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Community storage for small urban units including dwelling and small businesses

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To my family:
My mom, who is an inspiration to me
My dad, who made me believe that I am able to do anything
My sister, who is and always will be my rock

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Abstract

This dissertation focuses on analysing the effect that aggregation of demand and photovoltaic (PV) generation of building units, from commercial and residential sectors, and the use of battery storage systems have on the self-consumption rate, the self-sufficiency degree and the profitability of the system, by analysis of the internal rate of return and the payback period.

For the residential sector a condominium consisting in the aggregation of 14 or 7 dwellings was considered as a single building unit. Regarding the commercial sector, three different building units were studied: a bank branch, a restaurant and a hotel.

The control strategy considered that the generated photovoltaic electricity is primarily used to fulfil the consumption needs of the units. If there is a storage available, if the generation is higher than the demand, the excess power is fed to the battery. If the photovoltaic production is insufficient to meet the consumption, the difference will be provided by the battery, if charged, otherwise it will be supplied by the grid.

The system configuration was tested for installed PV powers in the range up to the contract power (when the peak power equals the maximum consumption).

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, was confirmed and supported by the results. In general, the aggregation of different residential and commercial units and the use of a battery system, reflects an increase on the self-consumption rate. A battery storage capacity of 0.5 to 1 kWh per installed PV power reflects an increase of approximately 12% to 20%. For a 1.5 kWh/kWp ratio the increase was from 25% to 30%, and from 30% to 36% for a 2 kWh/kWp.

The result also show that single sites feature lower self-consumption and lower self-sufficiency and less interesting economic value than aggregated units. The hotel is the exception to this premiss as, by itself, it achieves a high level of self-consumption, up to 90%, depending on the storage capacity.

Another result of this study is that even without batteries, self-consumption rates of photovoltaic systems increase with aggregation since the excess energy point is higher for aggregated units. When aggregating building units (the restaurant in comparison with condominium, bank and restaurant in a no battery scenario) our study shows an increase up to 30% in self-consumption. Self-sufficiency degree suffers a negative, albeit less pronounced effect, caused by the aggregation of users. The results show that the restaurant, or any aggregation including the restaurant, hardly returns the investment. All other system configurations feature positive internal rates of return, with some being higher than 5%, again confirming the benefits of aggregation as it leads to higher returns.

The values of payback period underline the conclusions from the analysis of the internal rate of return. All buildings and aggregated units, except for the restaurant, feature values between 8 to 18 years, with lower values for aggregation units and with a optimum for the no-battery configuration.

Keywords: photovoltaic, aggregation, self-consumption, community battery storage.

Resumo

O estudo realizado nesta dissertação baseia-se em armazenamento comunitário para agregação de consumos e geração fotovoltaica em edifícios do setor residencial e comercial em Portugal.

Em Outubro de 2014 foi aprovado o decreto-lei nº 153/2014, mais conhecido como a lei do autoconsumo, onde são regulados os critérios de instalação de sistemas fotovoltaicos para unidades de pequena produção (UPP) e unidades de produção para autoconsumo (UPAC). Para a instalação de fotovoltaico em unidades de consumo, a eletricidade fotovoltaica gerada deixa de ser diretamente injetada na rede, passando a ser autoconsumida. Os retornos financeiros deste regime baseiam-se não na eletricidade que não se consome da rede eléctrica, mas do sistema PV (que será tanto maior quando mais elevado for o preço da eletricidade) e numa remuneração da energia fornecida à rede. Este regime promove a instalação de sistemas PV de pequenas dimensões. Deste modo, o aumento da taxa de autoconsumo torna-se essencial para a rentabilidade de um sistema fotovoltaico. Para aumentar esta taxa é possível recorrer a DSM (*demand-side-management*), passando a utilização de eletrodomésticos para as horas de produção fotovoltaica, a sistemas de armazenamento e partilha de eletricidade gerada através de agregação de diferentes edifícios. Nesta dissertação foram analisadas as duas últimas situações.

Os objetivos são avaliar a forma como a taxa de autoconsumo e autossuficiência variam com o aumento do número de edifícios e com diferentes tipos de edifícios; otimizar um algoritmo para um sistema fotovoltaico com bateria tendo em conta o perfil de consumo; e avaliar quão economicamente vantajoso será este sistema (analisando a taxa interna de retorno e o período de retorno). Ao responder a estas perguntas será possível entender a relevância da agregação de edifícios e a utilização de armazenamento.

As unidades do setor residencial são relativos a 18 habitações localizadas em Lisboa com potências contratadas entre 3,45 e 20,7 kVA, com uma resolução temporal de 15 minutos. Os dados são referentes ao ano 2013. Destas 18 habitações, foram selecionadas e agrupadas num condomínio aquelas cuja potência contratada se encontrava entre 3,45 kVA e 10,35 kVA pois, por definição, um condomínio é uma agregação de habitações com características semelhantes. Com todas as habitações com potência contratada igual a 6,9 kVA foi considerado um segundo condomínio (condomínio 6,9kVA), de forma a analisar o efeito de agregação de carga com habitações que possuem ordens de consumos semelhantes.

Os dados do setor comercial incluem uma agência bancária, um restaurante e um hotel, com dados de consumo de eletricidade também com resolução temporal de 15 minutos. A agência bancária e o hotel referem-se ao período de Maio 2015 a Abril 2016 enquanto o restaurante apenas ao período de Outubro 2015 a Abril 2016. Todos os dados de consumo foram fornecidos pela empresa ISA (Intelligent Sensing Anywhere).

Os dados de produção com origem em geração fotovoltaica são correspondentes a um sistema composto por módulos de silício policristalino com ótima inclinação e orientação, situados na região de Lisboa. De forma a utilizar a informação da variabilidade do recurso, os dados foram divididos pela potência máxima registada, e adaptada para cada unidade singular e unitária multiplicando os dados pela potência nominal desejada. Os dados referem-se ao ano 2015 e foram registados com uma resolução temporal de 10 minutos. Devido à diferença na resolução temporal, comparativamente aos dados de consumo, foi necessário obter por interpolação os valores em falta para uma resolução de 15 minutos. Os dados de produção fotovoltaica foram fornecidos pela Faculdade de Ciências da Universidade de Lisboa.

No algoritmo desenvolvido, a eletricidade fotovoltaica gerada é primeiramente utilizada para satisfazer as necessidades de consumo. Se houver excesso de produção, a energia é armazenada na bateria.

Caso esta atinja a sua capacidade máxima, o resto será injetado na rede. Se a energia gerada é insuficiente para satisfazer as necessidades de consumo, o défice será retirado da bateria, caso esta se encontre carregada, de outra forma será fornecida pela rede elétrica.

O algoritmo foi aplicado nas unidades individuais (banco, restaurante, hotel, condomínio e condomínio 6,9kVA) e nas unidades agregadas no qual foram considerados como fator comum, para todos os cenários, um dos condomínios (condomínios com o banco, condomínio com restaurante, condomínios e hotel e condomínios com banco e restaurante). Foi considerado um intervalo de potência fotovoltaica dependendo do perfil de consumo e do rácio capacidade da bateria por potência fotovoltaica instalada de 0 a 2 kWh/kWp com intervalos de 0,5 unidades.

Para este algoritmo foram considerados parâmetros económicos e técnicos para o sistema fotovoltaico e bateria tais como: taxa de inflação, eficiência de carga e descarga da bateria,e perdas por auto-descarga da bateria. A taxa de inflação foi apenas considerada no preço da eletricidade (que reflete no que se poupa) e na remuneração da eletricidade injetada na rede. A inflação não foi considerada nos custos relacionados com a substituição da bateria nem do inversor.

A hipótese de que a agregação do consumo, a partir de diferentes utilizadores com diferentes perfis de consumo, conduzirá a uma melhoria do diagrama de carga coletiva, apresentando uma melhor combinação ao perfil de geração fotovoltaica, é confirmada nesta dissertação. Ao agregar unidades de consumo (o restaurante em comparação com condomínio, banco e restaurante num cenário sem bateria) há um aumento até 30% no autoconsumo. A agregação de unidades do setor residencial e comercial reflete um aumento na taxa de autoconsumo. Unidades singulares, de uma maneira geral, apresentam valores mais baixos de autoconsumo em comparação com unidades agregadas. O hotel é a exceção a esta premissa uma vez que atinge até 90% de autoconsumo no máximo de potência instalada, dependendo da capacidade de armazenamento. Este resultado é conseguido devido ao perfil de consumo do hotel, com um consumo tipicamente elevado durante o dia.

Dependendo da capacidade de armazenamento, as unidades de agregação podem ultrapassar a barreira de 90% para o autoconsumo. Uma capacidade de armazenamento de bateria de 0,5 a 1 kWh por potência fotovoltaica reflete um aumento de aproximadamente 12% a 20%. Para potência de 1,5 kWh/kWp verifica-se um aumento de 25% a 30% e de 30% a 36% para 2 kWh/kWp. Os resultados também indicam que, mesmo sem bateria, as taxas de autoconsumo dos sistemas fotovoltaicos aumentam com a agregação na medida em que o ponto de excesso de potência instalada é maior para unidades agregadas.

A agregação de unidades causa um efeito negativo e menos pronunciado no grau de autossuficiência. Este parâmetro é crucial para a configurações independentes da rede elétrica. Não sendo este o caso estudado nesta dissertação este parâmetro pode aqui ser considerado secundário.

Os resultados obtidos mostram que o restaurante, ou qualquer agregação que o inclua, dificilmente retorna o investimento. Todas as outras configurações analisadas apresentam taxas internas de retorno positivas, sendo algumas superiores a 5%, provando a rentabilidade e o benefício deste tipo de agregação e sistemas.

Todos os outros sistemas fotovoltaicos sem baterias são viáveis. À medida que a capacidade de armazenamento diminui, é possível observar um aumento no interesse económico do sistema.

Os valores do período de retorno reforçam as conclusões da análise da taxa interna de retorno. Todos os edifícios e unidades agregadas, com exceção do restaurante e agregações que o incluam, apresentam valores entre 8 a 18 anos, com valores menores para unidades de agregação, e com um mínimo para a configuração sem bateria. De uma forma geral, a agregação permite aumentar o autoconsumo e a taxa interna de retorno, e diminuir o período de retorno, embora seja necessário analisar o consumo da unidade para avaliar se é, de facto, favorável a um sistema fotovoltaico. Em conclusão, quanto mais compatíveis forem o consumo elétrico e geração fotovoltaica, maior serão o autoconsumo, autossuficiência e a taxa interna de retorno, e menores os períodos de retorno, concluindo-se que, de facto, a agregação causa um efeito positivo.

Palavras-chave: Fotovoltaico, autoconsumo, agregação, bateria comunitária.

Contents

List of Figures

List of Tables

List of Notations, Abbreviations and Acronyms

η_{Ch}	Battery charging efficiency
η_{Dch}	Battery discharging efficiency
C_{Ins}	Installation costs
C_{Inv}	Cost of inverter
C_{Mod}	Cost of photovoltaic modules
C_{PV}	Cost of photovoltaic system
$C_{Replace}$	Replacement costs
CF	Cash Flow
DOD	Depth of discharge
E_D	Electricity demand
E_{PV}	Photovoltaic generation
$E_{supplied}$	Electricity supplied to the grid
k	Time instant
m	Month
n	Lifetime
R_{UPAC}	Payment regarding the electricity supplied to the grid for an UPAC
SOC	State of charge
t	Year of the project
AC	Alternating Current
DL	Decreto-lei (Legislation)
DSM	Demand-side-management
IRR	Internal rate of return
LCOES	Levelised cost of energy storage
Li-ion	Lithium-ion
OMIE	Operador Mercado Ibérico de Energia (Iberian nominated Electricity Market Operator)
PV	Photovoltaic
RES	Renewable Energy Sources
RESP	Rede Elétrica de Serviço Público (Public power grid)
ToU	Time-of-use tariffs
UPAC	Unidade de Produção para Autoconsumo (Units of production for self-consumption)
UPP	Unidade de Pequena Produção (Units of small production)

1. Introduction

1.1 State-of-the-art

The European Commission set the goal of reducing, by 2050, the value of the emissions of greenhouse gases by 80 to 95%, considering the levels of 1990[1]. Along with this measure, it was also established to increase the amount of energy from renewable energy sources (RES) up to a 20% share [2].

In 2014, the statistics from Eurostat pointed to a share RES of 16% [3] in the gross final consumption of energy and of 27.5% [4] of the total EU-28 electricity consumption. By the end of 2013 the capacity installed and connected to the grid was able to provide 3% of the electricity demand in Europe. With the increase of the share of PV in the electricity mix, grid and market integration gains importance and becomes a challenge to the development of PV [5].

According to the Technology Roadmap Solar Photovoltaic Energy [6], released by the International Energy Agency (IEA), the PV share of global electricity will reach 16% by 2050, representing a share of 20% of all renewable electricity and 17% to all clean electricity. In order to reach these goals, the development of new storage capabilities, demand-side response, interconnections and flexible generation is necessary.

The variability of some RES, such as sunshine, creates the additional challenge of integrating the produced energy in the electrical grid. Integration is a particularly important issue in emerging PV markets as grid parity is achieved.

Providing incentives for distributed PV generation through tariffs for energy and/or net energy metering is an important step to increase PV shares after parity is achieved. In more mature markets, incentives for self-consumption through time-of-use electricity rates is part of the key actions to be taken in short term [6].

The decreasing price of rooftop systems and the rising prices of electricity enable grid parity [7]. Together with less feed-in-tariffs and support from the government, PV expansion is more driven towards self-consumption.

The consumption of electricity, in time schedule and/or in amount, in a small business and a household is different, having between them distinct consumption patterns. The profile of consumption of small businesses will depend on their type of activity. Commercial buildings tend to have a higher correlation between the load profile and the PV production which can prove profitable for a PV-community storage system. An optimization according to the self-consumption and self-sufficient rate for a community energy storage with both sectors has not been explored yet. Self-consumption with storage has become a feasible possibility with the improvement and development of batteries with larger capacity.

The net-metering system works like a free battery, where the consumers store their energy on the grid creating a energy credit. Thanks to high electricity prices, net-metering and investment grant, a quick development of the residential market became possible [5]. This may create a problem in the near future with the increasing number of net-metering systems. Hence the PV production will occur when there is an abundance of power and the majority of prosumers will collect their energy in the evening, bringing unbalance to the energy market [8]. For this reason the net-metering points towards a change in the policy, more inclined to self-consumption, like it happened in the state of Hawaii in October 2015 [9].

In October 2014 a new legislation (DL 153/2014) which regulats installation of photovoltaic system was implemented in Portugal, replacing the legislation of micro-production (DL 363/2007) and mini-production (DL 34/2011) [10]. DL 153/2014 provides the legal framework for units of small production (UPP) and units of production for self-consumption (UPAC). This legal framework replaced feed-in tariffs for self-consumption. Self-consumption in the UPAC is based on the four principals:

1. Produced energy is intended to be consumed in the dwelling associated with the production unit;
2. The installed power cannot be two times higher than the connection power;
3. It is possible to sell photovoltaic generated electricity to RESP, market price, of the electricity excess;
4. The producer benefits when the production unit is sized considering the consumption necessities of the dwelling.

This legislation does not favour the installation of large photovoltaic systems, since a compensation fee for the use of the grid has to be paid if the PV system has an installed power higher than 1.5kW. Furthermore, since excess energy is undervalued, the installed power of optimum PV systems ought to be lower than weekdays demand at noon (in the residential sector) when virtually nobody is at home, or lower than weekends (in the commercial sector) when the shop/office is empty and not working.

One of the major challenges to self-consumption of PV in households is the mismatch between peak demand and peak power production. While in the majority of households demand peaks are specially high in the morning and in the evening, the optimized generation of electricity follows the course of the sun, and hence the potential of self-consumption for residential units is limited. There are some measures, such as storage and demand response, that can be applied to increase the rate of self-consumption and self-sufficiency [11].

Another measure, although a less common one, is to install solar panels in a non optimum orientation or inclination. In the northern hemisphere the optimum orientation for solar panels is generally facing south with a tilt approximately the same as the latitude, getting this way the most exposure to sunlight during the day. By changing the orientation to West, the PV generation shifts the hours of the maximum production from midday to the afternoon when people will be more likely to be at home. Installing solar panel in the façade of the building will provide more power in winter and less in summer. It will also have influence in the hours of higher production, generating more in the early and late hours of the day [12–14].

Self-consumption solutions are emerging as an alternative dissemination mechanism for distributed photovoltaic due to the end of feed-in tariffs. Increasing self-consumption not only enables the wider deployment of photovoltaic systems in the residential sector but also may contribute to technical grid integration challenges such as frequency regulation, power ramps and avoiding exceeding voltage limits.

There are several studies regarding strategies to improve the adjustment between photovoltaic generation and the load diagram, which include demand-side-management, storage systems and shared photovoltaic production.

Luthander et al show that relative self-consumption is increased by 13 to 24% points with the implementation of a battery storage capacity of 0.5 to 1 kWh per installed PV power (kW) while demand-side-management can improve from 2% to 15% [15]. They also mention the importance of combined load, by aggregating different buildings, and how that it would positively affect self-consumption metrics. Although the study of communities with shared energy storage system has become more frequent, there are several approaches yet to analyse.

According to Parra et al. in *Optimum community energy storage system for PV energy time-shift* [16], sharing an energy storing system appears to be an attractive alternative to the single dwelling storage.

According to the authors, with this structure it is possible to reduce the levelised cost of energy storage (LCOES) by 37% when comparing a 10 household community with a single storage system in the 2020 scenario, with the possibility of reaching 66%.

Baetens et al analyze the electrical balance for a neighborhood with 33 net zero-energy-buildings with integrated PV systems, in Belgium. Simulation results showed that aggregation improves both self-consumption and self-sufficiency in all scenarios, although its impact is more relevant for smaller photovoltaic systems [17]. The modelled dwellings showed a self-consumption of approximately 26% at building level and 33% at neighbourhood level. Aggregation leads to the smoothing of individual building daily load patterns but does not have a strong effect on the seasonal mismatch between PV (peaks in the summer) and load (peaks in the winter, due to heating loads).

A case study, developed by Mahran et al, is based on the analysis of a smart neighborhood model considering peer-to-peer electricity trade which consists of 3 households, two of them with PV rooftop systems, one office building, a small industrial complex, a PV generator and the public grid [18]. They show that self-consumption can exceed 60% without storage, with potential to achieve full grid independence if implementation of a storage system. Although a significant storage capacity may be required to cover the entire load demand.

To study the impact of storage, Osawa et al performed an optimization in a scenario of power interchange among 10 households in a community in Japan, in which 40% had PV-rooftop systems whilst the others provided electric storage with plug-in electric vehicles [19]. The simulation used hourly measured data for both solar radiation (which is then converted to PV generation) and domestic load. The impact of the power interchange was an increase on the self-consumption in 10% (from 42 to 52%) and the increase of 4% in self-sufficiency degree.

Considering that storage systems specific cost drops with increasing storage capacity, Volker et al compared the deployment of distributed and centralized district storage for improving PV self-consumption [20]. They modelled a neighbourhood in Germany with 10 homes, with different occupancy levels, using 1-minute resolution. For their case study, without storage integration the self-sufficiency rate was 37%, reaching up to 80% with large scale centralized district storage. For the same storage capacity, a distributed storage scenario required significantly more storage capacity installed (+18%). They also highlight that in modern buildings it is not always convenient, or even possible, to accommodate on-site storage.

Merei et al. present *Optimization of self-consumption and techno-economic analysis of PV-battery systems in commercial applications* results of optimization regarding self-consumption and degree of self-sufficiency for a small commercial unit, a supermarket in Aachen, Germany [21]. According to the authors, although it is specially attractive to invest in a PV system, the implementation of battery storage does not lead to a significant reduction in the overall electricity costs, and self-sufficiency is just slightly increased with large battery size.

Most of the literature focus on the residential or the commercial sector but not both cases. However, urban places are typically composed by dwellings and small business, bringing to light the problem of evaluating the possible advantages of implementing a community energy storage unit serving both types of consumers.

There are several types of energy storage devices such as compressed air, hydrogen, flywheels, thermal and batteries. The latter are the most versatile and are the most common type. For these reasons, this thesis will focus on them. Several companies like Tesla and Nissan have already launched home energy storage batteries, even with reused eletric vehicle batteries [22].

There are several types of batteries suitable for residential and small commercial use as lithium-ion(Li-ion), lead-acid and other batteries with a nickel cathode.

According to R.Luthander et al. the size of the battery is important not only because of the larger amount of energy stored but also because of the reduced lifetime of smaller batteries, mainly due to the increasing stress of the system [15]. A battery with a larger capacity will reduce the depth of discharge of the cycles, increasing the lifetime. Although the previous facts are relevant, the main problem of purchasing a battery as a storage unit, regarding the consumer, is the price.

1.2 Dissertation objectives and outline

Based on this analysis, the research aim/question of this dissertation is: How does the self-consumption rate changes with the increase of the aggregation and demand of dwellings and small business units?

With the following sub-questions:

- Optimization of a community energy storage with dwellings and businesses units.
- What is the optimal level of aggregation of the community energy storage, composed by a small business and dwellings?
- How profitable would it be to have a community energy storage which includes dwellings and a small business unit?

By answering the research aim/question and the following sub-questions it will be possible to understand the relevance of the aggregation and storage, and if it is a viable option. This thesis will also allow an understanding of the optimization process for a community composed by residential and commercial units.

The outline of this dissertation is as follows:

- 2. Methodologies: in this chapter a definition of the used concepts is given. The algorithm is explained as well as the chosen parameters. The collected data and the data cleaning are also described in this section;
- 3. Input data: in this chapter the pre-processed data, that will be used in this dissertation, are described in detail;
- 4. Integrated PV-storage system: this chapter is separated in four different sections, namely, PV-storage systems for building units (where the results of the algorithm are shown), PV-storage systems performance for building units (the parameters self-consumption, self-sufficiency, IRR and payback period are calculated and analysed), comparison between building units and comparison with the reviewed literature.
- 5. Conclusion: the results of this dissertation are listed and discussed.

2. Methodologies

This thesis is based on the theoretical concepts of self-consumption, self-sufficient and the economical definition of internal rate of return and payback period.

Self-consumption and self-sufficiency will provide an understanding on how the system is performing and how it affects the energy supplied from and to the grid.

2.1 Performance of the systems

Self-consumption is 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 to 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.

According to the Portuguese legal framework DL nº153/2014, presented in Section 1, there is a strong economic incentive, related to the non-existence of feed-in tariffs, to maximize self-consumption.

Self-consumptin rate does not take in consideration the energy produced which is injected to the distribution, nor transmission grid, nor instantaneously withdrawn from the grid.[11, 15].

Figure 2.1 shows a schematic electrical load diagram of a household power consumption with on-site PV generation. The area A represents the total net electricity demand, area B the PV production, C the overlap between A and B corresponds to the direct self-consumption. D corresponds to the self-consumed energy supplied from the battery and E the energy supplied to the grid.

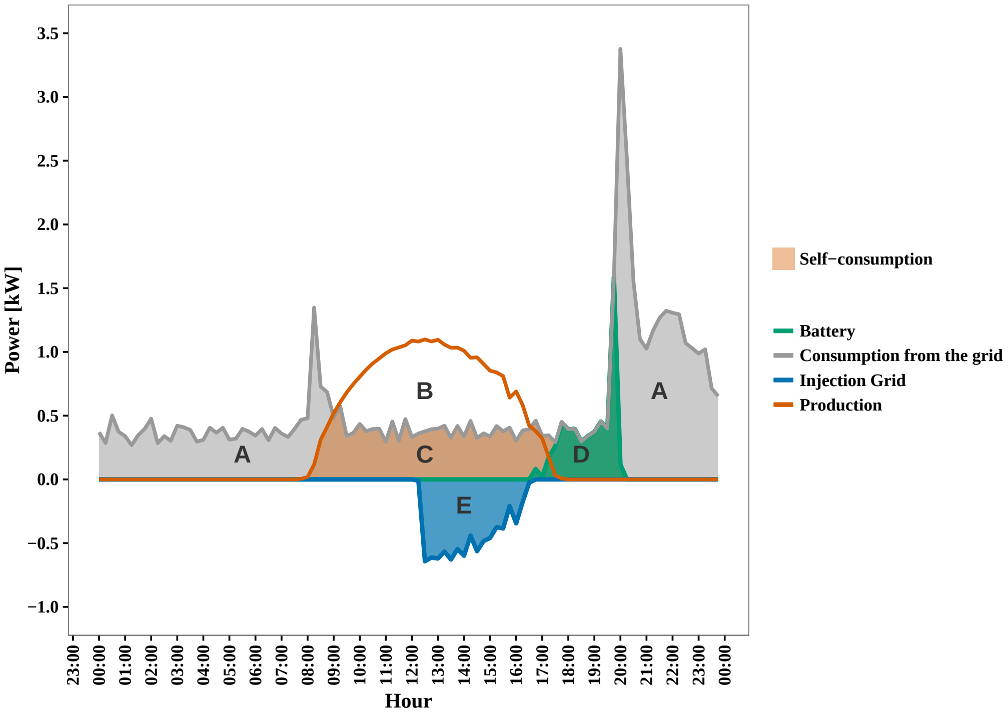


Figure 2.1: Schematic outline of daily net load (A + C), net generation (B + C), absolute self-consumption (C+D), direct self-consumption (C), self-consumed energy supplied by battery (D) and energy feed to the grid (E) in a building with on-site PV generation.

The rate of self-consumption is defined by Equation 2.1.

$$\text{Self-consumption} = \frac{C}{B+C} \tag{2.1}$$

If the building unit possess a storage system, the self-consumption rate will increase its value [15], as is defined by Equation 2.2.

$$\text{Self-consumption} = \frac{C+D}{B+C} \tag{2.2}$$

The other parameter commonly used to assess the performance of a photovoltaic system is the self-sufficiency. It represents the degree to which the on-site PV production is sufficient to fulfil the energy needs of the building unit, as presented in Equation 2.3. A 100% self-sufficiency degree means that the PV system provides all the electricity consumed locally.

$$\text{Self-sufficiency} = \frac{C}{A+C} \tag{2.3}$$

As in the self-consumption rate, self-sufficiency will increase its value if a storage system is used, as presented in Equation 2.4[15].

$$\text{Self-sufficiency} = \frac{C+D}{A+C} \tag{2.4}$$

2.2 Economic and policy analysis

The investment on a photovoltaic and storage system involves a considerable amount of capital, so for prosumers it is specially important to analyse the benefits and the risks of this renewable solution.

To asses the economic viability, the parameters investment and replacement cost, internal rate of return and payback period are considered. These parameters depend on the costs associated with the installation and maintenance (O&M) of the system, electricity purchasing costs, feed-in tariff and the interest rate.

The values used for this economic analysis can be found in Table 2.1.

Table 2.1: Economic parameters of the PV-storage system.

Parameter	Chosen Values	References
Cost PV [€/Wp]	1.8	[23, 24]
Cost inverter [€/Wp]	0.3	[24]
Cost battery [€/kWh]	470	[25]
OMIE [€/kWh]	0.05	[26]
Electricity cost [€/kWh]	0.1587	[27]
Inflation [%]	2	[21, 28]

2.2.1 Investment and replacement cost

The investment cost of a photovoltaic system (C_{PV}) includes the price of photovoltaic modules (C_{Mod}), an inverter (C_{Inv}) and installation (C_{Ins}).

$$C_{PV} = C_{Mod} + C_{Inv} + C_{Ins} \tag{2.5}$$

On a PV-storage system, the battery cost ($C_{Battery}$) represents a considerable portion of the investment. Most of the battery storage systems are still too expensive for residential use, as it will be shown below.

The total cost of a PV-storage system, Equation 2.6, depends on the sizing of the photovoltaic and storage.

$$C_{total} = C_{PV} + C_{Battery} \tag{2.6}$$

A project PV-storage is considered to have a lifetime equal to the lifetime of the PV modules, which is of around 25 years. The warranty of the battery and the inverter is approximately 10 years, consequently they will have to be replaced after that time. The costs presented in Equation 2.7 have to be taken into consideration when doing an economic analysis.

$$C_{replace} = C_{Inv} + C_{Battery} \tag{2.7}$$

2.2.2 Internal Rate of Return

The internal rate of return (IRR), defined in Equation 2.8, assess the profitability of the PV-storage system. It represents the discount rate of the project considering the net present value (difference between the present value of cash inflows and the present value of cash outflows) equal to zero. IRR (%) considers the cash flows (CF) of each year of the project (t) and the lifetime (n) [16].

$$0 = \sum_{t=0}^{n} \frac{CF_t}{(1 + IRR)^t} \tag{2.8}$$

Considering the complexity of Equation 2.8, in this work, the IRR was calculated using a function *irr* from the R package *Fincal* [29, 30]. The arguments of this function are all the cash flows of the project, where the first cash flow is the initial outlay.

2.2.3 Payback period

The payback period represents the time for which the investor receives its initial investment back. This is a simplistic way to evaluate the system since it does not consider time value of money nor the replacement of the battery and inverter.

As shown in Equation 2.9, payback period is calculated by the initial investment over the cash inflow of the first year [31].

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Cash inflow per period}} \tag{2.9}$$

2.2.4 DL nº153/2014

As previously mentioned, the legislation which governs the production of PV solar systems for small units production (UPP) and self-consumption units (UPAC) is the DL nº153/2014. This dissertation only addresses the UPAC since the main purpose of these PV-storage systems is to provide energy for the building unit, not the grid. This bill states all the necessary procedures and conditions for installing a PV system and, more relevant for this work, the payment regarding the electricity supplied to the grid $R_{UPAC,m}$ per month m.

Equation 2.10 represents the value of the revenue as a function of the monthly energy supplied to the grid ($E_{supplied,m}$), the monthly simple arithmetic mean of the closing prices of the Iberian nominated Electricity Market operator (OMIE) for Portugal (daily market) multiplied by 0.9 [10].

$$R_{UPAC,m} = E_{supplied,m} \times OMIE_m \times 0.9 \tag{2.10}$$

2.3 Analysis method

In this thesis two different levels of aggregation of households and business units will be analysed combined with different ranges of storage, including a no storage scenario.

At the individual level, it consists on a single building unit (commercial or residential). In the residential sector, a condominium, which consists in the aggregation of 14 or 7 dwellings, is considered as a single building unit. Regarding the commercial sector three different building units will be studied: a bank branch, a restaurant and a hotel.

The second level consists on different aggregation of the condominium with business units.

In order to study the effect that aggregation and PV-storage system have in the self-consumption rate, the self-sufficiency degree, IRR and payback period five storage scenarios were considered. In the first, storage is not be considered, only direct self-consumption will be studied. The second to the fifth scenario will consider different ratios of battery capacity over PV installed power, from 0.5 to 2 kWh/kWp with a 0.5 step. Higher values were not explored due to the current high price of battery solutions.

The system configuration was tested for installed PV powers in the range up to the contract power (when the peak power equals the maximum consumption). The installed PV system has a power range between 250 Wp and the maximum power consumption rounded to the unit by 250 Wp, for building with low and medium size (all cases which do not include the hotel). For the hotel, and aggregations including it, the power range was between 1 kWp and the peak power consumption of the building unit with 1 kWp steps.

Each analysed scenario contains a building unit, PV modules, an inverter, a battery storage system, a bidirectional meter and a charge controller as shown in Figure 2.2.

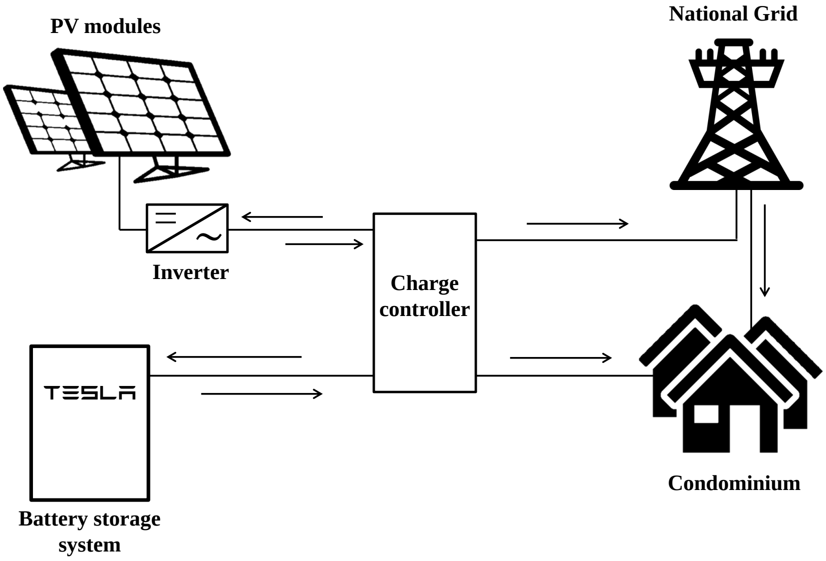


Figure 2.2: Schematic representation of the energy flows for the PV-storage system.

2.3.1 Algorithm

The control strategy considers that in the system, the generated photovoltaic electricity (E_{PV}) is primarily used to fulfil the consumption needs of the units. If there is a storage device available, in case the generation is higher than the demand (E_D), the excess power is fed to that battery. In case the direct photovoltaic production is insufficient to meet the consumption, the difference will be provided by the battery, if charged, otherwise it will be supplied by the grid.

The state-of-charge of the battery thus follows Equation 2.11.

$$SOC_k = SOC_{k-1} + \Delta SOC_k \tag{2.11}$$

Battery storage systems typically have a limited capacity range (Equation 2.12) which ensure the performance, lifetime and safety of this storage system. This limit will be considered on this dissertation.

$$SOC_{min} \leq SOC \leq SOC_{max} \tag{2.12}$$

The minimum state-of-charge of the battery (Equation 2.13) depends on the depth of discharge, a technical parameter which varies from battery to battery.

$$SOC_{min} = (1 - DOD) \times SOC_{max} \tag{2.13}$$

Another important characteristic of the battery which is important to consider is the charging/ discharging losses, since there are efficiency issues associated with the charging and discharging processes. These parameters have to be taken into account when assessing the available energy on the battery and when measuring, in fact, how much energy will the photovoltaic system supply.

There is another type of loss associated with the self-discharging process which also depends on the battery technology. In this algorithm this parameter is subtracted to the energy stored in the battery.

For this study, in the initial moment, the state-of-charge equals the SOC_{min}.

The collected data will be analysed by integrating the power flows for different parts of the system.

The algorithm for the first scenario (without storage system) is as follows:

1. Analyse the one year data with values with 15 minutes resolution for the demand and the PV generation.

2. Comparison between the PV generation and demand.

3. If PV generation is higher than the demand, the difference is exported. If the PV generation is lower than the demand, the energy generated with the PV system is used and the rest is bought from the grid.

Figure 2.3 represents the algorithm for a battery system scenario which is as follows:

1. Analyse the one year data with values with 15 minutes resolution for the demand and the PV generation.

2. Comparison between the PV generation (E_{PV}) and demand(E_D).

3. If the PV generation is higher than the demand, the state-of-charge of the battery (SOC) is analysed, as shown in Equation 2.11. If the battery is not full, the difference is used to charge the battery (Equation 2.14).

$$\Delta SOC_k = \max \left\{ (E_{PV} - E_D) \times \eta_{Ch}, SOC_{max} \right\} \tag{2.14}$$

Otherwise the energy is exported to the grid.

4. If the PV generation is lower than the demand, the state-of-charge of the battery is analysed. If the battery is not empty, it will discharge (Equation 2.15) until suppress the consumption or reaching the minimum SOC in which case the rest is provided by the grid. If the battery is empty, the difference is imported from the grid.

$$\Delta SOC_k = \min \left\{ \left(\frac{E_D - E_{PV}}{\eta_{dch}} \right), SOC_{min} \right\} \tag{2.15}$$

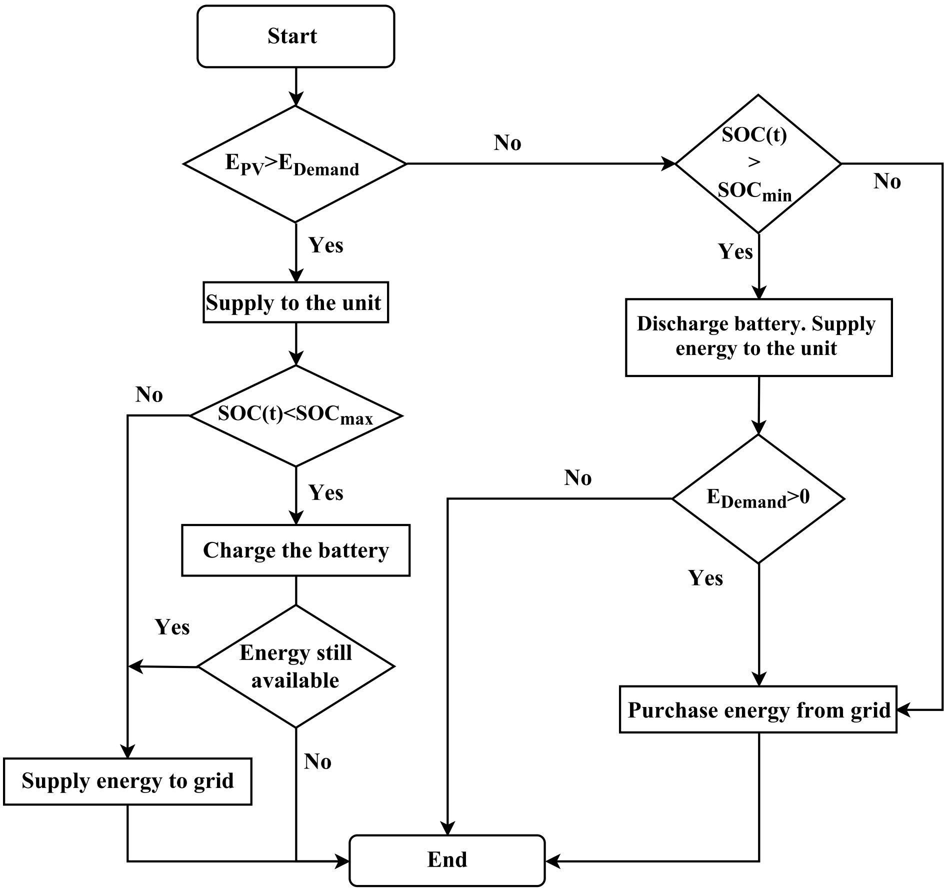
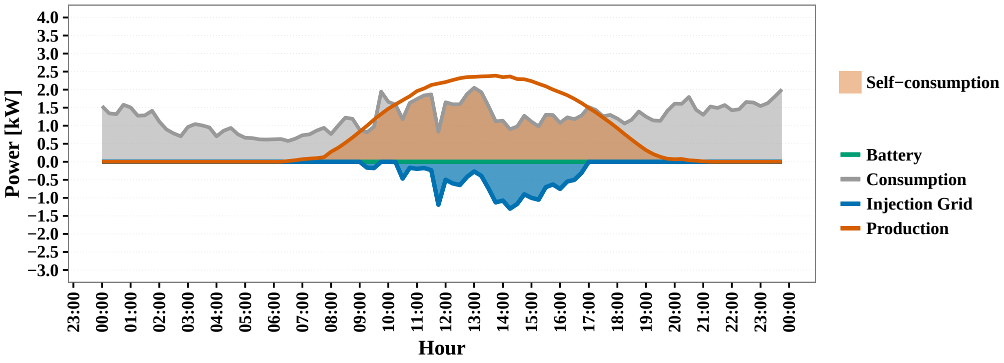
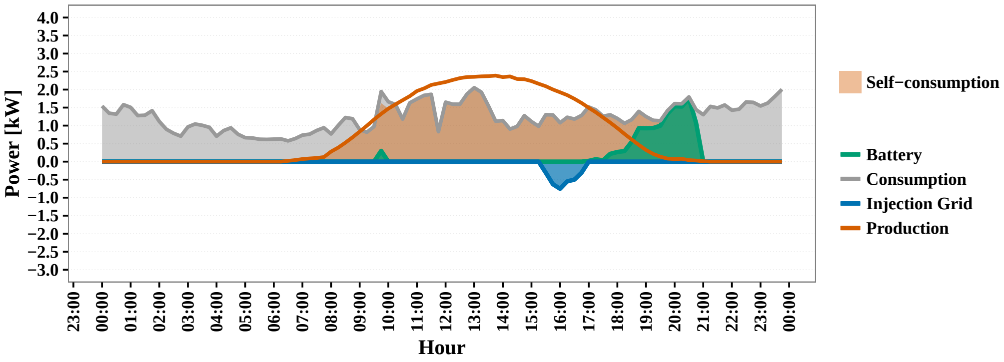


Figure 2.3: Flowchart representation of the algorithm for the three levels of aggregation in the second scenario (with storage system).

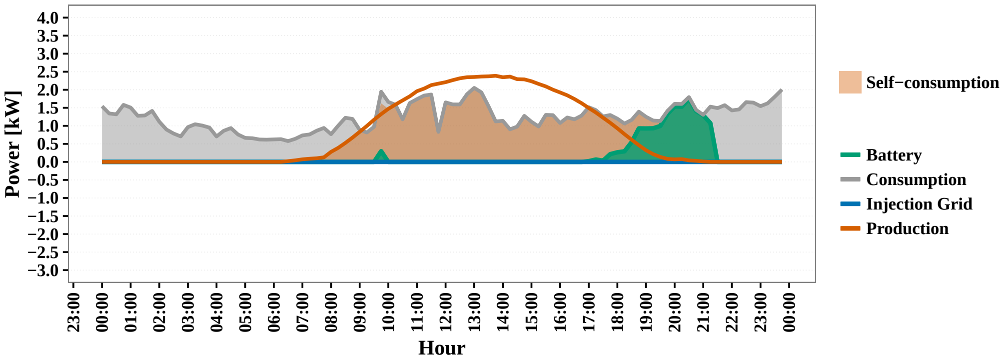
Figure 2.4 shows three examples of how the algorithm works: without battery, with a ratio battery capacity over photovoltaic generation of 1 and of 1.5.



(a) Ratio 0 - Without storage



(b) Ratio 1 - Battery capacity of 3.5kWh



(c) Ratio 1.5 - Battery capacity of 5.25kWh

Figure 2.4: Example on how the algorithm works with different ratios - battery capacity over photovoltaic generation.

In Figure 2.4a the excess generated energy is supplied to the grid, while in Figure 2.4b it is sold only after reaching 100% state-of-charge of the battery. In the third case (Figure 2.4c) none of the produced electricity is injected to the grid.

2.3.2 Battery and PV parameters

For this dissertation, a battery storage system based on the Li-ion battery Powerwall 2 by Tesla was considered. The performance specifications used on this algorithm can be found in Table 2.2 and the datasheet can be consulted in the Annex. The economic parameters used on this algorithm can be found in Section 2.2 (Table 2.1).

Tesla has recently started to invest in household batteries. The newest model Powerwall 2 would have a unit cost ($\rho_{Bat} C_{Bat}$) of 470 €/kWh including installation.

An electricity cost of 15.87 c€/ kWh was considered for all building units, with or without aggregation. To simplify calculation nor time-of-use tariffs (ToU) nor the difference in contracted power were considered. For a more detailed analysis it would be necessary to consider the power price, since battery systems are able to reduce the peak power demand of electricity users. It would be also necessary to know the power contract (ToU, contracted power) to each building unit to provide a more realistic scenario.

The monthly simple arithmetic mean of the closing prices of the Iberian nominated Electricity Market operator (OMIE), was considered 5 c€/kWh for all the months. This value corresponds to the average for 2015.

The inflation rate was only considered to calculate the saving (price of electricity) and the payment for the electricity injected to the grid ($OMIE$). It was not considered to affect the increasing price of the replacement of the inverter and battery.

In this algorithm photovoltaic degradation rate was not considered and the efficiency of the PV modules was taken constant during all the lifetime of the project.

Table 2.2: Operating and technical parameters of the PV-Battery storage system.

Parameter	Chosen Values	References
AC Energy (Capacity) [kWh]	13.2	[25]
Depth of discharge [%]	100	[25]
Roundtrip efficiency (RT) [%]	89	[25]
Warranty [years]	10	[25]
Losses battery [%]	1% per month	[32]
Inverter efficiency [%]	97	[33]
Warranty PV module[years]	25	[23, 34]
Warranty PV inverter[years]	10	[33]

2.4 Data preparation

The consumption data for all residential and commercial units located in Lisbon were provided by ISA (Intelligent Sensing Anywhere). The data for the residential unit were a set of 18 dwellings with contracted power from 3.45 to 20.7 kVA, with a time resolution of 15 minutes. The data refers to the year of 2013.

The provided commercial units are those of a bank branch, a restaurant and a hotel, also with a time resolution of 15 minutes. The bank and the hotel data are from to May 2015 until April 2016 while the restaurant only refers to the period October 2015 to April 2016. The contracted powers of these commercial buildings were unknown.

Photovoltaic energy generation data, considered for all the analysed situation, refers to the year 2015 and was collected with a time resolution of 10 minutes. The system was composed by polycrystalline silicon modules in the optimum orientation/inclination in Lisbon region. These data were provided by the Faculty of Science UL.

In order to have all data referring to the same time points it was necessary to estimate the PV values corresponding to minutes 15 and 45 of each hour. This was done by linear interpolation, and the procedure will be explained in detail bellow.

The data were analysed and processed by the algorithm using *R*, a free software environment for statistical computing and graphics [30].

2.4.1 Data cleaning

Load data

The power consumption of a dwelling rarely has zero values, since the load curve has a base consumption level associated to devices plugged-in in standby mode. Therefore it was assumed that all zero values were a result of an error on the metering system.

Different interpolation methods were used according to the day of the week, data availability and the occurrence of holiday when the zeroes occur.

Usually on a holiday people do not follow their daily routine, so the interpolation only considers the values adjacent to the zero or, in case of consecutive zeroes, the non-zero values adjacent to the first and last zero of the sequence. This approach was applied to all zero-holiday values except those that occur on weekends, when presumably people behave as usual on weekends. All the values measured on holidays were not use to interpolate further zeroes. Thus it was necessary to operate with a different method on the day after/before, and on the week after/before any holiday.

During weekdays most people follow a daily routine, arriving and leaving home at the same hour. Generally this routine does not change between weeks. This considered, for zeroes that occur on Tuesday, Wednesday and Thursday the interpolation method uses values from the day before and the day after. Monday and Friday, because they proceed and precede the weekend, have to be treated with a different approach.

On weekends, although generally being resting days, the energy consumption between the two days can be quite different. Thus, the interpolation considered the values from the week before and after at the same weekday and time as the zero(s).

Due to the amount of zeroes, occasionally, the value necessary for the interpolation was itself a zero. In these cases it was required to search for a non-zero value within two weeks, following the same methodology.

The interpolation methodology applied was as shown, in Figure 2.5:

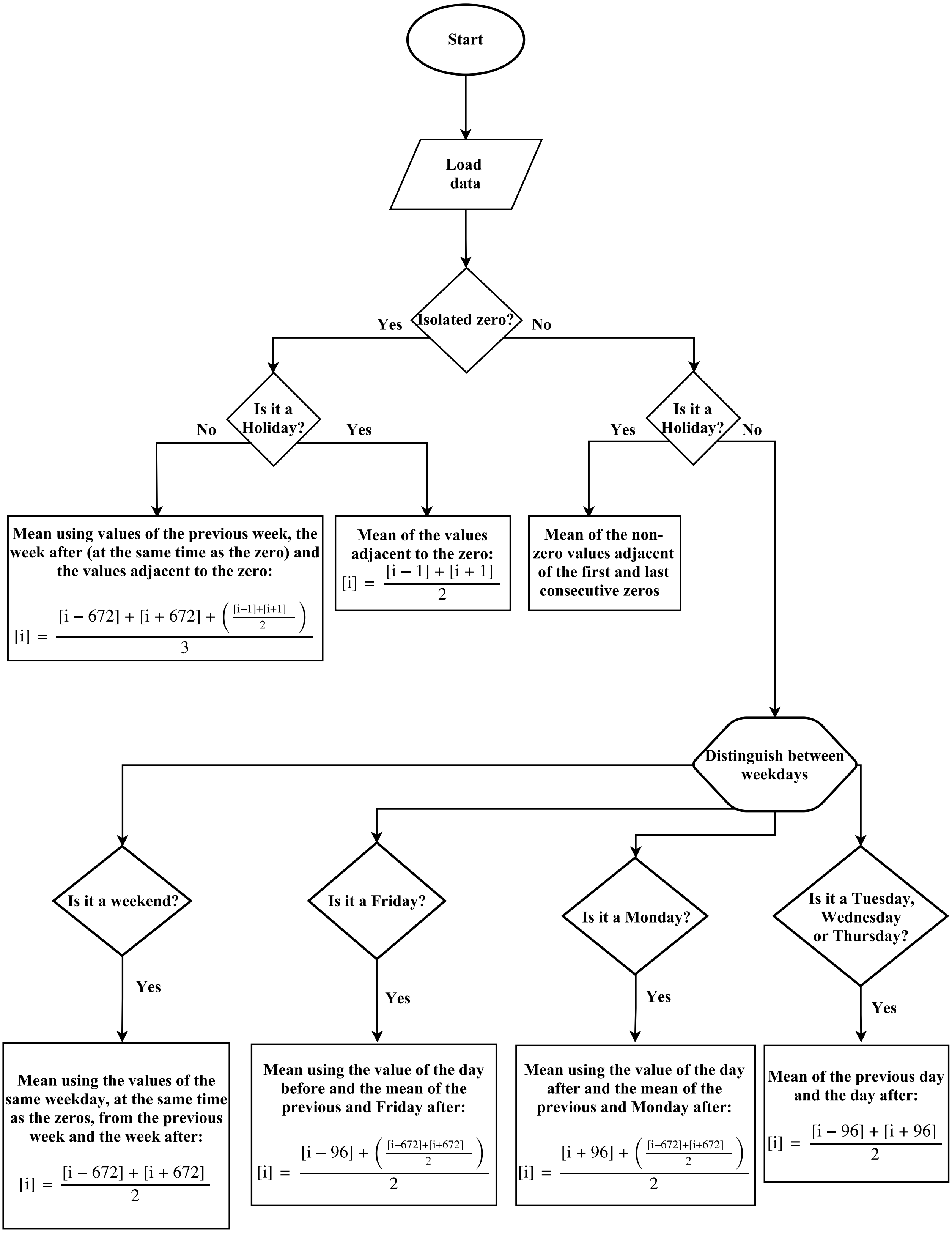


Figure 2.5: Flowchart of the interpolation methodology followed to replace the zero values in the load data.

PV generation data

As previously mentioned, the photovoltaic generation was registered at minutes 0, 10, 20, 30, 40 and 50 of each hour. The values for the 15 and 45 minutes were obtained by interpolation as the mean of the adjacent values.

The PV generation data were based on a polycrystalline silicon module, with a maximum registered power of 297 W and unknown nominal power. In order to adapt and use this data for all the PV-storage systems sized for the building units, a normalization was made. Considering the maximum power as the nominal power, all the values were divided by it, having new values from 0 to 1, which were, depending on the sizing, multiplied by the desired installed photovoltaic power.

The data collection occurs only when there is PV production, hence it was necessary to fill the data with zeroes at the time points corresponding to these periods using the same time scale. There were also missing data corresponding to periods where the system was not working correctly. In such cases the missing data were replaced by zeroes. These situations were a minority of the data corresponding to five days (1st and 2nd of June and from the 3rd to the 5th of July, corresponding to approximately 0.6% of the collected data).

Replicated data

Some of the collected data from the dwellings had between 2 to 9 weeks of replicated values in some households, as shown in Table 2.3.

Table 2.3: Replicated weeks of the load data.

Household	Weeks	Percentage of Replicated Weeks
HH1.2	from 50 to 53	4.5%
HH1.3	from 47 to 53	10.7%
HH1.4	from 1 to 6	10.0%
HH2.1	from 47 to 52	9.6%
HH2.2	from 1 to 10	17.4%
HH3.1	from 34 to 44	18.6%
HH3.2	from 1 to 4	5.9%
HH3.5	from 49 to 53	6.4%
HH4.1	from 1 to 3	3.7%
HH5.1	from 1 to 6	10.0%
HH5.2	from 30 to 34	7.0%

Two of the dwellings that had replicated values, HH1.3 and HH3.1, became unique after the interpolation. The replicated values were treated as unique data.

Table 2.4 outlines the contracted power of each household and the percentage of zeroes of each dwelling and commercial building.

Table 2.4: Contracted power and percentage of zeroes of the load data.

Building	Contracted Power	Zeroes
HH1.1	3.45 kVA	0.0%
HH1.2	3.45 kVA	0.0%
HH1.3	3.45 kVA	7.8%
HH1.4	3.45 kVA	0.0%
HH2.1	4.6 kVA	0.0%
HH2.2	4.6 kVA	0.0%
HH3.1	6.9 kVA	10.1%
HH3.2	6.9 kVA	0.0%
HH3.3	6.9 kVA	0.0%
HH3.4	6.9 kVA	0.0%
HH3.5	6.9 kVA	0.0%
HH3.6	6.9 kVA	0.0%
HH3.7	6.9 kVA	0.0%
HH4.1	10.35 kVA	0.7%
HH5.1	17.25 kVA	0.0%
HH5.2	17.25 kVA	0.0%
HH6.1	20.7 kVA	0.0%
HH6.2	20.7 kVA	1.1%
Total households	- kVA	1.1%
Restaurant	- kVA	3.0%
Bank	- kVA	0.0%
Hotel	- kVA	0.0%

2.4.2 Data corresponding to different periods

The collected data were measured in different periods. The dwellings refer to the year 2013 and the commercial buildings from 2015 to 2016. The year 2016 was a leap year, therefore the 29th of February 2016 was removed from the analysed data, for comparability.

It is assumed that the consumption on the dwellings did not change significantly between the years of 2013 and 2016.

This convenient approach also rejects possible correlations between the load of dwellings and the service buildings, and between dwellings and PV data (thus, solar radiation) which can occur due to heating/cooling loads (e.g. a cold winter week in 2015 without solar radiation would lead to increased consumption for heating which would perhaps not be “seen” in the corresponding week in the residential two years before).

The described methods will allow to analyse and process the data as presented in the next chapter.

3. Input data

3.1 Photovoltaics generation

As previously mentioned, the PV data were normalized to enable the sizing of the different PV systems accordingly to the building unit. To illustrate the solar irradiance variability, an example with 9 kWp is shown in Figure 3.1. In this system the annual energy production would be around 12.5 MWh. The produced power was higher around March, and more constant during the summer months.

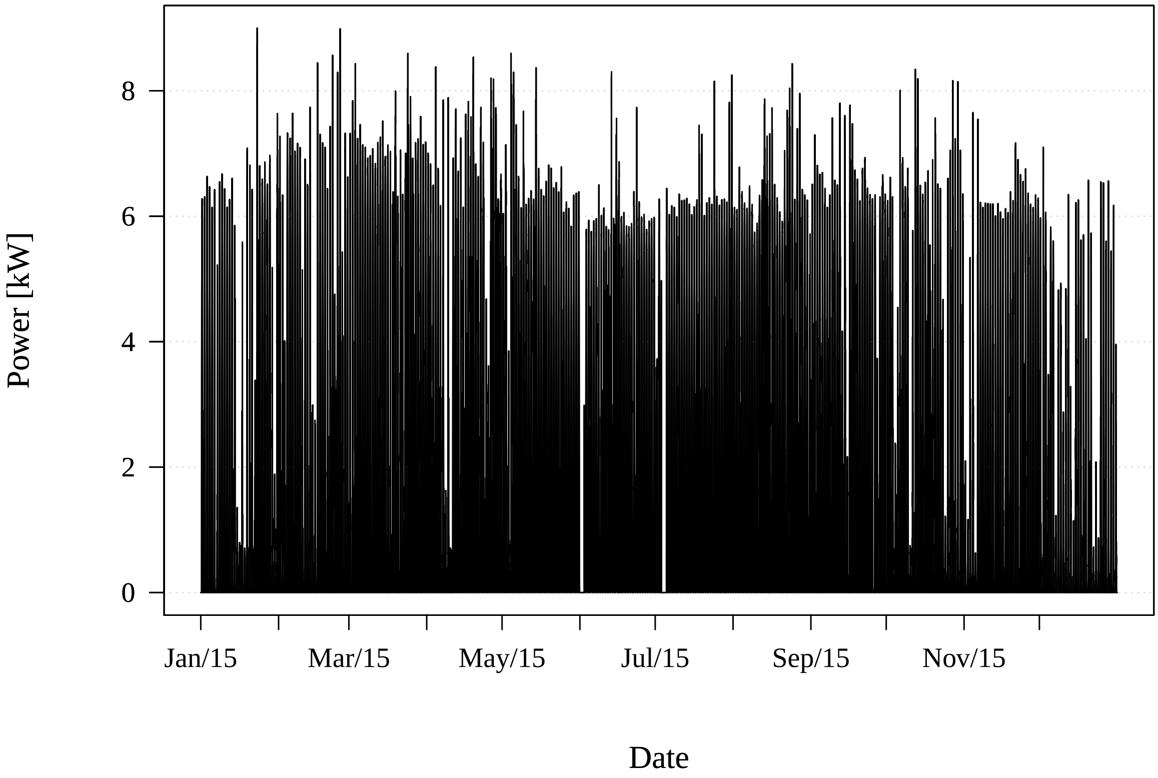
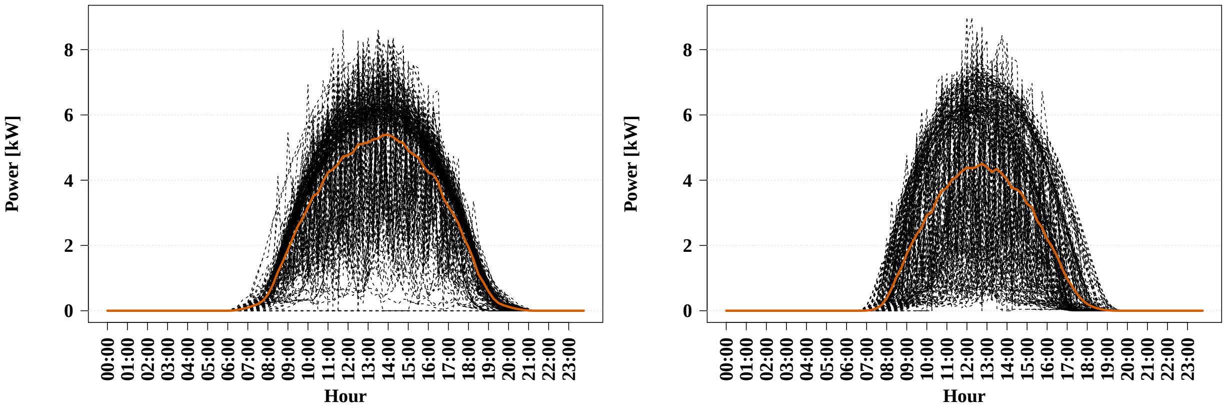


Figure 3.1: Annual PV production of a 9 kWp system.

As shown in Figure 3.2, during the summer there was more energy production, having the peak production around 2 pm. The mean power production is approximately 5.5 kW, and the average hour of sunrise and sunset is 6 am and 8 pm, respectively. In Figure 3.2a it is possible to observe some zero values during the hours of daylight which are presumably the five days in June and July when there was no register of the produced power.

In winter the mean power production peak occurs at 1 pm, corresponding to a mean generated power of 4.5 kW. As presented in Figure 3.2b, the mean hours of sunrise and sunset were 7 am and 6 pm, a smaller amount of sunlight in comparison with the summer as expected. PV modules characteristics dictate that the efficiency is improved by a lower temperature which can explain the fact that the maximum power occurs on the 23th January at 12 am.



(a) Power production (dashed lines) and average power production (solid line) of summer days

(b) Power production (dashed lines) and average power production (solid line) of winter days

Figure 3.2: PV production of a 9 kWp system: (a) Power production and average of summer days; (b) Power production and average of winter days.

All systems were simulated using these time series. The difference between systems is therefore the amplitude of the produced power, not its variability.

3.2 Electricity consumption

3.2.1 Commercial

The consumption of electricity in time schedule and/or amount depends, among other factors, on the type of business. It is expected that small businesses will have a higher correlation between the load profile and the PV production in comparison with dwellings. In order to get a clearer idea of the differences between distinct types of commercial units this work explores the consumption of a restaurant, a bank and a hotel.

Bank

The selected bank branch is located in Lisbon and has an unknown contracted power. The annual energy consumption, measured between May 2015 and April 2016, was 3.82 MWh. The maximum power recorded was 2.6 kW and the minimum was 0.1 kW.

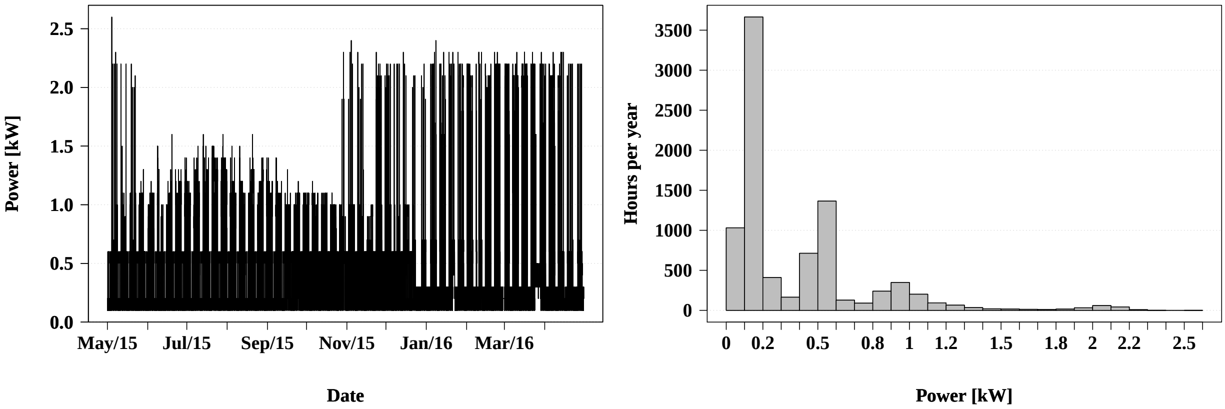
As shown in Figure 3.3a, there are a constant consumption base and patterns, with demand range between 0.1 and 2.6 kW. During the summer months the consumption pattern is more irregular with higher power energy consumption baseline which can represent cooling systems, but lower peak power consumption which may be due to fewer customers.

Figure 3.3b reveals certain routines in the use of electrical devices. The most frequent combinations are a power load between 0.1 kW and 0.2 kW, corresponding to the baseline when the bank branch is closed and between 0.5 kW, and 0.6 kW which represents the baseline of the working hours.

There are two distinct consumption patterns in the bank, for weekdays and weekends as shown in Figure 3.3.

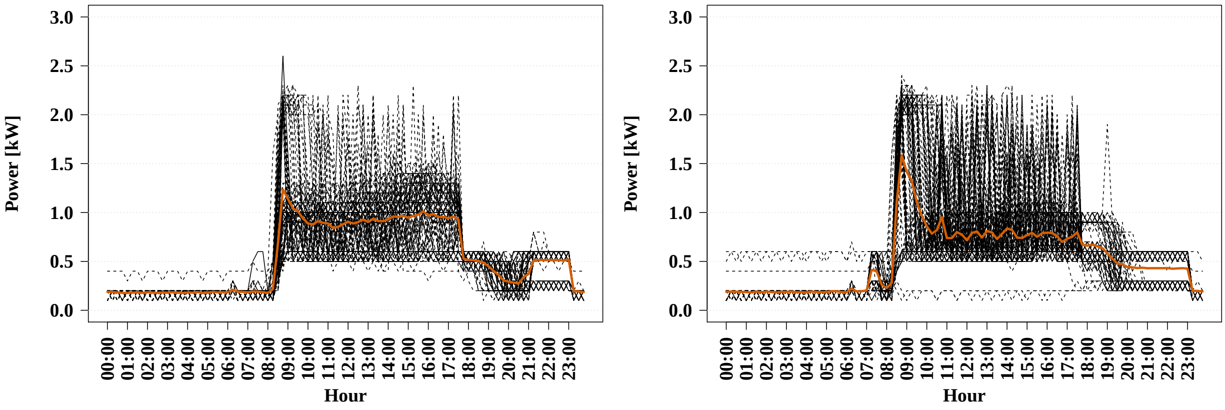
On weekdays there is an increase on the baseline from 0.2 to 0.5kW during working hours and a more irregular consumption at the early and later hours of the day, which are assumed to be the working hours of the employees.

During weekends all the bank branches are closed which can be confirmed in Figure 3.3 as the consumption is close to zero. Both summer and winter feature a constant demand of about 0.4 kW from 8 pm to 11 pm every day of the week. This consumption is, presumably, a result of a predefined and scheduled update and back-up of the bank data.



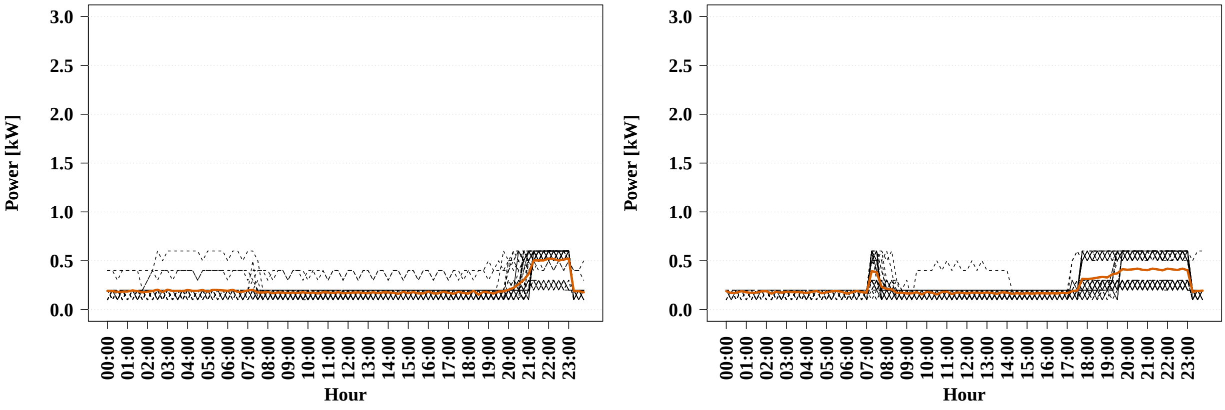
(a) Annual energy consumption

(b) Histogram of consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter

Figure 3.3: Bank: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

Restaurant

The restaurant considered for analysis is located in Lisbon and has an unknown contracted power. The data was collected over a time period of half a year from October 2015 to April 2016. The energy consumption of that period was approximately 3.7 MWh, with a maximum power listed of 4.1 kW and the minimum of 0.16 kW.

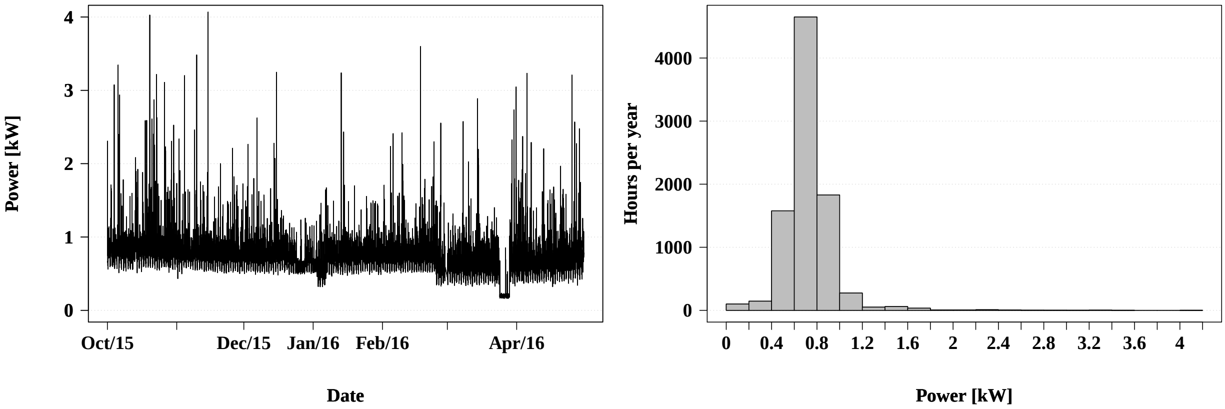
In Figure 3.4a it is possible to identify, in the end of March, a period with a constant low consumption (0.2 kW) which may have been caused by Easter holidays (29 to 31 of March).

The electrical devices which were turned-on more frequently, simultaneously, correspond to a power of between 0.6 and 0.8 kW as shown in Figure 3.4b. Rarely power consumption was higher than 1.8 kW.

From the end of February until April there was a decrease in the baseline possibly related to the increase of temperature and turning-off the heating system.

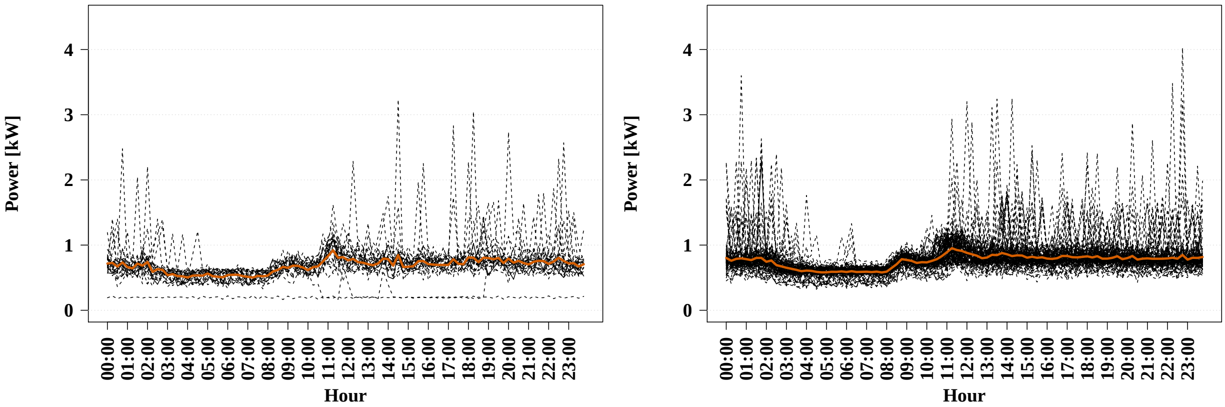
The average power, for summer and winter, showed in Figure 3.4, was in all cases slightly lower than 1 kW. Comparing weekdays with weekends and winter with summer it is possible to observe that, for this business, there is not a significant difference. There was a small decrease of power consumption from weekdays to weekends and from winter to summer, although we should keep in mind that the data available for the summer is much less extensive.

This restaurant has typically a low consumption with a constant baseline. It would be expected that the load profile would show an increase in energy consumption before and during meal hours (11 am to 3 pm and 6 pm to 9 pm). A possibility is the use of this building unit, which although labelled as a restaurant may, in fact, be a small cafe/bar. This would explain the load profile.



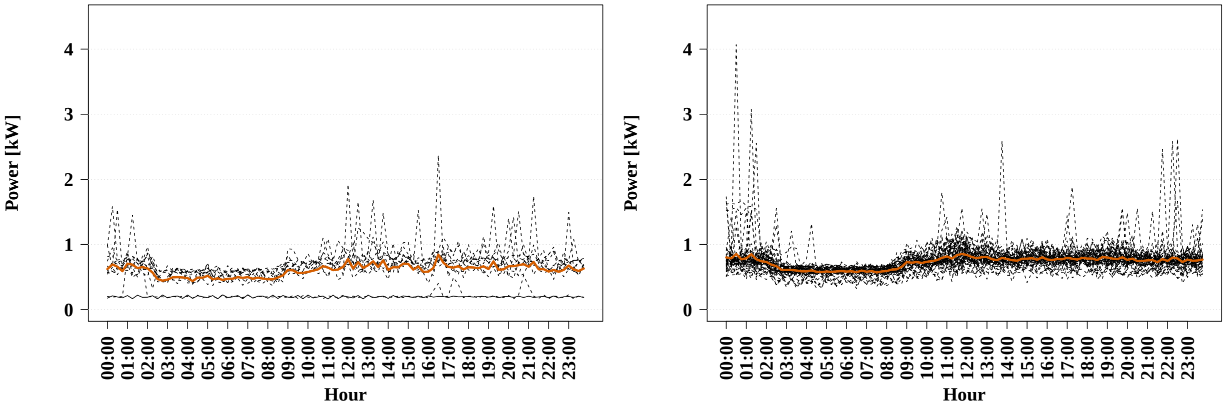
(a) Energy consumption during six months

(b) Histogram of consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 3.4: Restaurant: (a) Energy consumption during six months; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

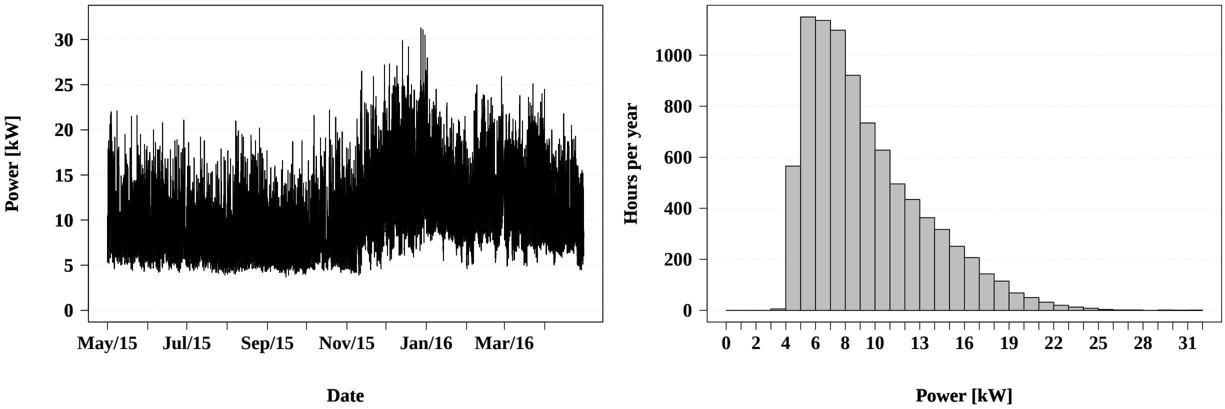
Hotel

The hotel considered in this study is located in Lisbon and it has an unknown contracted power. The annual energy consumption measured in the hotel, between May 2015 and April 2016, was around 83.1 MWh. Almost two orders of magnitude higher than the bank or the restaurant. It has a mean power of 9.5 kW, maximum and minimum power of 31.3 kW and 3.7 kW, respectively.

As shown in Figure 3.5a the consumption varies more in comparison with the other commercial units. During the winter months there is an increase in demand, which is probably related to the heating system and illumination.

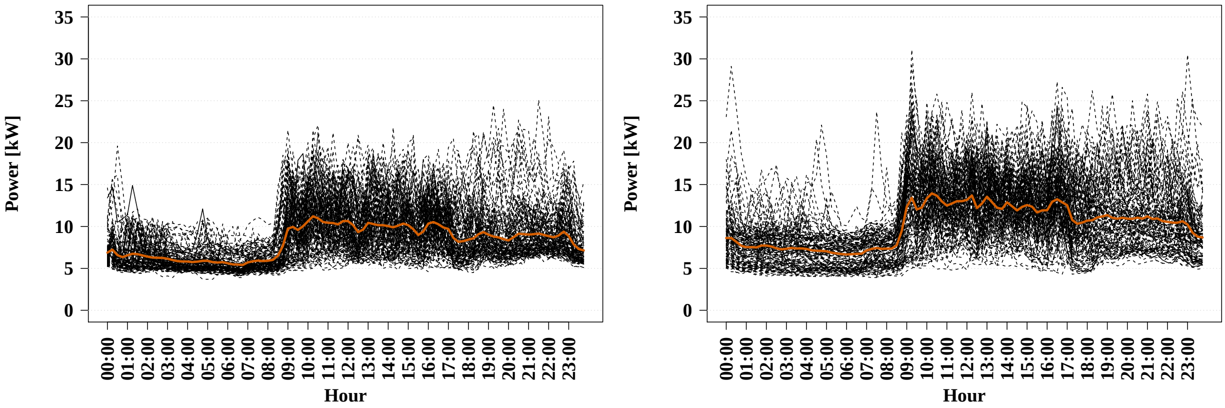
Contrasting with the previous cases, the values of power demand measured have a wider range. Most are between 5 and 6 kW, decreasing until 25 kW. In contrast with the restaurant and the bank, Figure 3.5b suggests there is not only a single power load consumption occurring more frequently, but several. This can be explained by the fact that a hotel has different guests with different routines of electronic device usage.

As shown in Figure 3.5 there seems to be no significant difference on consumption patterns between weekdays and weekends. Figure 3.5c, 3.5d, 3.5e, 3.5f all have a lower power load after midnight, followed by an increase after eight in the morning.



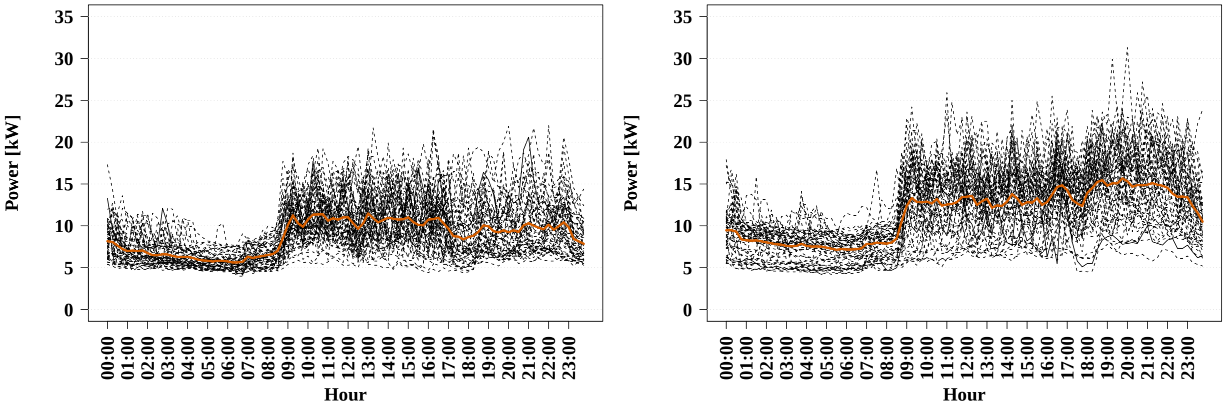
(a) Annual energy consumption

(b) Histogram of consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

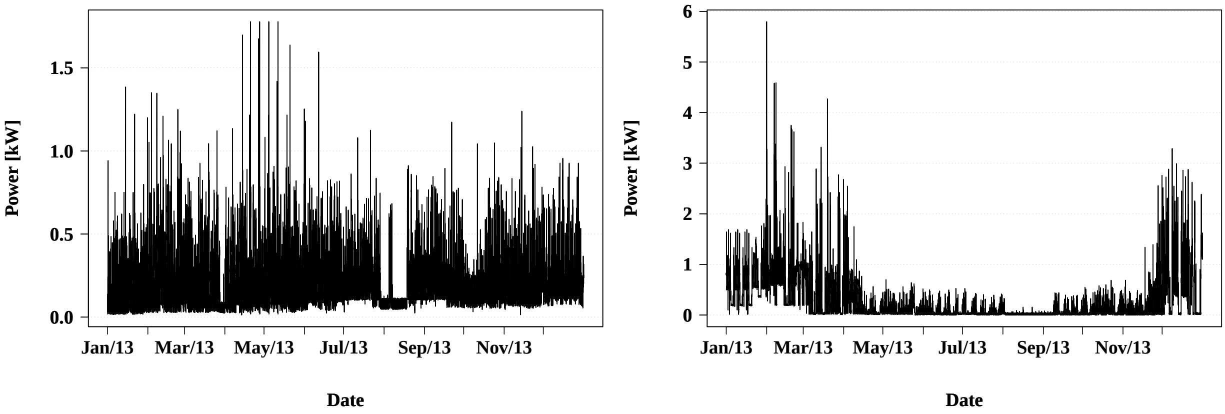
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 3.5: Hotel: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

3.2.2 Dwellings

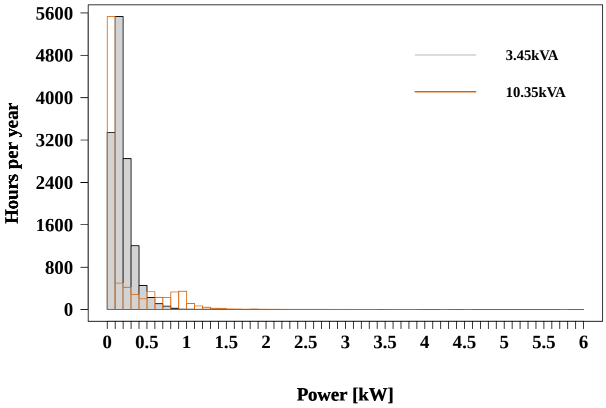
Eighteen different dwellings located in Lisbon were analysed, with six different values of contracted power: 3.45, 4.6, 6.9, 10.35, 17.25 and 20.7 kVA.

For 3.45 kVA and 10.35 kVA of contracted power, one example of load curve data is shown for illustrative purposes. In Table 2.4 it is outlined the contracted power of each household. All the measurements were taken between January 2013 and December 2013.



(a) Annual energy consumption - HH1.1 (3.45kV)

(b) Annual energy consumption - HH4.1 (10.35kV)



(c) Histogram of the consumed power: 3.45kVA - HH1.1 (Gray solid bars) and 10.35kVA - HH4.1 (Orange not filled bars)

Figure 3.6: Dwellings[3.45kVA and 10.35kVA]: (a) Annual energy consumption - HH1.1 (3.45kV); (b) Annual energy consumption - HH4.1 (10.35kV); (c) Histogram of the consumed power - HH1.1 (3.45kV) and HH4.1 (10.35kV).

3.45kVA

The selected househould with 3.45 kVA was HH1.1. The annual energy consumption of this dwelling was 1.65 MWh with a mean power of 0.2 kW.

Figure 3.6a presents a small value of base consumption which is close to the minimum value (0.013 kW). Most of the consumption occur with a power lower than 1 kW. Considering the Table 6.1 of electrical devices consumption (Section 6.1), the household HH1.1 has a considerably lower power consumption.

There are two periods of constant low power, the first occurring in the end of March which matches with being absent from home in Easter. The second one occurs from the beginning until mid August with a peak of power consumption in the middle. This most likely represents two periods of the owner holidays when nobody was at home.

10.35 kVA

The dwelling HH4.1 has a contracted power of 10.35 kVA and an annual energy consumption of 2.16 MWh. As mentioned before in Section 2.4.1 the first three weeks are replicated as shown in Figure 3.6b - 10.35 kVA.

Between mid April and mid November the used power per day is approximately half in comparison with the rest of the months which can be due to the use of a heating system during the winter or another factor. The mean power of HH4.1 is 0.25 kW with a maximum power of 5.8 kW and the minimum of almost zero.

Most of the consumption power is lower than 3 kW although occasionally it goes higher.

From the beginning of August until the second week of September the consumption is almost zero, which should have the same causes as in the other dwellings.

While HH1.1 has most of the hours of the years load between 0 and 0.4 kW (which included three classes of the histogram (Figure 3.6c)), HH4.1 has only one histogram class (0 - 0.2 kW) with hours per year higher than 800.

3.2.3 Condominium [3.45 - 10.35kVA]

The condominium analyzed is an aggregation of fourteen dwellings with a contracted power within 3.45 and 10.35 kVA presented in Figure 3.7.

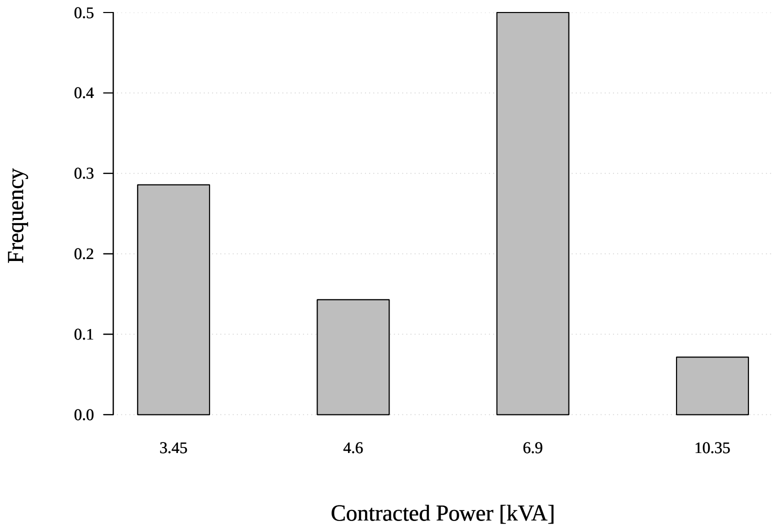


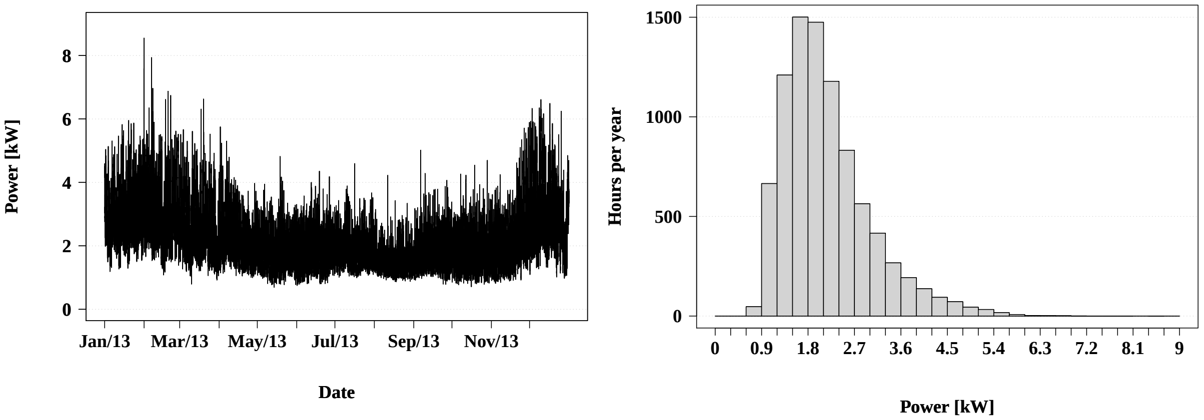
Figure 3.7: Contracted power of the dwellings that compose the condominium.

In Figure 3.8 it is possible to identify a more uniform energy consumption where people's routines become less visible. The annual energy consumption of this condominium is around 18.9 MWh with a mean power around 2 kW. The maximum power is 8.6 kW and the a minimum 0.7 kW.

The demand power range is wider during the winter months, probably due to the heating systems and the fact that people tend to stay more indoors during this period. The power range where the majority of energy is consumed is between 2 kW and 10 kW.

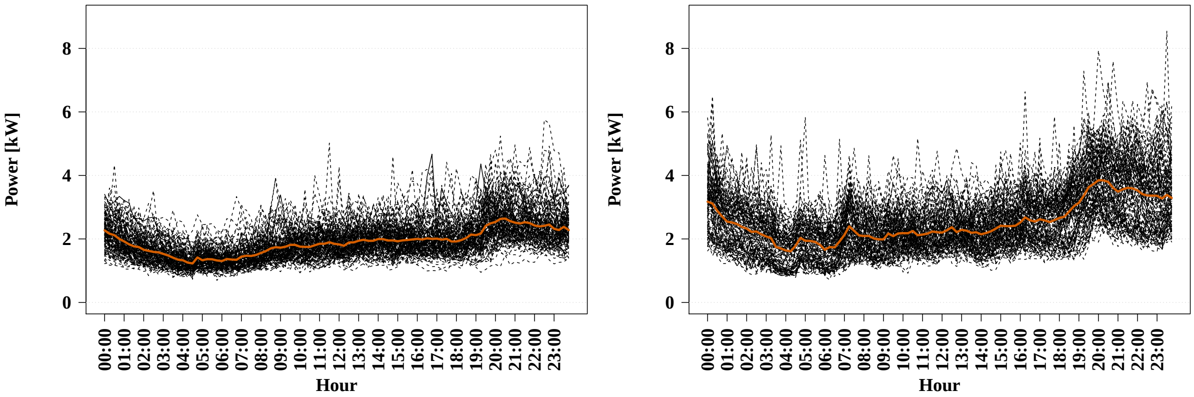
With the aggregation of the dwellings there is an increase in the range of power that is used. As shown in Figure 3.8 most measurements are in the interval 1.2 - 2.4 kW, with a smooth decrease after the 4 kW until 8 kW.

The consumption profile is similar between weekdays and weekends as shown in Figure 3.8. It is possible to observe a decrease, from the winter to summer, like in all the buildings studied so far, of approximately 1 kW.



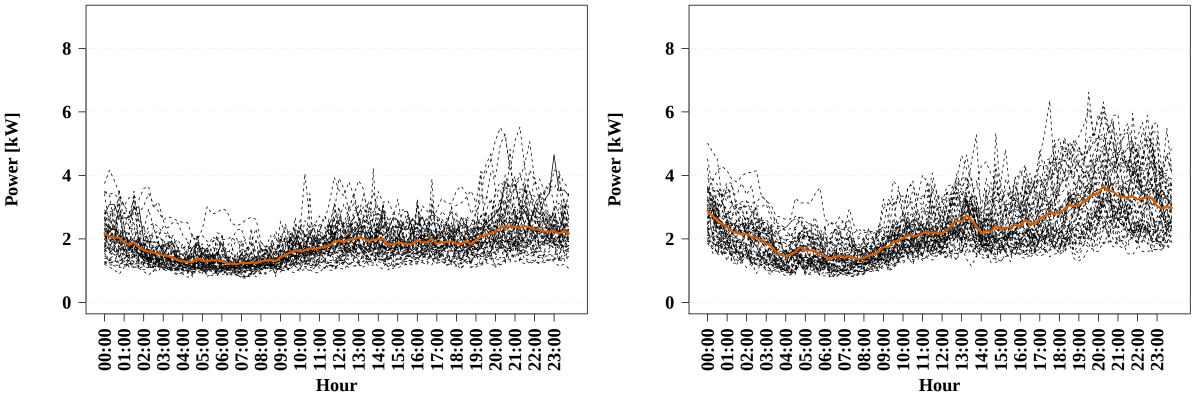
(a) Annual energy consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

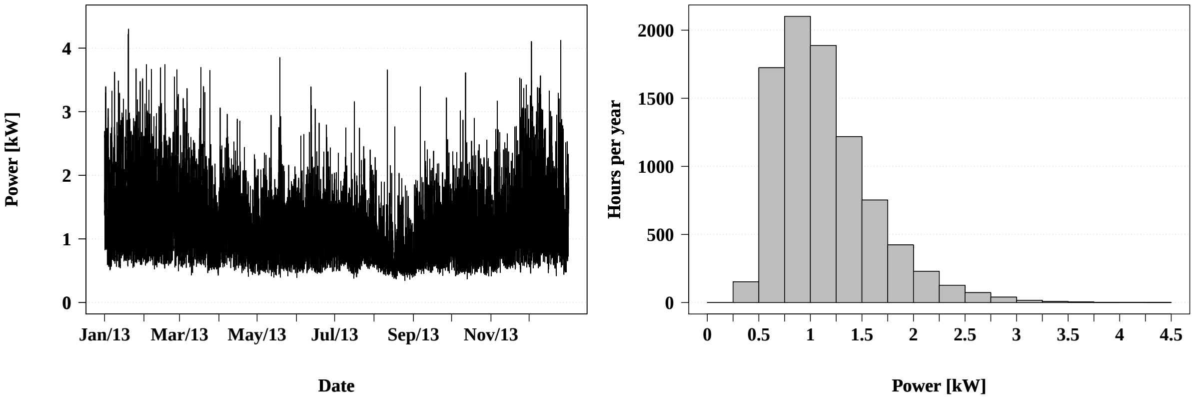
Figure 3.8: Condominium: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

3.2.4 Condominium [6.9 kVA]

In this study, a condominium constitutes an aggregation of dwellings which have approximately the same consumption/contracted power. Considering the collected data, households with 6.9 kVA are in higher number therefore it was analysed a condominium composed only by dwellings with 6.9 kVA of contracted power.

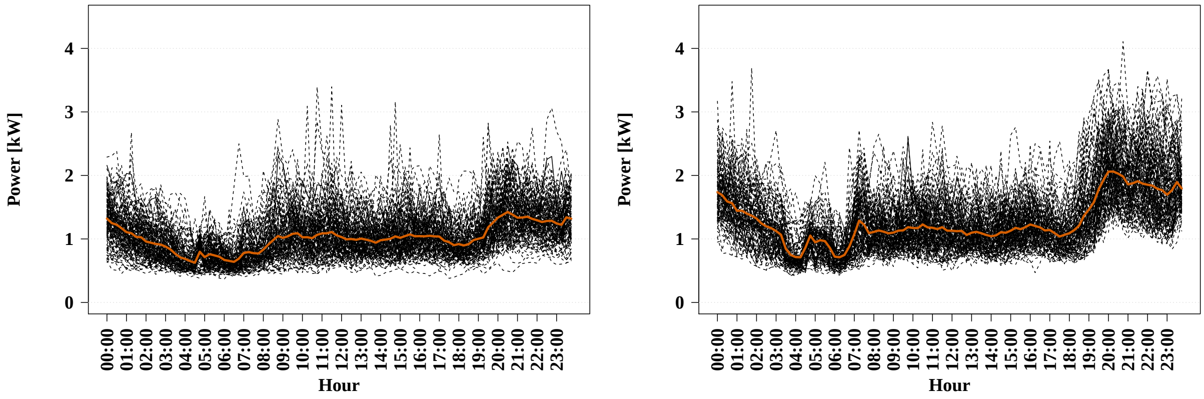
Figure 3.9 - condominium 6.9 kVA - is similar to Figure 3.8, having a decrease of energy consumption for almost half (annual energy consumption is equal to 10 MWh). This unit has a maximum power measured of 4.3 kW, a mean 1.1 kW and a minimum of close to 0.4 kW.

The daily profile consumption in the condominium 6.9 kVA is slightly more variable. This effect is due to the reduction of aggregated dwellings.



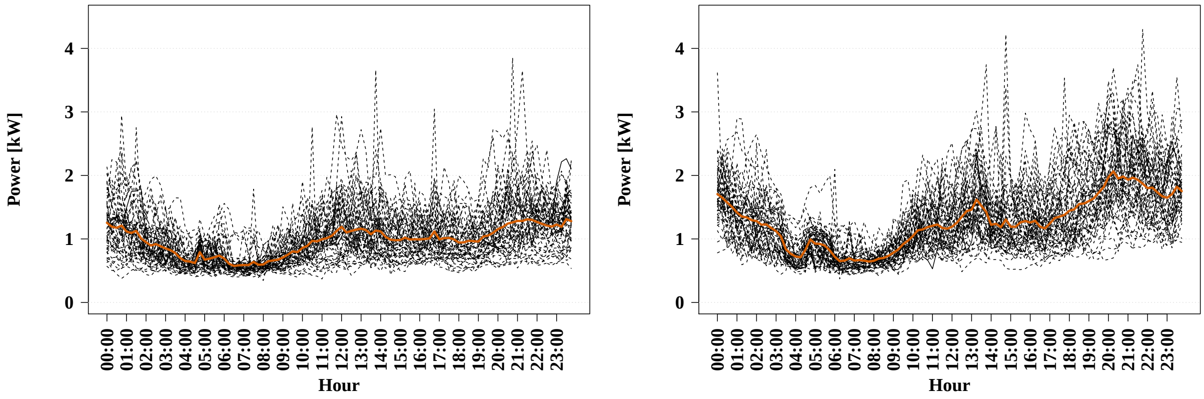
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 3.9: Condominium composed by dwellings with 6.9 kVA: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

3.2.5 Aggregation

To evaluate the effect of different level and types of aggregation, different situations combining the condominium with at least a commercial building were considered. The condominium is the common unit since it is one of the focus of this work (aggregation with dwellings).

Due to the high electricity consumption of the hotel it was considered that, the aggregation Condominium & Hotel consists in four condominiums and one hotel while Condominium 6.9 & Hotel consists in eight condominiums and one hotel.

The results obtained can be found in Table 3.1.

Table 3.1: Overview of electrical load parameters for the different sets of aggregation.

Aggregation	**Energy consumption [MWh]**	**Power interval [kW]**	**Mean power [kW]**	**Baseline [kW]**
Condominium & Bank	22.6	0.9 to 8.8	2.6	1
Condominium 6.9 & Bank	13.7	0.5 to 5	1.6	0.6
Condominium & Restaurant	16	1.1 to 9.3	3.2	1.6
Condominium 6.9 & Restaurant	10.3	0.6 to 6.3	2	1
Condominium, Bank & Restaurant	18.2	1.4 to 9.5	3.6	1.9
Condominium 6.9, Bank & Restaurant	12.4	0.9 to 6.9	2.5	1
Condominium & Hotel	157.8	7.5 to 49	18	10
Condominium 6.9 & Hotel	161.8	7.7 to 54	19	10

The load of the building and aggregated units studied in this section are processed using the algorithm presented in Section 2.3, within a range of PV installed power up to the contracted power of the building/aggregation and a ratio battery capacity over PV installed power from 0 to 2 kWh/kWp.

4. Integrated PV-storage system

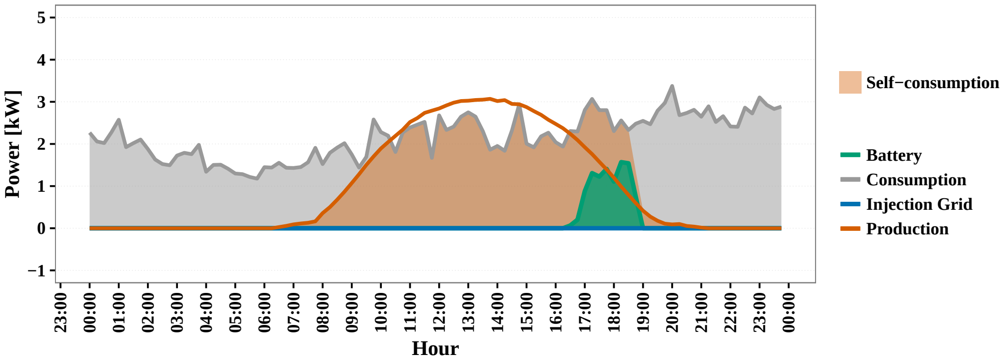
Following the analysis of the electricity consumption and PV generation discussed in the previous chapters, we now consider an integrated PV system with battery storage. For each building unit, or set of building units, an optimization model for the use of the battery is applied to determine the energy flows between the PV system, the battery and the grid as well as the state-of-charge of the battery. From these results, one can determine the performance and economic viability of the PV-storage system.

4.1 PV-storage systems for building units

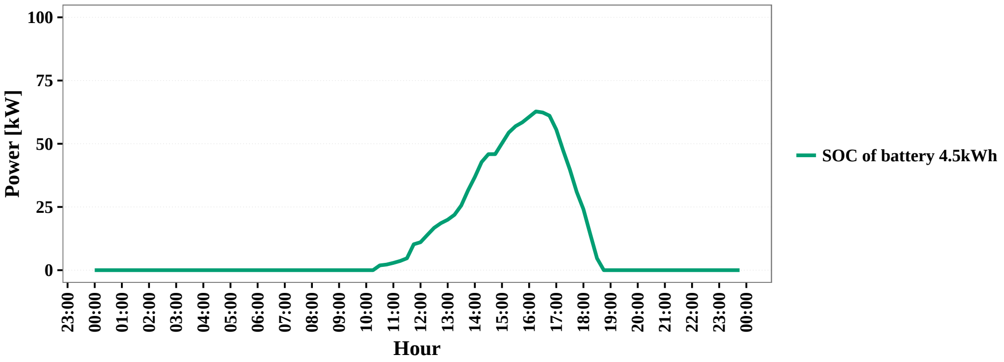
The typical performance of an integrated PV-storage system, sized for producing the minimum excess, is illustrated in Figure 4.1.

The presented case has a PV installed power of 4.5 kWp, half of the peak consumption power of the unit, and a 4.5 kWh battery capacity. This system covers partially or totally the consumption needs from 7 am to 7 pm. As it can be observed in Figure 4.1b the battery does not even reach a state-of-charge higher than 65%, therefore does not inject energy in to the grid on this day.

In general, for residential units, which have the majority of their consumption during the night, the role of a storage system with this ratio of capacity over PV power is simply to extend the self-consumption period in order to increase it.



(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill) and energy supplied from the battery (green)): Weekday summer

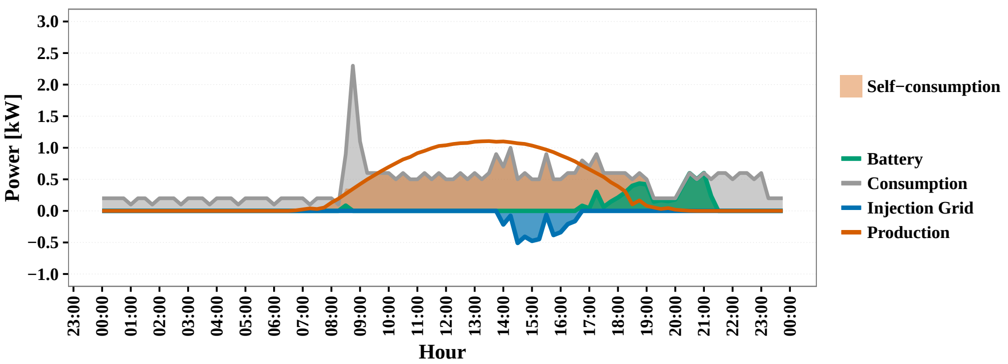


(b) Battery state-of-charge

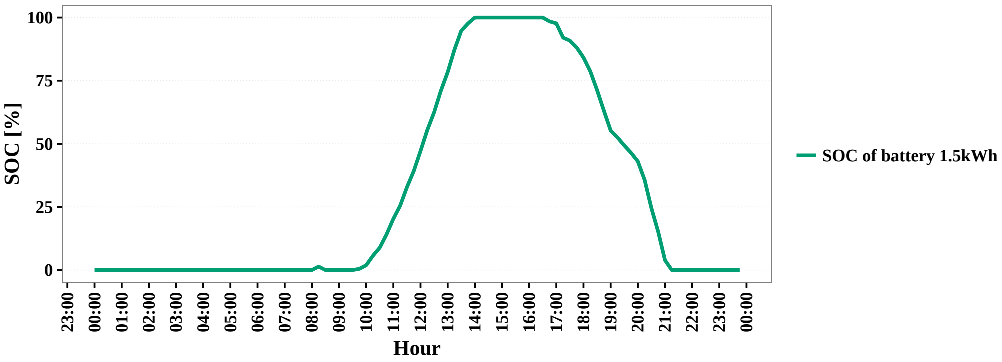
Figure 4.1: Electrical load diagram of the Condominium: Example of a weekday during the summer with a PV installed power of 4.5 kWp and a proportion battery capacity PV power of 1 kWh per kWp (a) Electrical load diagram ; (b) Battery state-of-charge.

For service buildings, there seems to be a better match between consumption and photovoltaic generation, as shown in Figure 4.2. Indeed, most of the photovoltaic generation occurs during the working hours, when the consumption reaches its highest values.

For this PV-storage system, with the same ratio (battery capacity over installed PV power) as the one in Figure 4.1, the battery has a more active role in fulfilling the consumption needs during the night. The battery is fully charged by 2 pm and it only starts to discharge after 5 pm. In between, the surplus energy is supplied to the grid.



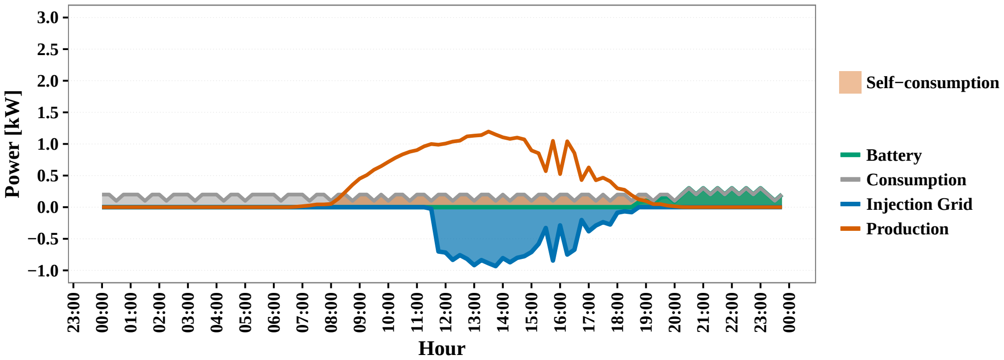
(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and energy sold to the grid (blue)



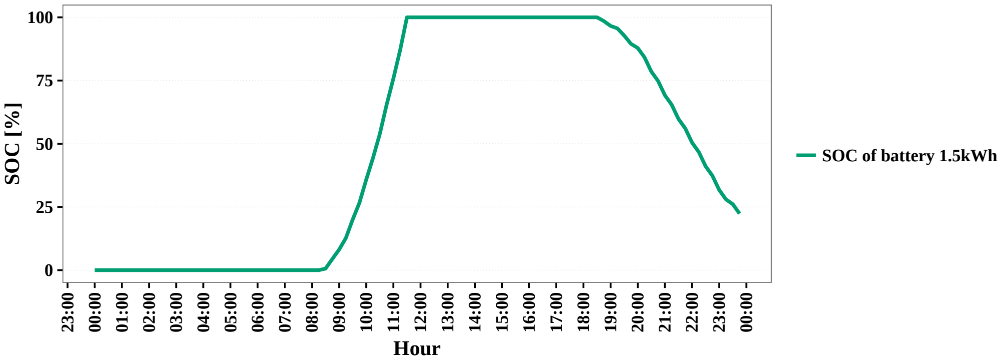
(b) Battery state-of-charge

Figure 4.2: Electrical load diagram of the Bank: Example of a weekday during the summer with a PV installed power of 1.5 kWp and a capacity of 1.5 kWh (a) Electrical load diagram; (b) Battery state-of-charge.

Applications as the above described raise other challenges, such as the differentiated use during weekends, as shown in Figure 4.3. In these situations, most of the generated PV electricity will be injected to the grid as the state-of-charge of the battery reaches 100% during the morning. This will cause the self-consumption, the payback period and the internal rate of return to decrease as the self-sufficiency rate increases.



(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and energy sold to the grid (blue).

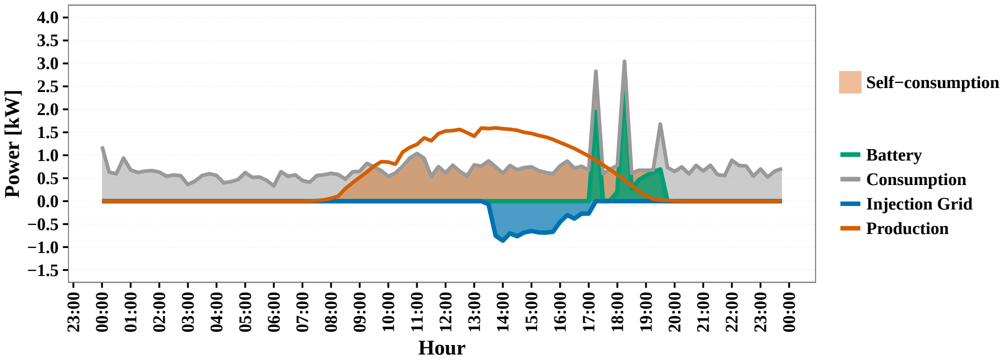


(b) Battery state-of-charge

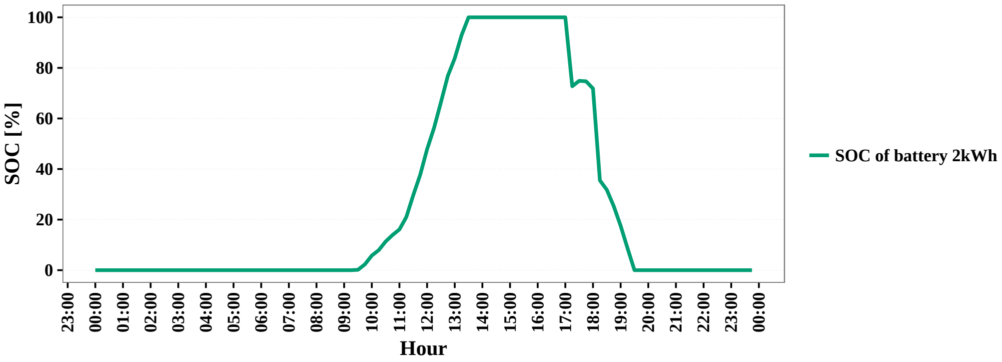
Figure 4.3: Electrical load diagram of the Bank: Example of a weekend during the summer with a PV installed power of 1.5 kWp and a capacity of 1.5 kWh (a) Electrical load diagram; (b) Battery state-of-charge.

The electricity consumption for the hotel case study is perhaps better matched to the PV generation, since it has a higher consumption after 8 am and it does not have the weekend effect discussed above. Other services, such as the restaurant, have a broader load diagram, much less pronounced at working/daytime hours, and therefore are much less suited for the PV system, as shown in Figure 4.4.

It is important to considered the load profile of this particular restaurant as mentioned in Section 3.2.1.



(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue).



(b) Battery state-of-charge

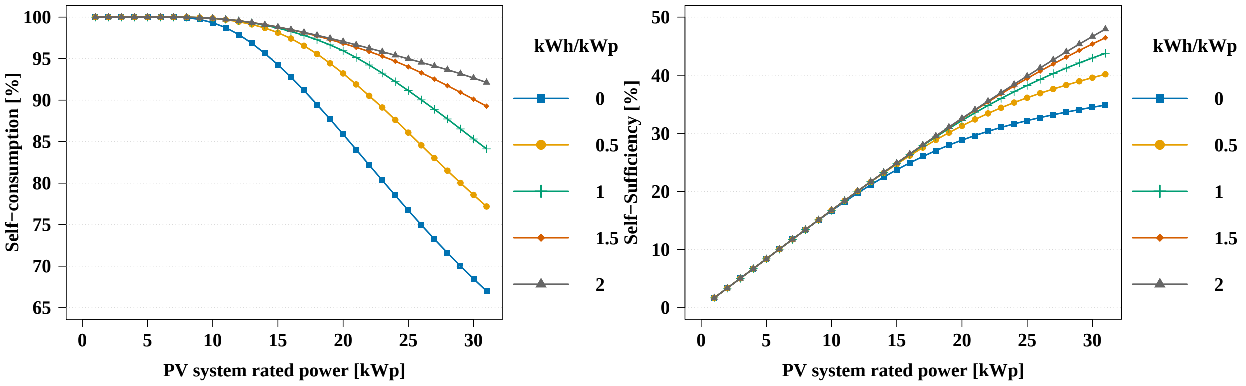
Figure 4.4: Electrical load diagram of the Restaurant: Example of a weekday during the summer with a PV installed power of 2 kWp and a capacity of 2 kWh (a) Electrical load diagram; (b) Battery state-of-charge.

4.2 PV-storage systems performance for building units

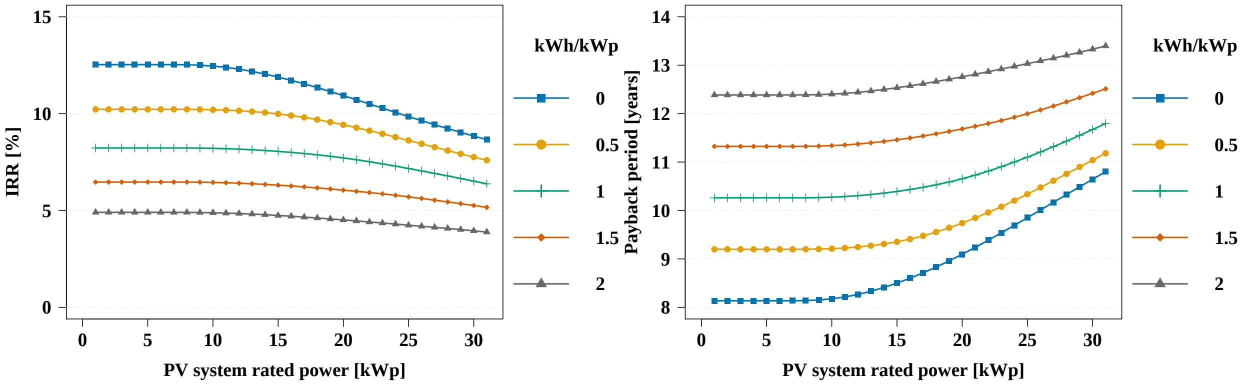
Following the discussion in the previous section, it comes with no surprise that PV-storage systems feature better results when the match between consumption and photovoltaic generation is higher. It leads to higher self-consumption, higher self-sufficiency, higher internal rate of return and lower payback periods. This can be observed in Figure 4.5, 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 unit 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 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 power, the level of self-consumption will decrease. How fast the it will decrease depends on the storage capacity. If the system has no or low storage capacity it will decrease on a faster rate, while a larger battery will have a smaller decrease rate. The level of self-sufficiency will also increase if a larger storage capacity is considered. The internal rate of return and the 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, large storage capacities are always less interesting than smaller systems from an economic point of view.

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



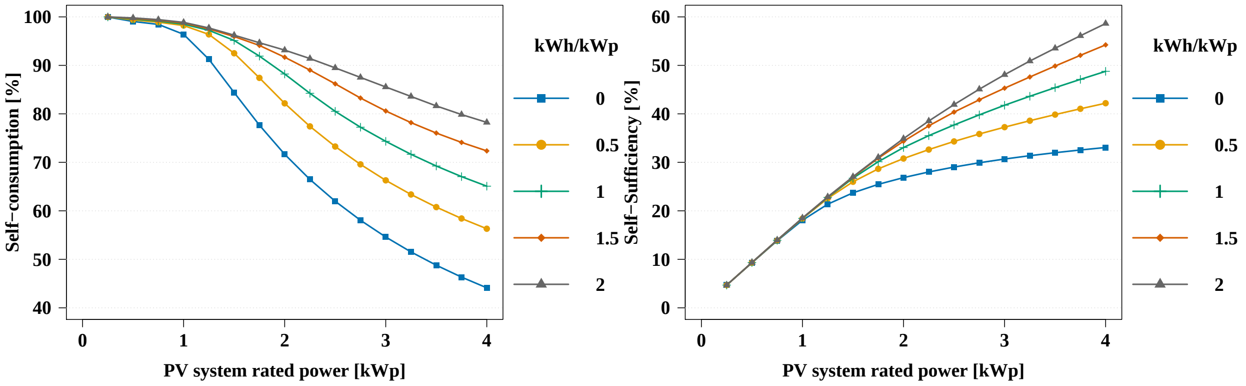
(a) Self-consumption **(b)** Self-sufficiency



(c) IRR **(d)** Payback period

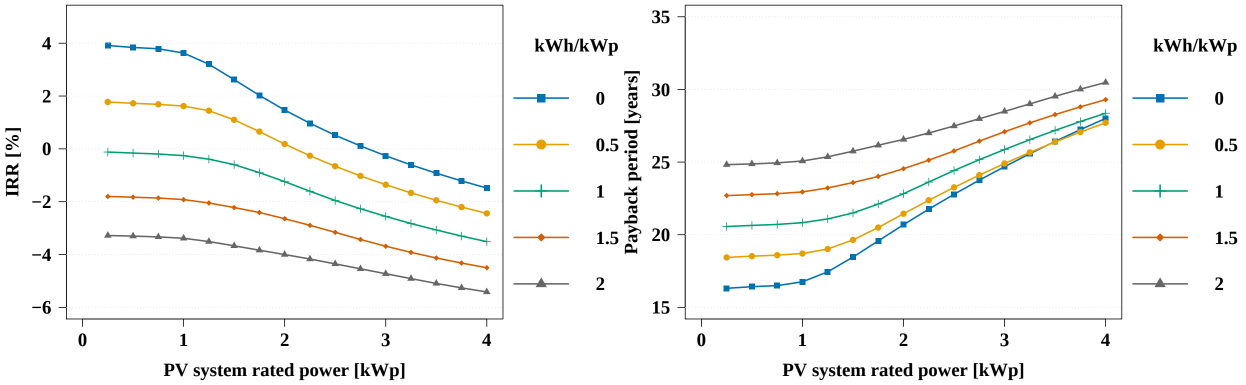
Figure 4.5: Parameters Hotel: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

It is noteworthy that the economic parameters for the restaurant are much less interesting than for all other system configurations, as shown in Figure 4.6.



(a) Self-consumption

(b) Self-sufficiency



(c) IRR

(d) Payback period

Figure 4.6: Parameters Restaurant: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

The corresponding plots to all building units or their combinations are shown in the Annex (Chapter 6) of this dissertation.

4.3 Comparison between building units

The hypothesis that prompted the work for this dissertation is that the aggregation of electricity consumption from different users will lead to a collective load diagram better adapted to the photovoltaic generation profile.

The excess energy point, defined as the installed power before self-consumption drops below 97%, varies from case to case. Figure 4.7 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. This means that aggregation will lead to a better match between installed PV power and load profile. As expected, the aggregation of commercial and residential units allows to increase photovoltaic penetration without producing an excess of energy, which makes it a more profitable and attractive project considering the Portuguese law.

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.

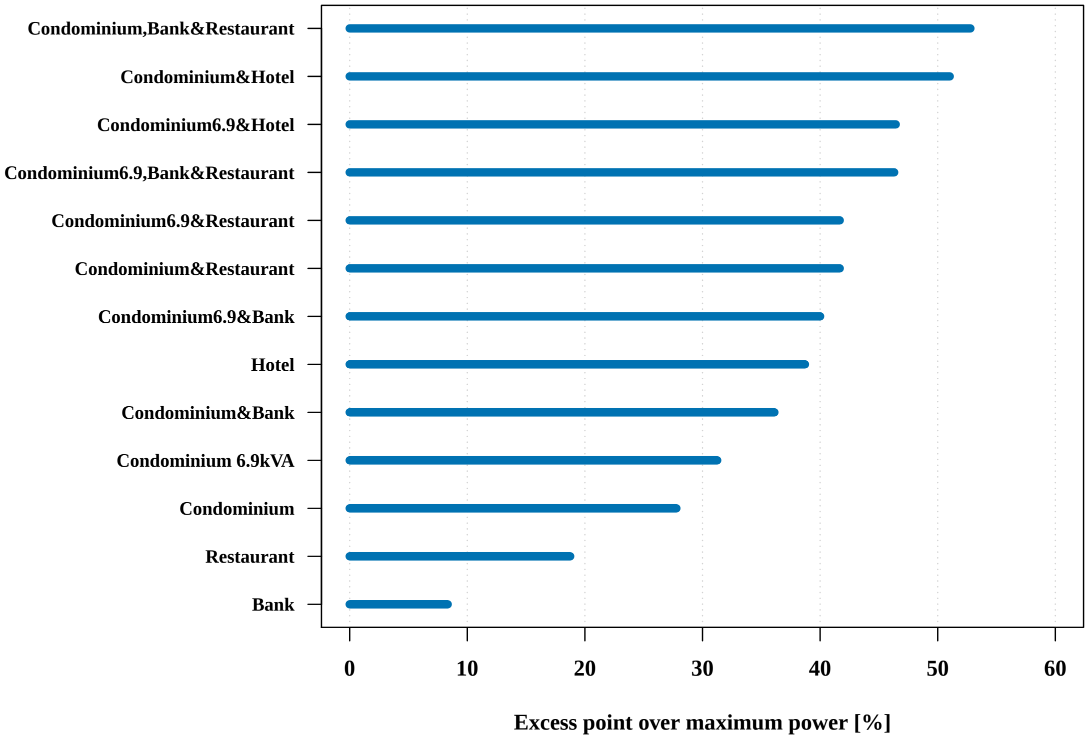


Figure 4.7: Excess point over maximum installed PV power for all the aggregations and single building units.

Figure 4.8 shows the self-consumption of the different sets of building units studied, for maximum peak power (which corresponds to the maximum PV installed) and the different levels of storage capacity, from zero (no battery) to 2 kWh/kWp.

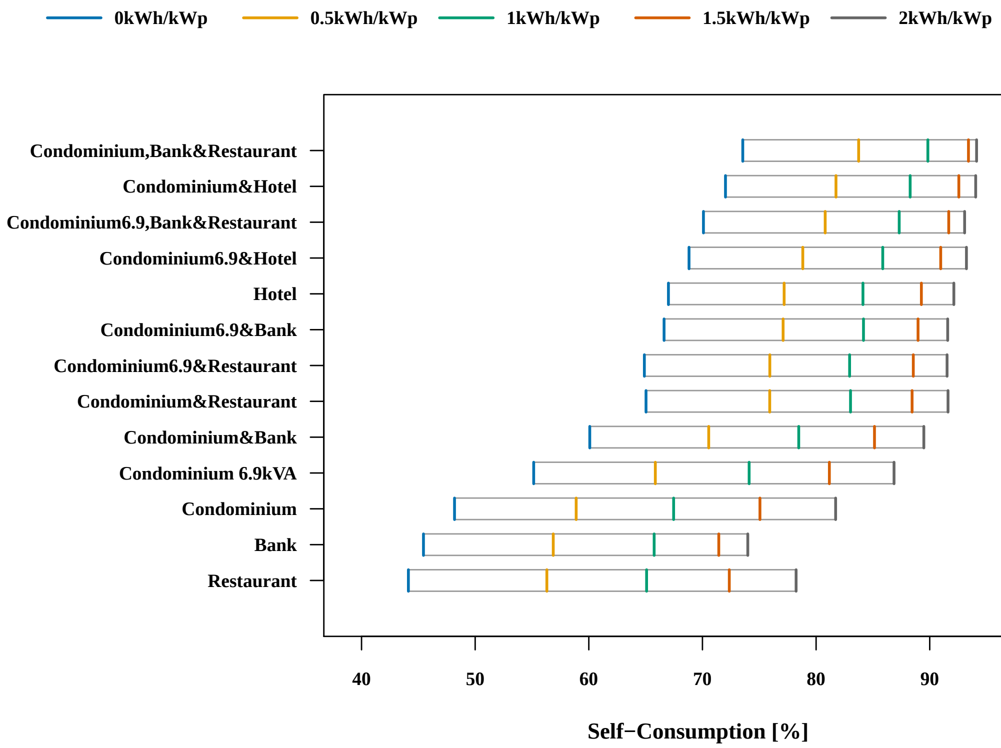


Figure 4.8: Self-consumption rate for all the ratios, battery capacity over PV installed power, in their maximum installed power.

From Figure 4.8 we conclude 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 to 90%, depending on the storage capacity).

In general, the self-consumption rate increases with different users, hence 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.

Regarding self-sufficiency, shown in Figure 4.9, the effect of aggregation of users is less pronounced and even has a negative effect on self-sufficiency.

The bank, which has the best match between load and PV curves, features the highest levels of self-sufficiency (50 to 80%, depending on the storage capacity). Other units have much lower levels of self-sufficiency, even if aggregated with the bank.

In general, the load aggregation of diverse users leads to decreased self-sufficiency since the consumption increases not only in the hours of sun but generally as whole. It is important to keep in mind that the maximum consumption power of the aggregation is not usually the sum of the maximum power of the individual units because the needs for grid electricity occur at different times of the day/year. Therefore, the generated photovoltaic, although higher, is not able to compensate the increased consumption needs.

The degree of self-sufficiency of a PV-storage system is particularly important on an off-grid situation. When the building unit is connected to the grid it does not necessarily need a high level of self-sufficiency for it to be a profitable good investment.

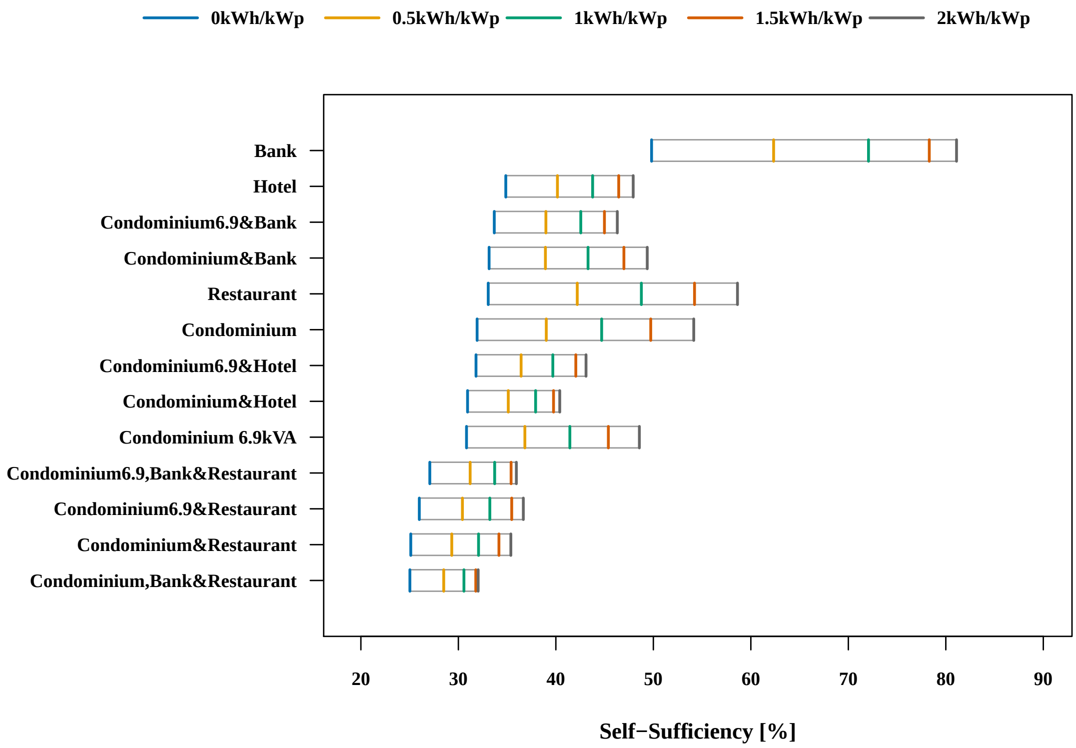


Figure 4.9: Self-sufficiency degree for all the ratios, battery capacity over PV installed power, in their maximum installed power.

As far as economic parameters are concerned, Figure 4.10 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 currently high cost of battery systems.

Considering a plausible threshold of 5% for 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 with higher penetration of storage, hence with higher self-consumption/self-sufficiency.

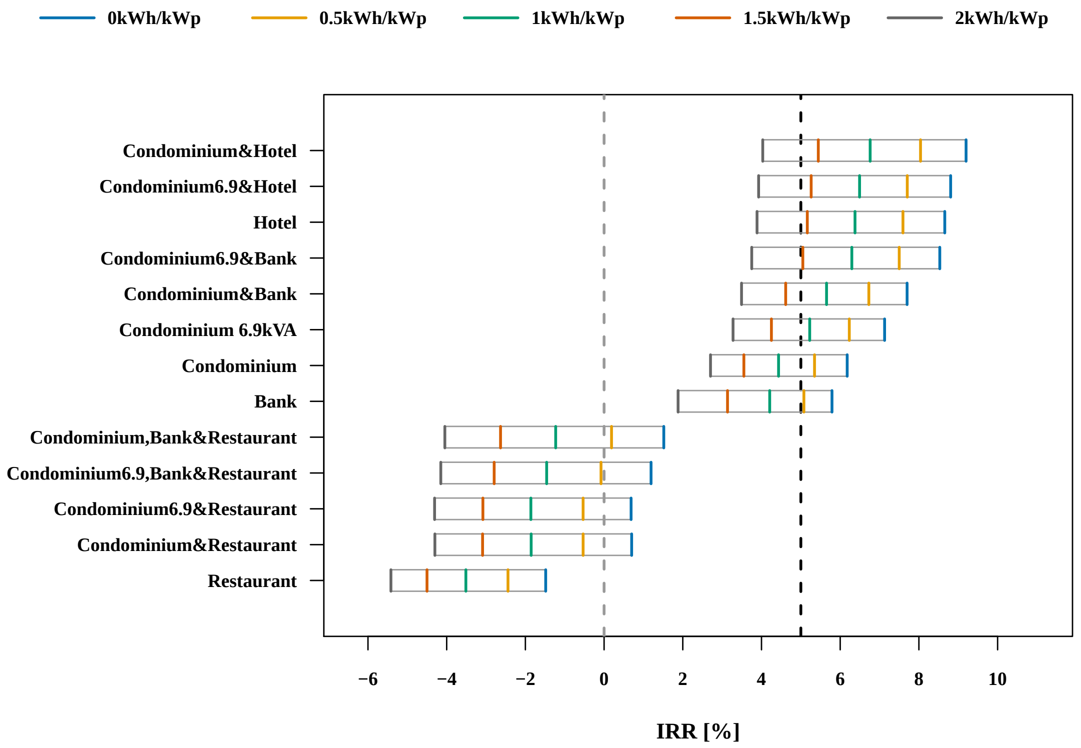


Figure 4.10: IRR values for all the ratios, battery capacity over PV installed power, in their maximum installed power.

When installing PV systems, considering the current Portuguese legal framework, it is rare to install the same value as the contracted power. A prosumers would chose between a range of power which would bring the highest investment return, a value close to the excess point.

Figure 4.11 shows IRR values for the different aggregation and buildings sets on their excess point.

The results show two different ranges of values, between -3.5% and 3.5% for the restaurant, on its own or when in combination with other users. Although they improved their profitability, in comparison with the maximum installed PV power, it still does not reach the threshold of 5%. All the other sets are located between 4.5% and 12.5%, in which only the ratio 2 kWh/kWp does not surpasses the 5% level, confirming the profitability of the systems.

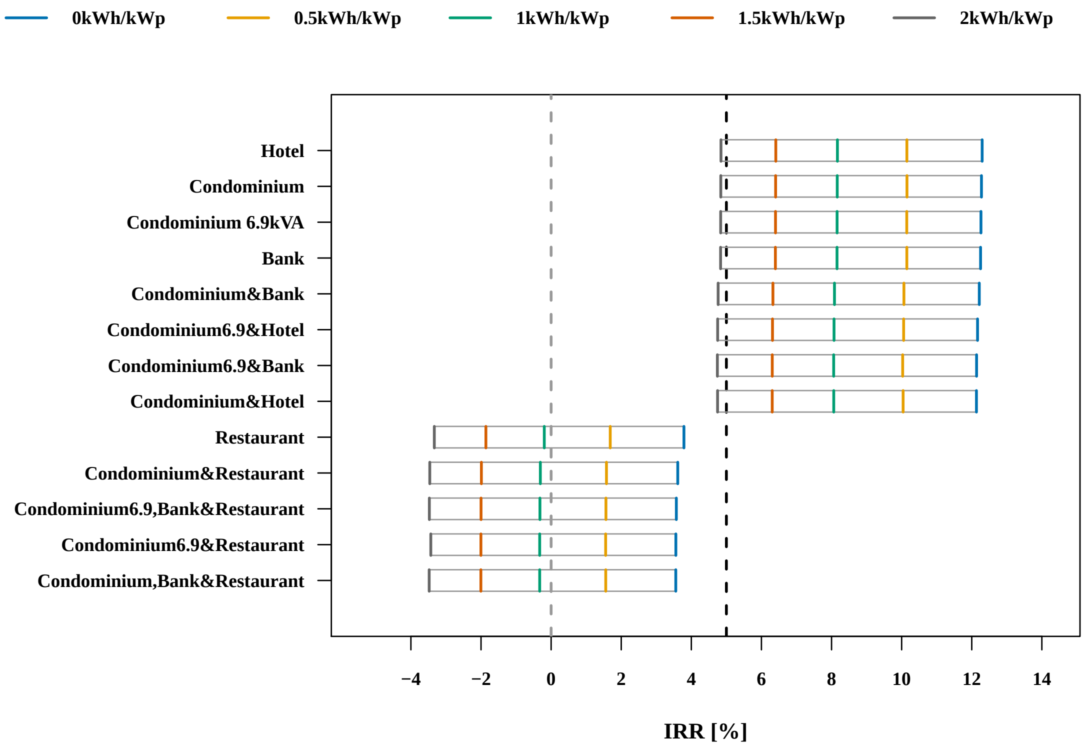


Figure 4.11: IRR values for all the ratios, battery capacity over PV installed power, in the excess point.

The analysis of the payback period (Figure 4.12) again highlights that the restaurant has the lowest economic performance, with payback periods of the order of 30 years. The aggregation of the restaurant with other users slightly decreases the payback time, which is kept above 20 years, regardless of the use of batteries.

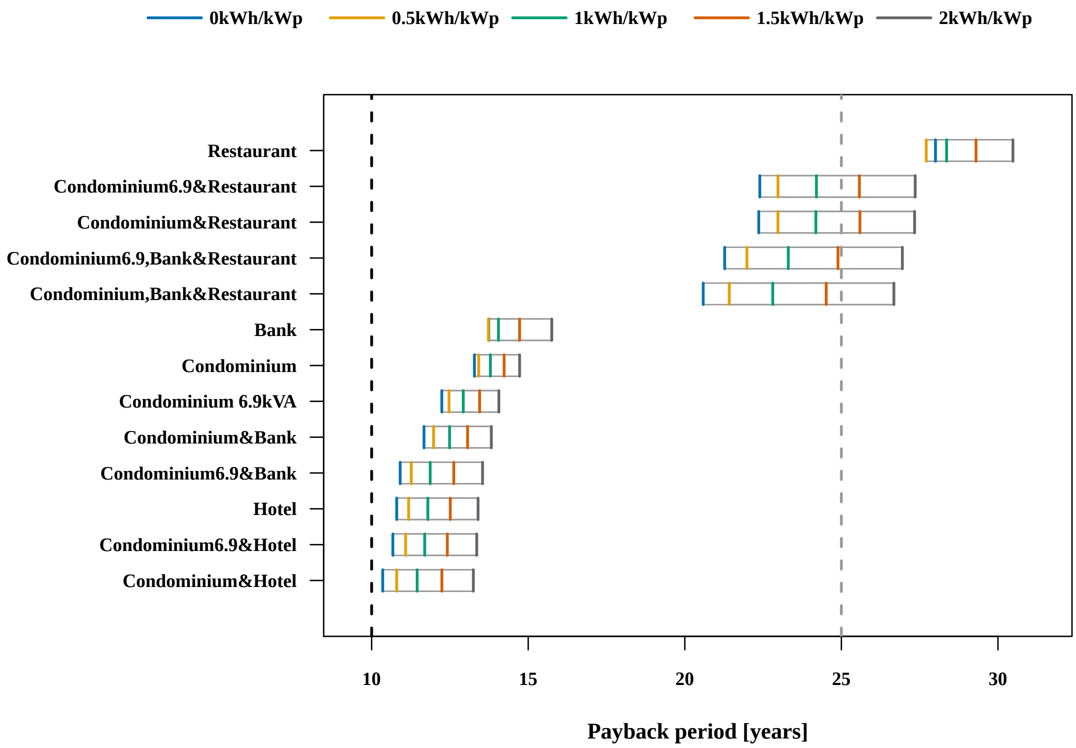


Figure 4.12: Payback Period values for all the ratios, battery capacity over PV installed power, in their maximum installed power.

All other cases feature payback periods in the range of 10 to 18 years, with slightly lower value for aggregation units and with minimum for the no-battery configuration. These results underline the conclusions of the analysis of the internal rate of return.

The bank and the restaurant are the only building units which have the same or lower value, respectively, for the ratio 0.5 kWh/kWp when compared with a no-battery scenario.

Figure 4.13 shows the values of payback period for the different aggregation and buildings sets on their excess point.

The results show, as in the plot of IRR values for excess point, two different ranges of values. The restaurant, on its own or when in combination with other users, present values between 16 and 25 years; all the other sets are between 8 and 13, with the values corresponding to a ratio 0 and 0.5 kWh/kWp, reaching payback periods lower than 10 years.

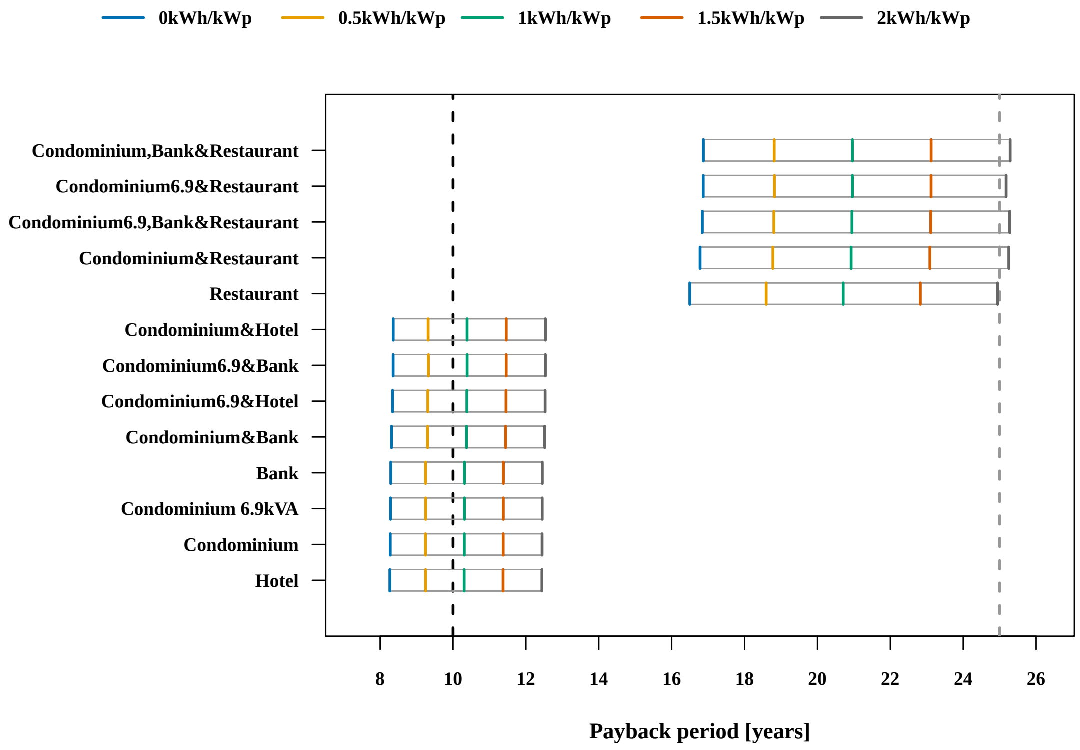


Figure 4.13: Payback Period values for all the ratios, battery capacity over PV installed power, in the excess point.

It ought to be noted that the presented values are consistent with those usually quoted in the literature (between 8 to 12 years, typically, depending on the publication and/or author). These numbers are obviously dependent on the parameters used for the economic model and the legal framework considered, which makes it highly speculative and controversial. The present model is the most accurate possible according to the cited sources. The evolution of the cost of grid electricity, lifetime of the different system components, among other factors, can only be accurately predicted up to a certain point.

We believe that the behaviour of the different building units and their combination will follow the same relative economic performance, as long as the cost of batteries is much higher than the rest of the system components.

4.4 Comparison with the reviewed literature

The conclusions from this work are consistent with the findings in the reviewed literature. Luthander et al show that relative self-consumption is increased by 13% to 24% with the implementation of a battery storage capacity of 0.5 to 1 kWh per installed PV power [15], while in this study there is an increase of approximately 12% to 20% for the same ratio range. The values are slightly lower but still in the same magnitude. Our results also present an increase of the self-consumption rate from 25% to 30% for a 1.5 kWh/kWp ratio and from 30% to 36% for a 2 kWh/kWp, as illustrated in Figure 4.8. Considering a neighborhood with 33 net zero-energy-buildings with integrated PV systems, Baetens et al show a self-consumption of approximately 26% at building level and 33% at neighborhood level [17]. Our study shows an increase up to 30% in self-consumption when aggregating building units (the restaurant in comparison with condominium, bank and restaurant in a no battery scenario). This is consistent with the hypothesis that aggregation leads to the smoothing of individual building daily load patterns.

The case study developed by Mahran et al, shows that self-consumption can exceed 60% without storage for single users as well as for an entire community [18]. In our work, considering quite similar conditions, single units can reach up to 65%, while aggregations can reach up to 70%. It is important to keep in mind that the single unit that reaches the threshold of 65% is the hotel, which is the unit showing the better match between load and solar generation.

Osawa et al using a community of 10 houses and batteries of electrical vehicles, present an increase on the self-consumption in 10% (from 42 to 52%) and an increase of 4% in self-sufficiency degree [19]. In our study, the Condominium and Condominium 6.9kVA also present an increase (up to 36% depending on the ratio) on self-consumption rate with the use of a battery storage system. The Condominium 6.9kVA appears to present a better match of load profiles, which is perhaps due to the fact that it only aggregates dwellings with the same range of consumption.

Volker et al compare the deployment of distributed and centralized district storage, modeling a neighborhood in Germany with 10 homes [20]. In their case self-sufficiency is 37% without storage integration, reaching up to 80% (+43%) with large scale centralized district storage. In the study conducted for this dissertation the Condominium and Condominium 6.9kVA only increase up to 25%.

Merei et al. show that for PV-battery systems in commercial buildings the implementation of storage systems with large battery sizes just lead to a slight increase in self-sufficiency degree. In this dissertation, the size of the battery system considerably affects the self-sufficiency degree, when considering the maximum photovoltaic installed power (up to 30%). As shown in Figure 4.9, the effect of the battery size is less pronounced for aggregated buildings.

The results present an increase on the self-consumption rate and the profitability of most of the studied sets.

5. Conclusion

The research aim of this dissertation work is to assess how the self-consumption rate changes with the increase of the aggregation and demand of dwellings and small business units, in addition to assess how profitable would it be to have a community energy storage in these conditions. Therefore, scenarios including fourteen dwellings (aggregated as a condominium), a bank, a restaurant and a hotel, were analysed . The collected data was used to optimize an algorithm for the PV-storage system which featured a PV system range depending on the consumption of the studied building/aggregation unit, and a storage system defined as a ratio from 0 to 2 kWh/kWp.

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.

In general, the aggregation of different residential and commercial units reflect an increase on the self-consumption rate. The result shows that single sites feature lower self-consumption and higher self-sufficiency and less interesting economic value than aggregated units. The hotel is the exception to this premiss as, by itself, it achieves a high level of self-consumption, up to 90%, depending on the storage capacity. This result is achieved because of the consumption profile of the hotel, with typically high consumption during the day. Aggregation units may overcome the 90% barrier for self-consumption in a number of situations, depending on the storage capacity.

The results of this study also indicate that even without batteries, self-consumption rates of photovoltaic systems increase with aggregation as the excess energy point is higher for aggregated units.

Self-sufficiency degree suffers a negative and a less pronounced effect caused by aggregation of users. As mentioned before, this parameter is crucial for off-grid configuration. Since this issue is not approached in this the study, it was considered as secondary.

The results show that the restaurant, or any aggregation including the restaurant, hardly returns the investment. All other system configurations feature positive internal rates of return, with some being higher than 5%, proving again the benefits of aggregation as it leads to higher returns. We can conclude that all other photovoltaic systems without batteries are viable. As expected, as the storage capacity decreases it is possible to observe an increase on the economic interest of the system.

The values of payback period underline the conclusions from the analysis of the internal rate of return. All buildings and aggregated units, except for the restaurant, feature values between 8 to 18 years, with lower values for aggregation units and with a minimum for the no-battery configuration.

Typically, aggregation allows to increase the self-consumption and the internal rate of return and lower payback period. Although, it is necessary to analyse the consumption of the building unit to assess if it is in fact favourable to a PV system. As expected, PV-storage systems feature better results when the match between consumption and photovoltaic generation is higher, revealing higher self-consumption, self-sufficiency, internal rate of return and lower payback time periods.

One of the current problems of the increasing PV system penetration is the impact that excess energy production has on the grid. Managing surplus PV generation can cause problems and extra cost to the grid, making aggregation with PV-storage systems a viable interesting solution. Increasing internal rates of return and decreasing payback periods, are incentives to increase the penetration of photovoltaic without increasing cost to the grid nor to the consumer. This will enhance penetration of battery storage systems which otherwise could only occur when and if batteries have their price significantly reduced.

Currently batteries are still too expensive to be a viable solution.

Regarding the portuguese law for renewables, these results recommend 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.

The are several limitations within this study: some of the provided data had a considerable percentage of error and missing data. Although unlikely, the analyses of the restaurant may be undervalued due to the lack of data (there was only data for half a year as discussed in Section 3.2.1). The analysed data, for the commercial and residential sectors, are specific cases and may not form a representative sample. Aspects such as the solar irradiance on the exact location and the available space in the buildings units were not considered.

There is still a gap in legal framework regarding the implementation of storage systems, as a single or a community user, and sharing generated photovoltaic electricity. There is also a lack of financial support solutions to invest in renewable energy solution such as the one studied in this dissertation. This would encourage residential (dwellings and condominiums) and commercial units to install.

It is also noteworthy that the resolution of 15 minutes only gives us a partial view on how the electricity consumption will be, which means, there will be over and sub estimation of the energy consumption. In fact Beck et al studied the influence of different time resolutions would have on the self-consumption rate [28]. For a set of 25 different households in Germany, a 15 resolution would overestimate the rate of self-consumption with a relative error up to 10% depending on the analysed dwelling and its consumption (higher values would lead to a higher relative error). This values were calculated assuming a comparison with a time resolution of 10 seconds, which it is assumed to correspondent to the real load.

In an overall analysis the aggregation of building units from commercial and residential sectors are an advantage for the prosumers, as well as the installations of battery storage systems.

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6. Annex

6.1 Annex A: Electrical devices load

Table 6.1: Electrical devices load [35].

Electrical device	Power range[kW]
Illumination (Ten 50W DC incandescent)	0.5
Iron	1
Air dryer	0.5-2.5
Television	0.02-0.2
Freezer	0.2
Fridge	0.2
Washing machine	2.5
Dishwasher	3
Microwave	1
Computer	0.25
Electric cooker	5
Oven	2
Oil Filled Radiator	2

6.2 Annex B: Powerwall 2 datasheet

POWERWALL 2 AC

The Tesla Powerwall is a fully-integrated AC battery system for residential or light commercial use. Its rechargeable lithium-ion battery pack provides energy storage for solar self-consumption, load shifting and backup power.

Powerwall's electrical interface provides a simple connection to any home or building. Its revolutionary compact design achieves market-leading energy density and is easy to install, enabling owners to quickly realize the benefits of reliable, clean power.

PERFORMANCE SPECIFICATIONS

AC Voltage (Nominal)	208 V, 220 V, 230 V, 277 V, 100/200 V, 120/240 V
Feed-In Type	Single & Split-Phase
Grid Frequency	50 and 60 Hz
AC Energy[1]	13.2 kWh
Real Power, max continuous[2]	5 kW (charge and discharge)
Real Power, peak (10 s)[2]	7 kW (discharge only)
Apparent Power, max continuous[2]	5.8 kVA (charge and discharge)
Apparent Power, peak (10 s)[2]	7.2 kVA (discharge only)
Imbalance for Single-Phase Loads	100%
Power Factor Output Range	+/– 1.0 adjustable
Power Factor (full-rated power)	+/– 0.85
Depth of Discharge	100%
Internal Battery DC Voltage	50 V
Round Trip Efficiency[1,3]	89.0%
Warranty	10 years

[1] Values provided for 25°C (77°F), 3.3 kW charge/discharge power.
[2] Values region-dependent.
[3] AC to battery to AC, at beginning of life.

ENERGY GATEWAY SPECIFICATIONS

User Interface	Tesla App
Connectivity	Wi-Fi, Ethernet, 3G
AC Meter	Revenue grade
Operating Modes	Support for wide range of usage scenarios
Backup Operation	Optional automatic disconnect switch
Modularity	Supports up to 9 AC-coupled Powerwalls

ENVIRONMENTAL SPECIFICATIONS

Operating Temperature	–20°C to 50°C (–4°F to 122°F)
Storage Temperature	–30°C to 60°C (–22°F to 140°F)
Operating Humidity (RH)	Up to 100%, condensing
Maximum Altitude	3000 m (9843 ft)
Environment	Indoor and outdoor rated
Enclosure Type	NEMA 3R
Ingress Rating	IP67 (Battery & Power Electronics) IP56 (Wiring)
Noise Level @ 1m	<40 dBA at 30°C (86°F)

MECHANICAL SPECIFICATIONS

Dimensions	1150 mm x 755 mm x 155 mm (45.3 in x 29.7 in x 6.1 in)
Weight	122 kg (269 lbs)
Mounting options	Floor or wall mount

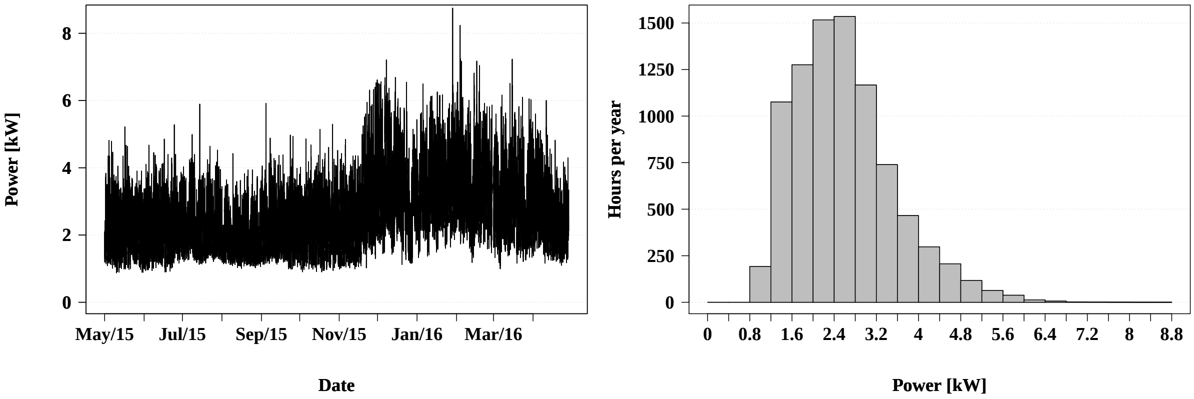
COMPLIANCE INFORMATION

Safety	UL 1642, UL 1741, UL 1973, UL 9540, UN 38.3, IEC 62109-1, IEC 62619, CSA C22.2.107.1
Grid Standards	Worldwide Compatibility
Emissions	FCC Part 15 Class B, ICES 003, EN 61000 Class B
Environmental	RoHS Directive 2011/65/EU, WEEE Directive 2012/19/EU, 2006/66/EC
Seismic	AC156, IEEE 693-2005 (high)

TESLA 2016-11-01 POWERWALL 2

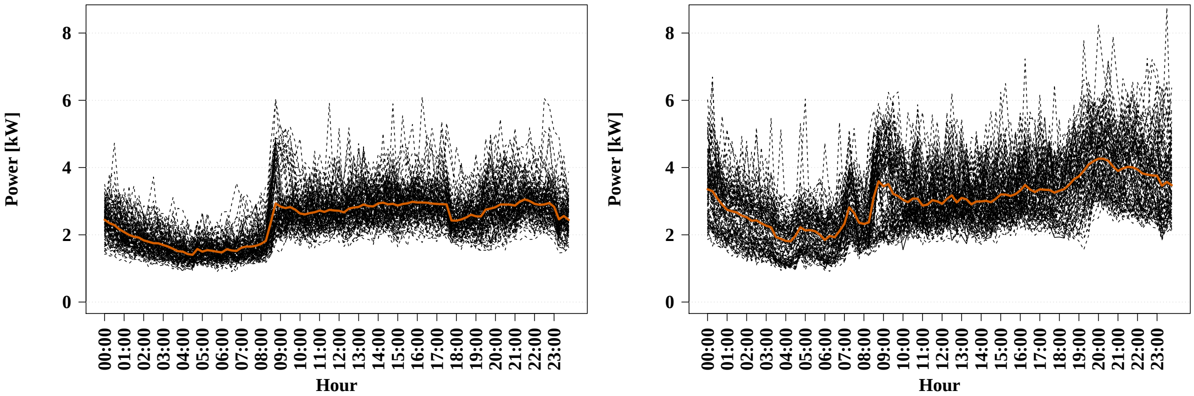
Figure 6.1: Powerwall 2 datasheet [36].

6.3 Annex C: Electricity consumption



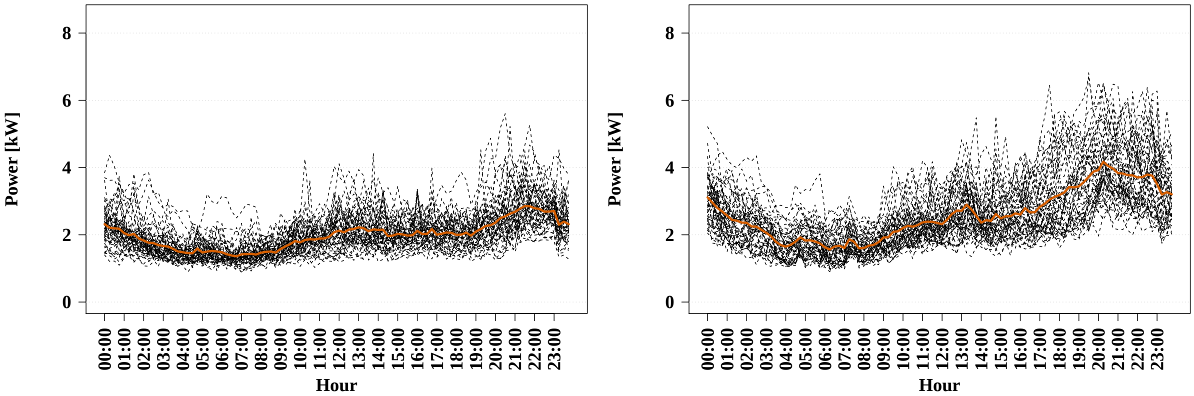
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

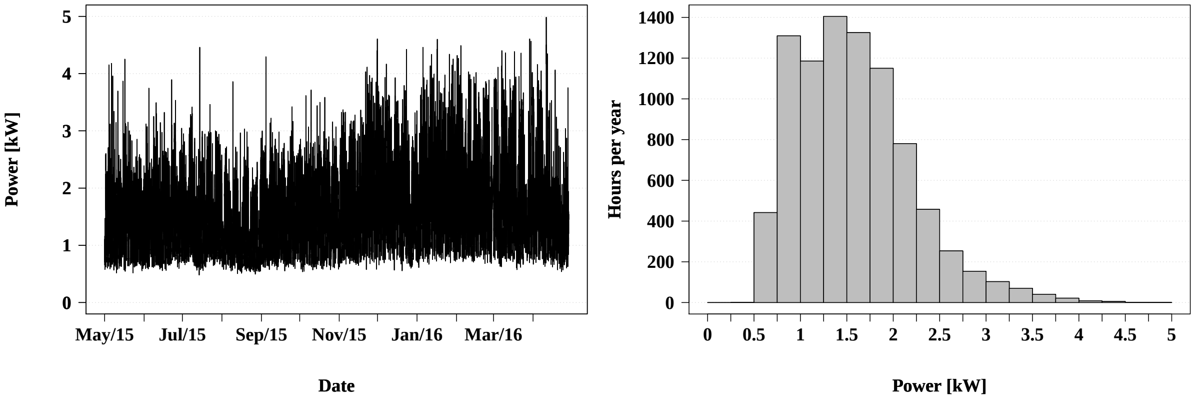
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

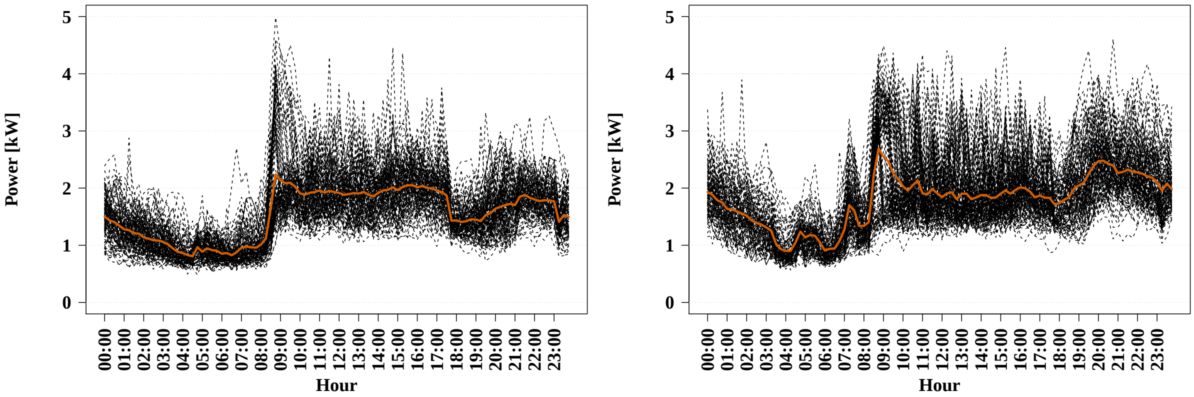
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.2: Bank and Condominium: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



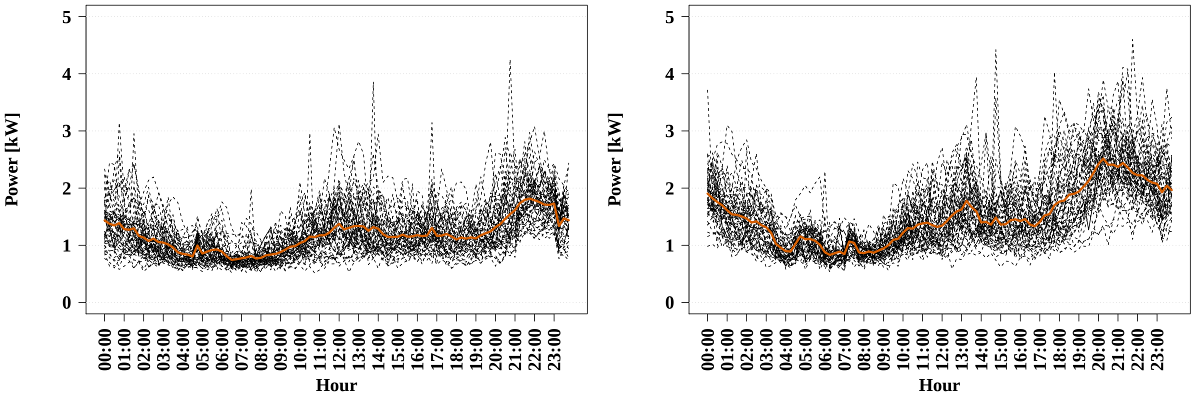
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

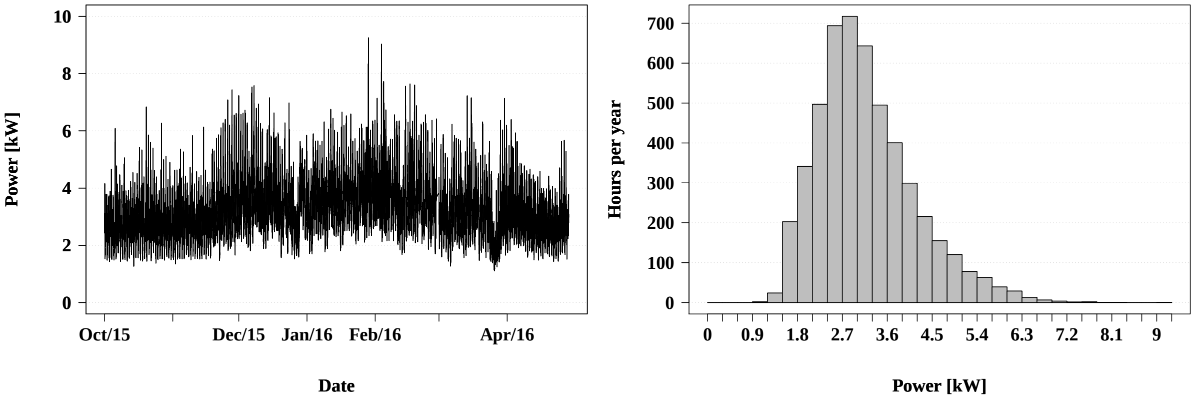
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

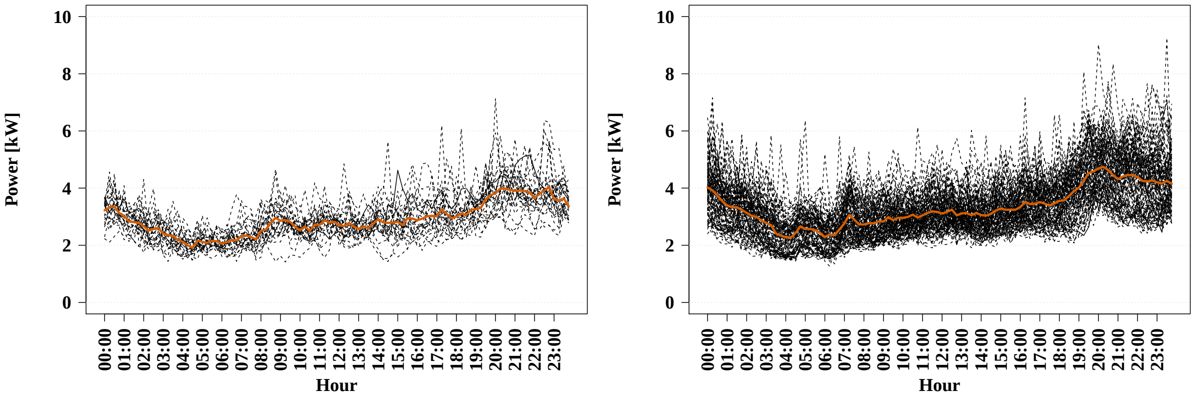
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.3: Bank and Condominium 6.9kVA: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



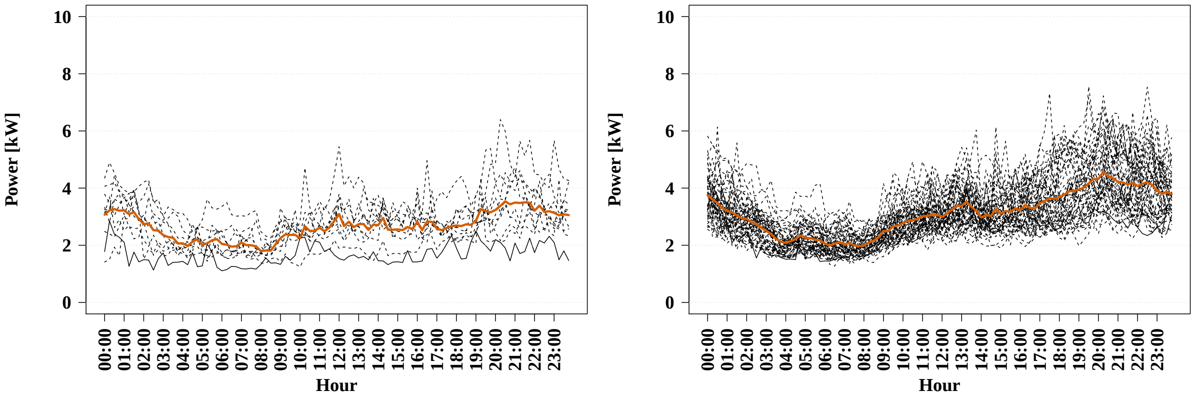
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

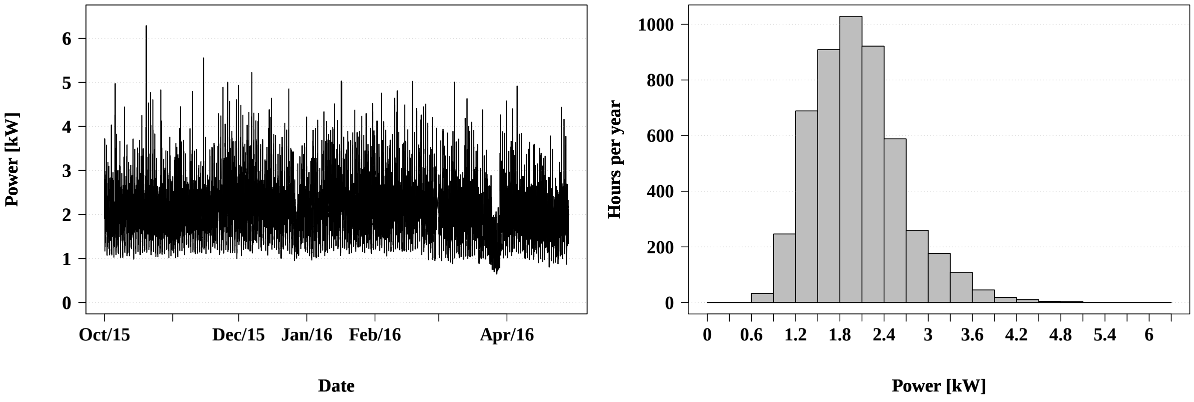
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

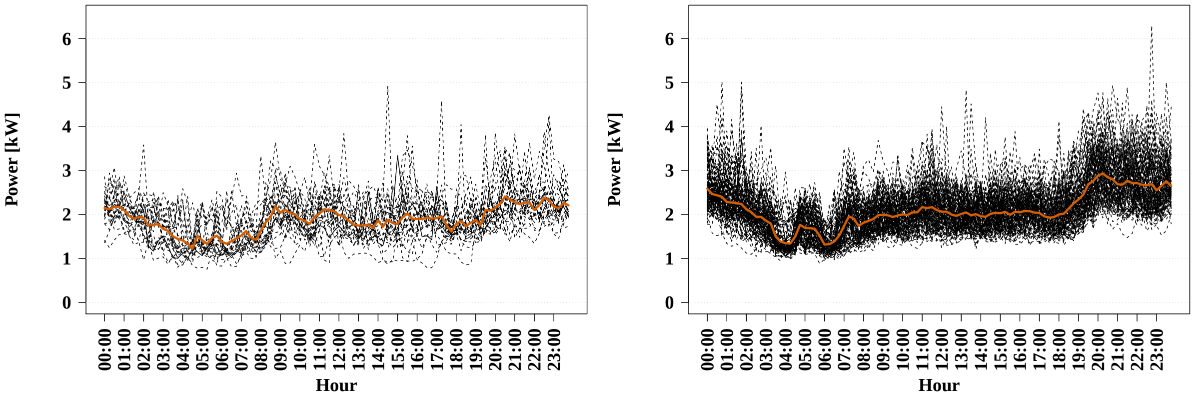
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.4: Restaurant and Condominium: (a) Energy consumption during six months; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



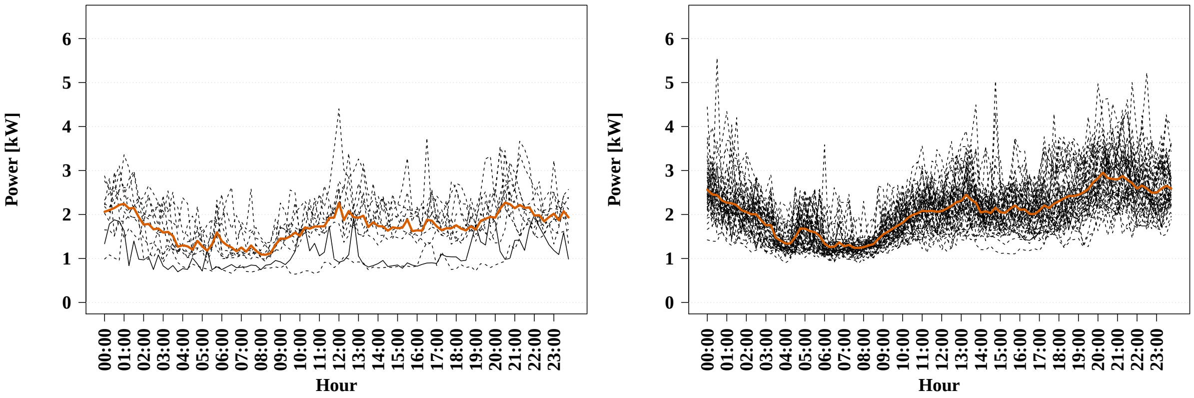
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

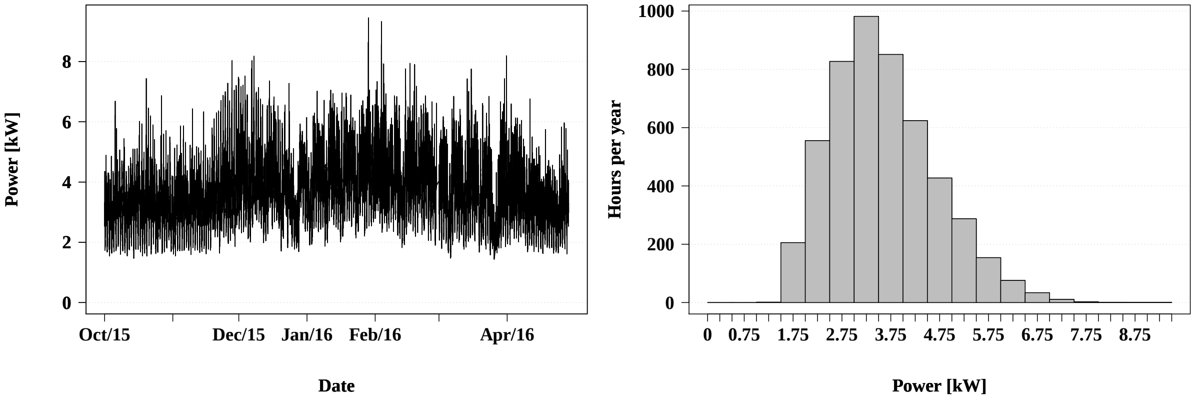
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

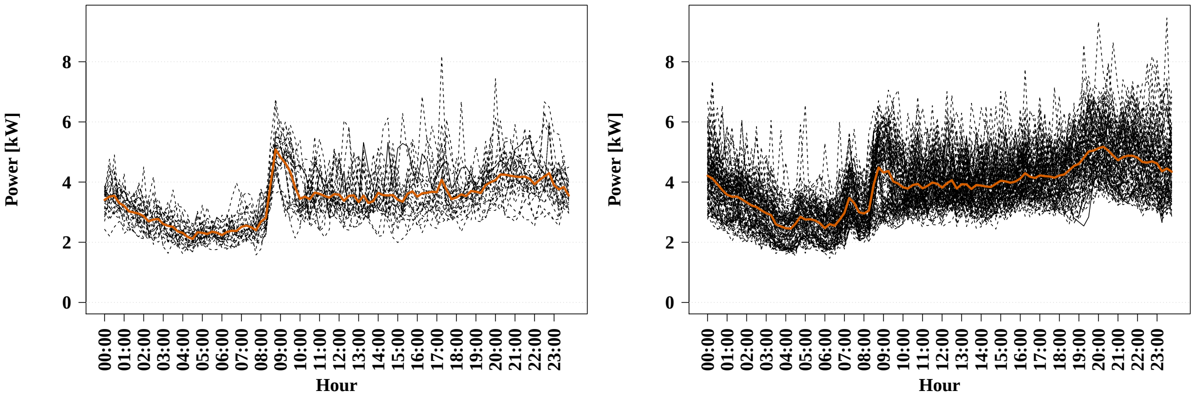
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.5: Restaurant and Condominium 6.9kVA: (a) Energy consumption during six months; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



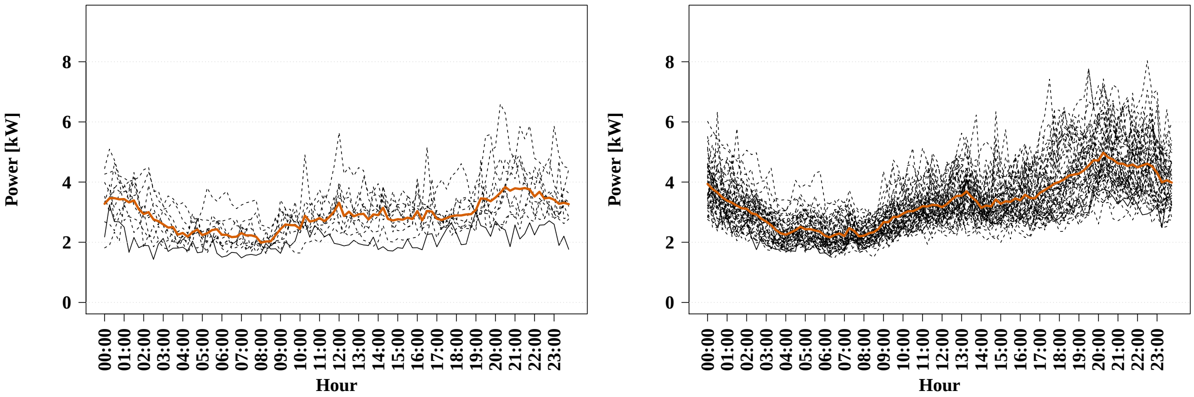
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

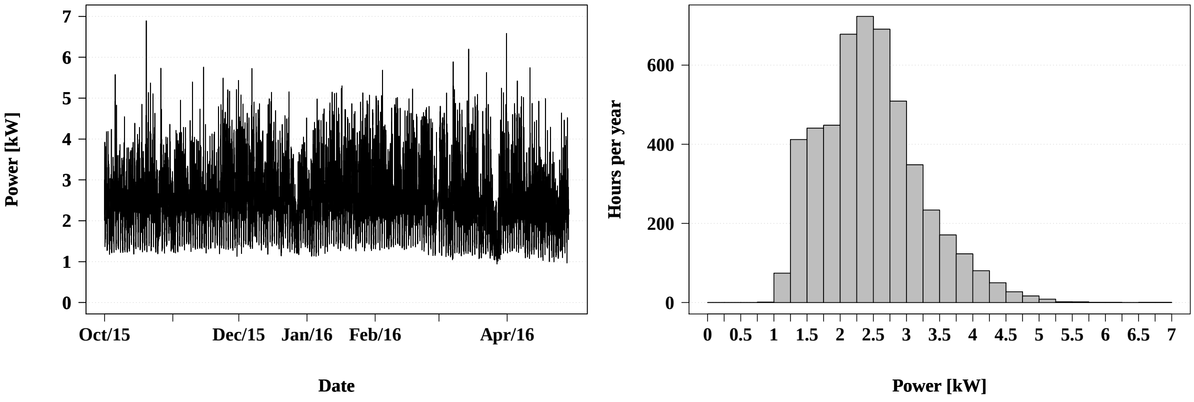
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

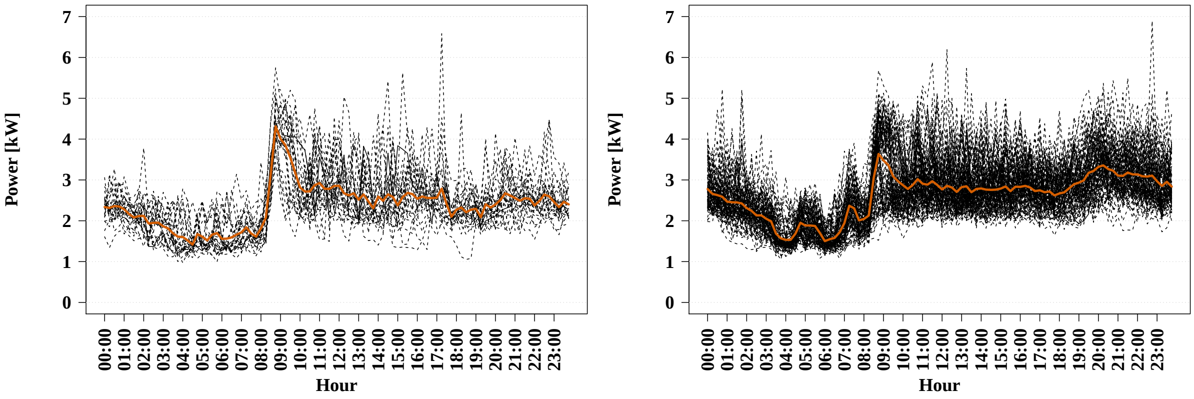
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.6: Bank, Restaurant and Condominium: (a) Energy consumption during six months; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



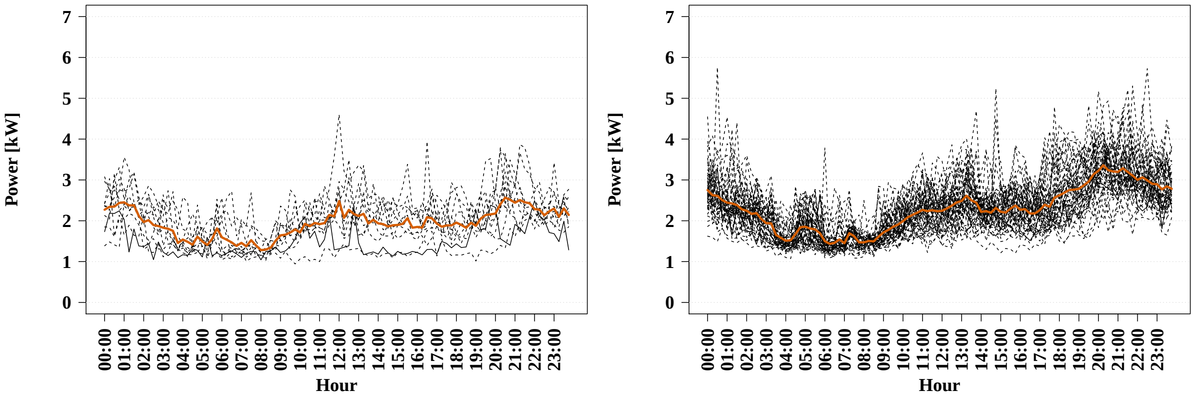
(a) Annual consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

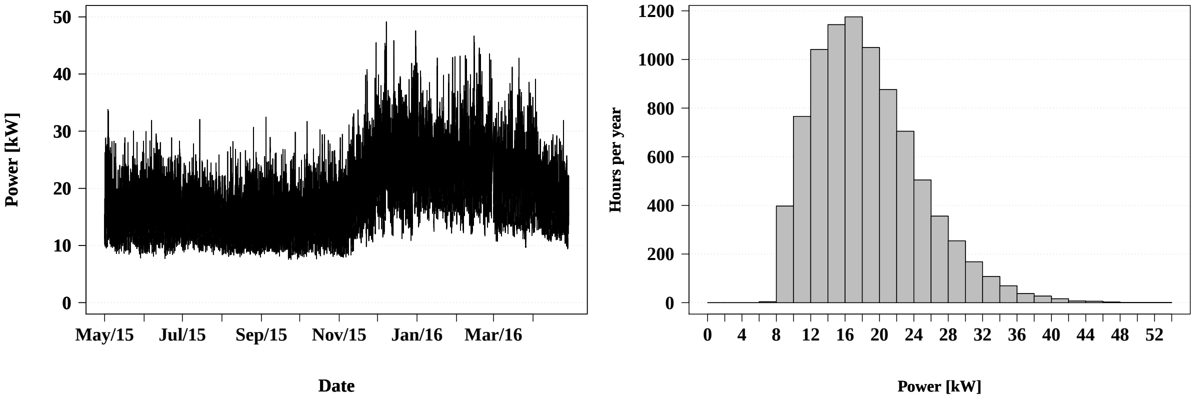
(d) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

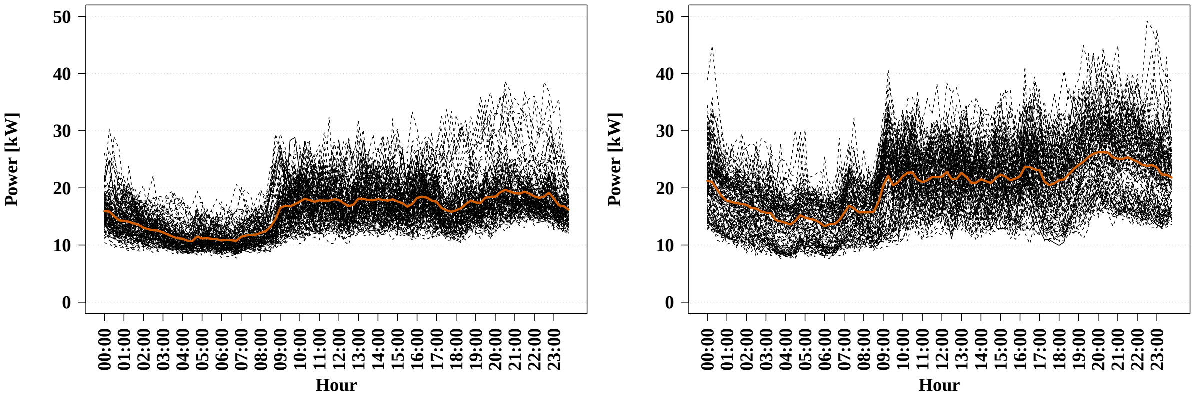
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.7: Bank, Restaurant and Condominium 6.9kVA: (a) Energy consumption during six months; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



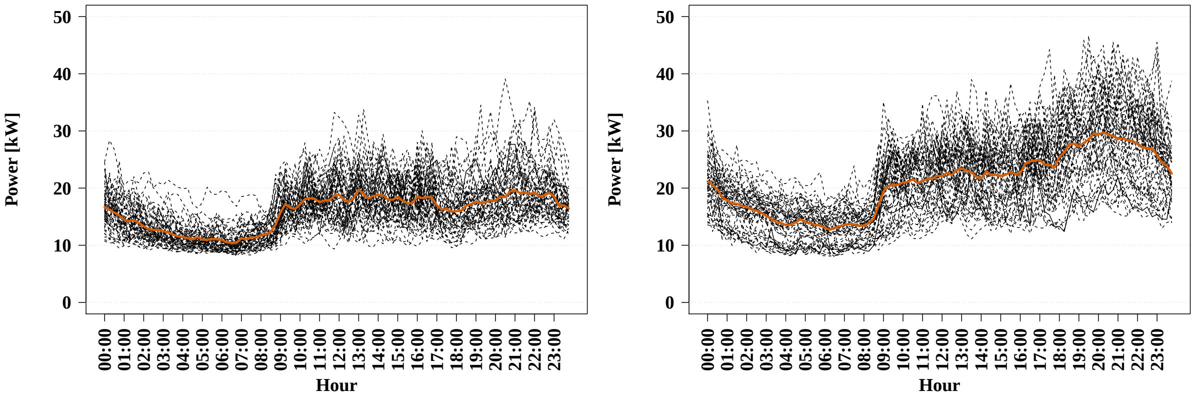
(a) Annual energy consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

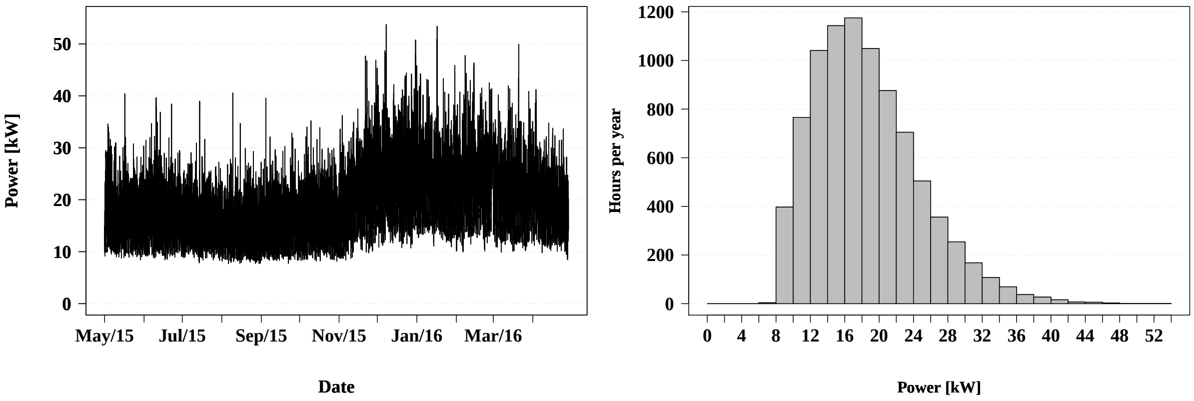
(d) Power consumption(dashed lines) and average power consumption (solid line) of all weekdays in winter



(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

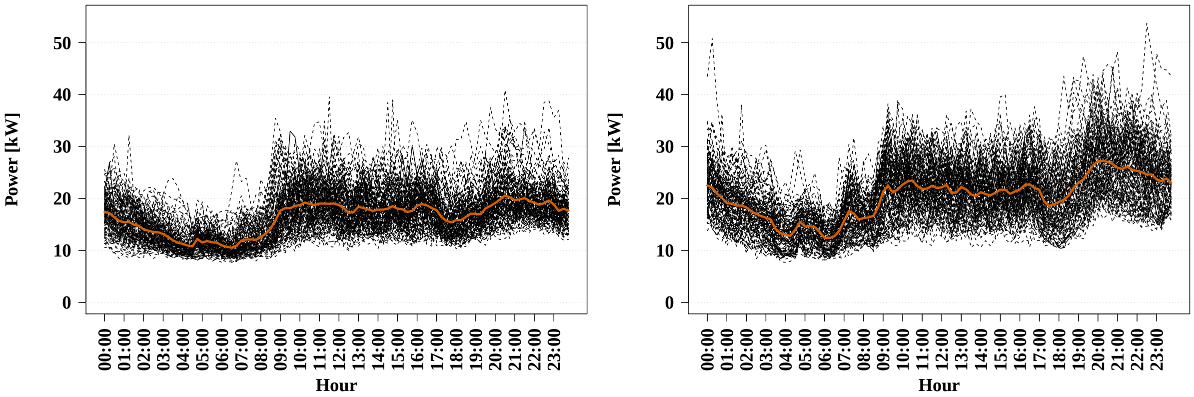
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.8: Condominium and Hotel: (a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.



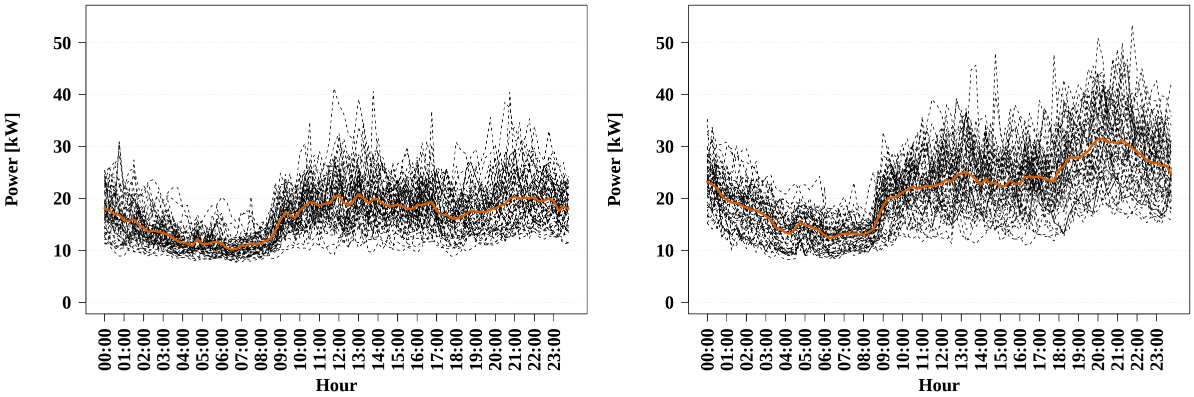
(a) Annual energy consumption

(b) Histogram of the consumed power



(c) Power consumption (dashed lines) and average power consumption (solid line) of all weekdays in summer

(d) Power consumption(dashed lines) and average power consumption (solid line) of all weekdays in winter

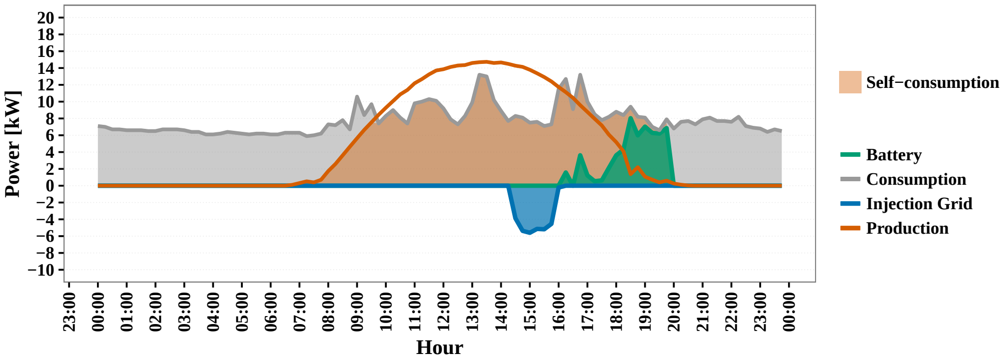


(e) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in summer

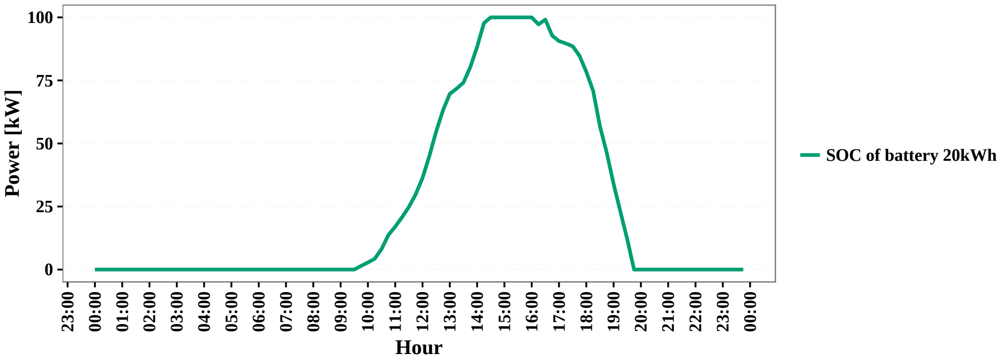
(f) Power consumption (dashed lines) and average power consumption (solid line) of all weekends in winter

Figure 6.9: Condominium 6.9kVA and Hotel:(a) Annual energy consumption; (b) Histogram of consumed power; (c) Power consumption and average of weekdays in summer; (d) Power consumption and average of weekdays in winter; (e) Power consumption and average of weekends in summer; (f) Power consumption and average of weekends in winter.

6.4 Annex D: Load diagram

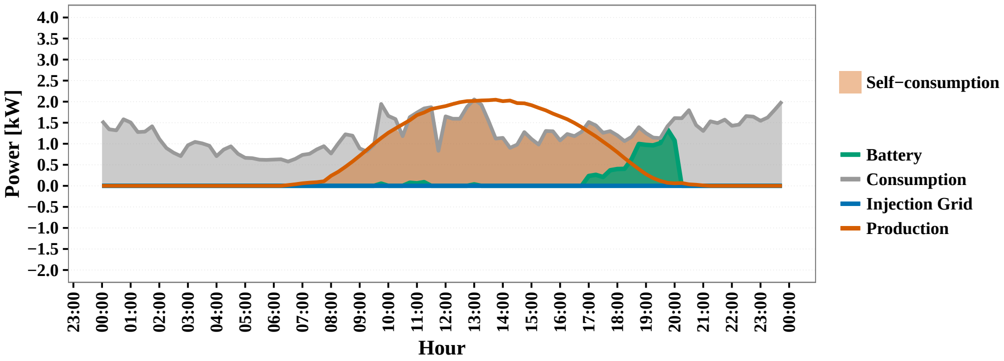


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

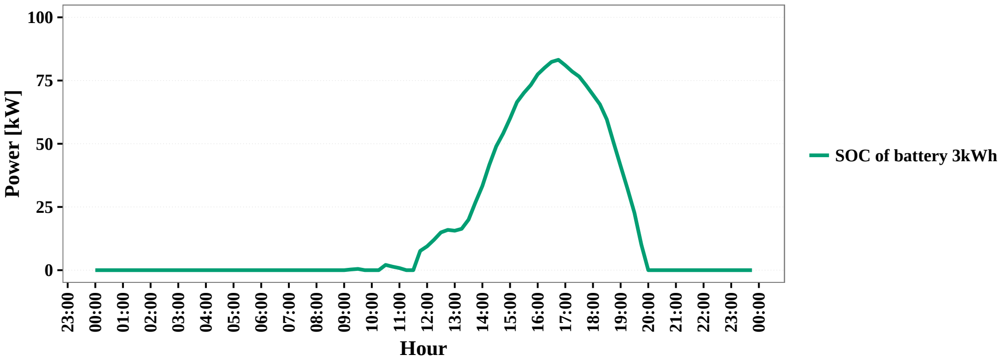


(b) Battery state-of-charge

Figure 6.10: Electrical load diagram of the Hotel: Example of a weekday during the summer with a PV installed power of 20 kWp and a battery capacity of 20 kWh (a)Electrical load diagram; (b) Battery state-of-charge.

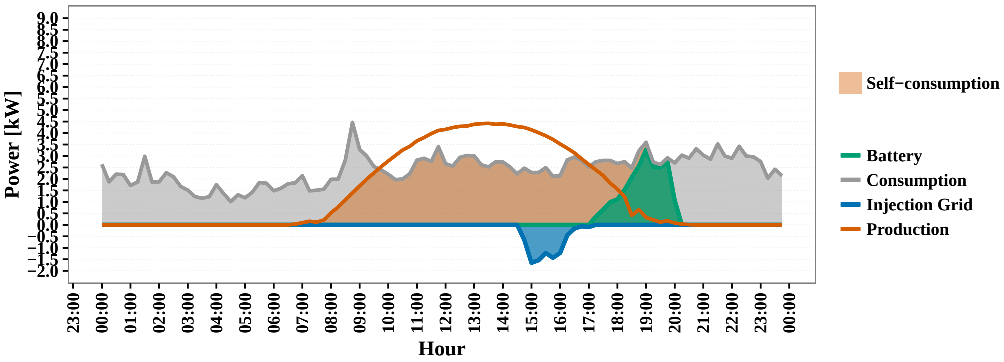


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

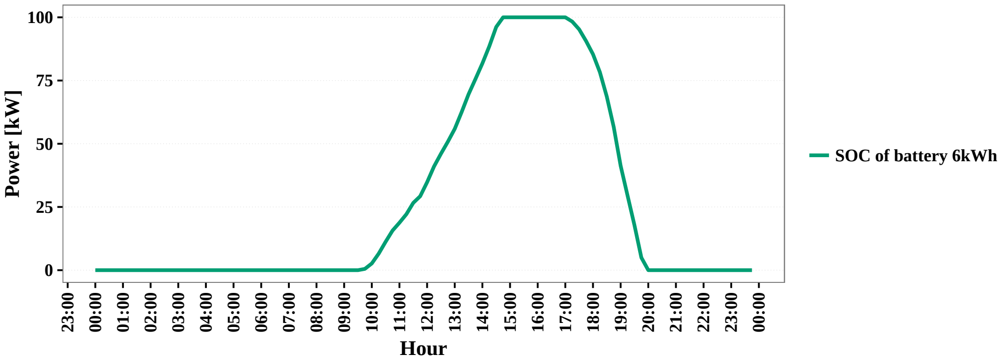


(b) Battery state-of-charge

Figure 6.11: Electrical load diagram of the Condominium 6.9kVA: Example of a weekday during the summer with a PV installed power of 3 kWp and a proportion battery capacity PV power of 1 kWh per kWp (a) Electrical load diagram ; (b) Battery state-of-charge.

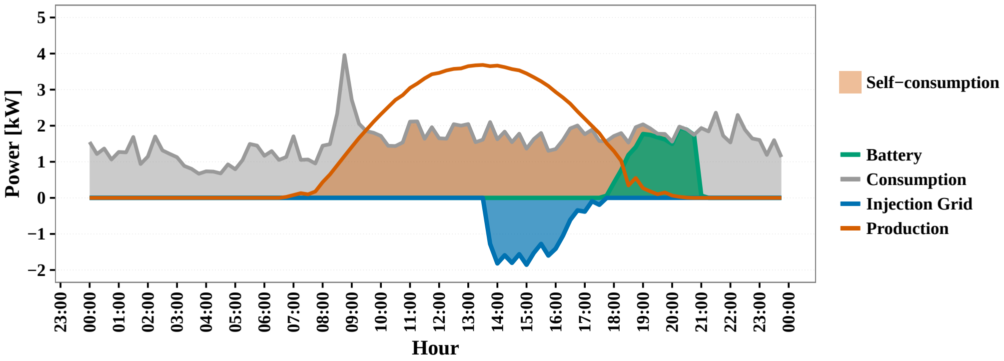


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

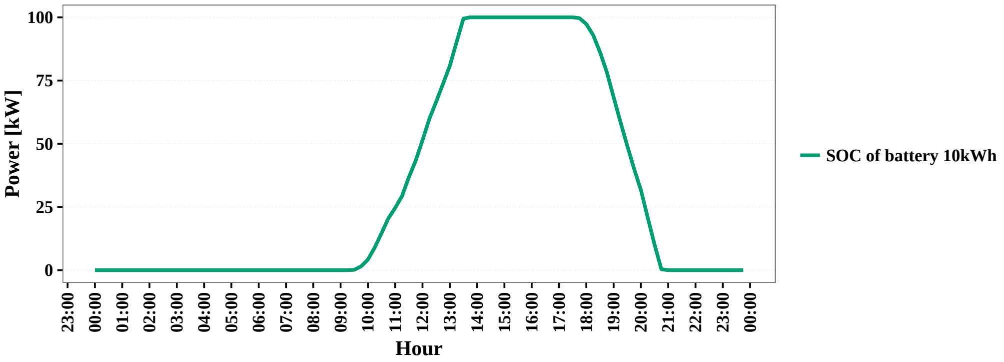


(b) Battery state-of-charge

Figure 6.12: Electrical load diagram of the aggregation Condominium and Bank: Example of a weekday during the summer with a PV installed power of 6 kWp and a proportion battery capacity PV power of 1 kWh per kWp (a) Electrical load diagram ; (b) Battery state-of-charge.

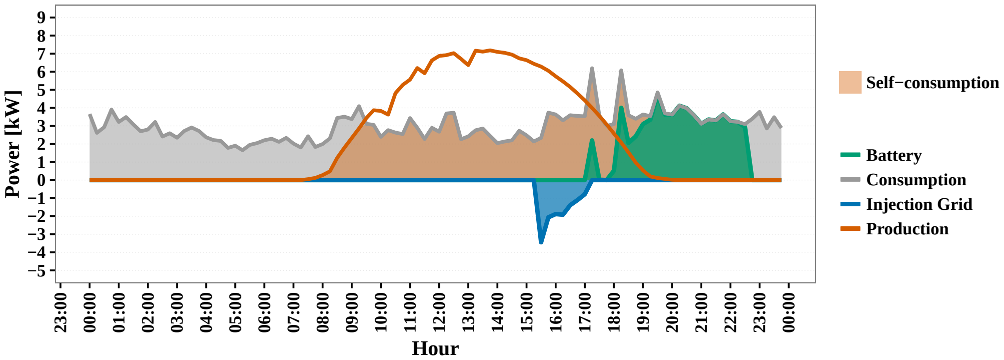


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

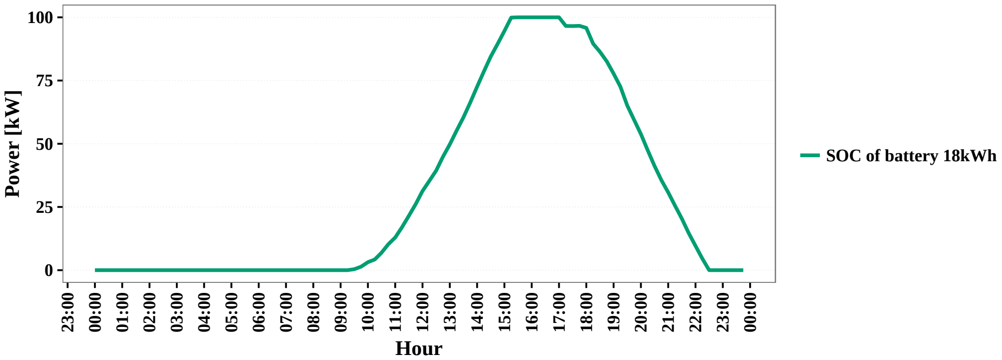


(b) Battery state-of-charge

Figure 6.13: Electrical load diagram of the aggregation Condominium 6.9kVA and Bank: Example of a weekday during the summer with a PV installed power of 5 kWp and a battery capacity of 10 kWh (a) Electrical load diagram ; (b) Battery state-of-charge.

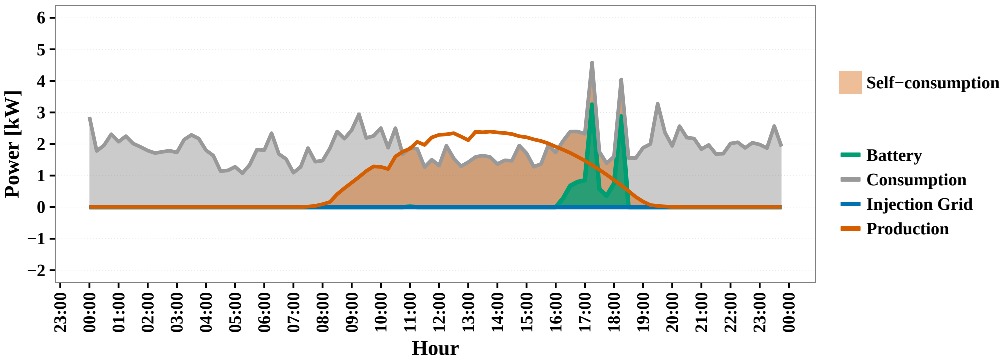


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

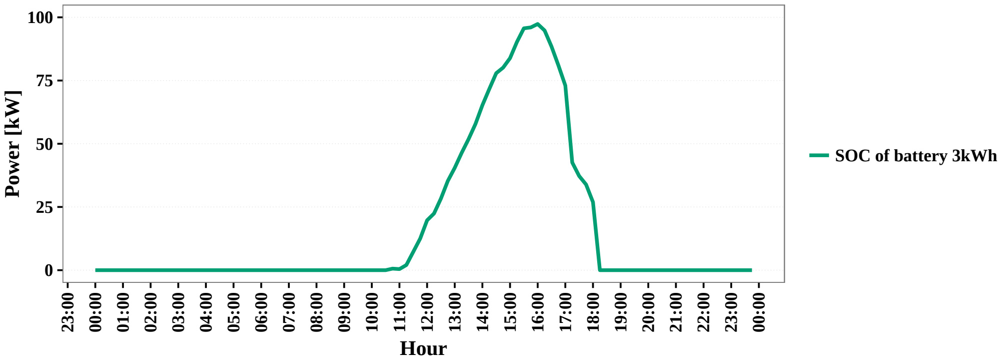


(b) Battery state-of-charge

Figure 6.14: Electrical load diagram of the aggregation Condominium and Restaurant: Example for of a weekday during the summer with a PV installed power of 9 kWp and a proportion battery capacity PV power of 2 kWh per kWp (a) Electrical load diagram ; (b) Battery state-of-charge.

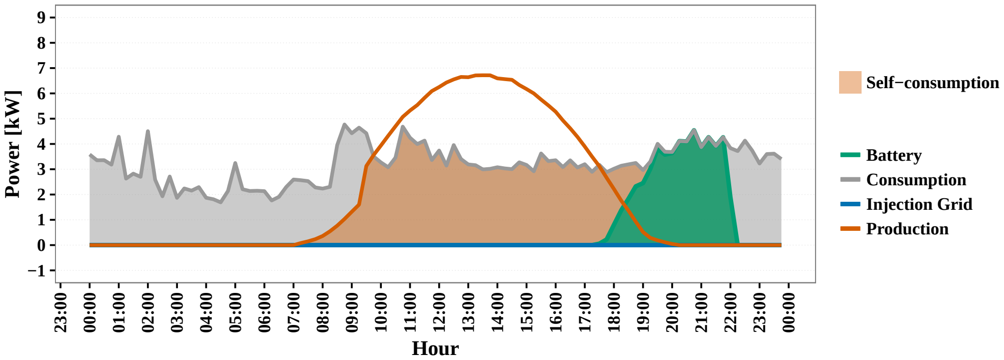


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

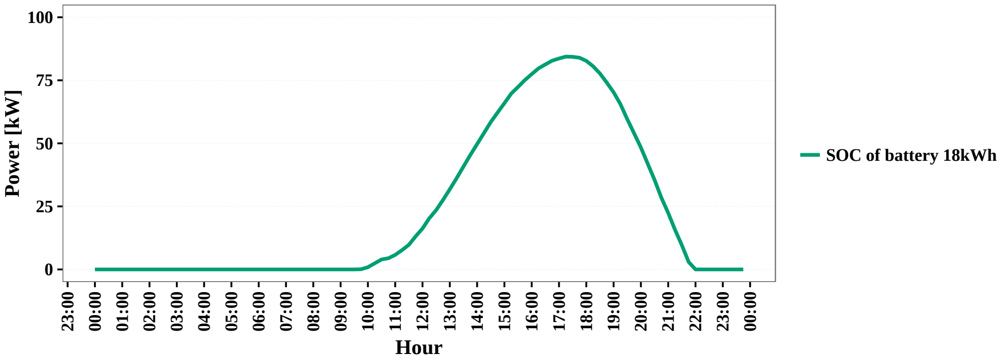


(b) Battery state-of-charge

Figure 6.15: Electrical load diagram of the aggregation Condominium 6.9kVA and Restaurant: Example of a weekday during the summer with a PV installed power of 3 kWp and a battery of 3 kWh (a) Electrical load diagram; (b) Battery state-of-charge.

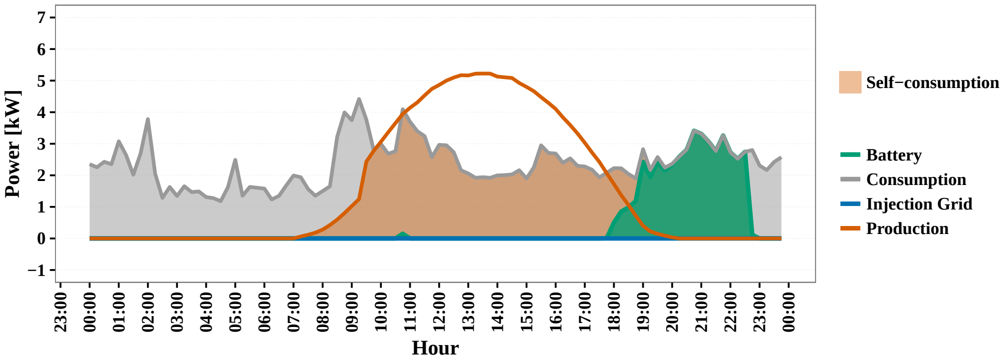


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

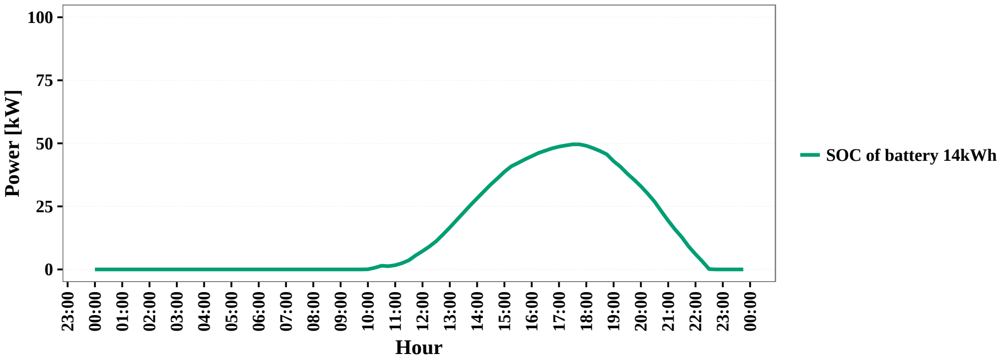


(b) Battery state-of-charge

Figure 6.16: Electrical load diagram of the aggregation Condominium, Bank and Restaurant: Example for of a weekday during the summer with a PV installed power of 9 kWp and a battery capacity of 18 kWh (a) Electrical load diagram ; (b) Battery state-of-charge.

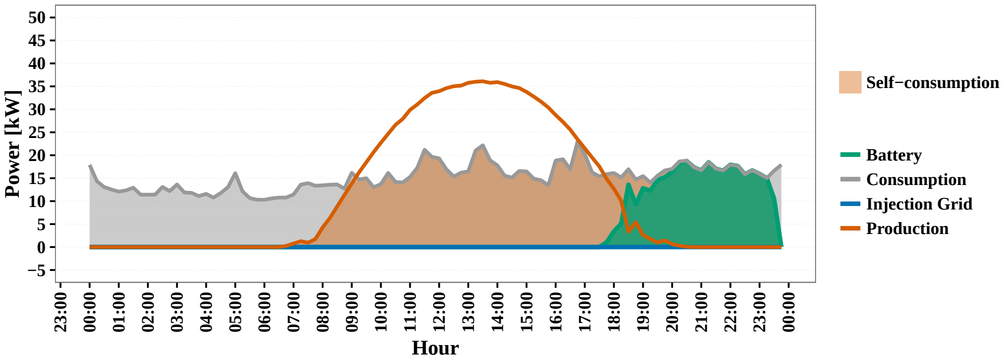


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)

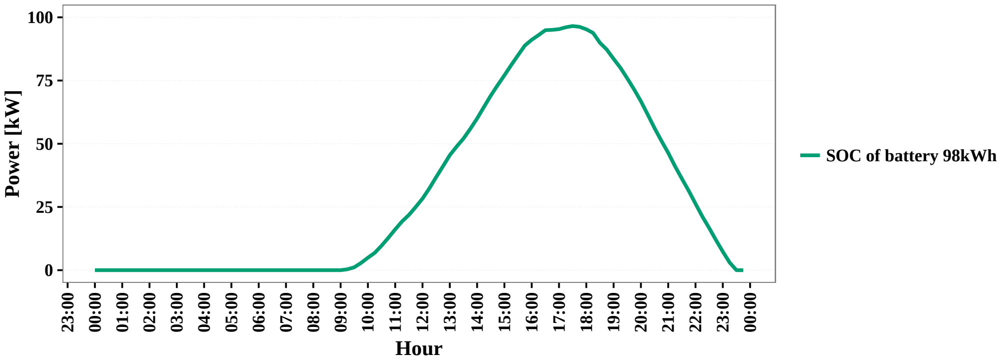


(b) Battery state-of-charge

Figure 6.17: Electrical load diagram of the aggregation Condominium 6.9kVA, Bank and Restaurant: Example of a weekday during the summer with a PV installed power of 7 kWp and a battery capacity of 14 kWh (a) Electrical load diagram ; (b) Battery state-of-charge.

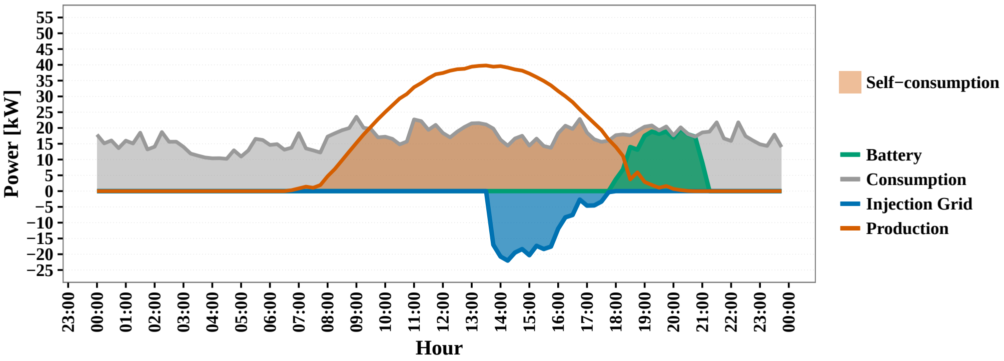


(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill) and energy supplied from the battery (green)

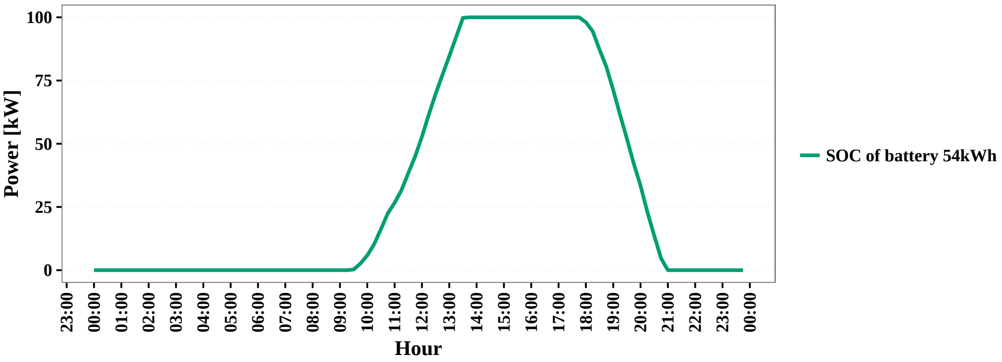


(b) Battery state-of-charge

Figure 6.18: Electrical load diagram of the aggregation Condominium and Hotel: Example of a weekday during the summer with a PV installed power of 49 kWp and a battery capacity of 98 kWh (a) Electrical load diagram ; (b) Battery state-of-charge.



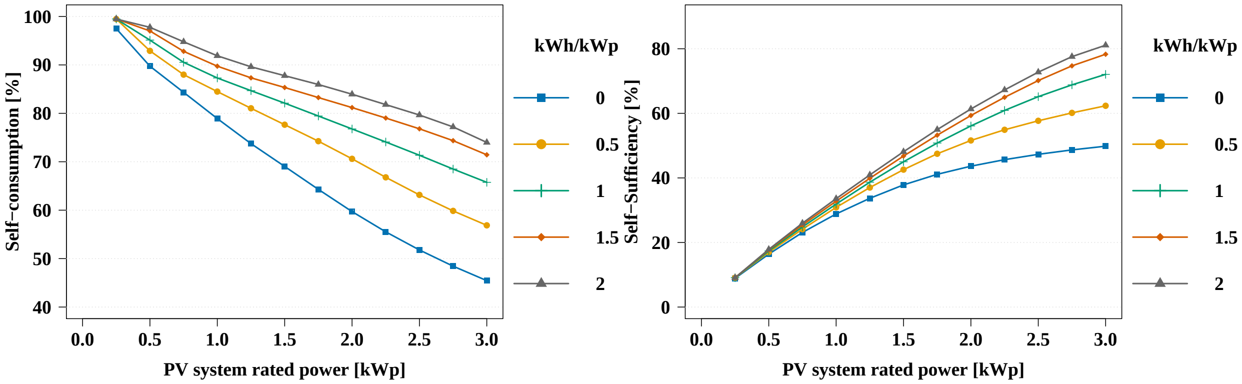
(a) Electrical load diagram (gray), PV generation (orange), energy consumed in self-consumption (pale orange fill), energy supplied from the battery (green) and enegy sold to the grid (blue)



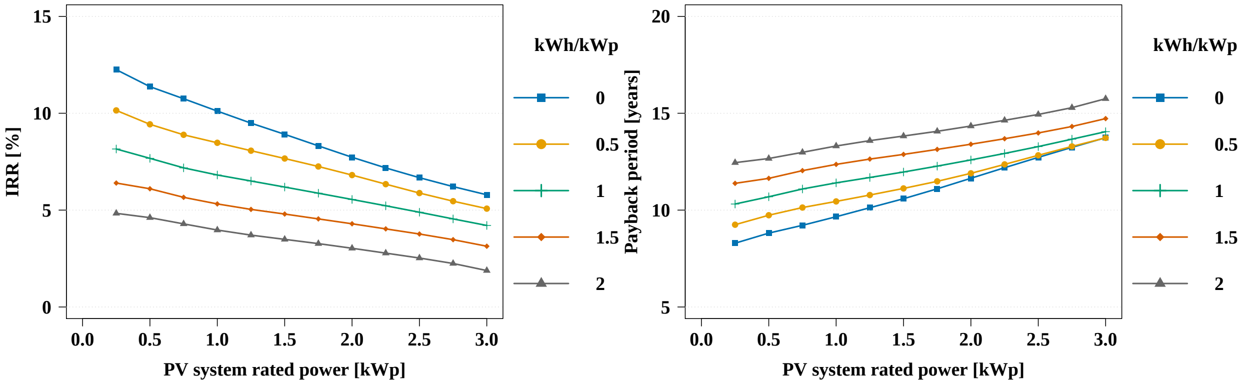
(b) Battery state-of-charge

Figure 6.19: Electrical load diagram of the aggregation Condominium 6.9kVA and Hotel: Example of a weekday during the summer with a PV installed power of 54 kWp and a battery capacity of 1 kWh (a) Electrical load diagram ; (b) Battery state-of-charge.

6.5 Annex E: Parameters

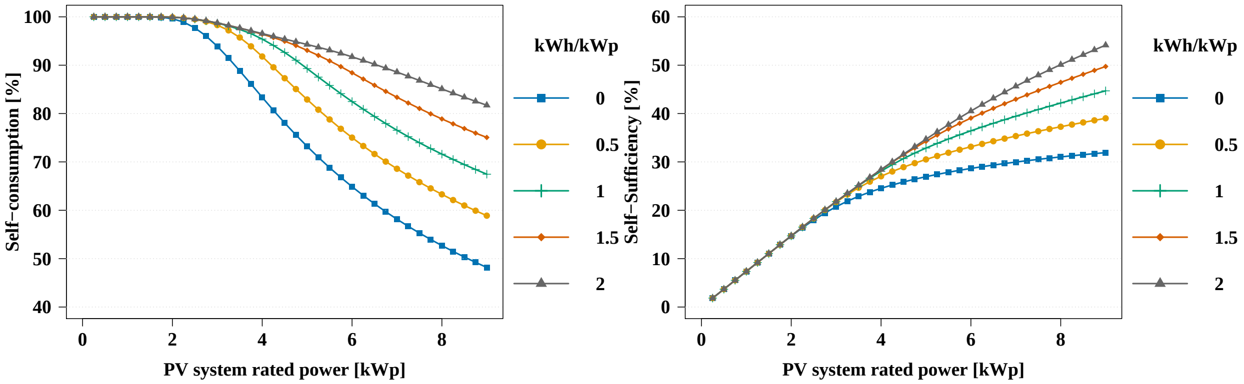


(a) Self-consumption **(b)** Self-sufficiency

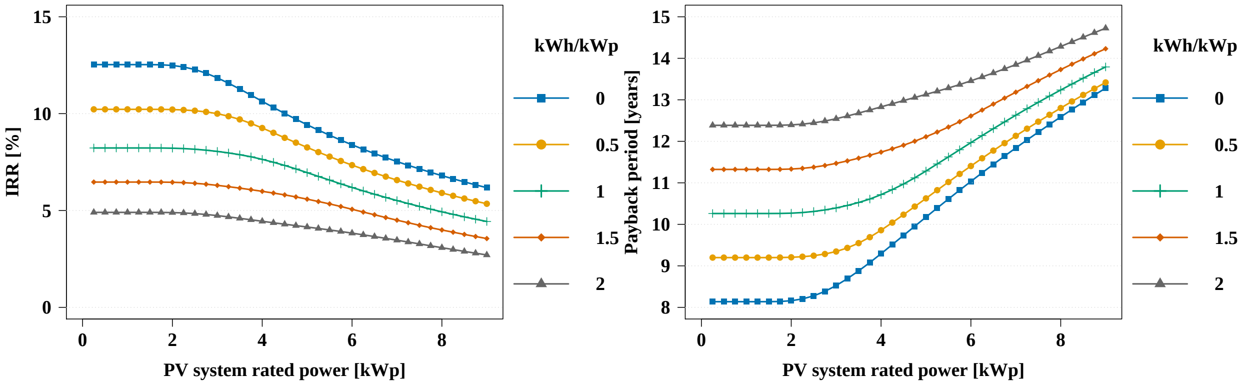


(c) IRR **(d)** Payback period

Figure 6.20: Parameters Bank: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

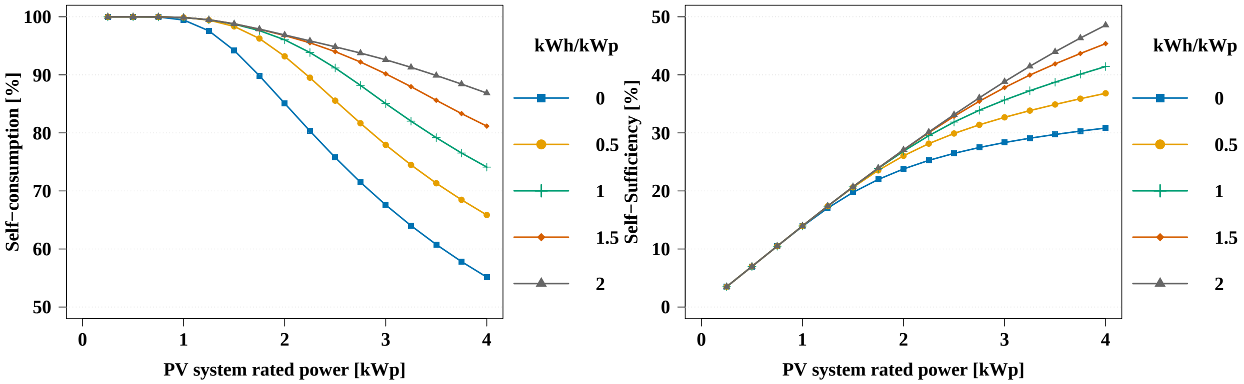


(a) Self-consumption **(b)** Self-sufficiency

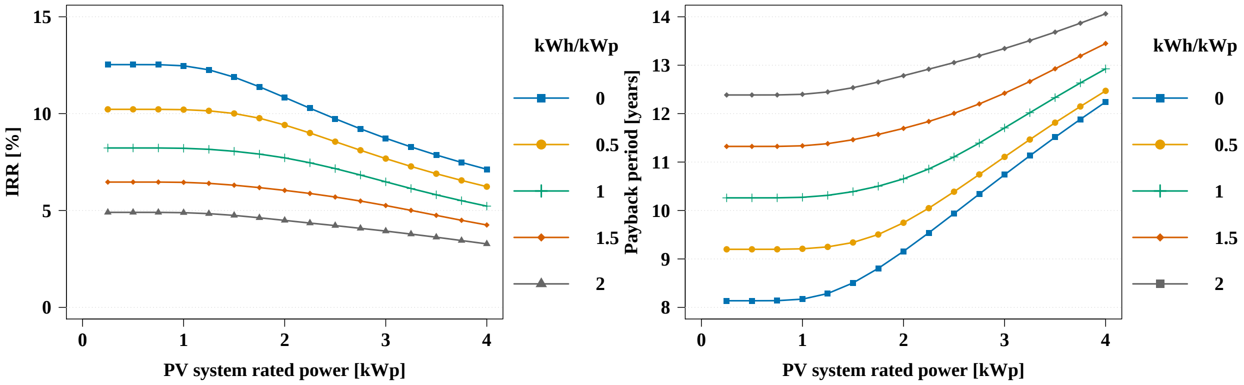


(c) IRR **(d)** Payback period

Figure 6.21: Parameters Condominium: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

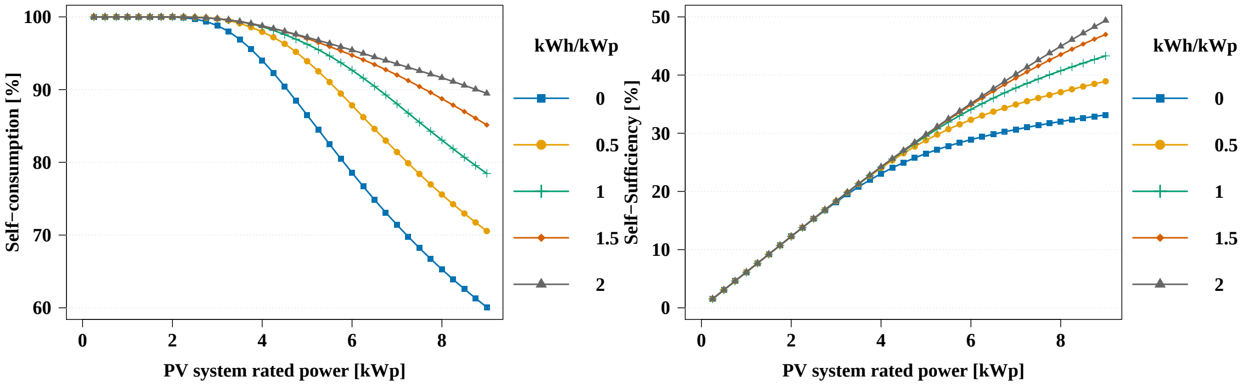


(a) Self-consumption **(b)** Self-sufficiency

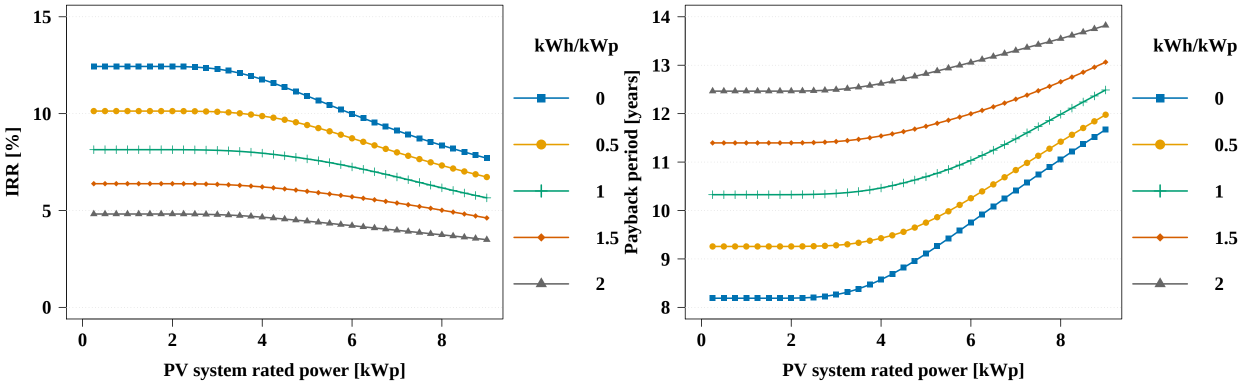


(c) IRR **(d)** Payback period

Figure 6.22: Parameters Condominium 6.9kVA: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

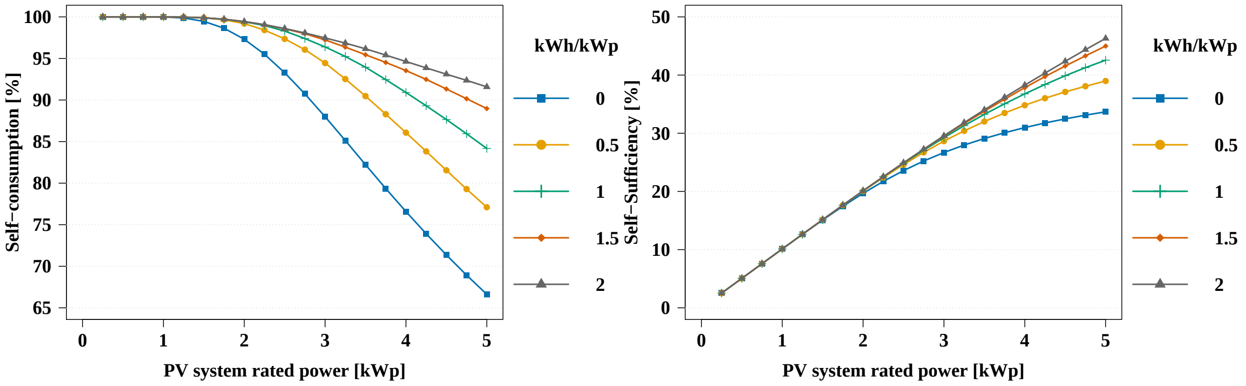


(a) Self-consumption **(b)** Self-sufficiency

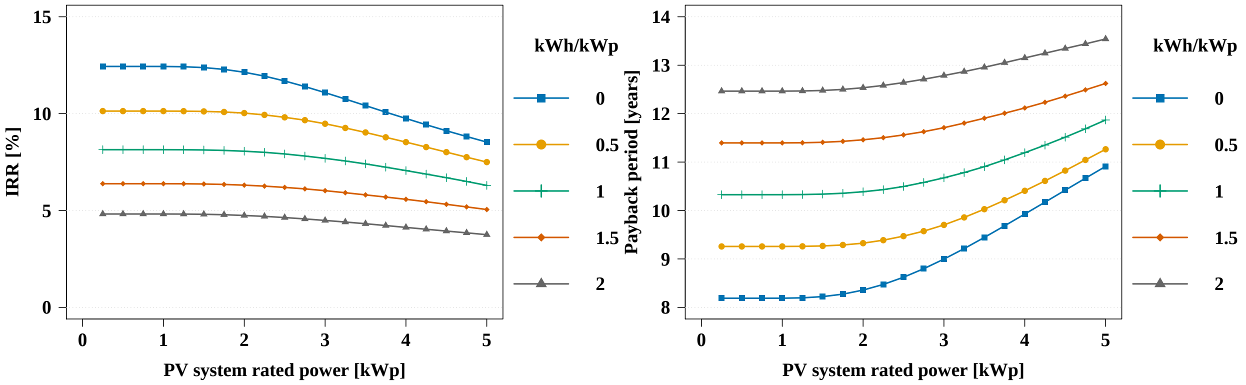


(c) IRR **(d)** Payback period

Figure 6.23: Parameters Condominium & Bank: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

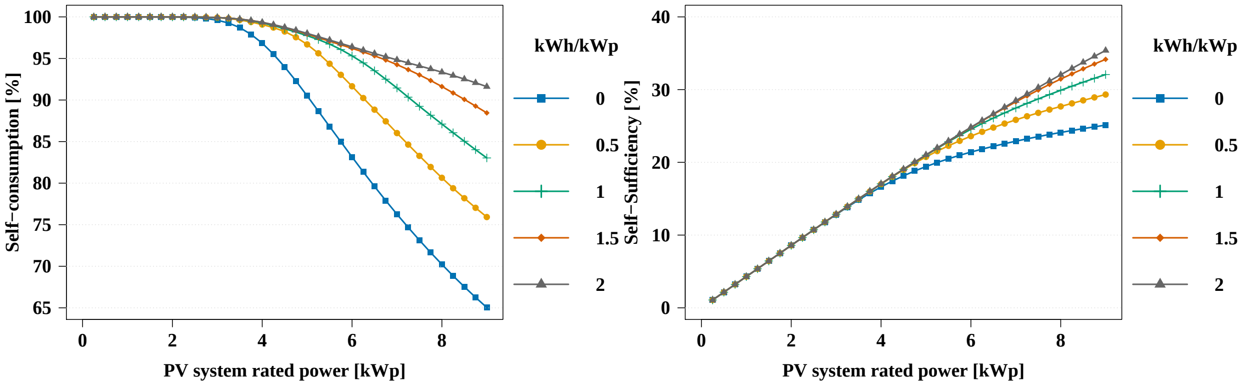


(a) Self-consumption **(b)** Self-sufficiency

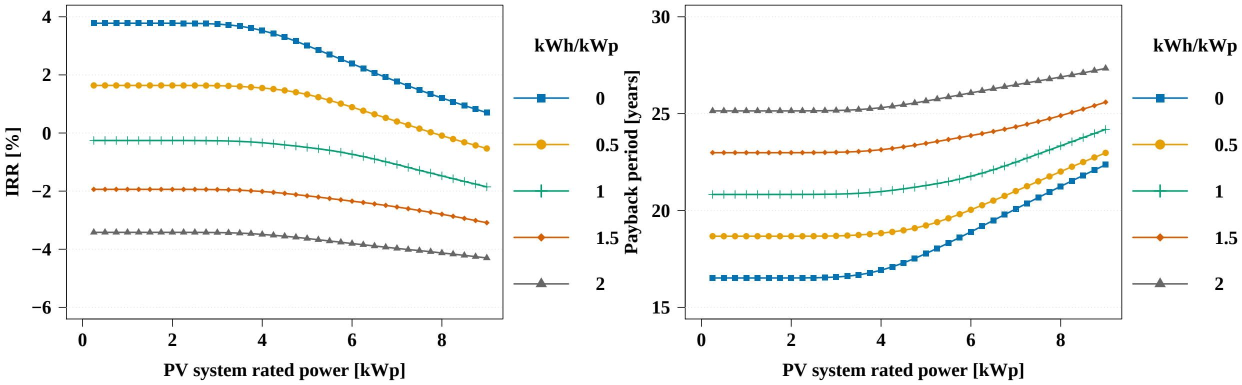


(c) IRR **(d)** Payback period

Figure 6.24: Parameters Condominium 6.9kVA & Bank: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

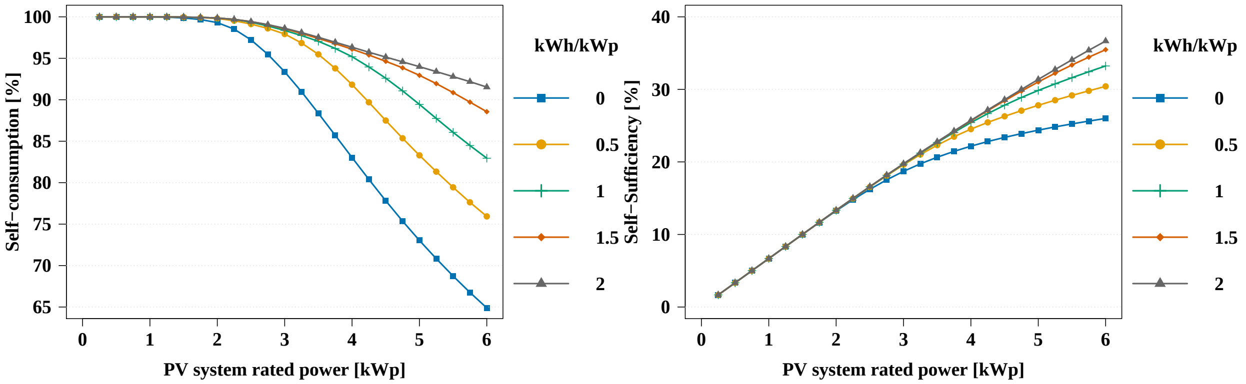


(a) Self-consumption **(b)** Self-sufficiency



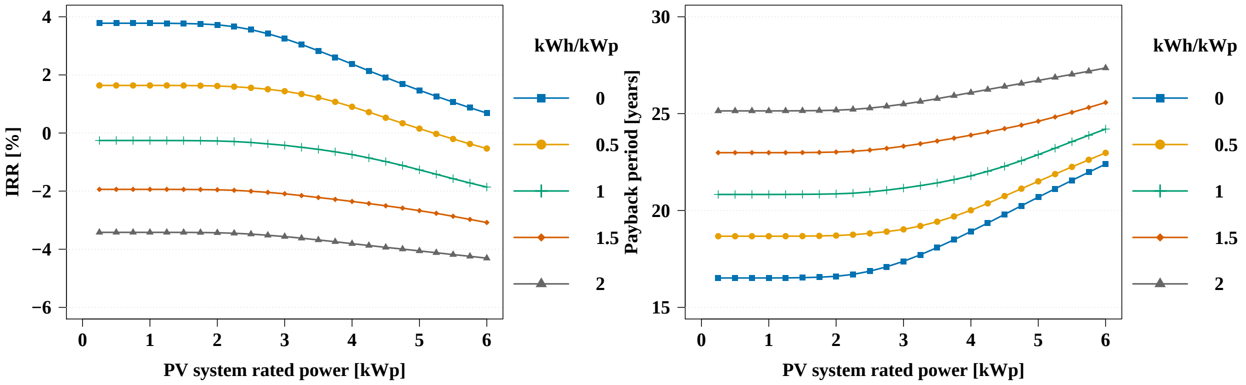
(c) IRR **(d)** Payback period

Figure 6.25: Parameters Condominium & Restaurant: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.



(a) Self-consumption

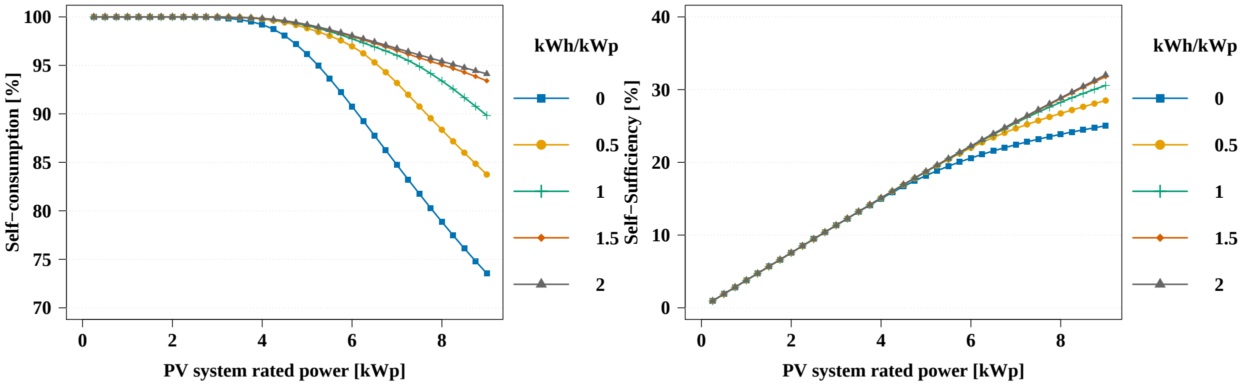
(b) Self-sufficiency



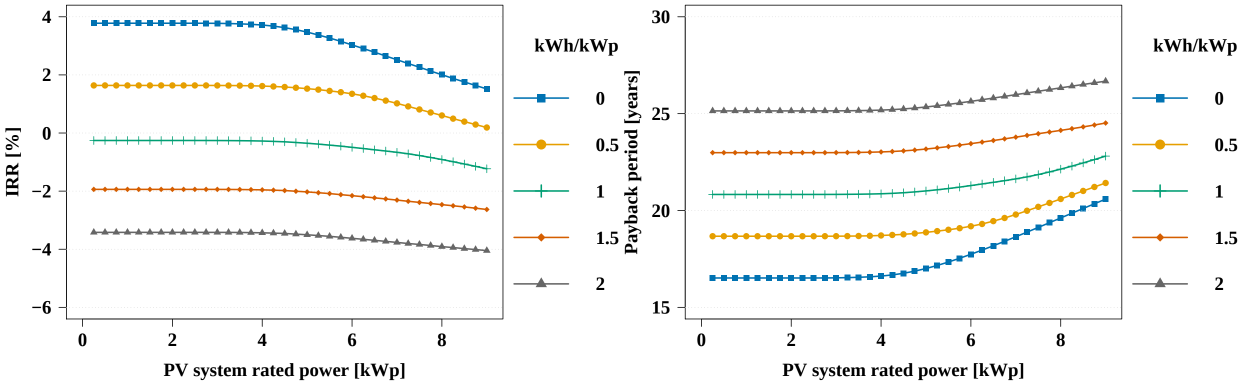
(c) IRR

(d) Payback period

Figure 6.26: Parameters Condominium 6.9kVA & Restaurant: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

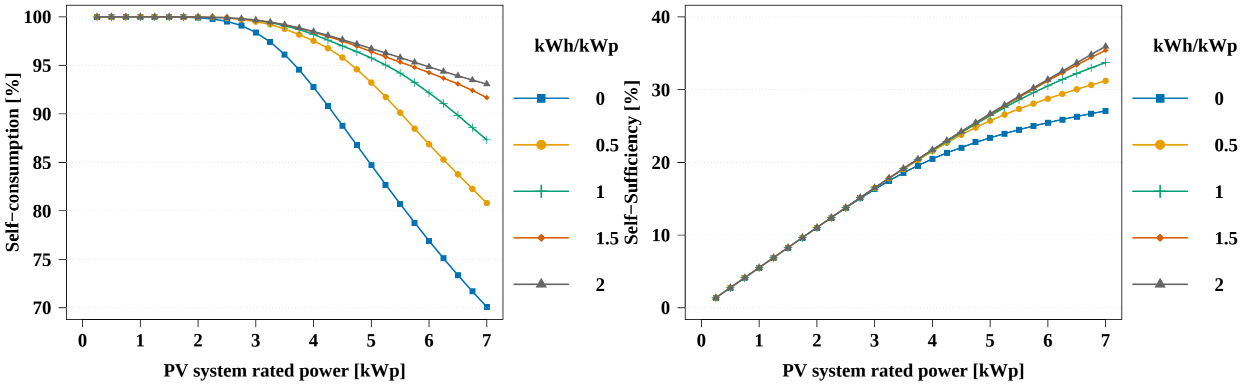


(a) Self-consumption **(b)** Self-sufficiency

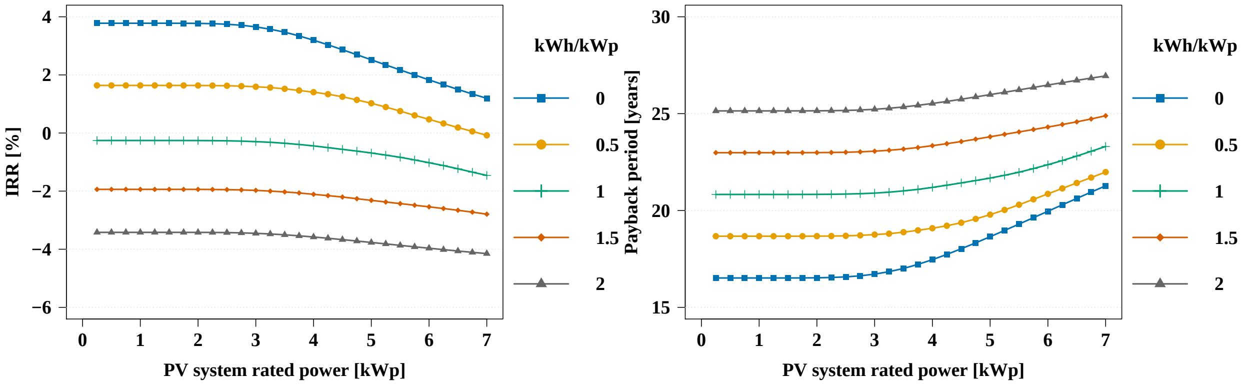


(c) IRR **(d)** Payback period

Figure 6.27: Parameters Condominium & Bank & Restaurant: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.

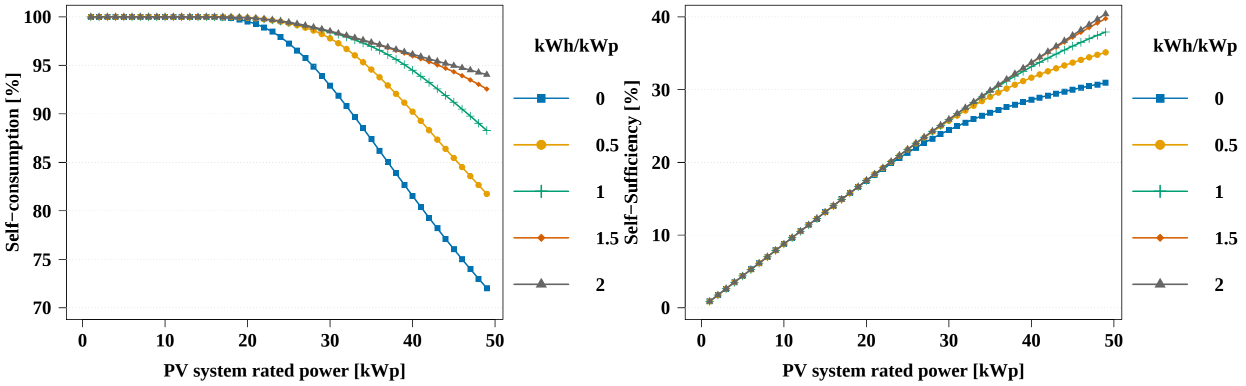


(a) Self-consumption **(b)** Self-sufficiency



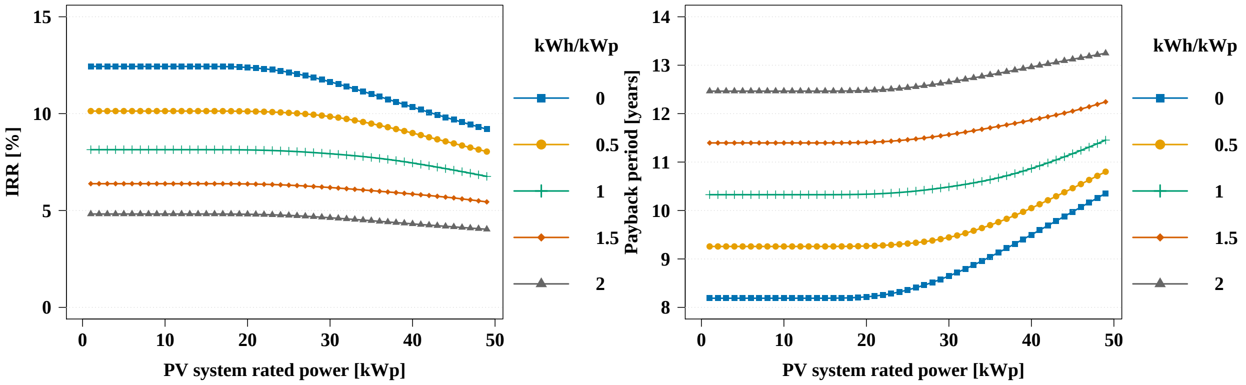
(c) IRR **(d)** Payback period

Figure 6.28: Parameters Condominium 6.9kVA & Bank & Restaurant: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.



(a) Self-consumption

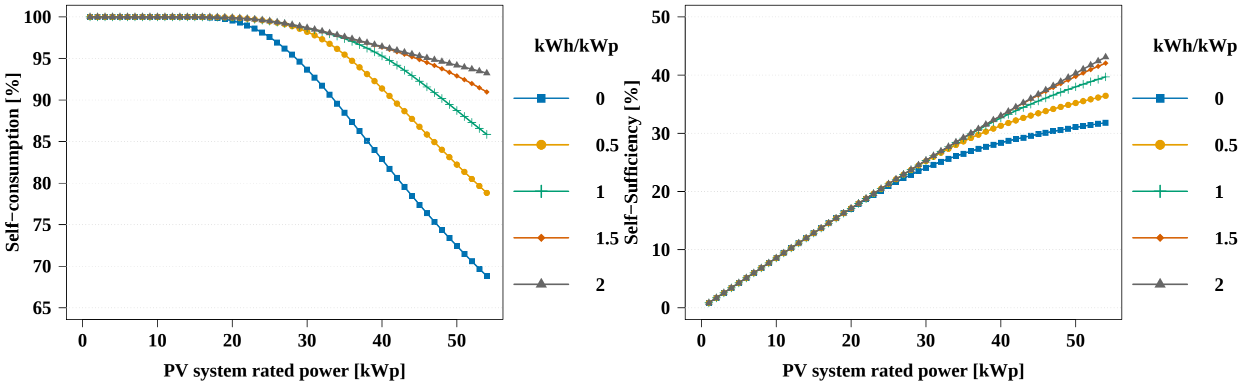
(b) Self-sufficiency



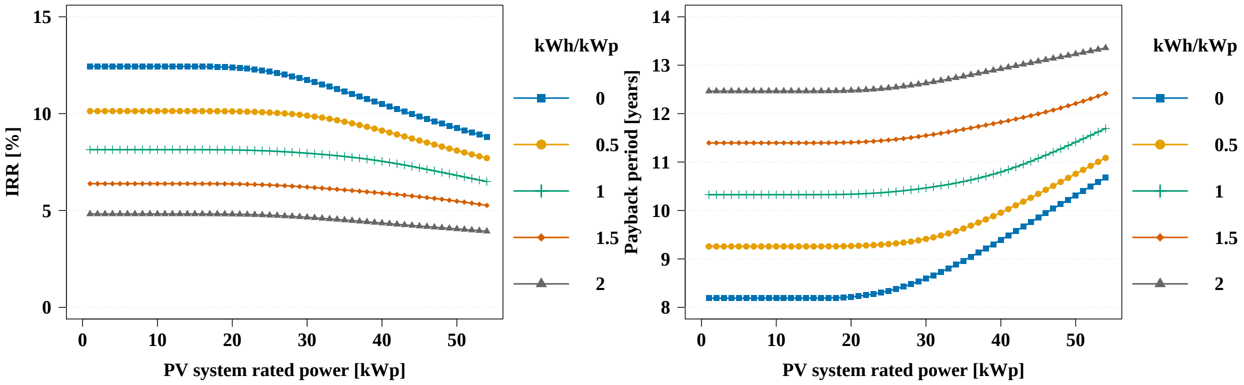
(c) IRR

(d) Payback period

Figure 6.29: Parameters Condominium & Hotel: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.



(a) Self-consumption **(b)** Self-sufficiency



(c) IRR **(d)** Payback period

Figure 6.30: Parameters Condominium 6.9kVA & Hotel: (a) Self-consumption; (b) Self-sufficiency; (c) IRR; (d) Payback period.