Highlights

Photovoltaic Self Consumption Analysis in a European Low Voltage Feeder

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- Electricity self-consumption to reduce dependency from distribution networks
- Solar Photovoltaic generation
- Energy storage at consumer level
- IEEE European LV test feeder
- Energy management and coordination at demand side

Photovoltaic Self Consumption Analysis in a European Low Voltage Feeder*

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ARTICLE INFO

Keywords:
Distribution systems
Energy storage
Self-consumption
Photovoltaic

ABSTRACT

Electricity self-consumption consists in consumers installing their own small generators, solar photovoltaics mainly. They attempt to save money in the electric bill by producing part of their electrical energy, consequently reducing dependency on the distribution grid. Consumers that simultaneously become producers are usually known as *prosumers*. This work shows the techno-economical implications, in terms of electric energy, cost savings and grid voltage impact, if self-consumption is deployed in a European low voltage feeder. In the case study, the IEEE European LV test feeder was used. Real data for solar irradiance from 1985 to 2017 were considered for Gijón, a city in the North of Spain. Conclusions may be extrapolated to different locations.

1. Introduction

Self-consumption (SC), or auto-consumption, is based on consumers that produce electricity for their own use. These prosumers are able to reduce their dependence on the distribution network and contribute to the integration of Distributed Renewable Energy Sources (DRES) as well.

The most suitable generators for SC are the solar photovoltaic (PV) ones. They are simple and maintenance costs are low. They can include energy storage systems (ESS), or batteries, to take advantage of all the generated energy, even in periods during which consumption and generation do not match.

Beyond the technical viability, from the prosumer viewpoint, SC will be profitable if the cost of locally produced energy is lower than the market electricity price. The prosumer will also expect a reasonable payback period for the initial investment. Seen from this perspective, SC of electricity is becoming more feasible nowadays for a variety of reasons: Lowering prices of PV modules, fast advances on ESS technologies or increasing supportive energy policies [21] among others.

Some European countries apply supportive SC policies. Switzerland has been promoting SC for the recent years [27]; Electricity providers buy the electricity produced in excess at the same price than the delivered electricity. Moreover, SC communities are allowed, which means energy not self-consumed can be redirected to the neighborhood. In France, the sale of surplus energy is also allowed and there is an increasing tend to include more SC in near future [7]. In Germany, extra PV energy is also remunerated [10]. In Poland, the prosumer amendment [18] introduced the guaranteed tariff for people producing energy for their own use. In Spain, recent regulations include extra PV power remuneration and allows association and collaboration of prosumers to increase their benefits [26]. These are only a few examples, but many other European countries are committed to promote SC [22]. Under this techno-economical environment, SC is expected to be massively integrated into european distribution networks.

Wide deployment of SC might change the demand profile seen from the distribution network [23]. Moreover, a group of prosumers in a community might behave as a large user with a flexible and controllable load profile[15]. Thus, increasing the overall benefit while reducing the interchange with the distribution grid [24]. In this sense, retail customers might participate actively to improve the distributed network management [17].

On the other hand, there are still challenges with security of supply [1] and voltage issues that may result [4] in power systems with large ratios of intermittent stochastic generation (PV generation among other renewable sources).

This work aims at giving an integrated approach to technical and economical issues and constraints to be faced for profitable and secure deployment of SC in distribution networks. The European context will be studied, but the conclusions could be generalized to other regions.

The following section presents the state of the art and a detailed description of the paper contributions. The remain sections will describe the prosumer perspective first, then the distribution network viewpoint, and finally, the conclusion. A comprehensive economic study is described in an Appendix.

2. Literature review and contributions

Some related studies have been previously developed: The authors in [19] proposed a decision-making model for

*This work has been supported by grant FC-GRUPIN-IDI/2018/000241, from Asturian Regional Government and grant MINECO-17-ENE2016-77919-R, from the Spanish Ministry of Economy and Competitiveness.

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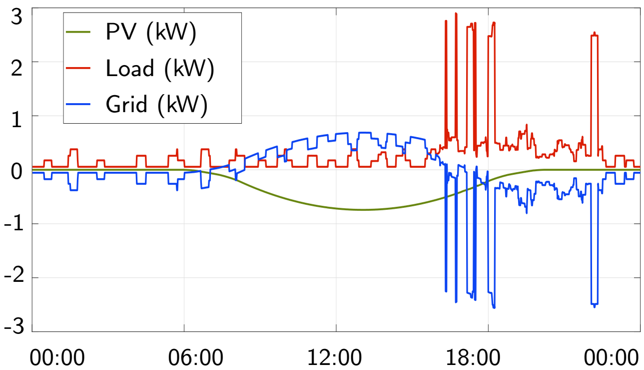

Figure 1: Grid, Load and PV generator power without Energy Storage.

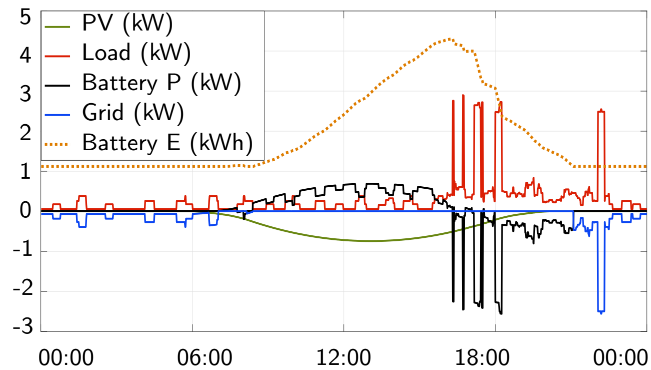

Figure 2: Load and PV generator with storage when charge from the grid is not allowed.

an electricity retailer with intermittent renewable generation with SC. The authors in [25] studied prosumer behaviors for different electric tariffs in Norway. These two works show an electricity market standpoint, but do not consider grid impact from a technical point of view.

In [28] a technical analysis is performed for a particular case on a distribution network in Slovenia. The authors assure that 30 % of SC penetration would be the best scenario. With more units, voltage and transformer loading issues would arise. However, the technical solutions would include better sizing of battery capacities, improved energy flow management and local reactive power control. The study lacks of economic perspective.

In [16], SC is evaluated in public buildings. According to the authors, the PV energy production and consumption match in time in public buildings. Thus, there is no need of energy storage, so the initial investment is reduced. In [14], the authors show a comparison for different prosumer profiles in the Netherlands. SC shows larger ratios for commercial consumers than for residential ones. Again, generation and consumption match better in commercial than in residential buildings. However, for a wide penetration of PV generation, also habitation places should be considered in the study.

The authors in [1] proposed a method to determine the SC installations profitability. They described a sizing procedure for PV generators including ESS and demonstrated that, with a proper dimension, the SC is viable. That study is given for different locations in France. The authors in [29] propose an optimal sizing procedure for PV, wind turbine with a diesel generator and storage systems to supply an isolated microgrid. Thus, the main grid interaction is not studied.

After reviewing related works and European policies, we can conclude that for secure deployment of SC in the distributions networks, several viewpoints have to be faced: Individual prosumer, community, Distribution Network Operators (DNOs), technical viability and economical profit. For that purpose, various requests have to be fulfilled: The SC facility has to be profitable for each prosumer individually, even when management strategies or electric tariffs are considered in group (building or microgrid levels).

Prosumer profitability depends on multiple variables: Initial investment, cost of energy, feed-in tariffs, energy savings and energy policies, among others.

On the other hand, from DNOs perspective, SC might be seen as an opportunity for voltage regulation and network upgrading without re-powering.

To these aims, the following questions are to be answered:

I. Prosumer viewpoint

- What are the energy and money savings?
- What are the considerations to assure profitability?
- What is the maximum initial investment for a reasonable payback period?

II. Network viewpoint

- Is the voltage profile modified by prosumers compared to conventional consumers?
- What are the considerations to prevent voltage constraint violations?
- Could SC coordination be employed for voltage regulation or grid supporting?

This paper forms a basis for investors (prosumers), Distributed System Operators (DNOs) and policy makers to derive a better understanding of SC and its impact on distribution networks. The main goal is that both perspectives, economical and technical are faced and evaluated at once. The research comprises PV generators and ESS sizing, annual saving computations for a given place, energy management strategies necessities and grid impact. The results obtained may be extrapolated to different locations by taking the corresponding latitudes and weather conditions.

3. Prosumer Installation

This section describes the prosumer behavior. Fig. 1 shows the daily power profiles for a given prosumer with a

PV generator without ESS. The load shape is the demand profile 55 of the European LV test feeder [13]. Power from the generator is plotted as negative. The demand is plotted as positive. The grid and the battery can behave as a load or as a generator, depending on the power flow direction. Thus, positive values imply they are consuming power, while negative values mean they are feeding power. The PV generator is sized to produce a daily energy similar to that demanded. Most of the consumed energy has to be taken from the grid while most of the PV energy is fed into the grid. This is quite common in residential dwellings because the demand does not match the PV generation.

To get full advantage of the PV source, this prosumer may install an ESS. Then, the surplus energy can be stored and consumed at peak hours. This new case is shown in Fig. 2. Battery response is plotted in terms of power and energy; the dotted line represents the energy (kWh) while solid lines are used for power (kW). The storage capacity was selected to store all PV energy produced when needed. Then, the energy injected to the grid might be near zero. Some iterations were conducted to determine the minimum storage capacity that guarantees the state of charge at the beginning of the day will be the same as at the end. This is possible because the generator is sized to produce almost the same daily energy as that demanded.

Depending on the used technology, the battery can store energy from the PV generator or can take energy from the grid as well. The case presented in Fig. 2 shows a prosumer that is not able to store energy from the grid. In that case, there is still some power taken from the main grid at peak hours. If the energy could be taken from the grid (not only from the PV generator) to be stored at any time, the demand could be shifted to off-peak hours, as it is shown in Fig. 3. In this case, the prosumer might take advantage from a period-discriminant tariff.

4. Case Studies

The European Low Voltage Test Feeder [13] presents a variety of case studies. It includes a typical European radial configuration for distribution and introduces quasi-static time series simulations. This features makes it suitable for the inclusion of several prosumers and for a whole day analysis. According to the Test Feeder Working Group, the European feeder was designed to fill a benchmark gap because, up to the date of its publication, all the test cases were focused on North American style configurations. The neutral conductor is supposed to be connected to ground at load side. However, in the considered location, the neutral conductors are connected to the ground only at some points, normally transformer secondaries, resulting in isolated neutral conductors at load side. Then, in this work, the original feeder network configuration has been replace by an isolated neutral configuration.

OpenDSS simulation tool was selected for being the most appropriated software to support renewable energy sources, energy storage systems and many types of analyses related to smart grids and modern distribution systems. This open

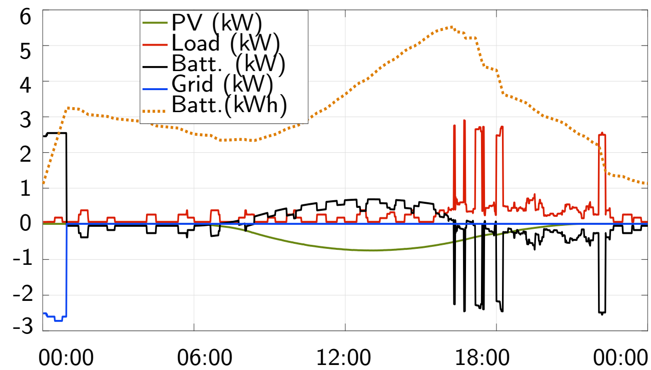

Figure 3: Load and PV generator with storage. Battery charges from the grid.

source software supports quasi-static simulations and the proposed feeder configuration. A detailed description of this software can be found at [6].

To account for the PV generation capacity, we have considered measured data of irradiance over a horizontal surface in $\frac{W}{m^2}$ for Gijón, a city in north Spain. The values were measured each 15 minutes for the period 1985 to 2017. For the study cases, the irradiance profile is computed every 15 minutes as the 33-year average value for each day of the year.

As explained before, battery sizing is based on daily produced and consumed energies. Thus, a particular day of the year has to be chosen for sizing purposes. If the criteria of minimum energy injected to the grid is adopted, the selected day should be the one with maximum energy production. If the battery is capable of storing the required energy that day, then it will be capable of doing so any other day of the year.

It is common practice to install PV modules over tilted surfaces, so the yearly produced energy is maximized. The optimal angle is different for each location, because it varies with latitude. In the city of Gijón, the latitude is 43.5º, thus the optimal angle is approximately 35º[12].

For a commercial PV module, the peak power (in W_p) is defined as the power that the module is capable of producing whit a solar irradiance of $1000\frac{W}{m^2}$, perpendicular to the module and with a cell temperature of 25ºC. These especial conditions can be replicated in a laboratory but are not usually given in real cases. So, for a given PV installed peak power, the estimated produced power P should be computed through the global performance ratio (PR) [12]. This ratio accounts for global efficiency loss due to

- Temperature,
- Wiring,
- Dispersion of parameters and dirt ,
- Maximum Power Point Tracking (MPPT) errors,
- Energy inefficiencies of inverter, battery, regulator, etc.

In this case study, a conservative value (according to [5]) of PR has been taken for all prosumers. Thus, to estimate actual power P given the irradiance, the PR and the peak power, (1) has been employed [12],

$$P = \frac{G_{dm}(\beta)\, PR\, P_p}{1000} \quad (1)$$

where $PR = 0.7$, P, in W, is the actual power for a given irradiance $G_{dm}(\beta)$, in $\frac{W}{m^2}$, over a tilted surface of angle β, for a PV generator of nominal peak power P_p, in W_p.

$G_{dm}(\beta)$ is obtained from real measured data in the city of Gijón over a horizontal surface $G_{dm}(\beta = 0^o)$. The angle correction to get $G_{dm}(\beta = 35^o)$ has been taken from [20].

For a given peak power, we might estimate the actual power per minute and the daily energy production per year.

For each consumer, the test system data [13] includes the daily demand profile. Then, an appropriate SC facility has been sized, including a PV generator and a battery.

The procedure to select the peak power and the battery capacity for each consumer is described in next section.

4.1. Prosumer Installation sizing

The procedure to size the SC units is performed for each prosumer, to maximize their benefit, considering that no remuneration is received for surplus energy. Thus, the maximum annual saving possible as a prosumer is the cost of their annual consumption.

The sizing procedure includes the PV generator and the battery at the same time, considering both prosumer and grid benefit. Regarding the PV generators sizing: The peak power is chosen to match the maximum daily energy production while the battery is chosen to manage that amount of energy. A larger PV generator sizing often may lead to an improved economic efficiency. However, it must be considered that typical residential and commercial buildings do not have much roof space. With the proposed sizing method, the PV generators are suitable for conventional commercial and residential buildings.

Once the PV generator sizing is fixed, the battery capacity has been chosen to manage the energy produced on the day of maximum production. Thus, the battery allows full energy management. Otherwise, the energy will be wasted or injected to the grid in periods when it is not needed. Moreover, the days of lower production, the capacity of the battery will be available to charge from the grid, when the energy might be cheaper (at night). In this way, we aim to minimize grid interaction and the prosumer will behave as a nearly zero-energy facility [8].

The allocations for different prosumers have been chosen randomly, because it is assumed any consumer could became a prosumer, independently or their location.

It must be remarked that different procedures for PV and battery sizing or for prosumer allocation might be considered, and the proposed algorithm will manage properly. Other methods that might be applied to define PV sizing and storage allocation can be found in [11].

With the available irradiance data, the daily energy production, for an installed power of 1500 W_p, is depicted in

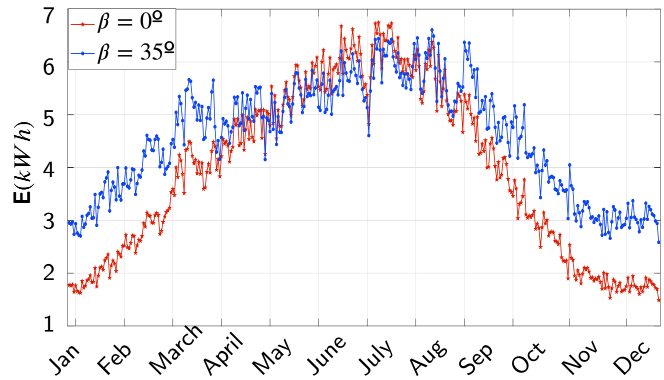

Figure 4: Daily Energy produced by a 1500 W_p PV installation.

Fig. 4 for a whole year. The plot includes two different surfaces: Horizontal (0º) and optimal tilted (35º). In the first case, the installation will give the maximum energy produced in a day (6.75 kWh on July, 11), being the annual energy 1442.3 kWh. In contrast, the installation will produce the maximum energy over a whole year in the second case; on the tilted plane, the annual energy production will be 1677.4 kWh. In that case, the maximum produced energy in a day is 6.6 kWh on August, 13. This day has been chosen to size the facilities. If the installation is capable of managing the maximum produced energy, on August, 13, it will manage the energy any other day. This sizing procedure satisfies two criteria: It maximizes the prosumer benefit and minimizes the distribution grid interaction.

The test feeder consists of 55 consumers given by their daily power demand profile. For each consumer a SC installation was sized as follows:

1. The daily energy demand is computed for the given consumer.
2. The PV generator peak power is chosen to produce a similar energy on August 13. Steps of 250 W_p are considered, as this is a typical value of commercial PV modules peak power.
3. The battery capacity will be chosen equivalent to the daily consumed energy. The nominal power will be equal to the maximum power required by the consumer, as observed in the demand profile. Other sizing algorithms might be applied instead [3].
4. A power flow solution is computed in OpenDSS for the new prosumer including the PV generation and the battery.
5. If the battery state of charge (SoC) at the end of the day is the same (or quite similar) as the SoC at the beginning of the day, the installation will be considered valid. Otherwise, we return to step 3, adjust the battery capacity accordingly and repeat steps 4 and 5.

The obtained results for all the prosumers in the feeder are described in the Appendix.

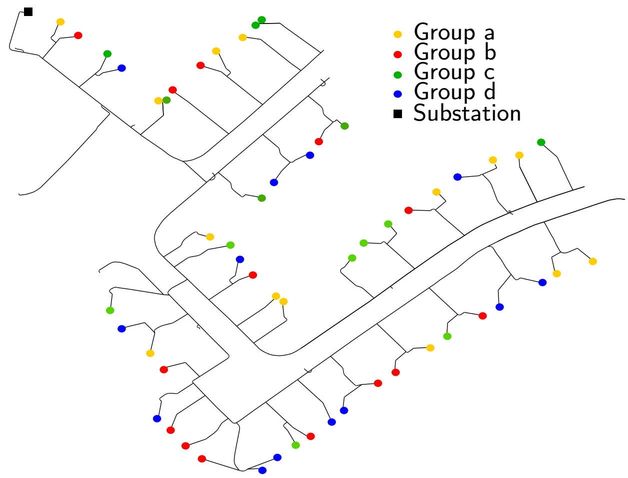

Figure 5: Prosumer distribution for different degrees of SC.

4.2. Prosumer Coordination and Grid interaction

The LV European test feeder [13] is employed in all case studies. Consumer locations can be seen in Fig. 5. Each prosumer is labeled with the same number as in the feeder input data. To define different degrees of SC penetration, consumers were classified into 4 different groups named a, b, c and d, as shown in the picture. The correspondence between prosumer number and group is shown in the Appendix, Table 2. Several case studies are proposed; 25%, 50%, 75% and 100% SC degrees of penetration. The different energy management strategies are: Prosumers with only PV generators (profile in Fig. 1), PV with battery that only stores energy from the PV generator (Fig.2) and PV with battery that can be charged from the grid in off-peak periods (Fig. 3).

In the last case, a coordination strategy among prosumers is implemented. The main objective is to prevent voltage constraint violations at the point of common coupling (V_{PCC}) for each prosumer. The coordination strategy was implemented as follows:

- Each group of prosumers a, b, c and d is assigned a time shift. In this case, a whole period of six hours between 00.00 and 6.00 am is considered. Each group is included in a particular shift.
- To prevent overloading, each group is allowed to charge their batteries from the grid only during their shift. In this case, shifts last for half an hour.
- If a prosumer needs to charge their battery and belongs to the current shift, it means charging is allowed. Then, the algorithm presented in Fig. 6 is executed. Otherwise, the prosumer should wait until their shift is available.

The algorithm in Fig. 6 is implemented individually at prosumer level. Each prosumer is responsible for voltage deviations at their PCC. When the voltage magnitude is under the target value, the battery changes to half the nominal power or even disconnects if needed. This coordination

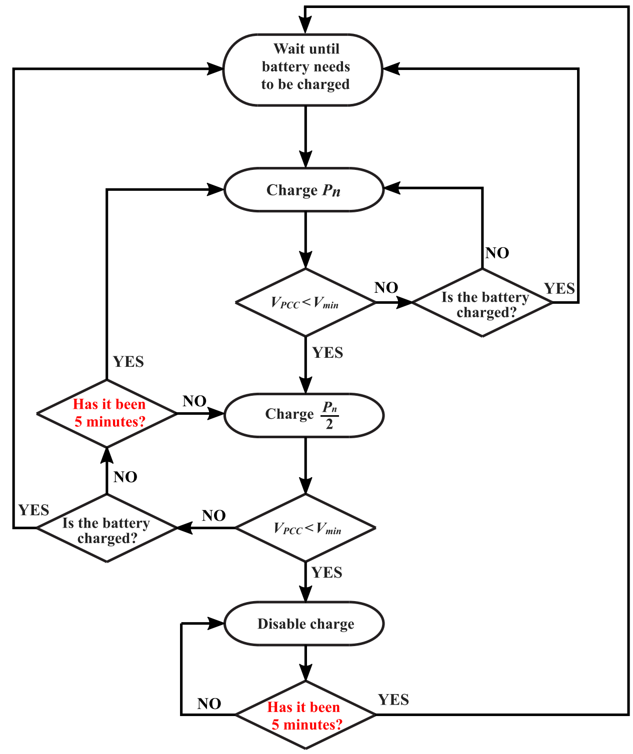

Figure 6: Coordination algorithm. Flowchart.

strategy might be adapted to different voltage specifications and to different shifts.

The inclusion of SC prosumers in the described coordination manner guarantees that the grid losses will be optimal. As explained before, a prosumer behaves as a nearly zero-energy facility, so the interchange of energy with the network is extremely reduced. Thus, the flowing currents through the distribution feeder are minimized as well as the resulting losses.

4.3. Results

In Fig. 7, the interchanges of active power among prosumers and the grid are displayed for different SC degrees. The results are shown for the day of greatest energy production, August 13. Battery charge from the grid is not allowed. 25 % of SC means only the consumers of group a (Fig. 5) are prosumers, 50 % means only group a and group b are prosumers, 75 % comprises groups a, b and c, and finally, 100 % means all consumers are prosumers. Red line represents the total aggregated demand, as it is initially defined in the test feeder. This demand will be covered partly by the prosumer facilities (PV and ESS) and partly by the distribution grid. With the adopted criteria, this demand is always positive. Other lines represent active power measured at the substation (slack), for the different degrees of SC penetration. Positive values mean the power is fed into the slack while negative values imply the slack is feeding power. As the number of prosumers increases, the power covered by the grid decreases, as it was expected.

In Fig. 8, the same cases are shown when battery charge

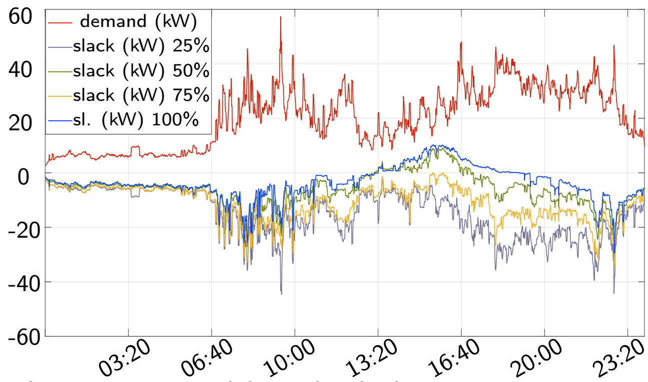

Figure 7: Aggregated demand and substation power injections for different degrees of PV penetration. No charge from the grid.

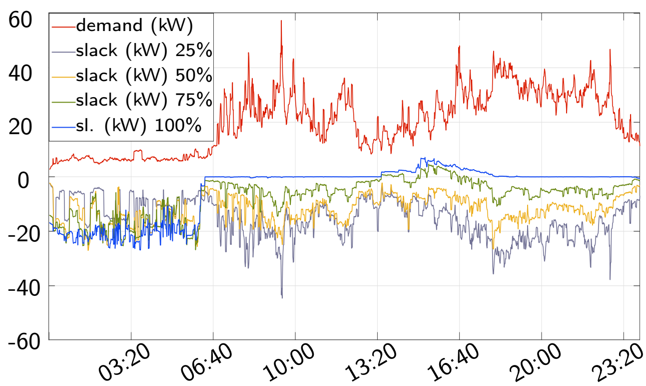

Figure 8: Aggregated demand and substation power injections for different degrees of PV penetration. Batteries charge from the grid.

from the grid is permitted. In this case, the charging processes have been coordinated to get a relatively flat aggregated demand, mainly to avoid voltage issues. As the degree of SC penetration increases, the coordination can be improved. Blue line shows the best scenario, in which the aggregated demand has been shifted to the off-peak hours and flattered during peak hours.

Comparing Fig. 7 and Fig. 8, it can be proved that a proper energy management strategy is critical as the grade of SC penetration increases. The reverse flows mentioned in [19] are also seen in Fig. 7. These flows, that increase with the number of prosumers, might give rise to voltage and transformer loading issues. However, results in Fig. 8 demonstrate that a proper management strategy avoids this issue and does not limit the SC penetration.

Fig. 9 shows voltage profiles for the different management strategies. The voltage magnitudes are measured at prosumer side, in the corresponding phase. Case study I is the base case, without SC. In case II, charge from the grid is not allowed, and cases III and IV include battery charge from the grid; case III does not include coordination among prosumers while in case IV the defined coordination strategy was implemented (Fig. 8, blue line). In this case, the voltage constraint (V_{min} in Fig. 6) is 0.98 pu.

It has been demonstrated that the and increasing penetration of SC presents improved voltage profiles, especially when coordination strategies are implemented. Even case III, with high penetration of uncoordinated SC, shows better profiles than the base case, without SC.

Table 1
PV facilities. Energy and cost as a function of peak power.

PV kW_p	PV $\frac{kWh}{year}$	€ savings	max. cost 8-year[1]	max. cost 10-year[1]	$\frac{€}{W_p}$ 8-year[1]	$\frac{€}{W_p}$ 10-year[1]
0.5	559	78	626	783	1.25	1.57
0.75	839	117	940	1175	1.25	1.57
1	1118	157	1252	1565	1.25	1.57
1.25	1398	196	1565	1957	1.25	1.57
1.5	1677	235	1878	2348	1.25	1.57
2	2236	313	2504	3130	1.25	1.57
2.25	2516	352	2817	3522	1.25	1.57
2.5	2795	391	3130	3913	1.25	1.57
2.75	3075	430	3443	4304	1.25	1.57
3	3354	470	3756	4696	1.25	1.57
3.25	3634	509	4070	5087	1.25	1.57
3.5	3913	548	4383	5478	1.25	1.57
4.25	4752	665	5322	6652	1.25	1.57

[1] Payback period.

4.4. Annual savings and budget

To account for annual money savings, the current price of electricity is considered. Feed-in tariffs are available in many countries, as stated in the introductory section. But, although other supportive policies are expected to keep in future, feed-in remunerations are supposed to dissipate eventually [2]. So, for the case studies, we will assume there are no remunerations for surplus power injected to the grid. The SC facilities should be profitable through the saved energy.

A prosumer facility is sized to cover as much demanded energy as possible, while minimizing the energy injected to the grid. Once the prosumer demand profile, the PV peak power, and the energy storage capacity are known, we will be able to calculate annual energy and money savings. A worthwhile payback period would not be higher than 8 or 10 years. It is assumed that the maximum payback is similar to the expected life of batteries. Then, we would obtain the maximun cost per facility. Table 1 summarizes the obtained results for different peak-powers, considering 0.14 € per kWh. This is an average price for the second semester of 2018 for this particular location [9]. The cost of installed power and taxes are not included.

For a given installed peak power, the annual energy production will give the maximum annual money saving possible, thus the maximum facility cost for 8- year and 10-year payback periods. The cost per installed W_p is also shown, being always the same, given the payback period. It has to be considered that this cost includes the PV generator and the battery.

Detailed results, particularized for each prosumer, are included in the Appendix.

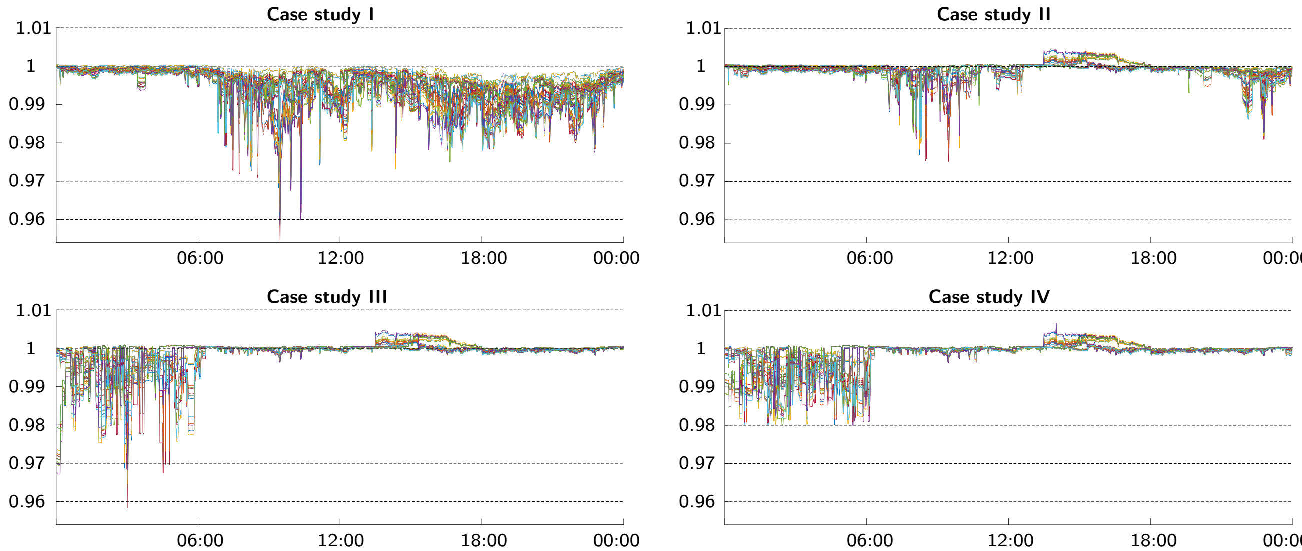

Figure 9: Voltages in pu with 100% degree of SC penetration. I: Without prosumers; II: Prosumers with only PV; III: Prosumers with PV+ non-coordinated ESS; IV: Prosumers with PV+ coordinated ESS.

5. Conclusion

Without an appropriate coordination strategy among prosumers, SC deployment might give rise to overloading or voltage issues in the distribution feeders. However, as it has been demonstrated in this work, adequate management strategies will prevent these drawbacks and bring many benefits to all the involved agents; At consumer level, economical benefits related to energy and money savings and at DNOs level, demand shifting to increase network reliability and improved voltage control.

This paper has presented an integrated approach to account for the different interests of prosumers and DNOs. It has been proved that for secure and reliable integration of SC in the distribution networks, the technical design is as crucial as the regulatory frame. Supportive policies such us feed-in tariffs are expected to disappear eventually, because they consider only the prosumer benefit individually, and they do not take into account the whole distribution grid benefit. A feed-in tariff might bring over sized facilities looking for increased economical benefits. Thus, to guarantee a common benefit for all the agents, the prosumer facility should be profitable through the saved energy only. This implies the maximum annual benefit would be the annual demanded energy.

As the presence of SC in distribution feeders increases, SC prosumers and DNOs should participate more actively in common energy management strategies at community and distribution levels.

This paper has answered the questions presented in the introduction section:

I. Prosumer viewpoint

- The maximum annual energy and savings for a given prosumer will be the annual energy consumption as a conventional consumer, before becoming a prosumer.
- The SC facility has to be sized for each prosumer accordingly to their demand profile.
- The maximum initial investment for a 10-year payback period is $1.57\frac{€}{W_p}$.

II. Network viewpoint

- Prosumers can modify the voltage profile in a more controllable basis compared to conventional consumers.
- As the degree of SC penetration increases, an appropriate coordination among different prosumers is needed to prevent voltage constraint violations.
- It has been proved that an appropriate SC coordination might be also employed for voltage regulation and grid supporting.

For each consumer, the maximum annual saving possible as a prosumer is the cost of their annual consumption. On this basis, the obtained cost for a reasonable payback period might not be available on the market nowadays, mainly because of the cost of the battery. This fact would explain why SC has not been widely deployed among residential and commercial feeders in all European countries. However, the price of commercial storage units will be reduced in the short to medium term, due to the fast development of these technologies. Then, the SC facilities are expected to be better received by consumers.

Further research will be conducted to study also massive inclusion of electric vehicles (EV) in the distribution networks. EV charging profiles will widely affect the energy management strategies, since an EV will introduce an additional energy storage element in the prosumer facility.

A. Appendix

A SC facility including a PV generator and a battery has been design for each consumer in the feeder, following the procedure described in section 4.1. The obtained results are shown in Table 2. The data for each prosumer are: Daily and annual demands in kWh, PV generator peak power, maximum daily energy production in kWh, daily energy storage capacity, in kWh, annual energy production in kWh, annual savings in %, annual electricity cost for the demanded energy, in €, savings per year in €. Finally, two different costs are included for a 8-year payback period: The maximum cost, considering annual savings for the PV peak power, and the maximum cost taking into account that the maximum annual saving cannot be ever higher than the energy demanded. This last cost is the absolute maximum, because the maximum energy that a prosumer can save is the total consumed energy.

These costs should include the whole facility, so for those consumers that need higher battery capacities, it might be more difficult to adjust to this budget. All these numbers were done assuming a cost of energy 0.14 € per kWh, but different values depending on the tariff or country might be considered instead. Taking into account that the cost of energy tends to increase with time, the actual payback might be lower, but the study presented in here aims at being conservative.

The feeder includes demand profiles both for commercial and residential consumers. According to the authors in [14], SC shows larger rates for commercial than residential consumers. In this case, similar SC rates are obtained if the battery sizing is adequate. For instance, if we compare nodes 3 and 5, the energy storage capacity of 3 is almost twice than of 5 to get similar SC rates, for similar values of daily energy, and the same PV installed power. This is due to the different demand profiles: For a residential feeder the storage capacity might be higher, in general, than for commercial prosumers.

References

[1] Aknin, Y., Bonnefous, C., Bottausci, M., Chouraqui-Quatremain, A., Seurat, N., 2017. Method to determine auto-consumption profitability. Energy Procedia 107, 193 – 198. doi:https://doi.org/10.1016/j.egypro.2016.12.170. 3rd International Conference on Energy and Environment Research, ICEER 2016, 7-11 September 2016, Barcelona, Spain.

[2] Appen, J.V., Braun, M., 2019. Sizing and improved grid integration of residential PV systems with heat pumps and battery storage systems. IEEE Transactions on Energy Conversion , 1–1doi:https://doi.org/10.1109/TEC.2019.2892396.

[3] Barcellona, S., Piegari, L., Musolino, V., Ballif, C., 2018. Economic viability for residential battery storage systems in grid-connected pv plants. IET Renewable Power Generation 12, 135–142. doi:https://doi.org/10.1049/iet-rpg.2017.0243.

[4] Camilo, F.M., Castro, R., Almeida, M.E., Pires, V.F., 2018. Assessment of overvoltage mitigation techniques in low-voltage distribution networks with high penetration of photovoltaic microgeneration. IET Renewable Power Generation 12, 649–656. doi:https://doi.org/10.1049/iet-rpg.2017.0482.

[5] Dhimish, M., Mather, P., Holmes, V., 2018. Evaluating power loss and performance ratio of hot-spotted photovoltaic modules. IEEE Transactions on Electron Devices 65, 5419–5427. doi:https://doi.org/10.1109/TED.2018.2877806.

[6] EPRI, . Simulation tool OpenDSS. URL: http://smartgrid.epri.com/SimulationTool.aspx.

[7] European Commission, 2018. 200 million in public support for renewable energy for self-suppliers of electricity in france. URL: http://europa.eu/rapid/press-release{_}IP-18-6168{_}en.htm.

[8] European Parliament and the Council of 19 May 2010, . The directive 2010/31/eu on the energy performance of buildings. Official Journal of the European Union .

[9] Eurostats European Statistics, . Electricity price statistics. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics.

[10] German Government, . Renewable energy sources act (erneuerbare-energien-gesetz)). URL: https://www.erneuerbare-energien.de/EE/Redaktion/DE/Dossier/eeg.html?cms{_}docId=73930.

[11] Ghiani, E., Vertuccio, C., Pilo, F., 2015. Optimal sizing and management of a smart microgrid for prevailing self-consumption, in: 2015 IEEE Eindhoven PowerTech, pp. 1–6. doi:https://doi.org/10.1109/PTC.2015.7232554.

[12] IDAE., 2009. Pliegos de Condiciones Tecnicas de Instalaciones Fotovoltaicas. Technical Report. Spanish Ministry for the ecological transition. URL: https://www.idae.es/tecnologias/energias-renovables/uso-electrico/solar-fotovoltaica.

[13] IEEE PES AMPS DSAS Test Feeder Working Group, . PES test feeders. URL: http://sites.ieee.org/pes-testfeeders/resources/.

[14] Litjens, G., van Sark, W., Worrell, E., 2016. On the influence of electricity demand patterns, battery storage and pv system design on pv self-consumption and grid interaction, in: 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), pp. 2021–2024. doi:https://doi.org/10.1109/PVSC.2016.7749983.

[15] Martirano, L., Parise, G., Greco, G., Manganelli, M., Massarella, F., Cianfrini, M., Parise, L., di Laura Frattura, P., Habib, E., 2019. Aggregation of users in a residential/commercial building managed by a building energy management system (bems). IEEE Transactions on Industry Applications 55, 26–34. doi:https://doi.org/10.1109/TIA.2018.2866155.

[16] Monteiro, A.C., Camus, C., Eusebio, E., 2018. Pv panel for self-consumption in public buildings, in: 2018 International Young Engineers Forum (YEF-ECE), pp. 43–49. doi:https://doi.org/10.1109/YEF-ECE.2018.8368937.

[17] Muthirayan, D., Kalathil, D., Poolla, K., Varaiya, P., 2019. Mechanism design for demand response programs. IEEE Transactions on Smart Grid , 1–1doi:https://doi.org/10.1109/TSG.2019.2917396.

[18] Polish Government, 2018. Act of june 7, 2018 amending the act on renewable energy sources and certain other acts. URL: http://dziennikustaw.gov.pl/DU/2018/1276/1.

[19] do Prado, J.C., Qiao, W., 2018. A stochastic decision-making model for an electricity retailer with intermittent renewable energy and short-term demand response. IEEE Transactions on Smart Grid , 1–1doi:https://doi.org/10.1109/TSG.2018.2805326.

[20] Prieto, J., Martinez-Garcia, J., Garcia, D., Santoro, R., Rodriguez, A., 2009. Mapa Solar de Asturias.

[21] Ramos, C., García, A.S., Moreno, B., Díaz, G., 2019. Small-scale renewable power technologies are an alternative to reach a sustainable economic growth: Evidence from Spain. Energy 167, 13 – 25. doi:https://doi.org/10.1016/j.energy.2018.10.118.

[22] RES LEGAL Europe, . Legal sources for renewable energy. URL: http://www.res-legal.eu/search-by-country/.

[23] Riaz, S., Marzooghi, H., Verbic, G., Chapman, A.C., Hill, D.J., 2019. Generic demand model considering the impact of prosumers for future grid scenario analysis. IEEE Transactions on Smart Grid 10, 819–829. doi:https://doi.org/10.1109/TSG.2017.2752712.

[24] Ruiz-Cortes, M., Romera, E.G., Lopes, R.A., Romero-Cadaval,

E., Martins, J., Montero, M.I.M., Barrero, F., 2018. Optimal charge/discharge scheduling of batteries in microgrids of prosumers. IEEE Transactions on Energy Conversion , 1–1doi:https://doi.org/10.1109/TEC.2018.2878351.

[25] Saele, H., Bremdal, B.A., 2017. Economic evaluation of the grid tariff for households with solar power installed. CIRED - Open Access Proceedings Journal 2017, 2707–2710. doi:https://doi.org/10.1049/oap-cired.2017.0556.

[26] Spanish Government, . Energy transition and consumer protection. Urgent actions. URL: https://www.boe.es/eli/es/rdl/2018/10/05/15.

[27] Swiss Federal Office of Energy SFOE, . Energy strategy 2050. URL: http://www.bfe.admin.ch/energiestrategie2050/index.html?lang=en.

[28] Turnsek, B., Papic, I., Blazic, B., 2017. Influence of self-consumption on distribution network operation: the slovenian case. CIRED - Open Access Proceedings Journal 2017, 1822–1826. doi:https://doi.org/10.1049/oap-cired.2017.0332.

[29] Yang, D., Jiang, C., Cai, G., Huang, N., 2019. Optimal sizing of a wind/solar/battery/diesel hybrid microgrid based on typical scenarios considering meteorological variability. IET Renewable Power Generation 13, 1446–1455. doi:https://doi.org/10.1049/iet-rpg.2018.5944.

Table 2
Prosumers characteristics

group	prosumer	demand $\frac{kWh}{day}$	demand $\frac{kWh}{year}$	PV kWp	PV (kWh) August, 13	ES $\frac{kWh}{day}$	PV $\frac{kWh}{year}$	annual saving	electricity cost per year before	savings per year	maximun cost (8 years)[1]	maximun cost (8 years)[2]
a	3	6.8	2489	1.5	6.6	8	1677	67%	348.53	234.78	1878.24	2788.22
	5	6.9	2536	1.5	6.6	4.5	1677	66%	355.06	234.78	1878.24	2840.51
	9	19.4	7068	4.25	18.7	11.5	4753	67%	989.52	665.42	5323.36	7916.13
	12	5.6	2053	1.25	5.5	6	1398	68%	287.45	195.72	1565.76	2299.58
	18	10.1	3679	2.25	9.9	6	2516	68%	515.00	352.24	2817.92	4119.97
	21	5.3	1928	1.25	5.5	4.5	1398	72%	269.96	195.72	1565.76	2159.69
	23	11.3	4136	2.5	11.0	8	2798	68%	579.10	391.72	3133.76	4632.81
	27	6.9	2516	1.5	6.6	6	1677	67%	352.21	234.78	1878.24	2817.69
	29	12.6	4587	2.75	12.1	5.8	3075	67%	642.15	430.50	3444.00	5137.19
	33	13.7	4992	3.25	14.3	8	3634	73%	698.87	508.76	4070.08	5590.95
	36	6.5	2354	1.5	6.6	5.5	1677	71%	329.63	234.78	1878.24	2637.01
	45	18.9	6892	4.25	18.7	10.5	4753	69%	964.82	665.42	5323.36	7718.59
	50	7.0	2573	1.5	6.6	6.5	1677	65%	360.16	234.78	1878.24	2881.30
	53	12.0	4374	2.75	12.1	8	3075	70%	612.29	430.50	3444.00	4898.32
b	1	10.2	3732	2.25	9.9	6	2516	67%	522.43	352.24	2817.92	4179.45
	7	10.2	3715	2.25	9.9	8.5	2516	68%	520.14	352.24	2817.92	4161.13
	8	15.7	5715	3.5	15.4	7.5	3914	68%	800.09	547.96	4383.68	6400.70
	16	10.6	3872	2.25	9.9	5.5	2516	65%	542.14	352.24	2817.92	4337.12
	20	13.0	4748	2.75	12.1	10.5	3075	65%	664.78	430.50	3444.00	5318.20
	26	5.6	2062	1.25	5.5	5.5	1398	68%	288.62	195.72	1565.76	2308.98
	31	6.9	2530	1.5	6.6	4	1677	66%	354.21	234.78	1878.24	2833.72
	32	15.0	5486	3	13.2	7	3355	61%	768.00	469.70	3757.60	6144.02
	38	11.9	4335	2.5	11.0	7.5	2798	65%	606.93	391.72	3133.76	4855.44
	39	5.0	1818	1.25	5.5	5.5	1398	77%	254.53	195.72	1565.76	2036.23
	41	6.7	2443	1.5	6.6	3.5	1677	69%	341.96	234.78	1878.24	2735.69
	46	9.6	3508	2	8.8	6.5	2237	64%	491.11	313.18	2505.44	3928.85
	47	4.1	1498	0.75	3.3	2.5	839	56%	209.66	117.46	939.68	1677.27
	51	8.3	3033	1.75	7.7	6.5	1957	65%	424.58	273.98	2191.84	3396.64
c	2	12.1	4418	2.75	12.7	12	3075	70%	618.48	430.50	3444.00	4947.83
	4	9.8	3584	2	8.8	5	2237	62%	501.82	313.18	2505.44	4014.58
	10	11.3	4135	2.5	11.0	5	2798	68%	578.86	391.72	3133.76	4630.85
	11	5.7	2098	1.25	5.5	5	1398	67%	293.76	195.72	1565.76	2350.07
	14	5.4	1968	1.25	5.5	3	1398	71%	275.53	195.72	1565.76	2204.25
	17	5.3	1948	1.25	5.5	4	1398	72%	272.70	195.72	1565.76	2181.60
	19	11.0	4023	2.5	11.0	5.5	2798	70%	563.17	391.72	3133.76	4505.38
	24	14.7	5351	3.5	15.4	11	3914	73%	749.12	547.96	4383.68	5992.93
	25	6.7	2445	1.5	6.6	3	1677	69%	342.29	234.78	1878.24	2738.35
	30	6.8	2488	1.5	6.6	6	1677	67%	348.37	234.78	1878.24	2786.99
	34	6.0	2199	1.25	5.5	5.5	1398	64%	307.92	195.72	1565.76	2463.35
	35	15.8	5760	3	13.2	10.5	3355	58%	806.36	469.70	3757.60	6450.86
	42	6.8	2496	1.5	6.6	6	1677	67%	349.42	234.78	1878.24	2795.33
	43	4.3	1558	1	4.4	2	1118	72%	218.12	156.52	1252.16	1744.96
d	6	5.4	1967	1.25	5.5	3	1398	71%	275.33	195.72	1565.76	2202.61
	13	10.2	3741	2.25	9.9	6	2516	67%	523.75	352.24	2817.92	4190.04
	15	6.1	2238	1.5	6.6	3.5	1677	75%	313.32	234.78	1878.24	2506.56
	22	4.9	1788	1	4.4	4.5	1118	63%	250.38	156.52	1252.16	2003.08
	28	1.8	666	0.5	2.2	1.5	559	84%	93.17	78.26	626.08	745.37
	37	7.6	2780	1.5	6.6	3.5	1677	60%	389.25	234.78	1878.24	3113.99
	40	4.0	1455	0.75	3.3	3	839	58%	203.75	117.46	939.68	1630.01
	44	5.2	1895	1.25	5.5	3	1398	74%	265.30	195.72	1565.76	2122.41
	48	10.7	3907	2.25	9.9	5.5	2516	64%	547.04	352.24	2817.92	4376.29
	49	8.0	2930	2	8.8	8.5	2237	76%	410.22	313.18	2505.44	3281.72
	52	5.8	2135	1.25	5.5	3	1398	65%	298.92	195.72	1565.76	2391.40
	54	9.4	3434	2.25	9.9	7	2516	73%	480.81	352.24	2817.92	3846.48
	55	7.2	2632	1.5	6.6	5.6	1677	64%	368.43	234.78	1878.24	2947.45
	TOTAL	**484.1**	**176711**	**106.5**	**469.2**	**326.4**	**119102**	**67%**	**24739.52**	**16674.28**	**133394.24**	**197916.15**

[1] Maximum initial cost with maximum expected annual savings for the given PV peak power and 8-year payback period.
[2] Maximum initial cost with annual demand (maximum saving possible) for 8-year payback period.