at p^{ex}), the grid parity is defined as:

$$LCOE_{PV} = \alpha \cdot p^{RR} + (1-\alpha) \cdot p^{ex} \tag{3}$$

According to (3) the grid parity could be achieved with a low self-consumption rate if p^{ex} is high. Subsidy scheme can have an impact on each parameter of (3). For instance, the French government implemented an upfront purchase subsidy which decreases the value of $LCOE_{PV}$ and the FITs allow a higher profit with a low self-consumption rate. A battery premium such as in Germany can highly affect α. Moreover, increasing the fixed component of the network tariff decreases the value per kWh of the retail rate. All these parameters will be analyzed according to the subsidy scheme. Furthermore, the PV investment could be profitable even if the grid parity was not reached if the retail rate increases over the years. In this paper, we assume a yearly increase of the retail rate, thus the grid parity is calculated by iterations. It is worth mentioning that the $LCOE_{PV}$ is linear according to the PV capacity because the PV and the inverter costs are a linear function of the sizing.

2.3. Net Present Value

The levelized cost of electricity is a useful metric to define if the grid parity is reached or not, but only under a flat tariff. The self-consumption profitability will also be studied with the Net Present Value (NPV) to compare the profitability under different tariffs. The profitability of the PV-Batteries investment for the household *i* is represented by:

$$NPV_i = \sum_{n=1}^{N} \frac{CF_n}{(1+d)^n} - I^{PV} - I^{Inv} - I^{Batt} + V^{Batt} \tag{4}$$

The NPV includes 5 terms. The first one is the cash flow (CF_y) which represents the avoided cost of the bill composed of the energy (p_t^{En}), grid (p_t^{grid}) and tax components by self-consuming (q^{SC}) the production. The prosumer makes profit by selling the excess generation (q^{ex}). The price p^{ex} depends on the subsidy scheme. The current support policy guarantees a FIT for 20 years. After this period, the excess generation is supposed to be sold at the current average spot price.

$$CF_n = \sum_{t=1}^{8760} [q_t^{SC} \cdot (p_t^{En} + p_t^{grid} + taxes)] + (q_t^{ex} \cdot p_n^{ex}) \tag{5}$$

The second term of the NPV is the PV investment costs (I^{PV}) which depends on the PV capacity (PV) and on the PV premium (Sub^{PV}). The PV investment is made once and PV lifetime is assumed to be 25 years (Hoppmann et al., 2014). The inverter is assumed to be replaced on the 12th year at the same cost. The battery investment costs depend on the cost of the first battery installed ($Cost_1^{Batt}$) and the battery premium (Sub^{Batt}). When the battery has reached the end of its life, it is replaced at cost: $\frac{Cost_{Batt}(n)}{(1+d)^n}$.

$$I^{PV} = PV \cdot (Cost^{PV} - Sub^{PV}) \tag{6}$$

$$I^{Inv} = PV \cdot Cost^{Inv} + \frac{PV \cdot Cost^{Inv}}{(1+d)^{12}} \tag{7}$$

$$I^{Batt} = Batt \cdot [(Cost_1^{Batt} - Sub^{Batt}) + \frac{Cost_n^{Batt}}{(1+d)^n}] \tag{8}$$

The last term (V^{Batt}) represents the remaining value of the last battery set up when the PV is obsolete (Bertsch et al., 2017; Kaschub et al., 2016).

$$V^{Batt} = \left(\frac{Batt_{25} - Batt_{min}}{Bat_{max} - Bat_{min}}\right) \cdot \left(\frac{Batt \cdot Cost_{25}^{Batt}}{(1+d)^{25}}\right) \tag{9}$$

2.4. Alternative policy

The retail rate and especially the network tariff have an important impact on the self-consumption profitability. In 2017, the French regulator implemented a new TOU tariff with four periods and wants to apply it to almost all residential consumers in a few years (CRE, 2019). Generally speaking, TOU tariffs usually decrease the PV self-consumption profitability because higher prices occur mainly in the evening during winter when the sun is missing (O'Shaughnessy et al., 2018). The incentivizing to invest in batteries depends on the Levelized Cost of Storage (LCOS) and p^{ex} (Figure 4). The value of the electricity stored is the retail rate but the prosumer faces an opportunity cost which is the electricity not sold at p^{ex} (Quoilin et al., 2016). The LCOS corresponds to the investment cost (I_n^{Batt}) divided by the amount of electricity discharged (q_n^{dc}) :

$$LCOS = \frac{I_1^{Batt} + \sum_{n=1}^{N} \frac{I_n^{Batt}}{(1+d)^n}}{\sum_{n=1}^{N} \frac{q_n^{dc}}{(1+d)^n}} \tag{10}$$

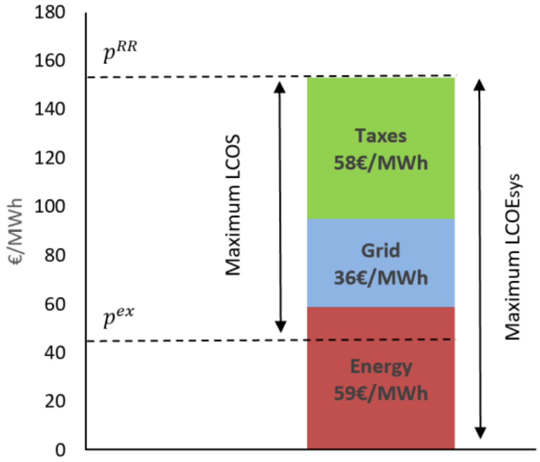

Figure 4: Breakdown of the regulated flat tariff[2] for a household with a power subscribed of 6 kW (data based on CRE 2017)

Stationary batteries could be a solution by storing PV generation during off-peak prices and releasing it during peak prices. However, the battery investment costs are high compared to the retail prices in France (Yu, 2018). To tackle this challenge, I introduced another subsidy scheme composed of an upfront purchase subsidy for PV and battery investments but the FITs are removed. Prosumers have to sell the excess generation at the spot price. The battery cost and the retail rate are known parameters but q_n^{dc} depends mainly on the battery degradation and on the excess generation stored into the battery. So, the premium will be estimated after the simulations (Section 4.2) according to the electricity stored into the battery for the households.

3 Data and case study

3.1. PV and battery

The PV load profiles are generated with the software "Renewable Ninja"[3]. 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 PV location is the south

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[2] The grid part represents the variable part and does not include the fixed part

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

of France which benefits of the highest irradiance corresponding to an annual production of 1626 KWh/kW. 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. The PV cost (without VAT) is €2140/kW and €400/kW for the inverter (I Care & Consult, 2017). We consider a lithium-ion nickel manganese cobalt (NMC) battery as it is the main technology used in the current market (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 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 to the reference case of the IRENA's review (IRENA, 2017). Battery cost is expressed in dollars so an exchange rate is applied to express it in euro. The current average rate of 0.9 is applied. Unlike all the other parameters, battery cost corresponds to the worst case scenario because installation costs are not taken into account. By applying these assumptions, battery cost is equal to 700€/kWh (VAT included) in 2020. Performances of lithium-ion batteries will be improved with the growth of battery market (Zubi et al., 2018). 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	Unit	NMC		
		2020	2025	2030
Depth of discharge (DOD)	%	90	90	90
Round-trip efficiency (η_{Batt})	%	95	96	96.8
Self-discharge (φ)	%/day	0.01	0.01	0.01
Calendar lifetime (N_{Batt})	years	13	16	18
Cycle life indicator (NB_{cycles})	cycles	4810	6060	7640
Battery cost (VAT excluded)	\$/kWh	645	465	335

The battery aging depends on many factors but it can be expressed as the calendar aging and the cyclic aging. We use the same expression from Hesse et al. (2017) to express the capacity degradation. The cyclic aging is calculated as:

$$V_{cycles} = \frac{0.5 \cdot \int |P_{batt}| dt}{NB_{cycles} \cdot Batt} \tag{11}$$

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 $Batt$ 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. The calendar aging is represented as a linear function of the time:

$$V_{cal} = \frac{\Delta t}{N_{Batt}} \tag{12}$$

The battery aging represents the sum of the calendar and the cyclic aging. When the battery capacity reaches 80% of its nominal capacity, the battery is replaced.

3.2. Load profiles

The Load profiles are generated by a software “LoadProfileGenerator” (Pflugradt, 2016). This software provides the power of each electric appliance 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 located in Carpentras (south of France). Both households have 3 children with an annual consumption of about 4.6 MWh. In the first household called “CH05”, both parents work outside the house whereas the one called “CH45”, one of the parents works at the house. For the last, the consumption is higher during the afternoon. These two households represent a situation with a low self-consumption rate (CH05) and a high one (CH45).

3.3. Current French subsidy scheme and tariffs

In France, prosumers benefit from an upfront purchase subsidy and a reduced VAT for capacities up to 3 kW. They also benefit from a free connection charge to the grid. A FIT 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 44€/MWh minus a margin for the buyer equals to €6/MWh[4]. For capacities above 3 kW, the incomes from the sale of the generation is subject to a levy. Subsidies are displayed in Table 2.

Table 2: Current self-consumption subsidy scheme in France

1st T - 2019	[0 – 3] kW	]3 – 9] kW
Upfront purchase subsidy	0.4 €/W	0.3 €/W
VAT	10%	20%
Tax system	None	15.5% of the excess generation revenue
Grid connection	0€	
FIT	0.10€/kWh	

The NPV is computed regarding 4 different tariffs: a flat tariff, a two-part tariff (TOU_2P), a two-part tariff with a seasonal differentiation (TOU_4P) and a capacity tariff (Pow_P). The first two tariffs are widely used in France. The two-part tariff corresponds to a peak and an off-peak price during the day. The corresponding hours are one of these applied by the grid operator in Carpentras (Table 3). The fixed component of the network tariff is charged according to the power subscribed by the household which represents its annual peak load. To set the capacity tariff, we divided the annual grid charge for both household and divided it by their power subscribed (6kW).

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 electricity supplier has yet proposed such a pricing scheme not the capacity tariff. 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). To compute the price of each period, we took the same supply and tax part from the two-part tariff. Then, we added the network tariff set by 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). All the components of each tariff are assumed to increase by 1%/year which corresponds to the average of the inflation these past 10 years in France. The discount rate is set at 5% (Yu, 2018).

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[4] This margin corresponds to the supplier’s margin set in the regulated price.

Table 3: Retail rates for a residential consumer with a subscribed capacity of 6 kW (CRE, 2017)

Tariffs	Flat	Peak period	Off-peak period	Pow_P
Volumetric charge (€/kWh)	0.1524	0.1710	0.1320	0.1164
Capacity charge (€/kW)	[5.24 - 7.67]	[5.24 - 7.67]		27.7
Periods		[7h to 14[[17h to 2h[	[2h to 7h[[14h to 17h[	

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

TOU_4P	December to April		April to December	
(€/kWh)	Winter Peak	Winter Off-peak	Summer Peak	Summer Off-peak
Energy	0.072	0.052	0.072	0.052
Taxes	0.061	0.054	0.061	0.054
Grid	0.056	0.033	0.013	0.010
Retail rate	0.189	0.139	0.145	0.116

4 Results

In this section, the profitability of PV self-consumption investments under different support policies are presented. First, the profitability without battery is examined under the current subsidy scheme and without subsidy (Section 4.1). Afterwards, the battery premium is defined (Section 4.2). Then, the profitability of PV-battery investments for different sizing is assessed (Section 4.3) and also the cost comparison of both policies (Section 4.4).

4.1. NPV with the current subsidies

Without subsidy, the $LCOE_{PV}$ is equal to 0.1232€/kWh which means that the grid parity is already reached in the south of France (Figure 5). Equation (3) allows us to calculate the self-consumption rate which generates a zero NPV under the flat tariff. The break-even point of the PV investment is reached with a self-consumption rate of 74% and 63% by taking into account the inflation. With the current subsidies, the $LCOE_{PV}$ is equal to 0.1008€/kWh which means that the PV investment is profitable even without self-consumption because the $LCOE_{PV}$ is equal to the FIT level. Without subsidy and under a flat tariff, the PV investment is profitable only for the household CH45 but for capacities from 1 kW to 1.5 kW. Under the current subsidy scheme and assuming that the excess generation is sold at the spot price, the break-even point is reached with a self-consumption rate of 43%. Both households reach this rate for capacities from 1 to 1.5 kW for CH05 and from 1 to 3 kW for CH45. Above these sizing, the PV self-consumption investment is not profitable.

As expected, the NPVs are low without subsidy and the tariff scheme does not have a huge impact on the profitability (Figure 6). Under the current subsidy scheme, the households are encouraged to install a PV of 3 kW. The maximum NPV reached is €2340 for CH45 and €1700 for CH05 under the TOU_2P tariff. Above 3 kW, the levy applied on the excess generation and the decreasing of the PV premium decreases the profitability. The tariff scheme has a higher impact on the profitability as the investment costs are lower. However, the difference in NPVs is not tremendous, except for the Pow_P tariff. For instance, for a PV capacity of 3 kW, the difference in NPV is about €230 between the TOU_4P and

TOU_2P tariffs for both households[5]. The lowest NPVs are reached with the Pow_P tariff because the PV generation does not allow the households to decrease their peak loads.

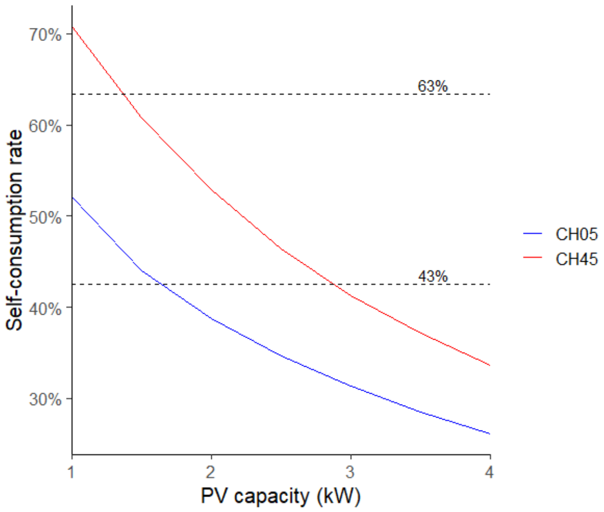

Figure 5: Self-consumption rate for different PV capacities and break-even points with PV subsidies (43%) and without (63%)

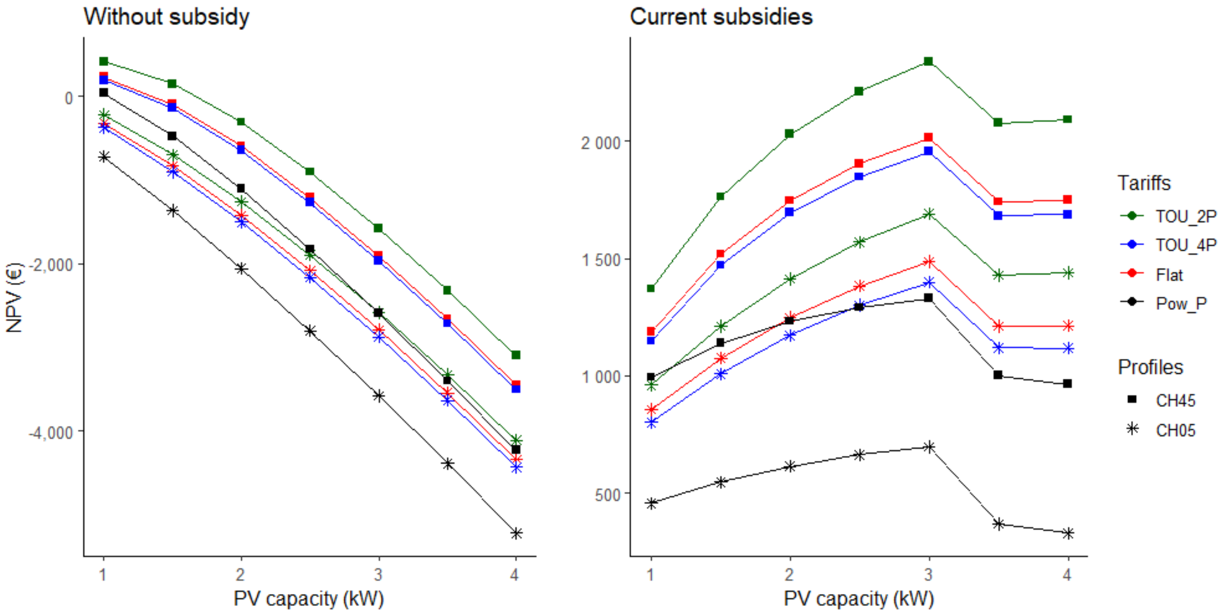

Figure 6: NPVs for both households without subsidy and under the current subsidy scheme

The NPV is higher with the TOU_2P because the self-consumption rate is higher during peak periods (Table 5). For the TOU_4P, the self-consumption rate is also higher during the peak periods but mostly in summer while the price is lower than the flat tariff.

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[5] The breakdown of the incomes and the investment costs are displayed in Appendix 2.

Table 5: Self-consumption rate according to the period (W: Winter; S: Summer)

CH05	Flat	Peak	Off-Peak	W/Peak	W/Off-Peak	S/Peak	S/Off-Peak
1 kW	52%	37%	15%	11%	4%	26%	11%
2 kW	39%	28%	10%	8%	3%	20%	8%
3 kW	31%	23%	8%	7%	2%	16%	6%

CH45	Flat	Peak	Off-Peak	W/Peak	W/Off-Peak	S/Peak	S/Off-Peak
1 kW	71%	55%	16%	16%	4%	39%	11%
2 kW	53%	42%	11%	12%	3%	30%	8%
3 kW	41%	32%	9%	9%	2%	23%	6%

4.2. Battery premium

We have seen that the TOU_4P and the Pow_P are less profitable than the other tariffs. Those tariffs are likely to be implemented in the future, especially the TOU_4P in France (CRE, 2019). The PV self-consumption investment could be highly impacted by these changes. A possibility to adapt the support policy to guarantee a profitable investment for the prosumers is to set a premium for the battery investment. Let us consider the storage parity under the current flat volumetric tariff. Figure 7 displays the LCOS according to the electricity discharge over the battery lifetime. We have seen in section 2.4 that the storage parity is reached when the LCOS is equal to the retail rate minus p^{ex} (0.1144€/kWh). If we assume no inflation over the years, the storage parity is reached with 6100 cycles (or kWh)[6]. However, the maximum cycles reachable by the battery is 4300, so currently, a premium is needed. In 2030, the break-even point for the battery investment is reached with 3500 cycles. Let assume that we set the battery premium according to this threshold. The break-even point is reached with a battery premium of 295€/kWh being 42% of the current costs.

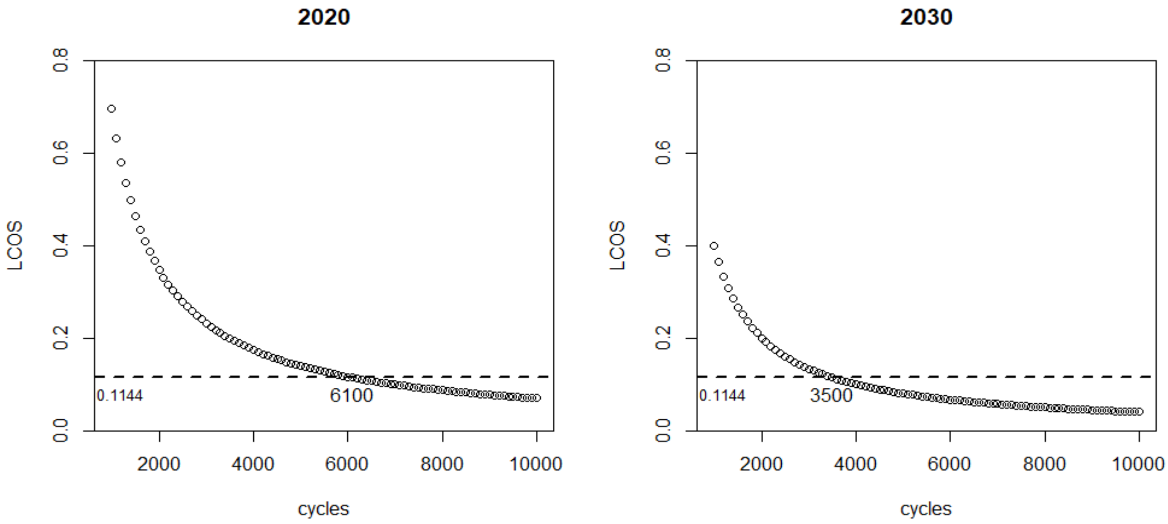

Figure 7: LCOS according to the number of cycles

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[6] We refer to the amount of electricity discharge as cycles because we assume here a battery of 1 kWh. For higher capacities, the number of cycles has to be multiplied by the battery capacity to get the amount of electricity discharged.

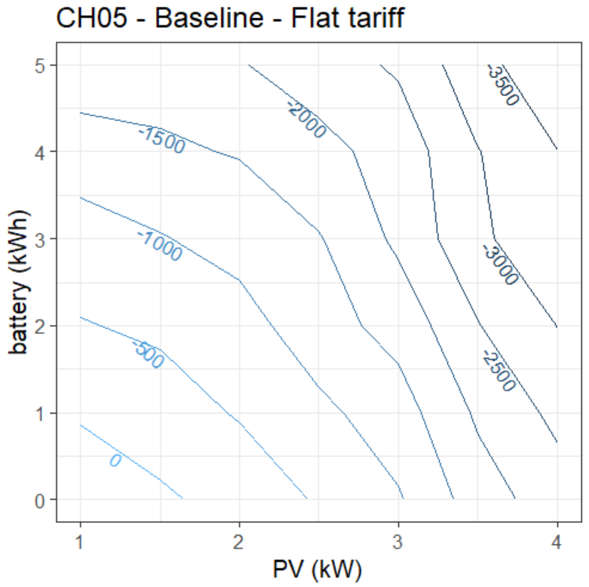
4.3. Profitability under the alternative support policy

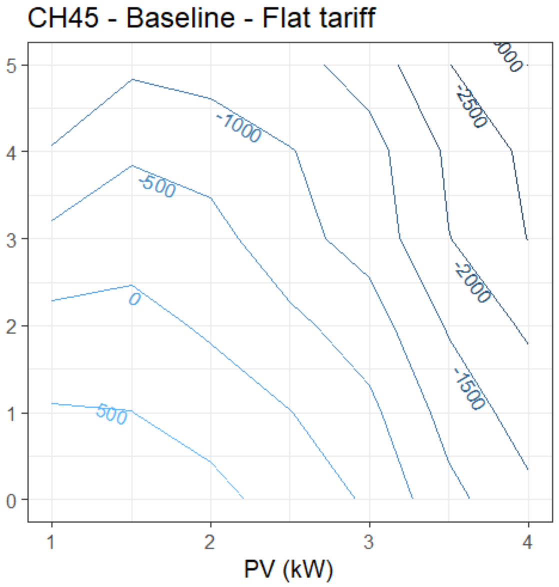
We now present the profitability of a PV/battery investment under the alternative policy scheme, that is to say, with the current PV premium (and the reduced VAT), the battery premium set in the previous sub-section (295€/kWh) and no FIT. The NPVs are evaluated according 3 different tariffs and battery strategies (Section 2.1): baseline strategy, the TOU strategy and the Peak load strategy.

The PV/battery investment is not profitable for household CH05 for every battery charge strategy except for low capacities: 1kW PV paired with 1kWh battery under the flat and the TOU_4P tariffs. For CH45, the investment is profitable with a PV up to 3 kW and a battery up to 2 kWh. Under the Pow_P tariff, the NPVs are negative for both households and for every PV and battery sizing. Even with a smart battery charge, the households can only decrease their peak load of 1 kW. In all cases, the PV/battery system marginal cost is higher than the marginal revenue leading to a decrease of the NPV with the increase of the sizing. Under an optimal decision, the prosumer would not invest. The NPVs under the flat ant the TOU_4P tariffs and the corresponding battery charge strategy are quite similar. Thus, the TOU strategy allows the prosumers to increase the profitability under a TOU tariff but the increasing of the self-consumption during peak periods is no enough to provide a better profitability compared to the flat tariff.

The NPVs are much higher with FITs because the increase in savings represents the retail rate minus the FIT: +0.052€/kWh under the flat rate. In the case of the TOU_4P, the shifting of the self-consumption from the Off-Peak periods to the peak periods increases the savings of 0.05€/kWh in winter and 0.03€/kWh in summer. As the self-consumption is higher is summer, the increase in earnings is low. Thus, the battery investment is interesting for households with a high annual consumption and especially during off-peak periods.

For small PV capacities, the battery sizing has a huge impact on the NPV. The more the battery capacity is, the lower the NPV is. When installing a small PV capacity, the excess generation tends to be low and so, the amount of electricity stored is low leading to high LCOS. For instance, for a 1 kW PV, the LCOS is from about €0.14 (1 kWh) to 0.34€/kWh (5 kWh). However, for PV from 3 to 4 kW, the LCOS is from about €0.13 to 0.15€/kWh meaning that the battery is always fully used.


CH05 - Baseline - Flat tariff


CH45 - Baseline - Flat tariff

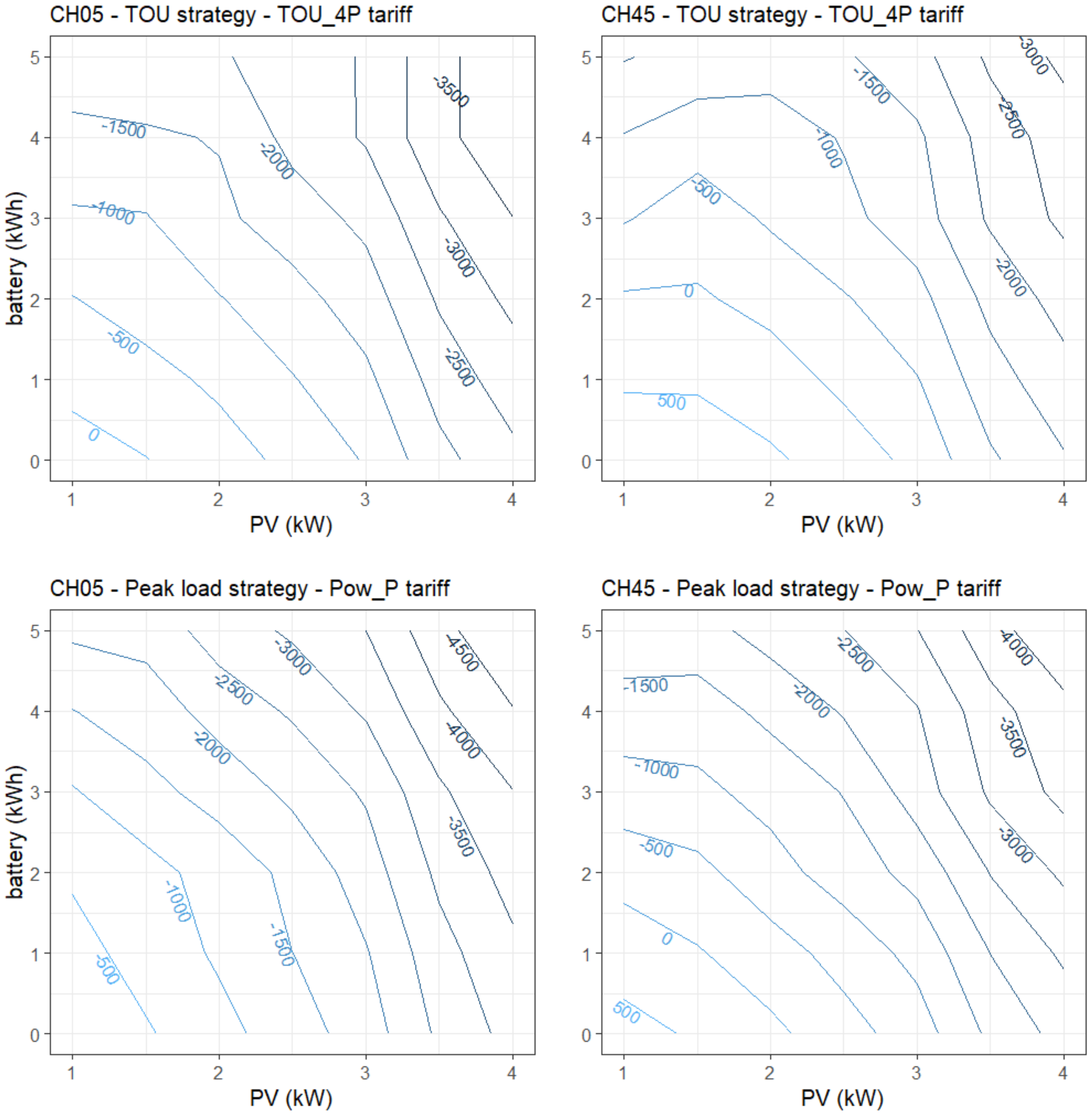


Figure 8: NPVs according to the tariff scheme and the corresponding charge strategy

4.4. Cost comparison of the policy

In order to compare the two subsidy schemes, we need to evaluate their costs. The FIT cost is equal to the difference between the kWh injected into the grid bought at the FIT minus the spot price at the corresponding hour (eq.13). It is worth mentioning that the estimation of the spot price over 20 years is not possible. In order to make an estimation, the spot price is supposed to be constant over the year and yearly increases according to the inflation.

$$FIT\ costs = \sum_{n=1}^{20} \frac{FIT - p_n^{ex}}{(1+d)^n} \tag{13}$$

The current policy support cost is calculated with a 3 kW for both households because it represents the optimal sizing. For the alternative policy, only the costs for an investment of a 2kW paired with a

2 kWh battery is presented[7]. The current support policy costs twice as much the alternative one per kWh produced and third as in absolute value because the PV size is lower and the FIT costs are much higher than the battery premium (Table 6). A battery of 7 kW would cost as much as the FIT. Nonetheless, we suppose that the excess generation is constant over the years but it could be lower if the household installed a battery but it is likely to happen in more than 10 years.

Table 6: Support policy costs comparison

Costs	Current policy CH05 – 3 kW	 CH45 – 3 kW	Alternative policy 2kWh/2kW
FIT	€ 2435	€ 2080	€ 0
PV premium	€ 900	€ 900	€ 600
Reduced VAT	€ 640	€ 640	€ 430
Battery premium	€ 0	€ 0	€ 590
Total	€ 4915	€ 4560	€ 1620
Costs/kWh produced	1€/kWh		0.5€/kWh

5 Policy implications

The photovoltaic self-consumption has been supported in France in the context of the energy transition. The subsidies are needed because there is a mismatch between the consumption and the PV production leading to low self-consumption rate. There is a need to incentivize the prosumers for increasing their self-consumption rate in order to decrease the current support policy costs. They are already encouraged to do it because the Feed-in Tariff is lower than the volumetric part of the retail rate. Nonetheless, there is an incentive to increase the PV capacity even with a low self-consumption rate because the Feed-in Tariff level is close to the $LCOE_{PV}$. For both households, they maximize their profitability with a 3 kW PV. The prosumers are encouraged to oversize their PV installations leading to higher excess generation sold at the Feed-in Tariff. This situation brings about more subsidies. However, implementing a lower premium for capacities above 3 kW limits the incentive to oversize the PV installation. Moreover, there is a need to increase the self-consumption during the peak loads or when the grid is congested. That is why, regulators over the European countries want to change the network tariff by increasing the fixed charge or by implementing Time-of-Use tariffs. It is not possible for prosumers to take advantage of these new tariffs without any smart electric appliances or storage. Indeed, the peak loads do not often occur during sunny time.

One way to tackle this challenge is to implement a battery premium and to remove the FIT. The model developed in this paper allows us to evaluate the Net Present Value regarding the PV-battery sizing and under different charge strategies. The profitability is low for both households: from €0 to €800 for a 25-year investment. It is low even with a high premium: 24% of the PV costs and 42% of the battery costs. Moreover, the simulations were conducted in the south of France which benefits from a high solar irradiance compared to the other regions. The implementation of new tariffs does not incentivize battery investment. In the case of the Time-of-Use, the spreads in price are too low compared to the levelized cost of the battery. For the capacity tariff, the battery does not allow the prosumers to decrease sufficiently their peak loads. However, in the alternative policy, the Net Present Values are the same under the baseline strategy and the Time-of-Use one. Shifting the grid pricing would encourage prosumers to self-consume more during peak periods leading to a decrease of the peak

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[7] There is no optimal PV/battery sizing, so the pair 2kW/2kW is chosen because it is close to the break-even point for CH45.

loads. It is also the case under the capacity tariff but the Net Present Values are low because the households are not able to decrease their peak loads. The results of the simulation show that the prosumers can decrease their peak loads to 2 kW except two times in the year. We can assume that the households are willing to decrease their load consumption twice in a year to save on the capacity charge. In that case, the battery investment could be an opportunity to decrease the peak loads and also the grid costs. It could also decrease the peak power injected into the grid during sunny hours.

It is necessary to find a cost-effective support policy in order to limit the costs endured by the end consumers. In this context, the alternative policy costs are much lower than the current one and it allows prosumers to tackle the challenge arising from with new pricing. In our case study, the battery subsidy costs are less than the Feed-in Tariffs and the prosumers are encouraged to install a lower PV capacity because the remuneration of the excess generation is low. The alternative policy is cost efficient and grid friendly because the less PV production is injected into the grid. However, it highly affects the profitability for both households under each tariff scheme. So, the issue is to find a way to increase the profitability under such policy schemes. One way to overcome this issue is to increase the PV/battery premium or to introduce new rules to encourage the provision of demand response in the energy and the balancing markets. By selling demand response to the grid operator or an aggregator, prosumers could increase the profitability of their investments.

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Appendix 1

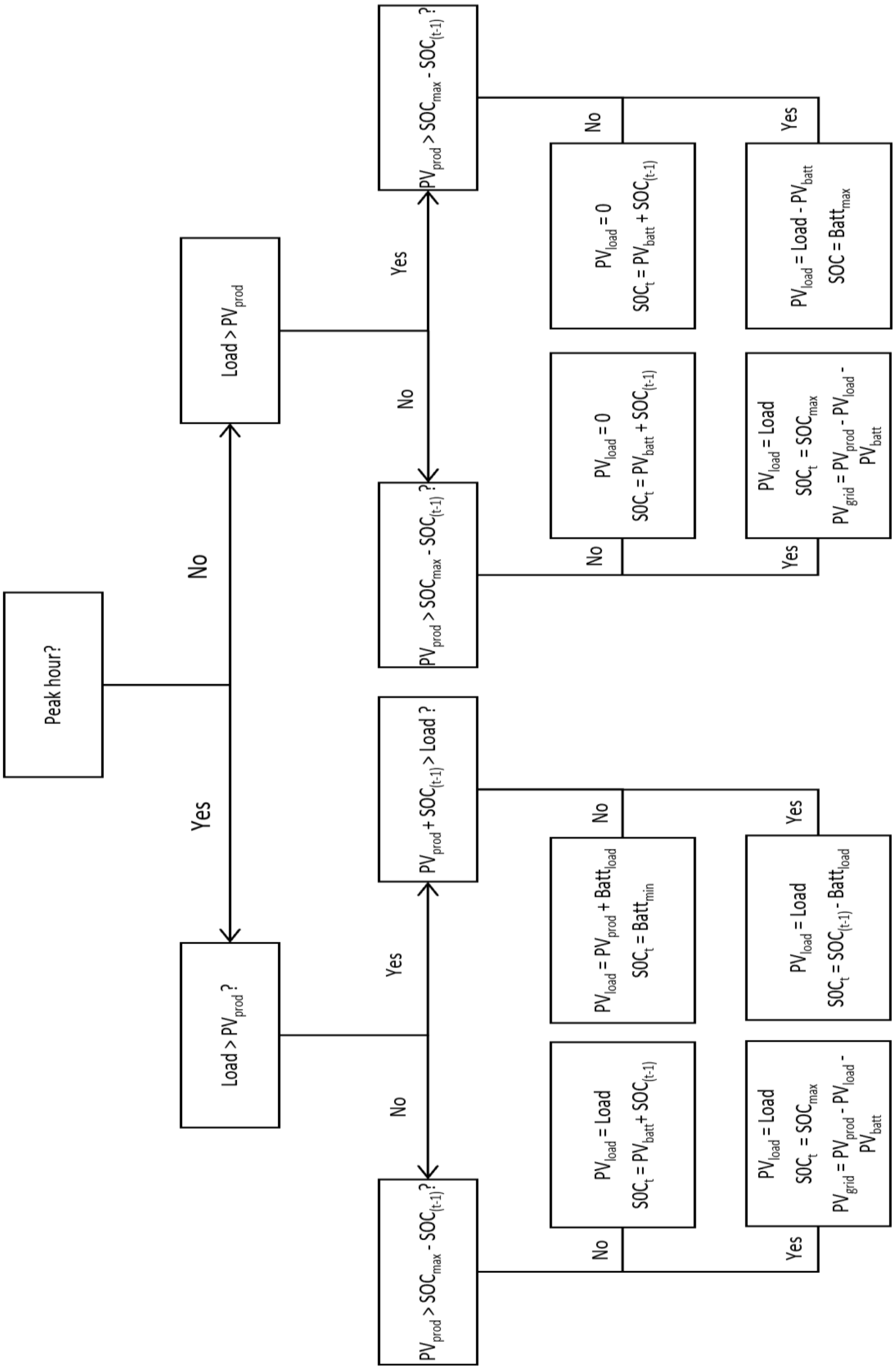

Figure 9: "TOU strategy" strategy derived from Young and al. (2019)

Appendix 2

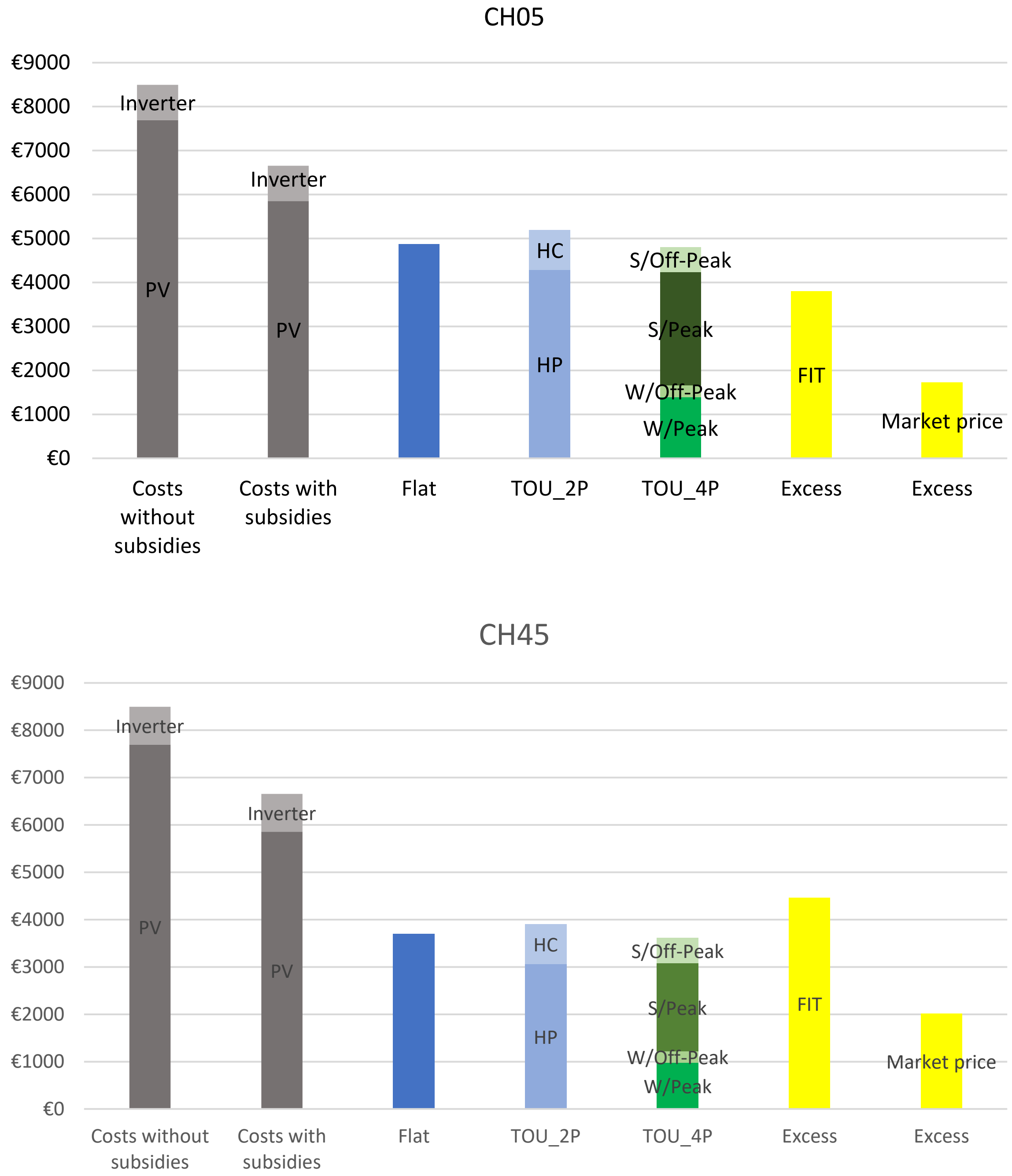

Figure 10: Breakdown of the costs and incomes from a 3 kW PV (W: Winter; S: Summer)

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