Residential PV systems with battery backup power attained already grid parity?

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***Abstract*— Due to the demise of FiT, PV grid connected systems focused towards self-consumption. A residential customer installing a grid-connected PV system, usually called a "prosumer", is paid for the exported electricity less than 5 c€/kWh (or nothing) by the electricity provider while charged about 16/17c€/kWh for the same kWh. At this exchange rate it is more economical to consume than to export. Residential consumption does not coincide with PV production and the majority of the energy produced will be exported to the grid instead of self-consumed. NPV maximizes at a 95% of self-consumption in the best case studies which usually is attained with small percentage of self-sufficiency and low power installed. With further increase of retail electricity prices and decrease of PV costs the business case for storage becomes economically viable for residential customers with the advantage of increasing self-sufficiency and energy efficiency (energy is generated locally).**

***Index Terms*—Grid-parity, PV, Residential, Self-consumption, Storage**

I. Introduction

Solar photovoltaic (PV) technology, which converts sunlight directly into electricity, is one of the fastest growing Renewable Energy Technologies (RETs) in the world [1]. PV, a clean, sustainable, renewable energy conversion technology is thus becoming a visible source in helping to meet the world's growing electricity demand. It draws upon the planet's most abundant and widely distributed renewable energy resource - the sun. The technology is inherently elegant - the direct conversion of sunlight to electricity without any moving parts or environmental emissions during operation. In Europe, from 2000 to 2014, solar PV deployment has increased at an annual average rate of 31% (40% between 2010 and 2012) almost reaching the 90GW in 2014 [2-3] (Figure 1).

Within various renewable energy technologies, PV, long known as one of the most expensive, is today becoming cost competitive with wind, hydro and other conventional thermal technologies in countries with a considerable number of hours of sun exposition and high PV technology availability. From 2004 to 2008, the price of PV modules remained approximately flat at €3.20 - €3.70/W, despite manufacturers making continuous improvements in technology and scale to reduce their costs. Much of this could be attributed to the fact that the German, and then the Portuguese and Spanish, tariff incentives allowed project developers to buy the technology at this price, coupled with a shortage of poly-silicon that constrained production and prevented effective pricing competition [4].

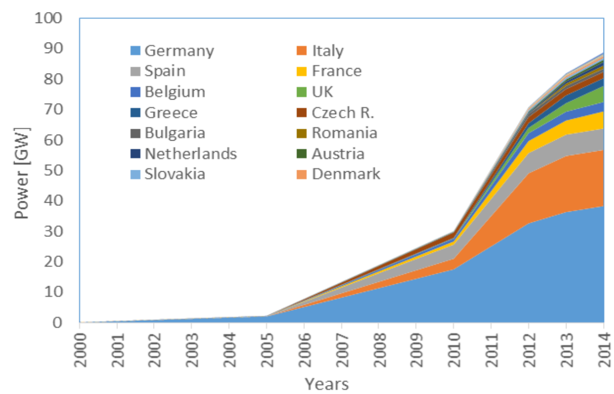

Figure 1. Evolution of PV capacity installed in Europe [2-3]

From 2008 onwards PV systems prices have decreased (Figure 2 [5]).

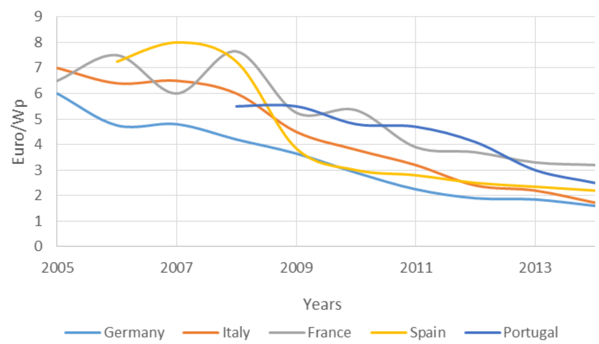

Figure 2. Evolution of PV systems prices in selected European countries

Many countries have had policies which directly subsidise small-scale PV systems for domestic applications but these have stopped in 2014/15 not only as a response to the economic crisis but mainly because solar PV has become able to compete without subsidies. The idea that PV producers could be considered as "prosumers" – both producers and consumers of energy – has been evolving rapidly and policies have been adapted accordingly in several countries. Net-metering policies have been considered in some countries such as, Denmark, Netherlands, Portugal, Sweden and Belgium and many countries are introducing a variant through self-consumption [6].

II. PV MARKET TRENDS AND SUPPORTING POLICIES

A growing important part of the Photovoltaic (PV) market has been formed by Rooftop or Building Integrated PV (BIPV) systems. This segment has been important for the deployment of PV because of two reasons: no additional space is required because the panels are mounted on existing or newly building structures and the energy is consumed locally reducing distributional losses and the need for network upgrades. The incentives towards micro-generation started in Europe strongly in 2008/9. In Portugal, for instance, the utilities offered a Feed-in Tariff (FiT) of 65 c€/kWh to micro-generators during the first 5 years, 35c€/kWh during the next 10 years and afterwards a net-metering scheme was allowed [7]. The high PV costs (more than 5000 €/kW) where then compensated with such generous FiTs. This has resulted in a strong growth in PV markets in Germany, Italy, Greece, Spain, Belgium, Czech Republic Austria and Portugal [6]. From 2008 till 2014, the price of PV modules have decreased and consequently PV systems prices to less than half the value of 2008 attaining (depending on the country) around 2000€/kW [5]. The FiT rate, determined by each country based on investment and maintenance costs to ensure adequate remuneration for the PV system owners, needed to be fine-tuned on a regular basis with the decreasing PV prices in order to avoid uncontrolled market development. In Portugal, in 2010, a new decree law lowered the initial FiT of PV micro-generation to 40c€/kwh [8], and from 2011 till 2013 new legal framework was introduced every year, lowering even more the FiT so that in 2014, it was only 6.6 c€/kWh for the first 8 years [9] (indeed 1/10 of the initial 65c€/kWh). In October 2014, a new degree law was set to incentivize self-consumption and the electricity exported to the grid should be paid to the PV generator at a 90% of the monthly average Iberian Electricity Market (IEM) price [10], which rounds the 4c€/kWh.

With the demise of FiT, PV grid connected systems focused basically on self-consumption. A residential customer installing a grid-connected PV system, is paid for the exported electricity less than 5 c€/kWh (or nothing) by the electricity provider while charged about 16/17c€/kWh for the same kWh. At this exchange rate it is obviously more economical to consume than to export. Residential consumption usually peaks at 8am and 8pm while PV production is at its highest between 10 am and 3 pm, and under these conditions the majority of the energy produced will be exported to the grid instead of self-consumed.

With further increase of retail electricity prices and decrease of PV costs the business case for storage is becoming economically interesting for residential customers.
According to industry executives, using batteries to retain energy from rooftop solar systems will be too expensive for at least two years [11]. The batteries capacity in these applications can be much smaller than those used in stand-alone solar systems as the convenience of the electricity grid remains at the household disposal. In off-grid operation, independent of the electric utility the battery bank has to be significantly oversized to account for possible 4-5 days of bad weather, (depending on the location), leading to a yet highly expensive system [12]. A few studies [13-15] have already investigated the economic viability of grid connected PV for self-consumption and all of them agreed that the solar resource, electricity prices and the daily energy dynamics of the "prosumer" are the main factors that influence the PV investment profitability.

For a BIPV grid connected system, considering that the investment cost lies between 2000-2500 €/kW, 25 years of life cycle and a discount rate of 6%, the levelized cost of energy (LCOE) generated from the PV system ranges 9.9 – 12.3 c€/kWh considering the radiation levels of the south of Portugal. When compared with retailer electricity prices around 16/17 c€/kWh, grid parity has already been surpassed. It would be needed at least a 47% - 68% of self-consumption in order to attain economic benefits and this is hardly difficult for households [5]. There are three options to improve self-consumption:

1) *Limit the PV power installed so that PV generation covers the majority of on-line consumption;*
2) *Demand side management strategies in order to shift load to PV generation periods;*
3) *Energy storage for balancing daily fluctuations.*

In this paper these options are analyzed and compared under different scenarios of retail electricity prices and PV and storage costs.

III. METHODOLOGY

In this section, self-consumption and related economic metrics are formally defined as well as input data and PV system modelling.

A. Solar regional data base and location selection

In this research PVGIS climate-SAF was used as reference solar database for the selected case study sites [16]. The main parameters influencing the PV system energy output in a specific location are the irradiation and air temperature. The annual Direct Normal Irradiation (DNI) for a fixed orientation of 35º for the PV modules was used in each case study.

B. PV energy generation modelling and simulation

The amount of energy produced by the PV modules is determined by developing a mathematical model of the PV array allowing the determination of the extracted electrical energy as a function of the solar radiation and the ambient air temperature. This model used is described in [5].

C. PV generation and daily energy balance

Figure 3 shows a schematic outline of the power profiles of on-site PV generation and power consumption. The area A+B is the total energy demand and the area B+C is the total PV energy generated. Self-consumption is thus the self-consumed part relative to total production (1).

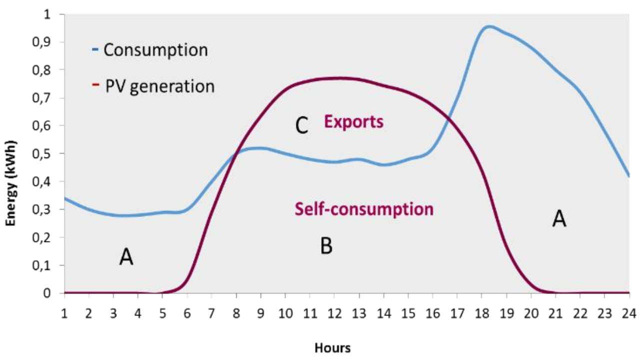

Figure 3. Schematic outline of a daily energy balance of a residential PV prosumer

$$self - consumption = \frac{B}{B+C} \quad (1)$$

The self-consumed part relative to total load is also a computed metric named self-sufficiency (2).

$$self - sufficiency = \frac{B}{A+B} \quad (2)$$

Let L_t be the energy consumed in hour t and P_t the PV energy generation. The energy generated and used on site in each hour is

$$M_t = min\{L_t, P_t\} \quad (3)$$

Self-consumption along a year can be computed (4).

$$\varphi_{SC} = \frac{\sum_{t=1}^{8760} M_t}{\sum_{t=1}^{8760} P_t} \quad (4)$$

And self-sufficiency (5)

$$\varphi_{SS} = \frac{\sum_{t=1}^{8760} M_t}{\sum_{t=1}^{8760} L_t} \quad (5)$$

D. Increasing Self consumption

The three different ways of increasing self-consumption are:

1) Limit the Power installed

This solution, increases self-consumption with a very small amount of self-sufficiency, because the PV power installed is very low (Figure 4).

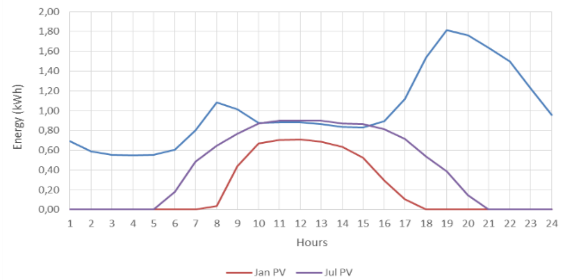

Figure 4. Limitation of power for self-consumption higher than 95%

2) Load Shifting for periods of PV generation

This solution is limited for a typical domestic consumer.

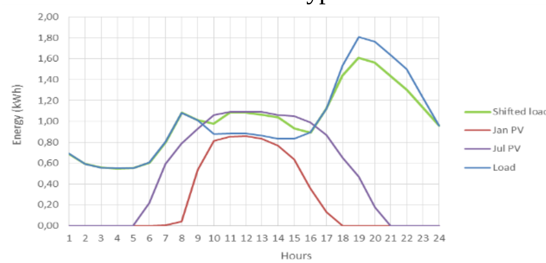

Figure 5. Limited load shifting allows less than 20% power increase

3) Energy storage for balancing daily flutuations

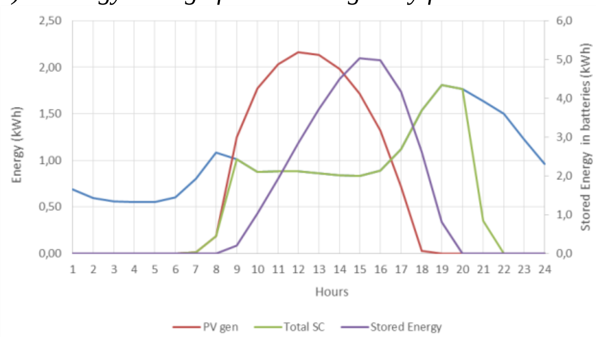

Figure 6. With energy storage, installed power can duplicate

This solution allows a considerable increase in both self-consumption and self-sufficiency but a loss of energy in the daily charging and discharging due to the battery performance. The surplus energy generated is directed for storage and when storage is full (S_{max}) the surplus is exported to the net.

The energy stored per hour (S_t) depends on the energy stored in the previous hour (S_{t-1}), and its use ($L_t > P_t$ and $S_{t-1} > 0$) or not ($S_{t-1} = 0$) by the load, and the surplus energy ($P_t > L_t$) at that time (6):

$$S_t = \begin{cases} 0, L_t > P_t \wedge S_{t-1} - (L_t - P_t) < 0 \\ S_{t-1} - (L_t - P_t), L_t > P_t \wedge S_{t-1} - (L_t - P_t) \geq 0 \\ S_{t-1} + (P_t - L_t), P_t > L_t \wedge S_{t-1} + (P_t - L_t) \leq S_{max} \\ S_{max}, P_t > L_t \wedge S_{t-1} + (P_t - L_t) > S_{max} \end{cases} \quad (6)$$

The energy used on site from the storage system (PS_t) (7) must be included in the computation of self-consumption (M_t) (8)

$$PS_t = \begin{cases} 0, S_{t-1} = 0 \vee P_t > L_t \\ L_t - P_t, L_t > P_t \wedge S_{t-1} \geq L_t - P_t \\ S_{t-1}, L_t > P_t \wedge S_{t-1} \geq L_t - P_t \end{cases} \quad (7)$$

$$M_t = min\{L_t, P_t\} + PS_t/\eta_{Bat} \quad (8)$$

A portion of the PV energy is still exported to the grid due to the limit of storage capacity (PE_t) (9)

$$PE_t = \begin{cases} 0, S_{t-1} + P_t - L_t \leq S_{max} \\ S_{t-1} + P_t - L_t - S_{max}, S_{t-1} + P_t - L_t > S_{max} \end{cases} \quad (9)$$

E. Economic Assessment

For a PV "prosumer" there are two kinds of benefits: The energy savings due to self-consumption and the revenues due to the surplus energy produced and exported to the grid. The costs associated are mainly investment costs in the PV system. The generation costs are computed using the *LCOE*. The *LCOE* is defined as the cost that, if assigned to every unit of energy produced by the system over the lifetime period.

$$LCOE = \frac{I_a + o\&m}{E_a} \quad (10)$$

Where I_a is the annualized investment cost, E_a the annual energy generated by the PV system and o&m the annual operation and maintenance costs.

Under different values of retail prices *(RP)* and PV sales price *(SP*), and considering the percentage of self-consumption, φ_{SC}, the *NPV* should be computed as in (11).

$$NPV = \left(RP - \frac{LCOE}{\varphi_{SC}}\right) \cdot E_a \cdot \varphi_{SC} \cdot k_a + SP \cdot E_a(1 - \varphi_{SC}) \cdot k_a \quad (11)$$

Where k_a is annuity factor considered for the investment life time *n* and discount factor *r*.

$$k_a = \frac{1}{r} - \frac{1}{r(1+r)^n} \quad (12)$$

With energy storage, there is an increase in the investment costs and self-consumption. Depending on the storage system size there could be also some energy exported to the grid and the second term of (11) must be $SP.E_a.\varphi_{ex}.k_a$, where the percentage of energy exported φ_{ex} should be computed (13)

$$\varphi_{ex} = \frac{\sum_{t=1}^{8760} PE_t}{\sum_{t=1}^{8760} P_t} \quad (13)$$

IV. Results and Discussion

In this section, the case study for a small residential PV system with and without storage is studied.

A. Location selection

For the case study a local in the south of Portugal (Évora) was selected. For a *1kW* of installed power, in a fixed system with 35º inclination, with an annual DNI of *2150 kW/m²*, can generate *1580kWh*/year. The hourly DNI was taken from the [16] database.

B. Typical residential loads

The loads used had different profiles according to the season and are depicted in Figure 7.

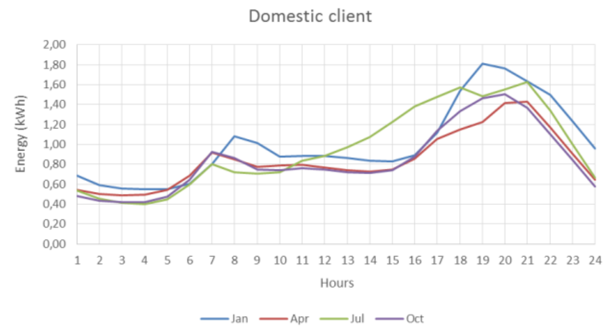

Figure 7. Domestic load profiles

C. PV generation and daily energy balance

The model used for PV generation uses the local DNI data and the selected PV module to compute the hourly PV energy production, as described in [5]. The integration between the load profiles and PV generation allows the definition of the adequate number of modules to be used setting the installed power. Figure 8 shows how NPV, SC and SS evolve with the PV power installed. In this case, NPV is maximum at 95% of self-consumption which is attained at 1.75kW of power installed.

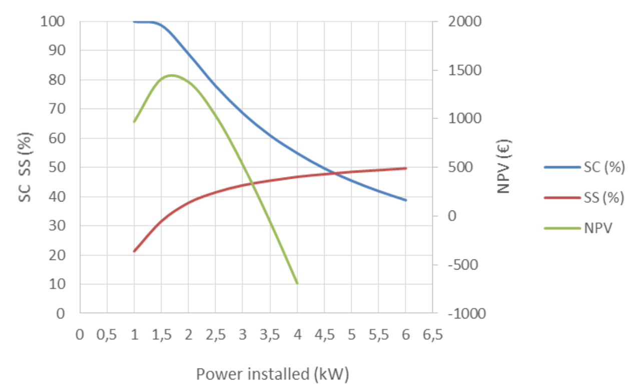

Figure 8. Evolution of NPV, SC and SS with PV power installed regarding a typical load profile of a "prosumer" in the south of Portugal

Using a storage system to store the surplus energy generated, the PV power installed can be increased with the adequate battery capacity to keep a high level of self-consumption.

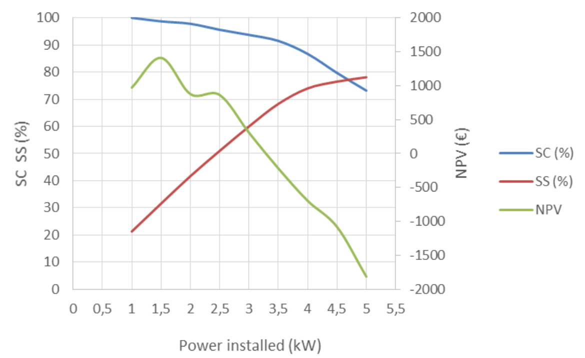

Figure 9. Evolution of NPV, SC and SS with storage from 2kW of power installed

Table I summarizes the case studies for actual prices considering a 5kWh storage capacity for a 3kW PV installed. With the actual prices, storage isn't yet the best solution. For the same household, it is better to keep the PV power as low as 1.75kW rather than increase PV power along with self-sufficiency. Observing the $LCOE/\varphi_{SC}$, for the backup battery case study (≈0.16€/kWh), it can be considered that grid parity was attained.

TABLE I. RESULTS FOR PRESENT CASE STUDY

Case study	no storage	Storage
Project life time (n)	25	
Discount rate % (r)	6	
Capital Cost PV (€/kW)	2500	2500
Capital Cost Bat (€/kWh)		350
Battery life (years)		12
Battery performance (%)		80
Electricity price (€/kWh)	0.16	
Export tariff (€/kWh)	0.043	
PV generation (kWh/kW)	1580	
Power installed (kW)	1.75	3
Bat capacity (kWh)		5
Total investment (€)	4375	11269
$LCOE/\varphi_{SC}$ (€/kWh)	0.124	0.1598
Self-consumption(%)	94	93
Self-sufficiency (%)	35	60
NPV (€)	1444	306

Simulations with lower PV and battery prices and higher retail electricity costs, indicates that a storage system should become indicated to increase self-consumption, self-sufficiency with a positive and higher NPV. For instance, for the same case study, table II shows a simulation where the storage system becomes more profitable.

TABLE II. RESULTS FOR THRESHOLD SIMULATION

Case study	no storage	Storage
Capital Cost PV (€/kW)	2000	2000
Capital Cost Bat (€/kWh)		330
Electricity price (€/kWh)	0.18	
$LCOE/\varphi_{SC}$ (€/kWh)	0.098	0.13
NPV (€)	3034	3072

V. CONCLUSION

PV self-consumption becomes the logical way to decrease energy costs with environment benefits (renewable energy) and energy efficiency as energy is generated and consumed locally. With further increase of retail electricity prices and decrease of PV costs the business case for storage is becoming economically viable for residential customers. In fact, it is possible for a residential customer to produce about 60% of the electricity consumed with a PV plus battery system as the $LCOE/\varphi_{SC}$ equals the retail electricity price.

With the actual retail electricity prices and PV and battery costs it is more profitable to install a PV system with limited capacity that maximizes NPV at a 95% of self-consumption and only 35% of self-sufficiency with no battery backup power although PV with battery backup is attaining grid-parity.

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