Reis, Vera; Almeida, Rita H.; Silva, José A.; Brito, Miguel C.

Article

Demand aggregation for photovoltaic self-consumption

Energy Reports

Provided in Cooperation with:
Elsevier

Suggested Citation: Reis, Vera; Almeida, Rita H.; Silva, José A.; Brito, Miguel C. (2019) : Demand aggregation for photovoltaic self-consumption, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 54-61,
https://doi.org/10.1016/j.egyr.2018.11.002

Energy Reports 5 (2019) 54–61

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

Demand aggregation for photovoltaic self-consumption

Vera Reis [a], Rita H. Almeida [b,1], José A. Silva [b], Miguel C. Brito [b,*]

[a] Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

HIGHLIGHTS

- Real demand data for residential dwellings and small business.
- Prosumer aggregation more efficient than battery.
- Aggregation of 10 households has significant impact on self-consumption rates.
- Aggregation of different demand profiles is very effective.

ARTICLE INFO

Article history:
Received 20 April 2018
Received in revised form 3 September 2018
Accepted 13 November 2018
Available online xxxx

Keywords:
Photovoltaics
Self-consumption
Demand aggregation
Solar community

ABSTRACT

The mismatch between photovoltaic generation and residential load leads to relative modest rates of self-consumption of solar electricity unless expensive storage solutions are locally available. One alternative to batteries is the aggregation of demand of different prosumers, as the collective load diagram might be better adapted to the solar resource. This hypothesis is tested for empirical data from 18 dwellings and 3 small businesses in the city of Lisbon, Portugal. Results show that a relatively low number of dwellings and a local small shop with a PV system without any storage will reach 90% self-consumption rates at a much lower cost than an individually owned PV system with 1 kWh/kWp storage system.

1. Introduction

The impressive cost decrease of photovoltaics in particular during the last decade (IEA) led it to reach grid parity in many countries, at least at the retail level (sometimes called plug parity) (Breyer and Gerlach, 2013). Overcoming the grid parity threshold creates conditions to replace feed-in tariff incentive mechanisms by no-subsidy PV self-consumption business models which are being implemented in many communities (Coughlin et al., 2012; Cucchiella et al., 2017). Conceptually, this approach is based on a prosumer who owns a rooftop PV system, avoiding some demand during sunshine hours when his or her home is (partially) powered by solar electricity, feeding eventual excess energy into the grid, while being a 'regular' grid customer when the sun is not shining. Except for special net metering arrangements, most of these self-consumption solutions provide high value for self-consumed solar electricity while penalizing excess energy fed into the grid (Comello and Reichelstein, 2017). This regulatory setup promotes the deployment of small PV systems, sized in such a way that PV peak power corresponds to minimum daytime demand (Silva et al., 2016). For a typical working family, away from home when the PV has higher production, this often means an almost residual PV power system. Furthermore, individual load profiles feature very high variability, especially when analyzed with a sub-hourly resolution (Cao and Sirén, 2014), which further reduces optimal PV peak power for self-consumption customers. Small PV systems benefit less from economies of scale and therefore this market conditions may be argued to limit the full deployment of photovoltaics, in particular in the distributed residential market.

One possible option to increase the self-consumption rate of photovoltaic-generated electricity is the use of a battery bank that stores excess solar electricity during sunshine hours which is later used in the evening (Jallouli and Krichen, 2012; Gitizadeh and Fakharzadegan, 2014; Lupangu and Bansal, 2017). However, current and expected battery prices for the next few years are too high to make this option price competitive in most situations (Bendato et al., 2018).

A complementary approach is the aggregation of different electricity customers. The central limit theorem states that the variability of independent random variables will decrease with the square root of the number of variables which suggests that the load

* Correspondence to: FCUL, DEGGE, Ed. C8, 1749-016, Campo Grande, Portugal.
E-mail address: mcbrito@fc.ul.pt (M.C. Brito).

1 Currently at Instituto de Energía Solar - Universidad Politécnica de Madrid, 28031 Madrid, Spain.

https://doi.org/10.1016/j.egyr.2018.11.002

Table 1
Overview of characteristics of load diagram for different units and their aggregation. †Due to the relative high demand of hotel, these sets combine the load of the hotel with 4 and 8 times the load of the 7 and the 18 dwellings, respectively.

Units	Energy consumption [MWh/year]	Power range [kW]	Observations
Residential units	0.3 – 3.1	0.0 – 5.8	Typical residential load diagrams
Bank	3.8	0.1 – 2.6	Almost flat consumption during working hours
Pub/restaurant	7.4	0.2 – 4.1	Higher demand in the evenings
Hotel	83.1	3.7 – 31.3	Higher demand in winter
Condominium	18.9	0.7 – 8.6	Aggregation of all 18 dwellings
Condominium 6.9	10.0	0.35 – 4.3	Aggregation of the 7 dwellings with 6.9 kVA
Condominium & bank	22.6	0.9 – 8.8	
Condominium 6.9 & bank	13.7	0.5 – 5.0	
Condominium & pub	16.0	1.1 – 9.3	
Condominium 6.9 & pub	10.3	0.6 – 6.3	
Condominium & hotel	157.8	7.5 – 49	8x the load of the condominium†
Condominium 6.9 & hotel	161.8	7.7 – 54	4x the load of the condominium 6.9†
Condominium & bank & pub	18.2	1.4 – 9.5	
Condominium 6.9 & bank & pub	12.4	0.9 – 6.9	

aggregation of different prosumers[2] would lead to a less variable load, increasing the rate of self-consumption of PV systems. This statistical effect has been identified, and quantified (Salom et al., 2011) but, as it has been pointed out by Luthander's recent review on photovoltaic self-consumption in buildings (Luthander et al., 2015) there is a lack of evaluation of this aggregation effect using empirical data.

Osawa et al. (2012) simulated a community with electric vehicles, based on measured demand data for 50 homes in Tokyo, Japan. Their results show that the impact of aggregation of 10 homes is to increase self-consumption from 42 to 52%, with an increase of 4% in self-sufficiency. The case study developed by Mahran et al. (2016) for two typical days in Konstanz, Germany, shows that self-consumption may exceed 60% without storage for single users as well as for an entire community. Luthander et al. (2016) evaluated high-resolution irradiance and power consumption data from a community of 21 single-family houses in Sweden and observed that self-consumption ratio increased +15% when using shared instead of individual storage. Merei et al. (2016) show that a PV system can be a very attractive investment for a supermarket in Aachen, Germany, whilst the implementation of storage systems with large battery sizes just lead to a slight increase in self-sufficiency degree at a high cost.

The main objective of this paper is to contribute with empirical data to the evaluation of the impact of load aggregation on the rates of self-consumption and self-sufficiency of PV electricity and its potential to reduce storage capacity. In particular, it explores the potential of combining the load of residential and small local shops, with very different load profiles and higher demand during daytime, which offers an even higher potential to increase the rate of self-consumption of PV electricity.

A full economic analysis is performed to assess the impact of load aggregation on the internal rate of return and payback time of the PV systems. The analysis is performed for current market conditions in Portugal but its conclusions are at least qualitatively valid for all markets allowing PV self-consumption. The data set includes sub-hourly demand data for 18 individual households and 3 commercial customers (one bank, one pub/restaurant and a small hotel).

The rest of the paper is structured in a Methods section, describing the details of the input data, the PV and storage models, and the economic parameters, which is followed by the Results section reporting on the results for the load aggregation of residential prosumers and its aggregation with the small shop's load. In the end, Conclusions and comments regarding future work are summarized.

[2] Load profiles of different prosumers are not exactly independent random variables since demand patterns are often determined by common drivers such as lighting, cooking or heating/cooling needs.

2. Methods

For this analysis, measured load data for residential and commercial units are used to assess the potential self-consumption and self-sufficiency of photovoltaic systems with a range of installed powers, extrapolated from locally measured PV generation data, and different levels of storage.

2.1. Load data

This work is based on electricity consumption data residential and commercial units located in Lisbon, Portugal, for 2013, which was provided by ISA (Intelligent Sensing Anywhere http://www.isasensing.com). The residential units were a set of 18 dwellings with contracted power from 3.45 to 10.35 kVA; 7 of these dwellings have the same contracted power (6.9 kVA) and in the analysis are considered as 'condominium 6.9' to test the impact of a more homogeneous sample.

The commercial units are those of a bank branch, a pub /restaurant and a hotel. The contracted powers of these commercial units are not known. Table 1 summarizes the most relevant characteristics of the load diagrams of the different units considered and their aggregation.

Time resolution for load data is 15 min and, for privacy issues, there was no geographical information on either the residential or commercial units. Missing data were addressed by linear interpolation considering the day of the week (separating week and weekend days) and local holidays. For further details on the interpolation procedure refer to Reis (2017).

2.2. PV system

The photovoltaic energy generation data is for a single location, also in Lisbon, with a time resolution of 10 min. The measured data was obtained from a south facing polycrystalline silicon modules with the local optimum inclination (34°). These data were linearly interpolated to a 15 min resolution, for synchronization with the demand data, and normalized for kWh/kWp.

For each building unit or combination of building units, the simulated system configuration consists of the PV array, an inverter, battery storage system (when available) and bi-directional meter. The PV installed power and storage capacity are model parameters. Table 2 summarizes the relevant technical parameters for the PV-battery system. Battery lifetime and self-discharge losses assume lithium-based battery, which have been shown to be more appropriate as residential electricity storage (Krieger et al., 2013).

The energy management strategy gives priority to the use of solar energy: the generated PV electricity is primarily used to fulfill

Table 2
Operating and technical parameters of PV-battery system.

Parameter	Value	Unit
PV module warranty	25	Years
Inverter efficiency	97	%
Inverter warranty	10	Years
Round trip efficiency	89	%
Battery losses	1	%/month
Battery warranty	10	Years

the consumption needs. If generation is higher than demand, excess power is sent to the battery or, if the battery is totally charged, fed to the grid. If generation is not enough to fulfill demand, the energy stored in the battery will be used before using the grid.

2.3. Assessment

Self-consumption is here defined as the fraction of photovoltaic -generated electricity that is consumed by the producer on-site or by associates directly contracted to the producer. The excess of electricity can either be injected into the grid or stored to be consumed when needed. This delayed use is also accounted as self-consumption. A 100% rate of self-consumption means than no photovoltaic generation is fed to the grid. Note that this definition means that electricity loss in charging/discharging a battery is also considered self-consumption.

Following the nomenclature of Luthander et al. (2015), if $L(t)$ is the instantaneous load, $P(t)$ the photovoltaic production and $S(t)$ the power to and from the battery ($S(t) < 0$ when charging and $S(t) > 0$ when discharging), the rate of self-consumption is defined by Eq. (1) where $M(t) = \min(L(t), P(t) + S(t))$ is the instantaneously overlapping part of the generation and load profiles:

$$SC = \frac{\int M(t)\,dt}{\int P(t)\,dt} \tag{1}$$

The rate of self-sufficiency, defined in Eq. (2), represents the degree to which the on-site PV production is sufficient to fulfill the energy needs of the building unit.

$$SS = \frac{\int M(t)\,dt}{\int L(t)\,dt} \tag{2}$$

The PV system economic assessment is based on the discounted payback period and the internal rate of return, which are defined as usual. The payback is the number of years it takes for the initial cost of the project to equal the discounted value of expected cash flows. The investment comprises the initial expenditure, e.g. the costs of the PV, the inverter, the battery (when available) and the installation, operation and maintenance costs (1%/year) and replacements costs (both inverter and battery are assumed to have operational lifetimes of 10 years and hence need to be replaced twice during the duration of the project). The cash inflow is the sum of the (avoided) cost of electricity bought from the grid and the revenue from the electricity fed into the grid.

For numerical simulations, the particular case for Portugal (as established by the Law Decree 153/2004) was used. These economic parameters are summarized in Table 3.

3. Results

Results are presented by considering the aggregation of residential units only and then, in Section 3.2, the aggregation of residential and the local commercial units.

Table 3
Relevant parameters for the economic assessment.

Parameter	Value	Unit	References
Cost PV	1.8	€/Wp	(Collares Pereira et al., 2016)
Cost inverter	0.3	€/Wp	(FF Solar, 2017)
Cost battery	470	€/kWh	(The Tesla Powerwall, POWERWALL 2 AC, 2016)
Feed in price	0.05	€/kWh	(OMIE, 2017)
Electricity cost	0.1587	€/kWh	(ERSE, 2015)
Inflation	2.0	%	
Project lifetime	25	Years	

3.1. Aggregating residential systems

The impact of the load aggregation of the 18 residential units was performed by considering 100 random combinations of pairs, triplets, etc. of different loads, without any restrictions regarding repetitions. The PV installed power was varied from one 250 Wp module up to the load peak power. The storage capacity varied from zero (no battery) to 2 kWh/kWp.

The particular results presented in Fig. 1 are representative of all simulations. The boxplot represents the median, the 25th and 75th percentiles the most extreme data points not considered outliers, which are plotted individually. They were obtained for maximum PV power (i.e. PV installed power equals the peak consumption of the instantaneous sum of the load of the dwellings considered, rounded to the nearest integer number of 250 Wp modules) and 1 kWh/kWp storage capacity. Increasing storage capacity leads to higher self-consumption and self-sufficiency but with diminishing economic performance due to the present high cost of batteries.

One can observe that, on average, the self-consumption increases from about 50 to 80% when the number of dwellings increases from single unit to about ten homes. Aggregation of more dwellings does not seem to lead to significant changes in self-consumption. It is also noticeable that the self-sufficiency range is very wide, hence this factor is very sensitive to the particular load diagrams of the residential units considered (e.g. the self-sufficiency for a single home may vary between 20 and 100%). Of course, this result reinforces the relevance of behavior impact and demand management strategies as complementary approaches for improved self-consumption. This variability decreases with the number of aggregated dwellings.

Another impact of load aggregation is the reduction of the self-sufficiency rate. This result is expected as the smoothing not only reduces the number of instances when the generation exceeds the load (with a high impact on self-consumption) but also reduces the number of instances when the load exceeds the generation. This anti-correlation between self-consumption and self-sufficiency has been clearly shown in Luthander et al. (2015). Again, the impact of load aggregation is not very significant above ten homes.

The impact on economical parameters follows closely the behavior of the self-consumption rate since the IRR and payback times critical depend on the high value of avoided consumption from the grid and the low value of surplus photovoltaic electricity fed into the grid. For this particular PV-storage system configuration, the impact of load aggregation leads to a potentially risky investment for single homes to a clearly attractive project when including more than 6 dwellings, with average internal rates of return above 5%.

3.2. Aggregating residential and commercial units

A better match between consumption and photovoltaic generation leads to higher self-consumption, higher self-sufficiency,

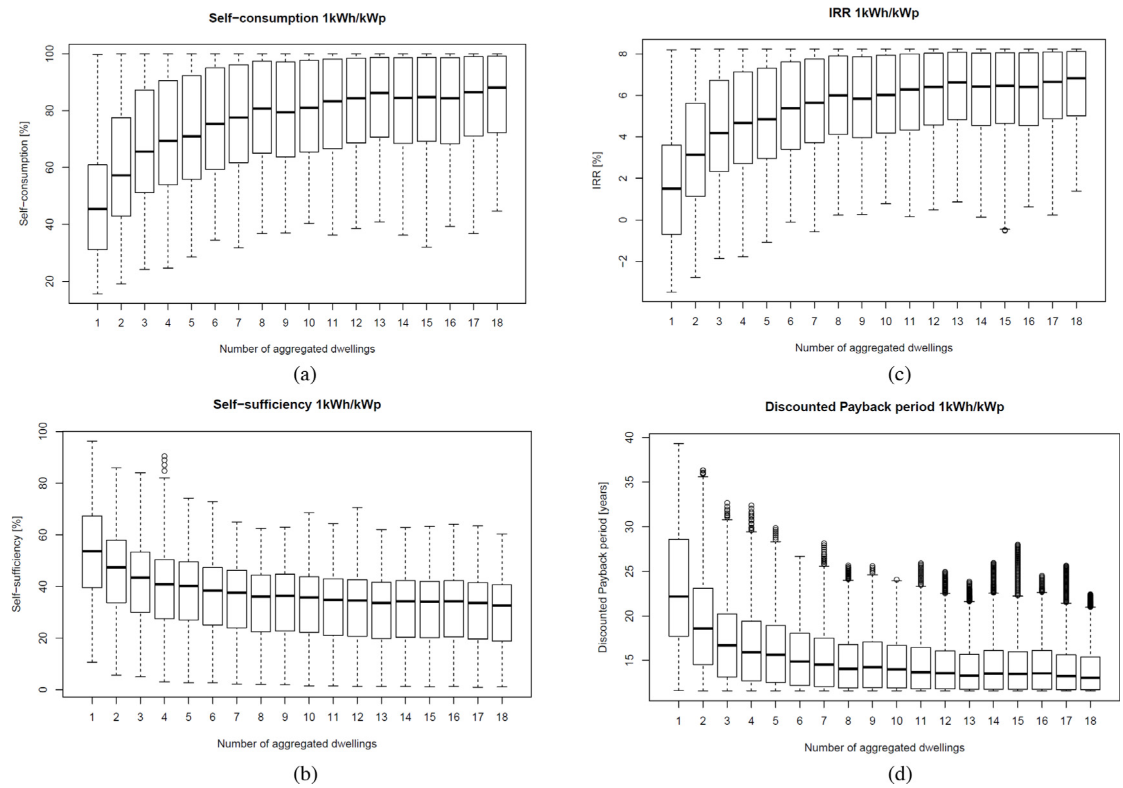


Fig. 1. Impact of number of residential units on (a) self-consumption, (b) self-sufficiency, (c) internal rate of return and (d) discounted payback period. Results for peak PV power and 1 kWh/kWp storage.

higher internal rate of return and lower payback periods. This can be observed in Fig. 2, which presents these four parameters for the ranges of peak power and storage capacity for the hotel case study. For low installed PV power, below 10 kWp, all the generated photovoltaic electricity is consumed on-site which leads to local self-consumption and linearly increasing self-sufficiency. The internal rate of return decreases proportionally to the storage capacity because the battery is not being used and higher storage capacities are more expensive. The discounted payback period follows the opposite trend, for the same reason.

Above 10 kWp, some of the generated solar electricity will not be consumed instantly, being either temporarily stored in the battery or sold to the grid. This means that above this PV installed power, the level of self-consumption will decrease. The decrease rate depends on the storage capacity. If the system has no or low storage capacity, the self-consumption will decrease rapidly, while a larger battery will slow the decreasing rate. The level of self-sufficiency will also increase if a larger storage capacity is considered. The internal rate of return and the discounted payback period will tend to converge, as more expensive (high capacity) batteries are more fully used. Nevertheless, the cost of storage solutions is so high that, for the range of ratio battery capacity over PV power explored in this study, from an economic point of view, large storage capacities are always less interesting than smaller systems.

The self-consumption and the self-sufficiency, for a certain installed power and storage capacity, will vary from case to case but their general behavior is common to all case studies analyzed.

The excess energy point, here defined as the installed power before instantaneous self-consumption drops below 97%, varies from case to case (for instance, in the case of the hotel, presented in Fig. 2, the excess point is 10 kWp, or 38% of the contracted power). Fig. 3 shows the excess energy point as a fraction of the maximum contracted power for the different building units or combination of building units without storage. Results show that aggregation will lead to a better match between installed PV power and load profile. As expected, the aggregation of commercial and residential units enables higher PV dissemination without producing an excess of energy.

It is interesting to compare the excess point over maximum power for the condominium (28%) and condominium 6.9 (31%) with the excess points for the individual dwellings (**<**8%). In fact, in most individual dwellings the excess point does not exist, which means that 97% self-consumption would occur for installed PV power below the PV module unit.

The maximum installed power is never the most economic system configuration but it is nevertheless interesting to look at, since it is the situation leading to the maximum use of the battery. Fig. 4 shows the self-consumption of the different sets of building units studied, for the maximum PV installed (equal to the contracted power) and the different levels of storage capacity, from zero (no battery) to 2 kWh/kWp. These results can be compared to self-consumption rates of 26–58% for the average individual dwelling, for 0 kWh/kWp–2 kWh/kWp, respectively.

These results show that individual sites, the restaurant, the bank and the condominiums, feature the lower self-consumption rates. The hotel is a notable exception since, on its own, it achieves a high level of self-consumption (65–90%, depending on the storage capacity). In general, the self-consumption rate increases when different users, i.e. different load diagrams, are merged together. Depending on the storage capacity, the self-consumption level may overcome the 90% barrier in a number of situations. It is also important to note that even without batteries, the self-consumption of PV systems increases with aggregation of diverse users. Comparing with the results for single units shown in Fig. 1, one can notice that an aggregated condominium without any storage will feature higher self-consumption that the average dwelling with a typical 1 kWh/kWp.

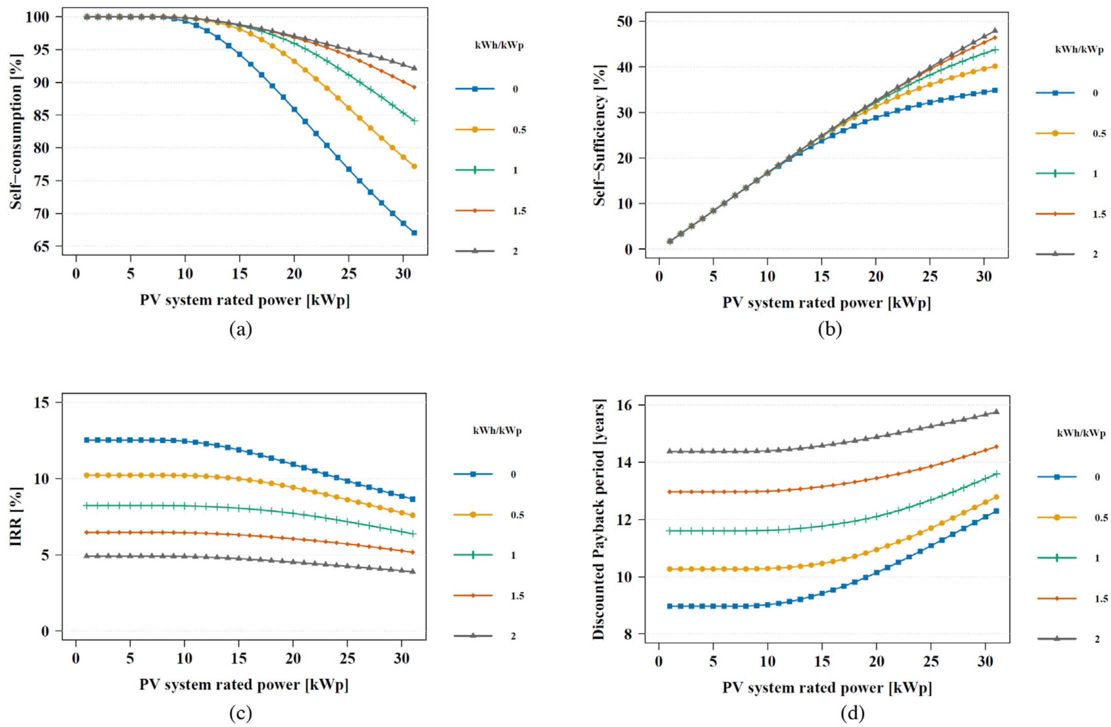


Fig. 2. Impact of PV installed power on (a) self-consumption, (b) self-sufficiency, (c) internal rate of return and (d) discounted payback period, for the hotel case study.

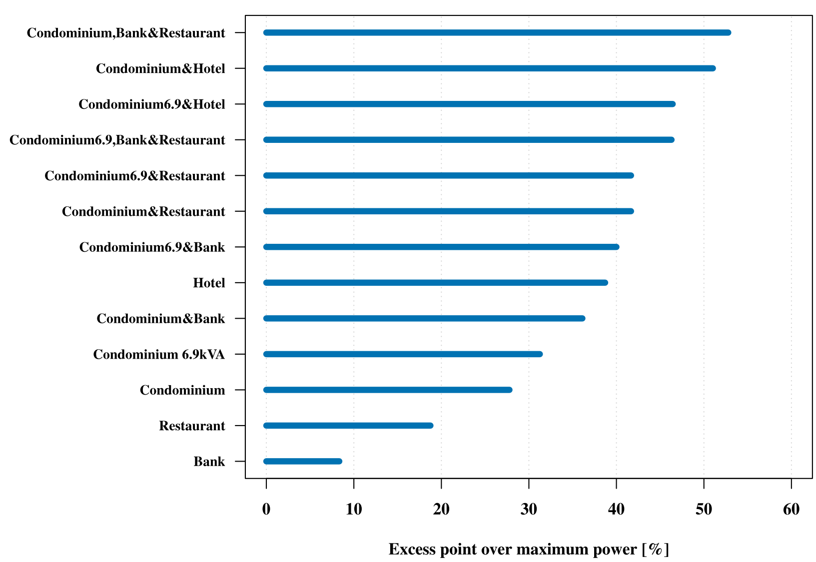


Fig. 3. Installed PV power for self-consumption above 97% (excess point) as a fraction of contracted power for single units and different aggregation sets.

As far as economic parameters are concerned, Fig. 5 presents the comparison of the internal rate of return, considering maximum peak power installations, for the different level of aggregation and PV-storage ratios. The results show that the investment is never returned for the restaurant, on its own or when in combination with other users. All other system configurations feature positive internal rates of return. Again, the aggregation of diverse users leads to higher returns. It is also worth noting that, as discussed above, the lower the storage capacity is, the higher the economic interest of the PV system will be. This relation is due to the current high cost of battery systems.

Considering a plausible threshold of 5% for the internal rate of return to validate the investment, we can conclude that all PV systems without batteries are viable (excluding the restaurant units, as mentioned before). Aggregated systems may reach viability even with some storage, hence with higher self-consumption. For the average individual dwelling, the internal rate of return ranges between 0 and 2.7%, depending on battery size.

The analysis of the discounted payback period (Fig. 6) again highlights that the restaurant has the lowest economic performance, with payback periods above the project lifetime. The aggregation of the restaurant with other users slightly decreases the payback time, which is kept above 25 years, regardless of the use of batteries. All other cases feature payback periods in the range of 10–18 years, with slightly lower value for aggregation sets and minimum levels for the no-battery configuration. These results underline the conclusions of the analysis of the internal rate of return. When lower PV installed power is considered (not shown

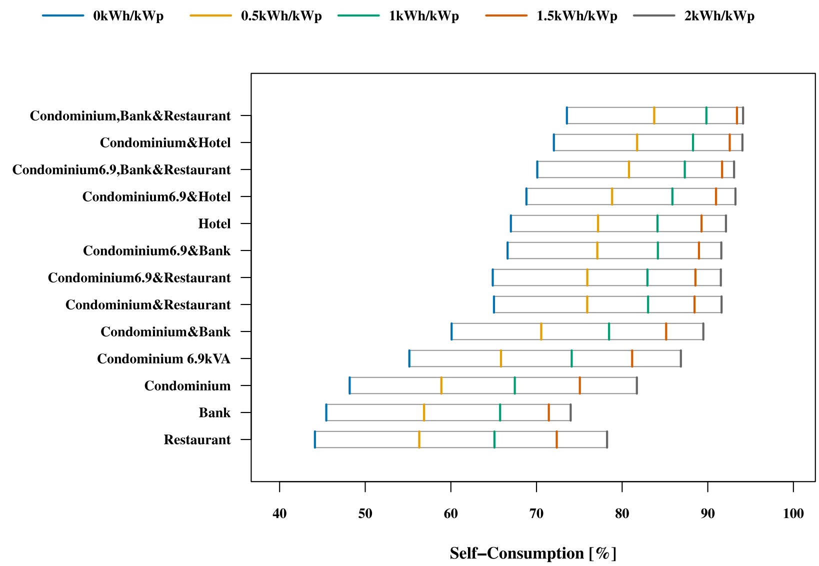


Fig. 4. Self-consumption rate for all PV-storage configurations, for maximum installed power for single units and different aggregation sets.

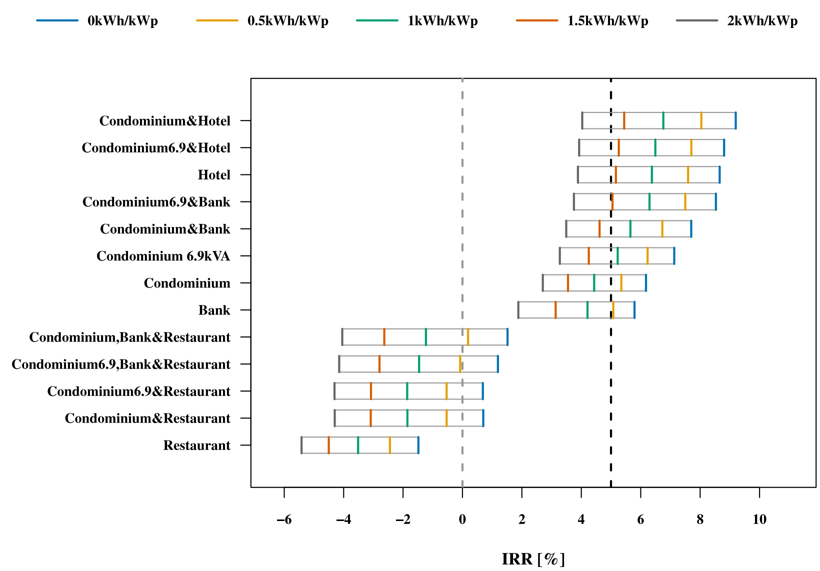


Fig. 5. Internal rate of return for all PV-storage configurations, for maximum installed power for single units and different aggregation sets.

in figure) payback periods are further reduced, from 8 to 12 years, depending on the size of the battery.

3.3. Sensitivity to storage costs

These results have shown that the cost of the storage system has a significant impact on the economics of the PV systems. Since an important reduction of storage costs is expected for the near future, a sensitivity analysis related to battery cost was performed. For that purpose, the economic parameters were assessed when the cost of the battery is reduced by 50%, a decrease projected to occur in a 5-years' time-frame (Berckmans et al., 2017). Results are shown in Fig. 7 for the aggregated 18 dwellings. One observes that the impact of cost reduction is of course more significant for larger storage systems and may more than double the internal rate of return for those configurations. This leads to a less pronounced relative advantage for lower storage systems. The discounted payback time may decrease by 40% for larger systems. Nevertheless, the relative benefit of load aggregation is maintained, as one can observe when comparing the no storage data points in Figs. 3–6

3.4. Limitations of this work

It is important to highlight that although based on measured load and PV generation data, this work is a simulation and therefore does not account with human behavior features such as, for example, the well-documented energy-saving behavior of owners of PV systems (Keirstead, 2007) or other not so well studied cooperative (or selfish) conducts in renewable energy communities (Facchini et al., 2017). The demand attitude of prosumers could certainly lead to different load diagrams that are expected to further improve self-consumption but that nevertheless require further study.

It is also relevant to mention that the data used in this study is from the region of Lisbon but not necessarily from the same street, due to data privacy issues. It is likely that if all dwellings belonged to the same building (typical dwellers with somewhat similar social-economic conditions and more similar demand patterns) the variability observed in Fig. 1 would probably be reduced.

The relatively coarse time resolution of 15 min provides itself a smoother vision of the load diagram. In fact, Beck et al. studied the influence of different time resolutions would have on the self-consumption rate (Beck et al., 2016) and showed that, compared

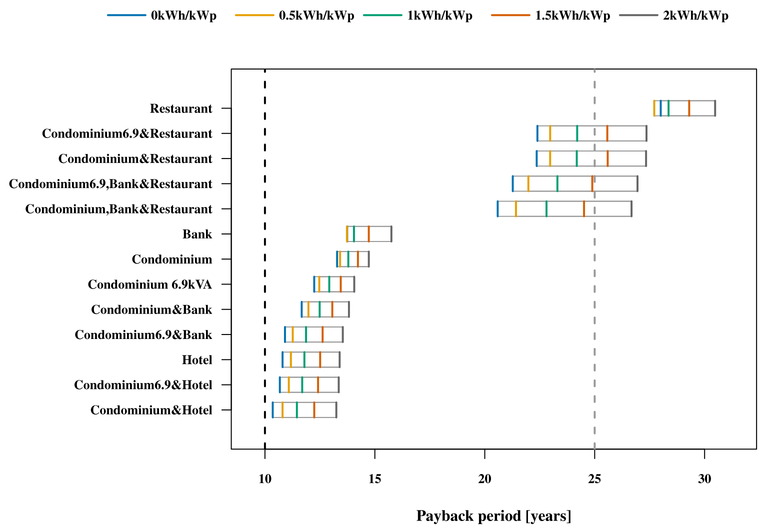
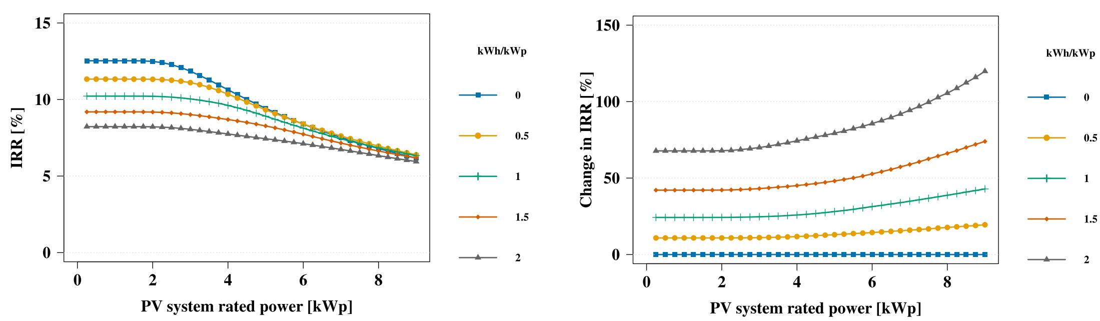


Fig. 6. Discounted payback time for all PV-storage configurations, for maximum installed power for single units and different aggregation sets.



(a) (b)

Fig. 7. (a) IRR values for increasing PV installed power, and (b) Change of internal rate of return for a 50% decrease of battery cost, for different levels of Wh/Wp storage systems.

to 10 s time resolution, a 15 min time step could lead to a 10% over-estimation of self-consumption. If taken into consideration in our study, this effect would probably increase the impact of load aggregation on the self-consumption rate perhaps increasing the optimum number of dwellings required.

The model results regarding self-consumption and self-sufficiency are generally in accordance with previous literature for other locations (as mentioned in Section 1). The economic parameters are very much dependent on the local legal-economic framework (which determines the price of the displaced consumption and fed in revenue) and solar radiation local resources and therefore their quantitative extrapolation for other countries/regions requires caution. Nevertheless, their qualitative variation with aggregation of different load diagrams, increasing installed power or storage capacity is expected to hold across a varied landscape.

4. Conclusions

The hypothesis that the aggregation of electricity consumption, from different users with different consumption profiles, will lead to an improvement of the collective load diagram, in the sense of being better adapted to the photovoltaic generation profile, is confirmed and supported by these results. The demand aggregation of up to 10 residential households leads to an increase of the average self-consumption from 50 to 80%, considering a storage level of 1 kWh/KWp. This increase is more significant than in earlier literature due to the diversity of demand profiles.

The internal rate of return at current costs easily reaches 5% for these shared systems. When the local small shop is included in the load diagram, the PV self-consumption may exceed 90%. These results go beyond the reviewed literature, which has focused on the aggregation of residential customers only.

We can conclude that self-consumption rate and project profitability increases with load aggregation of dwellings and small business units. A relatively low number of dwellings and a local small shop with a PV system without any storage will feature higher self-consumption rates than a much more expensive individually owned PV system with 1 kWh/kWp storage system.

Regarding energy policy recommendations, these results show that legal mechanisms to allow aggregation of demand, storage and PV generation could have a relevant role for further dissemination of PV, in particular in the urban environment, without extra costs for the grid and/or other consumers. This can help to bring new and more investment to PV-storage systems by prosumers from both commercial and residential areas.

5. Acknowledgments

The authors gratefully acknowledge ISA — Intelligent Sensing Anywhere for the data provided as well as the financial support by the MIT Portugal Program on Sustainable Energy Systems, the Portuguese Science and Technology Foundation (FCT), grants PD/BD/105851/2014 and SFRH/BPD/82540/2011, projects IDL (UID/GEO/50019/2013), and PVCITY (PTDC/EMSENE/4525/2014).

References

Beck, T., et al., 2016. Assessing the influence of the temporal resolution of electrical load and PV generation profiles on self-consumption and sizing of PV-battery systems. In: Applied Energy, vol. 173. pp. 331–342.

Bendato, Ilaria, Bonfiglio, Andrea, Brignone, Massimo, Delfino, Federico, Pampararo, Fabio, Procopio, Renato, Rossi, Mansueto, 2018. Design criteria for the optimal sizing of integrated photovoltaic-storage systems. Energy 149, 505–515. http://dx.doi.org/10.1016/j.energy.2018.02.056.

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., Van Mierlo, J., 2017. Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030. Energies 10, 1314.

Breyer, Christian, Gerlach, Alexander, 2013. Global overview on grid-parity. Prog. Photovolt. 21 (1), 121–136.

Cao, S., Sirén, K., 2014. Impact of simulation time-resolution on the matching of PV production and household electric demand. Appl. Energy 128, 192–208.

Collares Pereira, M., Joyce, A., Cunha Reis, P., 2016. O valor e o custo da eletricidade produzida por sistemas solares fotovoltaicos. In: Renováveis Magazine, vol. 25. pp. 46–47.

Comello, S., Reichelstein, S., 2017. Cost competitiveness of residential solar PV: The impact of net metering restrictions. Renew. Sustain. Energy Rev. 75, 46–57.

Coughlin, J., Grove, J., Irvine, L., Jacobs, J.F., Phillips, S.J., Sawyer, A., Wiedman, J., 2012. A Guide to Community Shared Solar: Utility, Private, and Nonprofit Project Development. National Renewable Energy Laboratory, pp. 1–68.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2017. The economic feasibility of residential energy storage combined with PV panels: The role of subsidies in Italy. Energies 10, 1434.

ERSE, 2015. Tarifas em portugal continental. http://www.erse.pt/pt/electricidade/tarifaseprecos/2016/Paginas/TTVCFPortugalContinente2016.aspx (visited).

Facchini, A., Rottondi, C., Verticale, G., 2017. Evaluating the effects of social interactions on a distributed demand side management system for domestic appliances. Energy Effic. http://dx.doi.org/10.1007/s12053-017-9510-y.

FF Solar, 2017. http://www.ffsolar.com/products/FF_lista_PVP.pdf (visited).

Gitizadeh, Mohsen, Fakharzadegan, Hamid, 2014. Battery capacity determination with respect to optimized energy dispatch schedule in grid-connected photovoltaic (PV) systems. Energy 65, 665–674. http://dx.doi.org/10.1016/j.energy.2013.12.018.

IEA, Technology roadmap: Solar photovoltaic energy - 2014 ed., Retrieved from https://www.iea.org/publications/freepublications/publication/technology-roadmap-solar-photovoltaic-energy---2014-edition.html.

Jallouli, Rihab, Krichen, Loti, 2012. Sizing, techno-economic and generation management analysis of a stand alone photovoltaic power unit including storage devices. Energy 40 (1), 196–209. http://dx.doi.org/10.1016/j.energy.2012.02.004.

Keirstead, J., 2007. Behavioural responses to photovoltaic systems in the UK domestic sector. Energy Policy 35 (8), 4128–4141.

Krieger, Elena M., Cannarella, John, Arnold, Craig B., 2013. A comparison of lead–acid and lithium-based battery behavior and capacity fade in off-grid renewable charging applications. Energy 60, 492–500. http://dx.doi.org/10.1016/j.energy.2013.08.029.

Lupangu, C., Bansal, R.C., 2017. A review of technical issues on the development of solar photovoltaic systems. Renew. Sustain. Energy Rev. 73, 950–965. http://dx.doi.org/10.1016/j.rser.2017.02.003.

Luthander, Rasmus., Widén, Joakim, Munkhammar, Joakim, Lingfors, David, 2016. Self-consumption enhancement and peak shaving of residential photovoltaics using storage and curtailment. Energy 112, 221–231. http://dx.doi.org/10.1016/j.energy.2016.06.039.

Luthander, R., et al., 2015. Photovoltaic self-consumption in buildings: A review. In: Applied Energy, vol. 142. pp. 80–94.

Mahran, A., et al., 2016. Optimising the self-consumption of solar powered smart micro grids. In: 32nd European Photovoltaic Solar Energy Conference and Exhibition. pp. 2686–2691.

Merei, G., et al., 2016. Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications. In: Applied Energy, vol. 168. pp. 171–178.

OMIE, 2017. http://www.omie.es/files/flash/ResultadosMercado.swf (visited).

Osawa, M., et al., 2012. Increase the rate of utilization of residential photovoltaic generation by ev charge–discharge control. In: 2012 IEEE Innovative Smart Grid Technologies - Asia. In: ISGT Asia 2012, vol. 1, pp. 1–6. http://dx.doi.org/10.1109/ISGT-Asia.2012.6303134.

Reis, V., 2017. MSc thesis, Faculty Sciences University of Lisbon.

Salom, J., Widén, J., Candanedo, J., Sartori, I., Voss, K., Marszal, A., 2011. Understanding net zero energy buildings: Evaluation of load matching and grid interaction indicators. In: Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association. pp. 2514–2521.

Silva, R.A., Casaleiro, A., Reis, V., Freitas, S., Brito, M.C., 2016. Dimensionamento de sistemas fotovoltaicos em autoconsumo residencial: A lei dos pequeninos. In: Renováveis Magazine, vol. 28. pp. 28–29.

The Tesla Powerwall, POWERWALL 2 AC, 2016.https://www.tesla.com/powerwall?redirect=no (visited),