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Community energy microgrids: the role of energy exchange between prosumers

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Abstract

In the European Union, the current energy paradigm promotes the deployment and integration of renewables, particularly of the distributed kind, as a way to increase the share of clean energy in the global energy mix. Investments made in this sense have simultaneously been allowing and leading towards the integration of energy produced at the local level on the distribution grid. Recent price drops in small and micro scale energy generation systems have allowed residential consumers to invest in small scale units for self-production. Due to its low maintenance requirements and modularity, photovoltaic panels are the preferred choice when it comes to small energy generation.

However, as solar energy alone cannot match all daily consumption needs, only by investments in energy storage units one can further decrease the dependency on the main grid. In this dissertation a second option is suggested – energy exchange between local prosumers in a smart microgrid.

The hypothesis was studied through the simulation, in AIMMS software, of an energy system intended to reproduce a typical urban neighborhood, composed by six prosumers of different activity sectors and, hence, having different daily load profiles. Considering that at least some of those will have an energy surplus during a part of the day, the idea of a local energy market for trading such surplus is introduced. For the management of this virtual energy market, two models were proposed: a centralized management model, which is intended to simulate a microgrid controlled by a single entity holding access to all data regarding production and demand of the microgrid participants, and a decentralized management model, simulating a scenario where prosumers individually manage their energy trades. Both models were optimized with mixed integer linear programming for cost minimization and simulated for four day-types, with hourly time intervals: winter week- and weekend-days and summer week- and weekend-days. A base scenario with no energy exchange between the prosumers, only with the main grid, serves as a reference for comparison. The results were quantified in terms of self-consumed power and financial balance analyses. Finally, a contextualization for the Portuguese legislation regarding self-consumption was made, in order to determine if this case-study and corresponding results could be adequate for the national legal situation.

The results show that very similar outcomes of self-consumption are obtained for both management approaches, with a maximum daily divergence of 2,3%. Considering the overall average for the daily self-consumption values obtained, the difference between the two models is below 1%. When comparing with the base scenario it was verified that, on average, an overall 10% increase in self-consumption is obtained for the micro-grid as a whole.

Regarding the financial outcomes, the application of a local energy market for energy exchange between microgrid *prosumer*s resulted in an energy surplus valorization of 135%, on average for the day types simulated, compared to the value stipulated by the Portuguese legislation for self-consumption units. As a logical consequence of this result, an average of 21,6% increase in overall revenues for the prosumers was verified, compared with the revenues in the base scenario. The highest increases on the revenues are verified in the winter week-day scenario, in particular for the office. On average, the individual costs' reduction is 1,2%, mostly due to savings during the summer.

An overall economic analysis on the expected electricity bill of each prosumer and for the microgrid as a whole, revealed that the local energy market can cause a bill reduction of 3,3% for the winter week, and 5,3% for the summer. It can be concluded that, when considering the whole microgrid, the overall economic benefits in terms of economic savings are not so relevant as the results obtained in terms of self-consumed energy, for this particular case-study, although a more profound economic evaluation would be interesting to fully acknowledge the impacts of the observed financial benefits on the overall implied investment.

When analyzing the results under the Portuguese legal framework it was concluded that 3 of the production units were oversized in terms of resulting connection power.

Key-words: microgrid, renewable energy, self-consumption, *prosumer,* local energy market

Resumo

No atual contexto de descarbonização da rede energética e da sua transição para um modelo de funcionamento mais distribuído e flexível, tem sido dado uma ênfase crescente ao papel que as micro redes poderão desempenhar na integração de fontes de energia descentralizadas e de pequena escala nas redes nacionais.

Por outro lado, o paradigma atual é de desruralização e crescimento e densificação das cidades, criando necessidade de fomentar a produção de energia próxima do consumo em ambiente urbano, mesmo com todas as limitações associadas, e.g. de espaço.

Uma das formas de aproveitamento descentralizado de energia mais utilizadas na atualidade é a conversão de energia solar em energia elétrica através de painéis solares fotovoltaicos. A nível global tem-se assistido a uma grande adesão a esta tecnologia, que pode ser explicada pelas políticas económicas de incentivo à sua utilização e constantes desenvolvimentos na tecnologia que levaram a uma queda no seu preço de mercado, tornando-a competitiva mesmo sem subsídios. Isto levou a que utilizadores e investidores de pequena escala apostassem em unidades para autoconsumo ou pequena produção, com ou sem ligação à rede elétrica nacional.

As pequenas unidades urbanas de produção de energia solar fotovoltaica têm vindo portanto a ganhar destaque, embora a sua curva de produção coincida com a da radiação solar disponível a cada instante, tornando indispensável o recurso a sistemas de armazenamento de energia, como baterias, ou a esquemas de venda de energia à rede em horas de produção excessiva, eventualmente beneficiando de tarifas subsidiadas, e à compra em horas de défice.

Uma terceira alternativa é exposta nesta dissertação – a da troca de energia entre consumidores-produtores (para os quais foi criada a designação de '*prosumers*') de uma micro-rede. Neste trabalho analisa-se um caso em que dado conjunto de *prosumers* com painéis fotovoltaicos instalados no espaço disponível da cobertura dos respetivos edifícios consumem em primeira instância a energia que produzem, sendo o excesso disponibilizado num mercado local de energia para venda aos restantes *prosumers*.

Para demonstrar os hipotéticos benefícios desta alternativa, dois cenários com modos diferentes de gestão de micro-redes, com troca de energia, foram comparados com um cenário base, sem troca de energia. Os cenários foram montados para o mesmo sistema energético, constituído por seis *prosumers* (dois prédios residenciais, um restaurante, uma escola, um pequeno escritório, e um banco). Os dois diferentes modelos de gestão são: (1) gestão centralizada , que pretende simular um cenário em que existe uma unidade central gestora que tem total conhecimento e acesso aos perfis de produção e consumo dos participantes da micro-rede durante o dia todo, e com essa informação gere os recursos; (2) gestão descentralizada, que simula uma situação em que cada *prosumer* gere a energia que compra no mercado energético consoante o preço desta em comparação com a da rede nacional. Os dois modelos incluem uma otimização matemática do balanço entre custos e receitas, com vista à minimização da conta da energia para os *prosumers* da micro rede em estudo.

Para fins de simulação, os consumidores foram considerados clientes da EDP, e divididos em escalões de potência contratada, de maneira a definir os preços a pagar pela energia da rede nacional. Os dados de consumo dos consumidores residenciais (dois prédios com vários apartamentos) e do banco foram cedidos pela Intelligent Sensing Anywhere, referentes a consumidores de Lisboa, com formatação de intervalos de quinze em quinze minutos. Os restantes perfis foram retirados de uma base de dados de

perfis padrão criada pelo Departamento de Energia dos Estados Unidos da América, com intervalos de tempo horários. Assim dos perfis anuais foram escolhidas semanas representativas da época de Verão e Inverno para cada consumidor, e destas foram selecionados dois dias representativos, um dia de semana e um dia de fim-de-semana.

Referentemente à produção fotovoltaica, foram feitos dimensionamentos dos sistemas fotovoltaicos com base na média do consumo diário para os dias considerados, permitindo, de acordo com as áreas consideradas como sendo utilizáveis para o efeito, determinar o número de painéis a instalar e a capacidade instalada para cada um.

De acordo com os resultados das simulações foi possível verificar as diferenças entre os modelos de gestão do mercado local e o cenário base sem troca de energia, em termos de autoconsumo, individual e coletivo, e balanço financeiro, bem como uma análise detalhada aos custos e receitas obtidos por cada um.

A análise das simulações permitiu verificar que as diferenças obtidas entre os modelos centralizado e descentralizado são pouco significativas– uma análise comparativa dos valores de autoconsumo do sistema para os dois casos demonstra uma diferença máxima de 2,3 %, no dia de semana de Inverno, sendo que para o dia de verão de fim-de-semana a diferença era inexistente. Para os restantes dias, o nível de autoconsumo no sistema estudado foi superior sob gestão centralizada.

Assumindo uma relação entre o aumento da diferença entre o autoconsumo para cada modelo e a quantidade de energia disponível no mercado local (no Inverno há menos produção pelos painéis fotovoltaicos e os consumos são superiores nos dias de semana), procurou-se demonstrar que estas diferenças podem ser explicadas como uma resposta aos preços praticados. Por outras palavras, no modelo descentralizado havendo menos energia disponível para venda no mercado local da micro-rede, a tendência será para os preços subirem, o que eu comparação com o preço de comprar à rede nacional pode tornar o mercado local uma fonte de energia menos atrativa. Já para o modelo centralizado, onde uma entidade gestora tem informação plena, terá presumivelmente capacidade para atribuir preços mais baixos à energia no mercado local, mesmo quando há pouca energia disponível, de maneira a aumentar o rendimento do sistema no seu todo.

Comparativamente ao cenário base, verificou-se que em termos diários se atingiram aumentos em média de 10% na quantidade de energia autoconsumida pela totalidade do sistema.

Uma análise às trocas de energia entre *prosumers* da micro-rede permitiu determinar que o restaurante é o que mais beneficia do mercado local de energia em termos de quantidade comprada, seguido pelos edifícios residenciais. Em média as poupanças nos custos rondaram os 1,2% para cada, e o aumento das receitas foi em média 21,6%.

Uma análise financeira revelou que a aplicação de um mercado local de energia resultou numa valorização média de 135% do excedente de energia, em comparação com o valor a este atribuído em linha com a legislação portuguesa referente.

Já para a micro rede como unidade, os balanços financeiros estimados para uma semana inteira de cada estação revelaram que a conta da eletricidade poderia ser reduzida em 3,3% no Inverno e 5,3% no Verão.

Embora estes valores não sejam muito elevados, permitem apoiar a ideia defendida nesta dissertação, e quantificar os seus benefícios, na medida em que a implementação de um modelo de troca de energia, quer centralizada quer descentralizada, permite benefícios económicos para os *prosumers* envolvidos e um maior grau de autoconsumo da energia produzida na micro-rede. Considerou-se importante frisar que para a atual legislação em vigor em Portugal para o que diz respeito a autoconsumo, esta seria uma

maneira de conseguir valorizar o excedente de energia produzida. De maneira geral um mercado local como o sugerido beneficiaria tanto consumidores como produtores, dando opção aos primeiros de comprar energia mais barata do que a vendida na rede nacional, e aos produtores uma opção viável de venda do excedente.

Uma análise crítica aos valores considerados de potência instalada e máximas potências injetadas na rede em comparação com os limites estipulados pelo Decreto-Lei 2014 referente a unidades de autoconsumo permitiu concluir que: 1) no que toca à potência instalada, os valores considerados constituem sobredimensionamentos em 3 casos; 2) relativamente à potência injetada na rede nacional, esta excedeu o limite estipulado apenas nos casos de sobredimensionamento. Com isto se conclui que os benefícios obtidos, em termos de autoconsumo e redução nos custos da eletricidade, poderão ter interesse no contexto nacional, uma vez que para alguns dos participantes da micro rede, não se verificando sobredimensionamento ou excedente de energia injetada na rede, foi possível beneficiar de melhorias no autoconsumo e redução dos custos.

A ter em consideração há que várias simplificações foram feitas neste estudo, tal como a atribuição de uma eficiência de 100% para o sistema de transmissão da micro-rede, ou a assunção de que não existem perdas no inversor e cablagem dos sistemas fotovoltaicos. É também de referir que a utilização de intervalos de tempo com dimensão de uma hora implica maiores erros que numa simulação de escala mais fina, uma vez que não retrata com tão grande aproximação uma situação real de produção e consumo de energia.

Palavras-chave: micro rede, energia renovável, autoconsumo, prosumer, mercado local de energia

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List of Notations

i, j	Set of prosumers from the microgrid
t	Set of time-steps, with value of one hour
Δt	Time gap
$EDemand_{t,i}$	Electricity demand of prosumer *i*, in time-step *t*
$PVoutput_{t,i}$	Electricity generated from the PV array of prosumer *i*, in time-step *t*
$EBoughtNetwork_{t,i}$	Electricity bought by prosumer *i* from the main grid, in time-step *t*
$ESoldNetwork_{t,i}$	Electricity sold by prosumer *i* to the main grid, in time-step *t*
$ESoldMG_{t,i}$	Electricity sold by prosumer *i* to other prosumers, time-step *t*
$EBoughtMG_{t,i,j}$	Electricity bought by prosumer *i* from prosumer *j*, in time-step *t*
$PriceSNetwork$	Revenue from selling energy to the main grid
$PriceBNetwork_{t,i}$	Cost paid by prosumer *i* to buy energy from the main grid, in time-step *t*
$PriceMG_{t,i}$	Price of the energy sold by prosumer *i* within the MG, in time-step *t*
$PVeff$	Photovoltaic panels’ efficiency
$PVArea_i$	Area with photovoltaic panels installed, for each prosumer *i*
$EDifference_{t,i}$	Difference between the energy being sold by and bought from prosumer *i*, in time-step *t*
$Irradiance_t$	Solar irradiance, in time-step *t*
$Costs$	Daily financial balance from the costs and revenues of the entire microgrid
$EBoughtFrom_{t,i}$	Energy bought from prosumer *i*, in time-step *t*
$TESoldBy_{t,i}$	Total energy sold by prosumer *i*, in time-step *t*
$TEBoughtBy_{t,i}$	Total energy bought by prosumer *i*, in time-step *t*
P_{pv}	Number of photovoltaic panels
$DailyLoad$	Daily energy consumption
P_{nom}	Nominal power of the photovoltaic panel

List of Acronyms

GHG	Greenhouse gases
EU	European Union
PV	Photovoltaic
DER	Distributed Energy Resources
DSO	Distribution system operator
LV	Low voltage
EMS	Energy management system
DL	Decree of Law
UPAC	Self-consumption units (Unidades de autoconsumo)
UPP	Small production units (Unidades de Pequena produção)
FiT	Feed-in Tariffs
SMG	Smart Microgrids
P2P	Peer to peer
CHP	Combined heat and power
MA	Multi-agent
TPES	Total primary energy supply
MILP	Mixed integer linear programming
P	Power
PR	Performance ratio
PSH	Peak Sun Hours

1. Introduction

At a global scale, recent efforts to mitigate global warming and pollutant emissions have led to reinforced investments in cleaner energy sources and energy efficiency technologies. The paradigm is changing from centralized to distributed energy production, and from total dependency on the main grid to self-generation, taking advantage of the continuous developments in available renewable energy technologies, accompanied by their price-falls – the best example is the price drop of photovoltaic (PV) panels, which decreased by as much as 80% since 2009 [1]. These tendencies are pushing towards a new scenario of smaller and smarter energy systems, i.e., mini smart grids.

Current efforts towards the integration of more renewable energy and distributed sources, the implementation of demand response, the optimization of the end-uses of electricity and the flexibility provided by new control technologies and are some of the main drivers for the deployment of smart-grids [2].

However, the existent power system infrastructure, mostly based on old national grids, is not designed to meet the needs of a continuously-changing electricity market, nor to face the increasing demands of a digital society and increasing use of renewable resources [3]. The existing grid model is a one-way channel where balancing of supply and demand in real time is accomplished by adjustments on the supply side [4], meaning that conventional power plants regulate their production in order to deliver nonfluctuating power according to a predefined schedule or real-time contingencies [5]. The non-dispatchability and difficult predictability associated with the production of energy from most of the renewable energy sources – wind, photovoltaics, run-of-river – are still major barriers for its integration in the national grid, since it poses a challenge to its stability and reliability of operation [2].

Nevertheless, there are other approaches that can use renewable and distributed energy sources as a means to improve power reliability: some countries and regions are deploying economic incentives to increase the level of local self- consumption or micro-production as a way to reduce dependency on the main grid, hence having more security of energy supply [6]. These economic incentives come in different forms across the European countries, depending on their policies, but their common goal is to allow businesses and households to increase the consumption of their own energy production, either instantaneously or in a deferred manner, by means of decentralized energy storage. Through the process of 'self-consumption', passive consumers are therefore becoming active 'prosumers', i.e., producers and consumers of renewable energy [7].

As around 75% of the European citizens live in urban areas, accounting for up to 80% of the total energy consumption in Europe and around the same share of CO_2 emissions, a lot of focus has been put on improving energy consumption and production in such areas [6].

In the European Union (EU), households accounted for 29% of the final energy consumption in the EU-28 by 2014, and around 30% of the total electricity consumption [8], placing the residential sector in the center of energy efficiency policies in the EU [9]. As shown in Figure 1.1 below, energy demand in cities is expected to rise approximately 26% by 2030.

In Portugal, the residential sector was in 2013 responsible for approximately 16% of the final energy consumption, and for 4,4% of the CO_2 emissions [10]. Both these values are substantially below the EU average, which can be attributed to the country's mild climate and relatively high energy prices [11].

According to an EuroStat analysis regarding cities across the EU countries (EU-28) [12], only 14.2% of the population lives in detached houses, against a majority of 59.9% that occupy flats (with more than two thirds of these living in buildings composed of at least ten separate dwellings). Thus, it has become increasingly important to invest in research and innovation towards city-integrated energy efficiency and generation, adapted to the current paradigm of highly concentrated housing, as that is expected to substantially contribute to the environmental, economic and social aspects of urban sustainability [6].

The goal of reaching energy self-sufficiency through renewable energy deployment in the urban context rises some challenges, due to the limited available space for installation [6]. Similarly, there some legal barriers for the installation of PV units on the rooftops of buildings with the intent is to supply energy to only a fraction of the building's occupants.

Figure 1.1 - Estimated Energy Demand in Cities of the EU-28 (Source: data from International Energy Agency (IEA) 2008)

For the commercial and industrial sector, these emerging self-consumption models open new opportunities for energy related costs' reduction, allowing them to better control their energy bills [13].

As for the residential sector, many other motivations arise. In this sector, electrification is an important contributor to the increasing power demand. Residential buildings account for about one-fourth of the global final energy consumption, making it a sector with great potential for substantial energy savings, and consequently minimizing its carbon footprint [14]. Moreover, by 31 December 2020, all new buildings in Europe shall be nearly zero-energy consumption buildings [15], meaning that they must be able to produce the amount of energy they consume. This comes as a major drive for adopting a larger portfolio of green energy options. The price fall in PV technology has also allowed for a sharp increase in the installed photovoltaic panel units on residential rooftops [16].

Local governments are starting to line up behind the idea of a decentralized energy future, and to face the challenge of consumers' communities, setting up private energy sharing alliances and interacting with other grid stakeholders [17]. This can be accomplished by small-scale local production of energy at community/aggregated level, or at individual level [4]. In these cases, the energy produced locally does not always cover entirely the demand, requiring that the system is connected to the distribution grid to fulfill the consumption when the net-load is positive.

Communities in the residential sector could further play a pivotal role in the democratization and decentralization of energy systems [18] . They have good opportunities for economic savings in the electricity bills and revenues from selling the excess production. Currently, in the case of energy excess production, the surplus is either sold to the grid, with a revenue that depends on local policies, or stored in an energy storage system. In this thesis, a third option will be explored: the selling of surplus energy to other consumers in a local energy market, with and without central management.

Considering that four out of five Europeans live in households located in regions where generating solar electricity on their rooftop is cheaper than buying it from the grid [19], it is increasingly more relevant to approach the hypothesis of energy generation near to the site of consumption.

Nevertheless, for a house to become net-zero based on solar PV energy, it will encounter the barrier of mismatch between peak production and peak-consumption [20], as well as no production during night-time when there is no solar radiation. As a way to compensate for that, energy storage units are regularly used, such as batteries.

Recently, mechanisms for energy exchange between prosumers in real time basis, based on blockchain technology, are being tested as another possible solution to enhance the self-consumption level. The idea behind it is that cities are constituted by buildings with different purposes and hence different consumption profiles. Therefore, the energy is used in different times of the day, resulting diverse profiles of excess or lack of energy, in particular when buildings have different purposes (residential, service and commerce purposes). In theory, this would allow for a higher usage of the produced and locally consumed energy. This also allows for a reduction in energy storage size, and hence cost. Buying from a production unit close to the site of consumption would allow for other benefits like reductions in energy losses through the distribution lines which could potentially mean further savings in the energy bill.

The idea of self-produced energy exchange within a local energy market is studied in this dissertation through the simulation of an urban energy system in the AIMMS software environment. The energy system is composed by several energy prosumers, belonging to different sectors (residential, commercial, services), typical of an urban neighborhood.

For the same energy system two models are tested: one with centralized management and the other completely decentralized. The differences between them and their results are analyzed. Finally, for a clearer understanding of the results, a comparison is be made between the outcomes obtained from both energy exchange scenarios and a third scenario for the same energy system but without energy exchange between prosumers.

1.1 Dissertation goals and outline

The research hypothesis of this thesis is that producing energy through renewable energy sources, in this case by the use of photovoltaic units, has more benefits for the prosumers when a group of buildings form a microgrid and exchange their excess energy between them and with the external grid, rather than a one-by-one power exchange of each prosumer with the external grid. Two important aspects here shall be demonstrated in order to support the supposed usefulness of this concept: improved self-consumption and economic benefits.

The improvements will be quantified by comparison with a base scenario with no energy exchange. From the simulation results, special focus will be paid to the relative self-consumption values, energy surplus valorization and revenues obtained, in order to determine if there could be benefits performing energy exchange in urban areas in Portugal. Furthermore, a relevant question to answer is whether this system would comply with the national legislation applied to self-consumption units, in terms of injected power and installed capacity.

Another goal of this dissertation is to compare the outcomes of two different microgrid management models, the centralized and decentralized management approach.

The outline of this dissertation is the following:

2) Framework: a literature review on the concepts of smart microgrids and energy markets at service of community energy systems, including a European and Portuguese contextualization;
3) Methodologies: a chapter with an overview on the AIMMS software environment and mathematical optimization models used for the simulations, a detailed explanation of the methodologies used for data preparation and price structure considered for the financial considerations of this dissertation;
4) Results and discussion: where all relevant results are displayed and briefly discussed;
5) Conclusion: in this chapter an overview of the results of this dissertation is made and a critical discussion is done in order to conclude whether the dissertation goals were positively accomplished.

2. Framework

Throughout the literature review all concepts associated to the proposed energy system are introduced, as well as the present European and Portuguese framework.

2.1 Micro Energy Grids

The distributed power generation has emerged as a solution for enhanced deployment of renewable energy sources, which is one of the most important EU targets. As a result of end-users owning and operating DER assets, distribution system operators (DSOs) are looking for ways to adapt to more proactive controls in several parts of the grid [21] . At the time being, grid operators still have to deal with some limitations from the centralized system when it comes to control this increasing number of distributed sources [17], for instance the lack of flexibility from the energy demand side to adapt to the fluctuance of renewable energy production.

The concept of the microgrid was introduced to solve this problem. Although classical microgrid is not designed to operate in parallel with utility supply there is a trend for resourcing to microgrid technology for increasing the interaction between DER within microgrids and the main grid, as this brings benefits such as improved economies due to energy sharing, reserve capacity, and other ancillary services. This has broad implications on microgrid business practices and technical aspects [21].

A microgrid can be defined as a low voltage contiguous section of the grid and its interconnected energy resources (generators, loads, storage devices, electric vehicles) such that they can operate as an independent electrical island if needed, with no degradation of the service [21]. This island feature requires the employment of smart grid tools to optimize energy flows, which is crucial to managing the economic and technical operation parts.

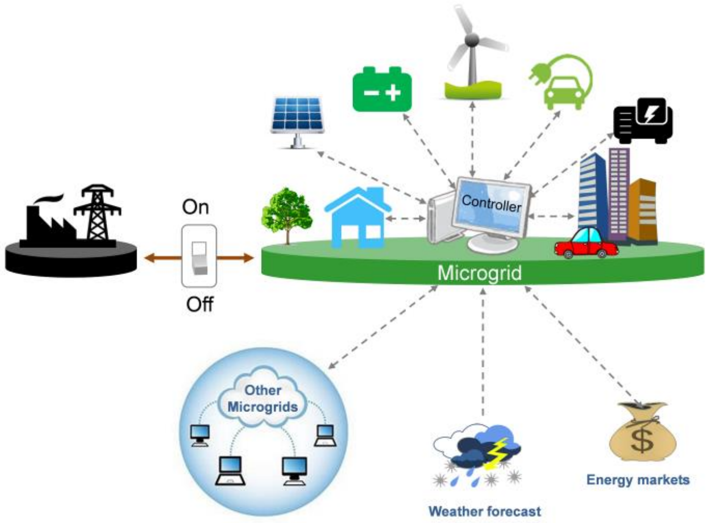


Figure 2.1 - Microgrid schematic (Source: Berkeley Lab)

It may range from individual backup power systems of houses to self-sufficient medium voltage systems consisting of multiple generators and stakeholders, as well as one or multiple kinds of renewable power generation centers. It offers the possibility of coordinating the distributed resources in an automated and intelligent way so that they can behave as a controlled entity, with clear contracts defining the roles of the different parties involved, and totally independent of the main grid, if needed. In this way, distributed resources can provide their full advantages in a more consistent way [17][21].

There are six types of different strategies for the electricity consumer and/or producer clustering: Embedded Networks, Virtual Power Plants, Prosumers Clustering, Local Prosumers Clustering, Smart Embedded Networks or Microgrid [22]. The classification depends on its components, electric boundaries, off-grid capacity and main grid interaction. The distinguishing trait of a microgrid is the mandatory capability for islanding mode, which is not present in any other strategy [22]. A virtual power plant, often mentioned in conjunction with microgrids, differs from it in that a virtual power plant is typically associated with energy resources but not with specific grid sections [21].

Currently there are over seventy projects identified in the world as fully operational microgrids implemented in urban areas. This kind of projects were first developed in the USA and Japan, motivated mainly by the need for resiliency and energy security [22].

A microgrid system comprises several stakeholders as illustrated in Figure 2.1. Inside the microgrid, four different roles can be distinguished: the owner, the electricity producer, the operator and the final user. These roles can be played by a single actor or many. Outside the microgrid there are interfaces with multiple players: the main grid owner, the main grid operator, regulatory institutions and external electricity retailers. An interface can also be present between the microgrid final users and the external electricity retailer, who could supply them even if the sold electricity is generated outside the microgrid.

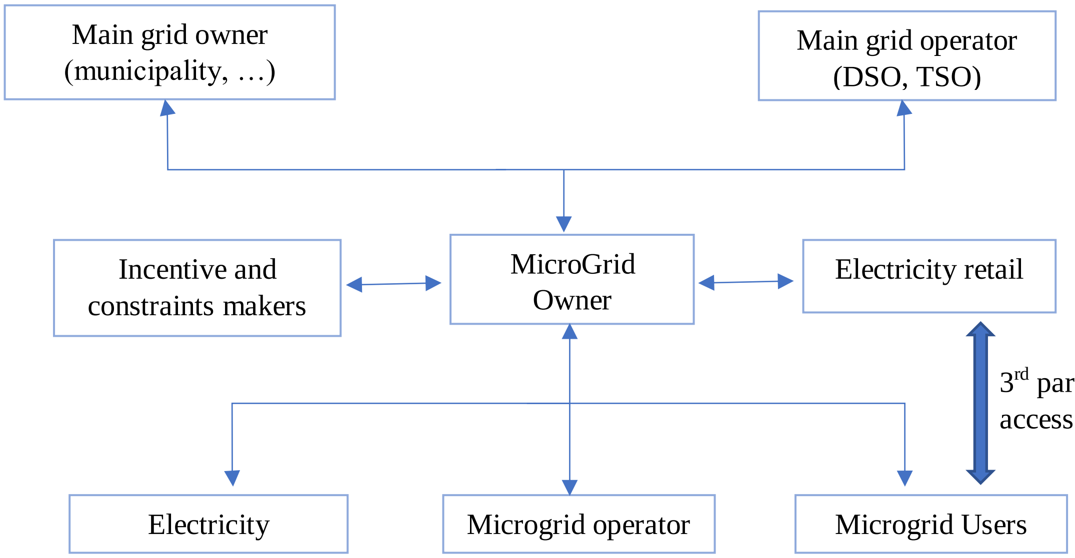


Figure 2.2 - Schematic of a microgrid, stakeholders and connections (Source: ENEA Report, 2017 [22])

In short, some of the major benefits associated with microgrids include [21]:

- Provision of energy services tailored to the microgrid end-users' requirements;
- Enabling of parallel operations with the main grid for improved financial performance through economic exchange of energy and ancillary services between the two;
- Enabling of parallel operations with the main grid for improved service reliability through coordinated response during emergency situations to serve critical loads and to reduce outage impacts;
- Leveraging and/or deferring capital investments on critical energy and grid assets;
- Enabling of innovation of new energy technology and services that have broad societal impact beyond local energy delivery.

- Reducing main-grid usage by allowing to lower the main-grid capacity due to limiting the peak load, with the help of energy storage.

Microgrids are considered to be one of the most relevant tools in the process of decentralization of the electrical grid. Investments in this technology are expected to change the way distributed energy resources are integrated at urban level [21].

2.2 Smart-Grids

Smart-grids (SGs) are modern electric power grid infrastructures, built for enhanced efficiency and reliability through automated control, high-power converters, modern communications infrastructure, sensing and metering technologies, and modern energy management techniques based on the optimization of demand, energy and network availability [26]. One of the SGs biggest potentials is to allow for a more flexible power system, opening new business opportunities and operational possibilities specially regarding the integration of renewable energy sources (RES) into distributed system, such as microgrids [21].

They are qualified as smart grids because of their higher efficiency and capacity of control and operation, in comparison to the conventional ones, allowing to:

- safely integrate more renewable energy sources, smart buildings and distributed generators into the network;
- deliver power more efficiently and reliably through demand response and comprehensive control and monitoring capabilities;
- use automatic grid reconfiguration to prevent or restore outages (self-healing capabilities);
- consumers having greater control over their electricity consumption and to actively participate in the electricity market, since this technology allows for two-way communication between appliances and the electrical grid [15].

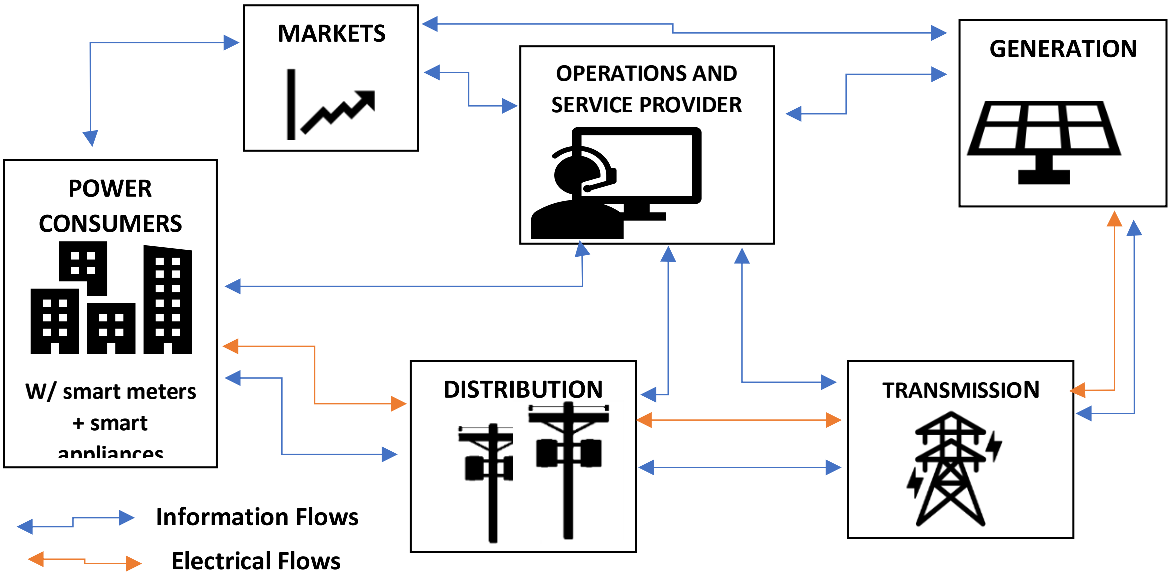


Figure 2.3 – Conceptual model of a smart grid (Source: The Impact of Control Technology flyer: «Control of Renewable energy and Smart-grids» [29])

Figure 2.2 shows the broad spectrum of entities and stakeholders covered by a smart grid. As it can be observed, the smart grid enables the extension of control to the consumer level [2].

By enabling bidirectional communication and power exchange between suppliers and consumers, through the incorporation of information and communication technologies, smart-grids are in position to shift the traditional paradigm of passive distribution into an active distribution and the consumers into active players [17]. This way, smart-grids also offer an encouraging prospect for the development of reliable and cost effective self-sustainable buildings and communities [15].

2.2.1 The European framework on Smart-Grids

In order to ensure a coordinated effort to drive the study and implementation of smart-grids throughout the EU, several programs have been developed:

- the EU 7th Framework Program, where smart grids solutions aim to be developed through the cooperation of member states;
- the Horizon 2020, where smart grids are addressed under the key challenge named “Secure, clean and efficient energy”;
- the EEGI, an industrial initiative for the development of the Union’s electricity networks, later updated to GRID+ project;
- the Smart Grid Task Force invested in assisting the Commission on policy and regulatory frameworks of Smart Grids;
- the EU energy infrastructure legislative package [2].

Across the EU member stated there were a total of 950 implemented projects on research and development and demonstration of smart grid technology. The European Union’s Grid4EU program has smart grid projects running in six countries, mainly implemented outside large cities, with relatively small number of loads. Their goals are to test the integration of DER generation into the existing distribution grid and the security of energy supply at local level, as well as its reliability when in island mode. Those projects are also useful to test the integration of distributed generation resources and storage management within buildings, and congestion power management in city infrastructures [23].

Regarding the GRID+ project, its white paper report predicts that geographically and topologically segmented markets will emerge as a response to the implementation of dynamic and granular locational marginal pricing on the distribution grid. In consequence, it is expected that occasionally customers will prefer to trade energy locally instead of interacting with wholesale markets. This will be possible by means of blockchain technology, which will facilitate the exchange of energy directly in a peer-to-peer (P2P) manner, rather than the current system of clearing on a centralized market. GRID+ plans to manage these local tradings until regulators make rules for P2P markets generally [23].

The BRIDGE initiative unites some of these programs to create a structured view of focal issues which are encountered in the demonstration projects and may constitute an obstacle to innovation. Since 2014 it has supported 32 projects in the domains of distribution grids, distributed storage, transmission grids, large scale storage and RES [27]. Over the years, it has identified as main barriers:

- the lack of standardized methods for data exchange;
- lack of, or limited, data and information sharing with energy market players;
- lack of market conditions for new services to be delivered, due to existing constraints for market participation, particularly affecting small scale players;

- lack of standard solutions and guidelines regarding P2P trading in order to carry out commerce;
- lack of appropriate control of data access;
- existing telecommunication infrastructure, whose reliability and robustness to support envisioned energy services is still uncertain, regarding both market applications and network management;
- current security services provisioning still under development and consideration;
- lack of standardized methodology for determining the flexibility potential of new installations.

Based on this, the BRIDGE working group has made some recommendations, for example: the creation of a common format for data exchange across Europe to facilitate interoperability of systems; general access of raw, real time data; empowering of households with consent option in cases of transfer of data to players for provision of services and development of privacy protection solutions [27].

According to the Joint Research Center, the United Kingdom is the leading country in what regards investments in SGs research and demonstration projects. It has several pilots to create incentives for higher demand response through smart meters and ancillary services, including the establishment of privacy and data-access arrangements for suppliers and DNOs. Also, a Smart Grid Forum was launched in 2011 to provide leadership to the industry on smart-grid issues [2].

Italy has also placed itself as one of the EU members stated that has been most impacted by the increase of intermittent generation. Its programs to incentive the deployment of smart meters have been a great success with smart meters, currently covering more than 95% of the Italian low-voltage consumer base [2].

As for other examples of municipal initiatives, Latvia and Lithuania's city capitals have both made available online the annual heat and energy consumption values of some residential buildings, with the aim of encouraging residential building's renovation and investment in the city, as all owners and tenants can find out how much their building's energy costs are per year, and how it compares to similar properties in their neighborhood. This online tool allows people looking for a new home to know the most energy efficient options [9].

In summary, European's current paradigm regarding SMGs application is still in its pilot phase, with limited definitions of what constitute a smart investment, which are still analyzed in a case by case basis, with a great focus on financial aspects [2].

2.2.2 The Portuguese case

In Portugal, the transition to a smarter distribution grid is led by EDP Distribuição, which resulted from a partnership of the DSO with academic institutes, technology and innovation firms, and metering equipment suppliers, resulting in the InovGrid project. It had its first pilot in Évora, called InovCity, through which 31.000 smart meters were installed in 2011. The infrastructure spans the entire municipality, reaching around 33.000 electricity customers [2] [28] .

The Portuguese paradigm is one where the level of renewable energy penetration in primary energy consumption amounts to 21%, and 44% in the electricity production. The incentive scheme supporting smart-grids is attributed in the form of a prize over the cost of capital, implying a sharing of the innovation’s risk by consumers. So, if a project is expected to provide for an overall efficiency gain, the regulator allows the DSO to benefit from the 1.5% prize return on the smart investments.

EDP Distribuição is currently deploying second-generation smart meters to 100.000 customers throughout the country. Concerning the mobility sector, between 2010 and 2011, a charging network for electric vehicles was implemented, with 1.350 smart charging stations accessible to end-users throughout the country [2].

Another project implemented in Portugal’s territory and funded by the Horizon 2020, the SMILE project, is responsible for a pilot in Madeira island. As the amount of solar energy generation increases, so does the difficulty in balancing the electric system. The project envisions an intelligent control and automation system implemented in the existing grid to provide for an overall better management of the distribution network. This involves the implementation of grid balancing and frequency control, installation of smart metering systems, demand side management techniques (including market mechanisms such as dynamic pricing) and storage technologies. Another goal of this project is to evaluate the integration of battery energy storage systems in this island, resourcing to its existing test bed of eighteen micro-production sites. The existing electric vehicle network on the island will moreover be expanded and integrated with the control system via smart charging software [2][29].

Although several pilot programs have been implemented by utilities using smart meters and energy management systems, ranging from simple in-house feedback displays to programmable systems endowed with actuation on loads, Portugal has not yet decided in favor of a large-scale smart meter roll-out. Consequently, demand response programs and direct load control activities have only had an experimental basis with limited results.

According to inquiries to a sample of the Portuguese population, households frequently engage in many different energy usage, control, and investment behaviors, but across all respondents there were two less frequent energy behaviors: providing meter readings to the utility and buying more efficient equipment. Although 76% of respondents stated they read the electricity bill “frequently or even “always”, they rarely provide meter readings to the electricity supplier (only 32.6% stated “frequently” or “always”). According to the Directive 2009/72/EC, 80% of end-users are expected to be equipped with smart metering systems by 2020 [30].

However, most Portuguese end-users still have meters requiring manual readings (either performed by the utility technicians or end-users), supposedly to enable more precise billing.
The transition to smart grids also comprises the increasing adoption by end-users of technologies such as demand-response enabling technologies, electric vehicles and local micro-generation. Results revealed that only 7% of respondents used electricity monitoring devices (e.g. in-house displays). Less than one third (28.7%) currently uses time-of-use controlling functions on their appliances (e.g. programming or time-delaying) [30].

Results from the same study regarding end-user’s availability to accept load control actions over appliances (shifting time-of-use, turning off, redefining operational settings) show that the majority of respondents was not willing to accept direct load control from the utility, even in a hypothetical future scenario of dynamic pricing. Only 34.9% was willing to accept control of their appliances by the utility.

2.3 Self-consumption and the prosumer

Since the price has been falling in small scale renewable energy units, it has become common for households to have their own production units, such as solar photovoltaic panels, combined heat and power, etc. These units are usually used to meet internal energy demand, while the surplus generation is sold to the main grid or stored in a decentralized energy storage device [20].

The neologism «prosumer» refers to an electricity consumer that produces part of his power needs from his own power plant and uses the distribution network to inject excess production and to withdraw electricity when self-production is not sufficient to meet his/her own needs [31].

According to some of the reviewed papers, prosumers are proactive energy producers and consumers that want to be in control of their energy generation and use, be it as house-owners or tenants, institutions or small businesses. Their main motivations are to reduce dependence on the main grid, optimize their energy consumption and minimize their energy bills. They are actively engaged in producing more energy than they would utilize in order to trade/share the excess to other prosumers [19] [32].

Prosumers can either act on their own or collectively through aggregators, as energy service companies, contractors or cooperatives, through social enterprises or through other local community energy projects [19].

In a context of continued growth of the number of prosumers, in the necessity to give response increasing connections between those and the existing macro-grids side, some problems arise:

1. The current centralized and restricted market doesn't allow for profitable business models to arise for small producers;
2. There's a lack of platforms that allow managing the energy and information flow between local energy producers and bigger scale potential consumers.
3. Problems on a contractual level are expected to arise as a consequence the introduction of decentralized energy producers and small independent energy markets, due to the high complexity for such dynamic and competitive markets.
4. Stability of the electric network may be at risk if there is no optimized management capable of keeping up with the introduction of thousands of micro/mini-producers [19].

It is considered that the use of blockchain technology and of smart-contracts could potentially address challenges for local energy consumption managed at micro grid level, by allowing micro/mini producers to negotiate the sale of the energy they produce in a safe, reliable, fast and flexible way [19]. These tools would imply, for instance, the creation of new platforms for negotiating the purchase and sale of energy, allowing micro-producers to have an additional source of income, and consumers the option of choosing the cheapest supplier [22] [23].

Considering a scenario where solar panels are installed on the rooftop of a multi-apartment building, the electricity generated on site is consumed at least partly by the building's tenants. That self-produced energy is firstly consumed as electricity delivered via the grid (it is purchased, delivered and billed by an electricity supplier) [19]. This situation poses a barrier to urban prosumers, since as mentioned earlier, most of the population lives in cities, and in multi-apartment buildings, being few of those the ones of have smart-meters at use.

For a tenant of a multi-apartment building to be able to access and consume his self-produced solar electricity, four types of situations may occur:

- Segmented self-generation (tenants rent and run a segment of a solar power plant on their own);
- Shared self-generation (the shared use of the solar power plant is part of the lease of the flat);
- Direct sale by the landlord or by a contractor (tenants are offered an in-house solar electricity tariff);
- Direct sale by an electricity supplier (tenants are offered solar electricity and electricity imported from the grid in one single retail electricity tariff) [19].

An assessment from a consumer perspective shows that direct sale models generally bear a lower risk for tenants. The contractual framework provides a higher level of transparency regarding costs and benefits. Moreover, the administrative burden for the tenant tends to be much lower. However, in legal terms, a broader definition of self-consumption is required to include these models.

Self-consumption is commonly mistaken with self-sufficiency. While the first describes the local (or remote under some schemes) use of self-produced electricity, the second describes how self- production can cover the needs of the place [31]. In Figure 2.4 the self-consumption appears from the overlapping of the consumption and self-production profile.

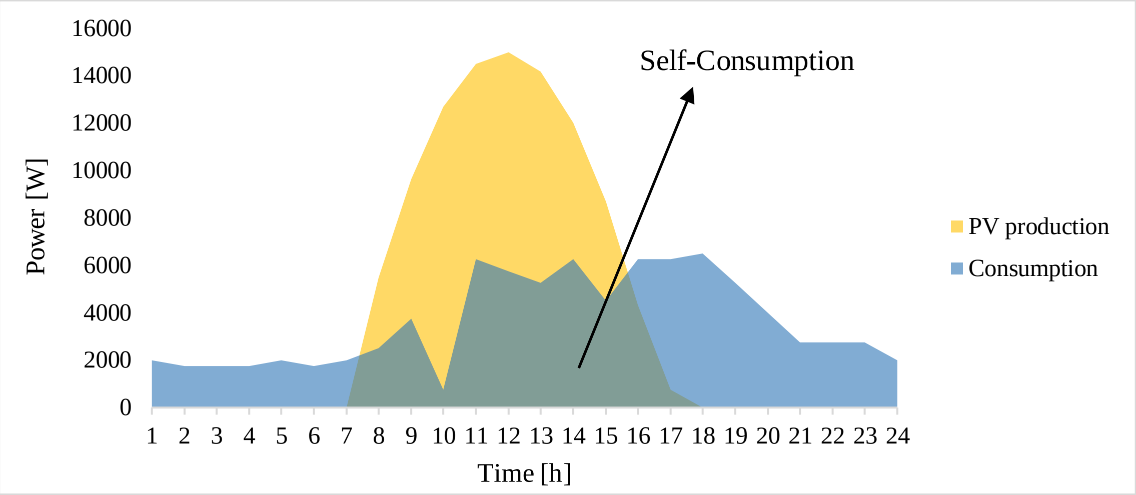


Figure 2.4 - Daily load profile with PV production and self-consumption

2.3.1 The European framework on self-consumption and prosumers

According to the latest studies, around 80% of European households could generate solar electricity at lower price than the cost of buying it form the grid [19]. It is believed that to reach the full potential on self-consumption in urban environment it is essential to align specific regulation and incentive policies [17].

Financial incentives given to prosumers vary across EU territory, as there is no strong harmonized structural approach to prosumer support. Many countries motivate net metering schemes, which means that the energy fed as excess electricity into the grid is deducted from the bill of the owner of the power plant during a certain period in time [34]. Sometimes a country may employ more than one financial incentive; for instance, Denmark employs fixed premiums and net metering; Germany uses guaranteed price feed-in tariff, and Italy adopted guaranteed price feed-in tariff, fixed premiums and net metering.

Other options employed are tax reductions and capital subsidies and loans or tradable green certificates [34].

Besides some efforts from some countries to include a friendlier policy for small-scale prosumers, it is considered that, at the moment, there are no real markets for prosumers due to lack of motivation, incentives and information [35].

Nevertheless, some cities around Europe are succeeding at powering through the energy transition towards more sustainable urban environments. Eindhoven for example, is motivating its residents to invest in local renewable energy by encouraging their participation in citizen energy cooperatives. The members of the cooperative produce renewable energy through small-scale installations and the organization’s profits are used to keep people’s energy bills down and fund new renewable projects. The municipality also makes tools available to calculate the return on investment for private solar panel installations [9].

On other way, Barcelona’s strategy is set on two objectives: reducing its greenhouse gas emissions by 40% by 2030 (compared to 2005) and producing enough energy locally to meet municipal needs. In 1999, the municipality adopted a thermal solar ordinance according to which new and retrofitted buildings are required to use at least 60% of solar energy to cover their hot water needs. As a result, the installation of solar panels reached 90.000 m2 by the end of 2012. Currently, the municipality has 50% of its internal needs covered by renewable energy (buildings, lighting, municipal vehicles, etc.) [6].

Barcelona also plans to set up a power supply company, aimed at developing new energy generation units in the city, making energy a public service accessible to all. The “self-sufficient Barcelona” website provides information and advice on local renewable energy production and energy efficiency, helping to raise public awareness for the issue [6].

Another example is the municipality of Frankfurt, aiming to have all its energy needs covered by renewable energy by 2050, which will be achieved by: reducing the energy use by 50% through building retrofitting and the use of new technologies; by renewable energy production within the city supplying 25% of the demand; 25% of the demand supplied by renewable energy produced in the metropolitan area [6].

Venice has joined forces with private investors to redevelop Certosa Island into a low-carbon urban park. The local business that teamed up with the city for this project decided to invest in medium-scale installations for multiple renewable sources (biomass plant, district heating and cooling, solar thermal, PV and micro-wind systems), which, aligned with a general power consumption reduction, has allowed the city of Venice to decrease its gas imports by 100.000 cubic meters and reduced CO2 emissions by 315 tons per year [9].

Nevertheless, it is still frequently mentioned on European reports that there is nearly no legal ground for tenants as far as solar self-generation policies in EU Member States, since the existent legislation is mainly designed for detached houses, it is hard for tenants to access this solar electricity [19][33].

2.3.2 The Portuguese framework on self-consumption and prosumers

Portugal's objective is to achieve as much as 40% of national energy consumption from renewable sources by 2030. For reaching this, most of the new renewable energy projects should focus on small generation, self-consumption generation, solar photovoltaic energy, as well as biomass [36].

Self-consumption in Portugal is regulated by the Decree-Law nº 153/2014, 20th October, Portaria nº 14/2015 and Portaria nº 15/2015. This legislation was specially adapted with the purpose of promoting further deployment of micro-generation renewable energy in Portugal [37].

Regarding financial incentives, the most relevant is a feed-in tariff for existing installations. The feed-in tariff consists of two elements: a guaranteed payment rate and an amount calculated by a set formula. For new small production installations, a remuneration regime has come into force in 2015 (the Decree-Law nº 153/2014). This remuneration regime is based on a bidding model in which producers offer discounts to a reference tariff [38].

According to the Decree-Law nº 153/2014, mini/micro production units are divided into self-consumption units or small production units. The so-called self-consumption units (UPAC's) are meant to satisfy the energy demand locally. The power that is produced is immediately consumed and any exceeding production is fed into the grid, to avoid any losses. The non-self-consumed energy is injected into the national grid and it is paid at 90% of the monthly average rate of the closing market price of energy by the Iberian market operator [38].

According to the Portuguese association for solar photovoltaic energy (APESF), in 2017, the majority of UPAC units in operation were by far photovoltaic ones, specifically units up to 20 kWp installed power (64,2%), followed by 20 to 100 kWp units (24%). In total, from 2015 to 2017, with the implementation of the legislation regarding micro production, a total of 1.714 units of RES for self-consumption were installed, and from the total of power attributed to decentralized production, 69% was of UPAC units. Wind energy and biogas units were installed in a very small proportion [39].

Values of 2018 show that 47% of the total PV installed power in Portugal comes from decentralized generation units, amounting to 269.312 kW by February 2018. It is possible to draw a conclusion that the DL nº 153/2014 had a visible impact on the promotion of decentralized generation in Portugal [39]. Although these results may sound encouraging, by 2017 the number of prosumers is still 11.000, which corresponds to roughly 0,11% of the entire population [30].

2.4 Community energy systems

Recently, a great amount of research has been focusing on finding solutions for decentralized energy systems' application at the local level. It has become clear that the outcome of such systems may vary in great scale according to economic, technical and environmental factors. It is also been proved pertinent to adapt them appropriately for each distinct scale (individual building, neighborhood or district level) [40].

In this context, the concept of community energy systems is starting to gain attention. According to the organization IRENA [41], community energy is the economic and operational participation and/or ownership by citizens or members of a defined community in a renewable energy project. It is not limited by size, taking place on both large and small scales. It states that community energy is any combination of at least two of the following elements:

1. Local stakeholders owning the majority, or all, of a renewable energy project;
2. Voting control rests within the community;
3. The majority of social and economic benefits are distributed locally.

As for real life energy community projects, currently, the biggest example is the Brooklyn Microgrid, running in a residential neighborhood. Resourcing to blockchain technology, a data platform was developed to allow for a localized energy marketplace. Through this platform, called Exergy, prosumers are able to transact energy autonomously in near-real time in their local marketplace. In this project the DSO is granted access to load balancing and demand response at negotiated rates [42].

The benefits of a community type of energy system include increased efficiency and reduced operating costs, due to economies of scale, increased reliability, reduced emissions and a broader choice of fuels (including renewable energy and low-grade heat). The same conclusions were drawn by other studies, such as Ref. [40], where the authors tried to simulate how the economic aspects and autonomy of an energy system varies with different scales of aggregation for energy residential systems (individual buildings, neighborhoods and district level). It concludes that a marginal increase in electrical self-sufficiency is significantly more expensive at lower aggregation scales (i.e. single buildings), benefiting the increased levels of aggregation.

In times of high energy generation, there are available options to make use of the energy in surplus, including storing it or feeding the energy to the main grid by employing net metering. However, exporting the excess energy to the grid can raise some issues, as the grid can put a cap on maximum power that can be fed. In addition, the energy producer might not earn the maximum returns on the energy supplied, since the payment is predefined by the grid's last resource buyer and not accordingly to its actual cost. Thus, it is possible for a prosumer to optimize his/her financial returns by directly trading with other prosumers through an energy exchange platform [32].

According to Ref. [1], only two types of business models are viable for renewables in the current energy market situation – behind the meter solar and large scale wind or solar, as for instance, mid-scale community solar farm or bioenergy projects are currently not cost effective. This can be justified due to certain constraints such as:

- the difficulty of negotiating a good power purchasing agreement with a retailer;
- the cost of the grid-connection;
- the high cost of using the grid, even if just transporting energy at short distances.

2.4.1 Management of a Community Smart Grid

One major approach to integrating distributed communication among prosumers is through multi-agent system technology [32][46]. In this context, each prosumer represents an agent, who can communicate inside the local grid and other agents outside its local neighborhood. This communication either happens through direct data flow between agents or through a central database, responsible for information storage and sharing.

Accordingly, we can refer to:

- Distributed control, if prosumers trade energy directly with each other in a P2P manner;
- Centralized control, if prosumers exchange energy through a central entity.

Within centralized coordination, decision-making is performed by one superior entity which can be an aggregator or the utility. In this case, in order to get efficient results, it is required detailed information about the homes involved in the energy system and control over the homes' appliances, which can be seen as neither practical nor well received by the consumers. In decentralized coordination, users are independent decision-makers who control their own electricity profile under the influence of a central entity and/or other users, according to price signals or personal preferences or needs [46].

Peer-to-peer energy trading represents direct energy trading between peers, where energy from small-scale distributed energy resources in dwellings, offices, factories, etc., is traded among local energy prosumers and consumers [45].

For a microgrid encompassing a P2P networking system, the trading of surplus PV energy among prosumers is an important issue for the economic operation. To trade, share or buy energy, some of the partakers involved in the exchange process are: the prosumers, that supply and consume energy, and a trader or local-grid operator, that buys energy to trade at a margin. Peer-to-peer energy transfer systems can reduce dependency on the main grid though the creation of a platform where the numerous distributed energy producers could transact energy, thus increasing grid reliability. Furthermore, this systems have the potential to reduce requirements for capacities to address energy generation or load uncertainties [32], since the production is sized to meet the consumption needs of a specific load aggregation, allowing for safer predictions on the consumption side and an overall better match between production and consumption. It also is expected to effectively improve network efficiency, because energy is used at or close to the point of production, which drastically reduces distance-related transmission losses and congestions on transmission lines [46].

In order to distinguish the electricity imported and consumed from the grid from the self- generated on a multi-story-building, the implementation of smart-meter schemes are vital. Smart metering allows for the computing of the self-generated electricity's distribution to the resident's appliances, by monitoring generation and consumption within a particular time period. Such metering systems, however, are not yet in place in many cities, what can pose a major set-back for a resident's self-production situation [19].

Another area that still limits opportunities for local governments is licensing barriers around the use of private wire across property boundaries. This wiring arrangements would be useful for situations where distributed generators seek to sell their excess power to their neighbors via their own wiring, avoiding the need for use of the distribution network and hence cutting on associated costs [46].

A virtual energy district represents an aggregation that allows easy energy exchange among neighbors (residential consumers, producers and prosumers) and related local market models. In Ref. [47] two models with a local electricity market platform are proposed: firstly, a local market model that doesn't consider any technical constraints on transport capacity; secondly a constraint local market model, which considers a maximum value for the transport capacity over which congestion on the distribution network can occur. The results stress the importance of considering the existence of constraints on a distribution network, being that the second model shows heavily reduced revenues in the virtual energy district and increased cost to buy the required energy. It also intends to demonstrate how the utility of the virtual energy district is limited without a city energy provider and local market.

The community energy system models have been encouraged as a substitute for battery storage units when it comes to saving the excess energy, and potentially as a way to go off-grid [48].

2.4.2 The European framework on community energy systems

The Horizon2020 underlines the importance of community energy systems, stating that by 2019 the investments made are expected to set up and/or support energy communities (consumer cooperatives, consumer collective purchase groups, and/or other consumer driven collective actions) to increase energy efficiency and/or optimize energy management to integrate a higher share of renewable energy (generated locally or provided from the grid) within the community by combining collective solutions to distributed generation, distributed storage, or demand-response aggregation. The program stresses the importance of identifying and addressing the existent regulatory barriers and contractual conditions for cooperative actions, and of demonstrating the benefits of collectively organized energy-related actions in community [25].

In Europe investments at the local level in sustainable systems have been to a certain extent made by community initiatives. The aim of such co-operative projects is usually either focused on enhancing the energy efficiency or substituting the provision of energy of the community from fossil fuel to renewable energy. As an example, in Brno, Czech Republic, the residents organized to invest in house insulation for more than 600 houses, having obtained an average annual energy consumption fall of 80% [49].

Many small communities around Europe by means of local investments or of shared ownership by local stakeholders, invested in the installation of wind parks or solar parks. The energy produced may be only for local consumption, as in the case of cities in Bulgaria, Denmark, France and Germany, or as a way to gain side-profit for re-investing in the community or in an enlargement of the RES. In a local town in Greece, the investment was made in bio-energy, through a shared investment in a pelletizer, which is fed with locally gathered biomass, and converted into thermal energy for house heating [49].

2.4.3 The Portuguese framework on community energy systems

In Portugal one of the most notorious community investments made in renewable energy was the Coopérnico co-operative, where 1.167 citizens helped finance over 600 PV projects, installed in rented roof-tops of socially valuable buildings. This way, this organization is investing in the community and getting some financial benefit from it, allowing the projects to continue [49].

2.5 Distributed renewable energy sources

Climate commitments, emissions reductions, increase of security of supply and existence of renewable endogenous resources have been the crucial influences for the development of renewable energy technologies and policies around the world [7]. One of the consequences of these investments is the progress of distributed renewable energy (DRE) resources availability [16].

Distributed renewable energy systems are energy systems that generate and distribute services independently of any centralized system, in both urban and rural areas. They can serve as a complement to centralized energy generation systems or as a substitute, offering an opportunity to accelerate the transition to modern energy services, both in remote and rural areas and densely occupied ones [50].

Associated with the integration of renewables into mini and microgrids they are expected to reduce dependence from fossil fuels. These systems represented about 6% of new electricity connections worldwide between 2012 and 2016, mainly in rural areas [50]. Its integration in urban areas is part of the main goals for many countries, as mentioned before in the example of the Horizon 2020 goals [25].

The proliferation of distributed energy resources, particularly of solar PV and wind energy, has changed the grid operational and planning requirements.

Integrating relatively low shares of variable renewable energy (VRE) can be managed with modest adjustments, such as improved resource forecasting, improved grid codes (interconnection standards), better real-time information flow on VRE output, and sensible planning of geographical dispersion and balancing of wind and solar power. For high levels of VRE penetration additional measures are needed, since they usually entail bi-directional flows of energy, which may require change to infrastructure and system operations as well as the elimination of some technical, physical, organizational and legal impediments to a high penetration in power grids, district thermal systems and their transport systems [16].

To date, most flexibility in power systems has been ensured by large scale transmission interconnections with neighboring systems and by flexible generation capacity, but these approaches are not keeping up with the fast-growing demand for VRE's grid connection. Enhanced forecasting tools, demand side management options, energy storage and others are some of the options foreseen to solve this challenge [16].

2.5.1 The European framework for distributed renewable energy sources

Since 1990, Europe has intended to quickly rise the share of endogenous energy resources, by promoting zero-carbon resources, establishing new industries, supporting clean technologies and transforming the energy framework at the time to a more distributed energy model [7].

The European Union 2020 climate and energy package, known as 202020, required the state members to comply with three main goals to be reached by 2020: lowering greenhouse gases emissions in 20%, reducing the primary energy consumption in 20%, and increasing in 20% the renewable share of final energy demand. Some of these targets have been reinforced for 2030, under the 2030 Framework for Climate and Energy, namely by reducing 40% the GHG emissions (below 1990 levels) and increasing by 27% the energy efficiency and renewable energy share [7].

Different stimulus where introduced to spark the integration of distributed renewable generation among the EU countries, mainly in the form of financial incentives, such as: feed-in tariffs, through which electricity produced by distributed renewable generation is sold at a higher rate than the electricity market, feed-in premiums, a bonus payment on top of the electricity market price, or quota obligations, establishing the amount of renewable electricity that must be produced, consumed or supplied in a given year [7]. However, distributed renewable production has become mature and incentives are decreasing, as the technologies achieved cost competitiveness starting to compete in market-based auctions with conventional energy sources.

2.5.2 The Portuguese framework for renewable energy sources in microgrids

Renewable energy accounted for 25,4% of Portugal's total primary energy supply (TPES) in 2014. This share is made up of biofuels and waste (12,6%), hydro (6,4%), wind (4,9%), geothermal (0,8%) and solar (0,6%). The renewable energy share of TPES in Portugal increased 15,1% between 2004 and 2014, reportedly as a result of a surge in wind power generation deployment. Wind power growth exploded since 2004, increasing by a factor of 14 until 2014, while solar increased fivefold, but it is still at moderate levels. For the same period, geothermal increased by 125% while hydro increased by 58%, albeit variable between years. Biofuels and waste declined by 7,5%. More recently, in the first quarter of 2018, renewable energy represented 61% of the total electric production in Portugal (mainland), mainly due to hydro and wind [10].

Portugal has the seventh-highest share of renewables in TPES among IEA members, from which the second-highest share of wind and the fifth-highest share of geothermal. Support mechanisms for renewable energy sources are based on feed-in tariff systems, tax benefits and small investment subsidies.

In similarity to other EU members, Portugal's renewable energy policy was aligned with EU 2020 targets. The country has defined a new national strategy for energy (ENE2020), which envisioned the promotion of competitivity, growth, and energetic and financial independence of the country, through investments in energy efficiency and renewable energy sources [10], adopting a national target for renewable energy to equal 31% of gross final consumption of energy by 2030. In addition to this overall target, Portugal and other EU member states have introduced a target for renewable energy to meet 10% of transport fuel demand in 2020.

The micro-production of electricity in low tension and with possibility of delivering the energy to the main grid was initially regulated by the Decree-Law n. º 68/2002. This DL predicted that the produced electricity was destined mainly for self-consumption, being that the excess energy could be delivered to a third-party or to the public grid, with a power limit of 150 kW. Five years after, due to the low adhesion from the public, a new decree-law was implemented in order to simplify the licensing procedure, replacing it by a simple registration regime [7].

The Government by then had recognized the potential of self-consumption as a way to promote energetic awareness on the demand side, specially by low-voltage consumers, because of their own load profile, which may lead to energy efficiency behaviors and contribute to the optimization of endogenous resources. So, in 2015 a unique regime for micro production came into force, covering two categories of generation:

- self-consumption (referred to as 'UPAC' units), in an installation connected to the respective generation unit (renewable or non-renewable based), whose installed capacity should be between 200 W and 1 MW (art. 2 and 4 DL 153/2014), with or without a connection to the main grid, and whose surplus energy can be injected into the public energy grid;
- small generation units (referred to as 'UPP' units), based on renewable energy sources whose power output is no more than 250 kW and exclusively intended for sale to the public power grid.

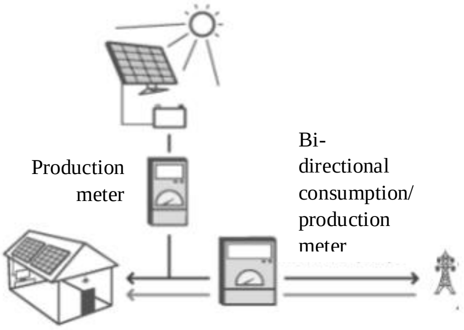


Figure 2.6 - Self-consumption unit's (UPAC) scheme according to DL-2014

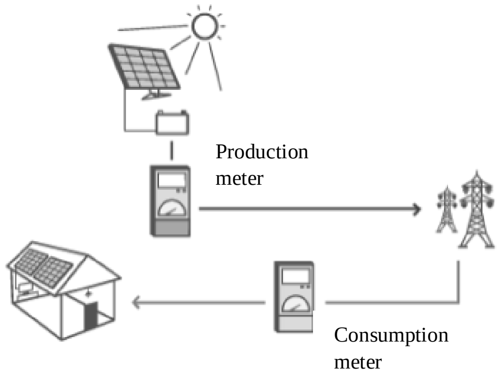


Figure 2.5 - Small production unit's (UPP) scheme according to DL-2014

The small generation units, UPPs, are supported through a bidding scheme where producers bid by offering discounts in relation to a benchmark tariff, which is set annually by the government.

The remuneration tariff varies according to the primary energy used and it's determined by applying different rates to the benchmark tariff. In 2017 the reference tariff was € 95/MWh and the feed-in-tariff (FiT) was 100% of this value for solar PV units. The connection capacity that may be attributed each year to UPPs cannot exceed 20 MW. The application of the remuneration tariff is limited to 2,6 MWh per year for all generation technologies except hydropower (for which the limit is 5 MWh per year), and this tariff will remain in force for 15 years following the date on which the producer started to supply electricity to the public energy grid. The remuneration tariff cannot be combined with other incentives [38].

As for self-consumption units, or UPACs, the maximum capacity allowed is higher although it is supposed to meet as closely as possible the consumption needs of the intended consumption unit. They can be connected to the main grid, in order to receive energy during night time or other hours of positive net-load, as well as to feed excess of electricity into the main grid, commercializing it on the electricity market. Owners of UPACs with an installed capacity of more than 1,5 kW connected to the main energy grid are subject for 10 years to pay a fixed monthly compensation, intended to recover part of the costs associated, which is calculated by the distribution network operator, stipulated as 10% of the closing market price defined by the Iberian energy market operator [38].

Units of self-consumption with an installed capacity exceeding 1 MW require the relevant licenses for installation and operation. UPACs with an installed capacity exceeding 200 W but no more than 1,5 kW, or whose electrical installation is not connected to the main grid, are required only to prior notify the system operator before commencing operation. Self-consumption units with an installed capacity of no more than 1,5 kW and whose owner intends to supply the electricity which is not consumed in the electrical usage installation (which may or may not be part of an electricity supply contract with a supplier) are subject to prior registration and operational certification. Self-consumption units with an installed capacity of no more than 200 W are exempt from any form of prior control. The information on the legal requirements associated with operation of UPACs according to their installed capacity are schematized on Table 2.1.

For existing photovoltaic installations as defined in DL 132-A/2010, the indicative average rate of the FiT is € 257 per MWh (DL 132-A/2010). As for existing concentrated photovoltaics up to 1 MW of capacity, up to a limit of 5 MW of installed power at country level the indicative average rate of the FiT is € 380 per MWh. For concentrated solar power installations with capacity up to 10 MW of capacity, the indicative average rate is € 267-273 per MWh (DL 225/2007).

Table 2.1 - Micro-Production in Portugal according to Decree-Law nº 153/2014

Decree Law	DL 153/2014	
Designation	Small production Units (UPP)	Self-consumption Units (UPAC)
Purpose	Production from RES, with preferred injection of the produced electric energy into the grid, sold to the last resource supplier 1 consumption unit = 1 production unit	Intended for meeting individual consumption needs, by RES or non-RES, with preferred injection of the produced energy into the consumption unit On or off-grid
Self-Consumption Criteria	<= 50% of the total produced energy	Production adjusted to the level of consumption
Power Limits	250 kW	1 MW (to be able to apply for remuneration tariff for surplus energy fed into grid)
Legal requirements	To access to remuneration regime and start operation, UPPs owner should make a requirement during the mandatory prior registration on SERUP (Electronic Registration System)	<0,2kW exempt from above controls 0,2-1,5 kW prior notification before operation start 1,5 kW-1 MW prior registration and operational certification >1 MW license for installation and operation
Remuneration regime	= Reference Tariff, defined annually (€ 95/MWh or 9,5 cent/kWh, in 2017)	= 90% of the average monthly closing market price as defined by the Iberian market operator
Limitations (for Solar PV Energy)	Installed capacity < 2 x Installation's contracted power	Installed capacity < 2 x Power of connection Power of connection < Installation's contracted power
Payment duration	15 years	10 years (can be renewed for a maximum of another 5 years)

2.5.3 Solar Energy

In 2017 the world added more capacity from solar PV than from any other type of power generating technology. More solar PV was installed than the net capacity additions of fossil fuels and nuclear power combined, being the top source of new power capacity in many major markets such as China, India, Japan and USA. The leaders for solar PV capacity per inhabitant were Germany, Japan, Belgium, Italy and Australia [16].

Some of the characteristics that place PV power as the most attractive option for renewable energy production are the availability of the solar resource, the capacity to operate at ambient temperature, the simplicity of the devices (no moving parts, meaning lower maintenance) and its modularity [7]. This last characteristic guarantees that its electric power conversion efficiency is not influenced by scale, even though the cost per unit of generating capacity is lower for utility-scale installations than for residential systems [7]. In recent years the rapid decline in investment costs has also been a major factor of attractiveness, since it has opened this market to a larger portfolio of investors.

Globally, market expansion was largely due to the increasing competitiveness of solar PV, but its applications in local energy production raises much interest. While most capacity additions globally have been in large centralized projects, there is an evident shift towards distributed solar production. In China alone about 19.4 GW of distributed capacity was added in 2017, registering a three-fold increase in new rooftop systems. The Chinese government sees this type of production as a way to lessen the burden on the transmission network. In India rooftop solar is growing at a fast pace, driven largely by commercial, industrial and government facilities seeking to reduce their electricity bills, leaving out residential customers that cannot afford those type of investments. In Japan can be observed a stable increase in residential solar-plus-storage solutions, and the number of community PV projects doubled the total capacity from 2016 values [16].

As for the EU, in 2017 around 6GW of installed capacity were installed. Although there is an increasing demand for self-consumption options due to motivating policies from the governments, the market is still trying to reduce its dependency on government supports, as FIT. In Germany about half the residential systems installed in 2017 were combined with storage capacity [16].

Australia’s investments in the sector, the residential market accounted for over 60% of new installations, a distributed solar-plus-storage options have become cheaper than retail electricity from the grid in several regions of the country.

2.6 Related work and projects

Most papers found on the topic of energy exchange between prosumers have a cost optimization approach, like the one proposed on this thesis, and for that include the implementation of a local energy market. Some examples of these structure are [44], [46] and [47]. In [44] a dynamic internal pricing model was formulated for the operation of energy sharing zone, defined based on the supply and demand ratio of shared PV energy. A cost model considering the prosumers willingness to shift the loads was also suggested. To solve the problem for a real data scenario, a distributed iterative algorithm was implemented. Results demonstrate that the proposed model allows for effective cost savings and local consumption of PV energy, compared with direct trading with the utility grid under the FiT.

In [46] a decentralized coordination method to reduce the electricity bills of the users was introduced. A scenario where renewable generation is shared among neighbors is studied, including appliance-scheduling features. The energy sharing algorithm focuses on increasing the utilization of renewable sources by control of the storage units. The study got positive results regarding the benefits of energy sharing, like reduction on the peak consumption, higher self-consumption and cost reduction.

In [47], in similarity with this thesis, a local electricity market was proposed for the electricity trade amongst a hypothetical community of prosumers and consumers. Two local market designs were implemented and compared – a direct P2P market and a closed order book market, as well as two agent behaviors: a zero-intelligence agent and an intelligently bidding agent. Although all market scenarios offered similar economic advantages, the P2P market with intelligent agents obtained the best results in terms of lowest average overall electricity price.

Other type of papers reviewed do not focus on economic approach, but in other aspects like [20],[51] and [52]. In [20] a model for local share of energy that minimizes system-wide efficiency losses is proposed. The system design includes a centralized control and achieves relevant reduction of energy losses (60%). In [51] the implemented energy management system for the operation coordination of two household prosumers aims at simultaneously minimizing the disconnection of the load, also referred as clustering, and maximizing the available generation. It was concluded that efficient results can be obtained when a cooperative operation scenario is implemented: maximized RES generation and minimum curtailment are reached.

In [52] a model for energy sharing between prosumers for cooperative demand side management is presented, considering for the simulations a six-user scenario. The optimization model is focused on maximizing surplus energy utilization on an hourly basis. The users with shortage at a given time-step are dealt one at a time based on a single or multiple prioritization criterion. Both resulted in reduction of the shortage of energy by energy surplus trade, with better results obtained on the multiple criterion approach.

Some of the papers consider other energy usage efficiency technique such as [51] and [20], which include energy storage systems (batteries), and [52], [46] and [44] make combined use of energy sharing models with demand side management techniques.

In [43], in similarity of what is developed on this dissertation, an aggregation of some building units, from commercial and residential sectors, with photovoltaic generation units is analyzed. Additionally on this work, an option of community energy storage unit is considered. Results revealed that when considering the units separately the outcomes for this energy system, in terms of self-consumption, self-sufficiency and internal rate of return from the investments, are less positive than when considering an aggregation of the profiles.

3. Methodology: Micro Smart-Grid Energy Exchange Optimization

This section is divided into four parts: a first one presents a brief introduction to the adopted software and the notion of mathematical programming, a second part presents a detailed explanation of the two models for the local energy exchange among the energy prosumers, including all the equations used in the simulations and in the analysis, as well as for the PV system performance. A third part presents an overview of the simulations data input, and a final sub-chapter presents in detail the costs and revenues that were assumed.

3.1 AIMMS Software and the mathematical programming

To study the behavior of an energy system connected to the main grid with a local energy market, two optimization models considering centralized and decentralized control, were developed and implemented in the AIMMS software. This is a prescriptive analytics software that allows for optimization modelling.

According to the AIMMS documentation [53], a model is a prototype of something that is real, and an optimization model is one of the classes of mathematical models. The following mathematical elements can be used to formulate a model:

- a set, with or without an index, which is a one or multidimensional array of elements
- mathematical concepts such as variables (unknowns) and parameters (symbols representing known data);
- operators such as unary operators (+, -, NOT), comparison operators (equal to, not equal to, etc.), algebraic operators (addition, subtraction, multiplication, etc.), logical operators (AND, OR, etc.), differential operators and integral operators;
- data, linking a model to a real-world situation.

The capability for optimized use of power systems is one of the most important aspects of the smart-grid technology. Various optimization techniques can be used for energy management. For this thesis a mixed integer linear programming approach was used. This type of programming involves the use of both integer and non-integer variables [52].

A solver is required for finding the optimal solution. AIMMS software offers many different solvers options, which are automatically assigned during the execution process, depending on the model type and mathematical programs involved. The results of this thesis have been obtained by using the CPLEX solver [52].

3.2 Performance of the system

Two approaches were tested for the simulation of the energy system: one of centralized management and the other of decentralized management. The two of them simulate a microgrid with surplus energy exchange between prosumers.

The centralized model intends to simulate how a microgrid behaves under a centralized management, where a single regulation entity would have hold of power consumption and production data from all prosumers, as well as authority to manage the energy flows between them and with the main grid, hence optimizing the system in a holistic manner. In this model there is no need for a price signal, since the trades of energy are not based on hourly price variations, but on the daily overview of all energy profiles.

The decentralized model consists of individual optimizations for each participant of the microgrid. In this scenario, each one of the participants has knowledge of the available energy to buy and its price, which emulates the behavior of a local energy market. At each timestep, a participant can choose to buy from the cheapest source of energy (either the main grid or another prosumer in the microgrid), trying to optimize its own costs to a minimum.

The market participants in this case are six prosumers: two residential buildings, a restaurant, a school, a small office and a bank, having each one a different energy demand profile, and installed PV capacity. The case study is explained in detail in Chapter 3.3. The simulation is set up in one-hour time slots, t, over the course of one day. Trading happens in real time, so over one-hour time-steps the energy trades happen according to the production and consumption of each one of the prosumers. The prosumers, indexed as i or j, and the time-steps, indexed as t, are the sets used in the models.
Table 3.1 contains the execution procedure algorithms of each model, which are explained in detail below. The table allows to visualize the common parts of the procedure between the two models and some of the major differences, like the use of a WHILE function, iteration count and extra constraints in algorithm 2 (corresponding to the decentralized model).

Table 3.1 – Main execution procedure algorithms for the centralized management model (algorithm 1) and decentralized management model (algorithm 2)

Algorithm 1 – Centralized Model	**Algorithm 2 – Decentralized Model**
1: Main Initialization	1: Main Initialization
2: Solve ***MinCosts (Equation 3.7)***	2: while ***iter*** <=100 AND |EnergyDifference|> 0.001 Solve ***MinCosts (Equation 3.8)***
3: Constraint by: ***Equation 3.2-3.4***	3: Constraint by: ***Equation 3.2-3.4*** ***Equation 3.9-3.11***
4: Put ***FinalResults***	4: Put ***FinalResults*** Rewrite ***EnergyPrice,*** according to ***Equation 3.12*** Rewrite ***FinalResults*** Actualize ***iter*** value endwhile;

Some equations used for creating the mathematical programs of these two scenarios are common to both models, which will be introduced first (Equations 3.2-3.7). In analytical approach the notion of energy results from the Equation (3.1):

$$Energy\,[kWh] = \Delta t[h] * P[kW] \tag{3.1}$$

The Δt symbol was not included in the formulation for the sake of simplicity, since the time step in this model is of one hour (Δt=1h), and so the value of the energy consumed or produced equals in value to the correspondent power value for that time-step t.

Equation 3.2 represents a general constraint for the model, ensuring the balance of energy flows for each prosumer i of the microgrid.

$$PVoutput_{t,i} + EBoughtNetwork_{t,i} + \sum_{j} \left(EBoughtMG_{t,i,j}\right) = EDemand_{t,i} + ESoldMG_{t,i} + ESoldNetwork_{t,i} \quad (3.2)$$

Two other constraints, both binary, were added to ensure the consistency of the model:

$$if\ U\_MG_{t,i} = 0\ then\ EBoughtMG_{t,i,j} = 0\ else\ ESoldMG_{t,i} = 0 \quad (3.3)$$

$$if\ U\_network_{t,i} = 0\ then\ ESoldNetwork_{t,i} = 0\ else\ EBoughtNetwork_{t,i} = 0 \quad (3.4)$$

These constraints imply that opposite pairs of action, like energy selling to/buying from the main grid and energy buying from/selling to other prosumers, cannot happen simultaneously in the same time-step t for any prosumer i.

Another common equation for both models is Equation 3.5, which defines the self-consumption variable.

$$SelfConsumption_{t,i} = EDemand_{t,i} - EBoughtNetwork_{t,i} \quad (3.5)$$

This means that the self-consumption of prosumer i, in timestep t, equals all the energy consumed that does not come from the main grid or, in other words, all the PV energy produced within the microgrid that is consumed individually.

Equation 3.6 is used to define the parameter representing the hourly price of energy sold to the main grid, or the revenue from every kWh sold back to the main grid, according to what is defined in DL 153/2014 for self-consumption units.

$$PriceSNetwork \ = P_{OMIE} * 0.9 \quad (3.6)$$

In Equation 3.6, the parameter P_{OMIE} represents the monthly average closing market price for the Iberic market operator. The value attributed per kWh of surplus energy sold to the grid corresponds to 90% of that price.

The execution statements necessary to solve the mathematical problem are written in ***MainExecution***, where they serve as a procedure to be executed by the software. For both models, the first order of the procedure is to read the input data file (this is in the ***MainInitialization***). After, there is an order to solve the problem.

For both models the mathematical program to be solved is the minimization of the costs' function. Its definition differs between the models, since they are supposed to simulate different microgrid management behaviors.

3.2.1 Centralized model

For the centralized model, costs are defined as in Equation 3.7.

$$Costs = \sum_{t,i} (PriceBNetwork_{t,i} * EBoughtNetwork_{t,i} - PriceSNetwork * ESoldNetwork_{t,i}) \tag{3.7}$$

It consists of a simple balance between the total system's costs and revenues, from both the commercial energy trade between the microgrids' users and with the main grid.

3.2.2 Decentralized model

The decentralized model is more complex since it involves the implementation of an iterative system for energy surplus pricing and individual optimizations at each time-step. It simulates a small trading market where prices would fluctuate at each time-step, according to each prosumer's energy provisions and buying preferences.

The goal of this optimization, like in the centralized model, is to minimize the overall costs for the users in the microgrid. In this model the problem is solved individually for each prosumer, as it would be in a microgrid without a central management, where users make independent decisions according to their needs and conveniences. The optimized energy prices used in the local energy market are those that benefit both the buyers and sellers involved in each exchange. In this model, the costs and revenues from the energy trades within the microgrid are considered in the costs function, as seen in Equation 3.8.

$$Costs = \sum_{t,k} (PriceBNetwork_{t,i} * EBoughtNetwork_{t,i} - PriceSNetwork * ESoldNetwork_{t,i} + PriceMG_{t,j} * \sum_{j} (EBoughtMG_{t,i,j}) - PriceMG_{t,i} * ESoldMG_{t,i}) \tag{3.8}$$

For this model some other equivalences were added in the ***MainExecution***, to further ensure consistency in the model, namely the ones Equations 3.9 to 3.11 imply, as shown below.

$$EDifference_{t,i} = \sum_{j} (EBoughtMG_{t,j,i}) - ESoldMG_{t,i} \tag{3.9}$$

$$TESoldBy_{t,i} = ESoldNetwork_{t,i} + ESoldBy_{t,i} \tag{3.10}$$

$$TEBoughtBy_{t,i} = \sum_{j} \left(EBoughtBy_{t,i,j}\right) + EBoughtNetwork_{t,i} \tag{3.11}$$

In the ***MainExecution,*** before the solving order of the mathematical program, a loop is added through the use of a *WHILE* function and an iteration count. Two conditions were attributed to the *WHILE* function to keep the loop running: the number of iterations should be less than 100 and the absolute energy difference, as defined in the Equation 3.9, higher than 0,001. Equations 3.9-3.11 are inside the loop, and the results of every parameter and variable involved are updated at each iteration or *iter*, as defined in the model. Before every loop finishes, the $EnergyPriceMG_{t,i}$ value is updated according to Equation 3.12 and the iteration count is updated (*iter=iter+1*).

$$EnergyPriceMG_{t,i} = EnergyPriceMG_{t,i} + 0{,}001 * EDifference_{t,i} \tag{3.12}$$

A schematic of this procedure can be seen in the figure below.

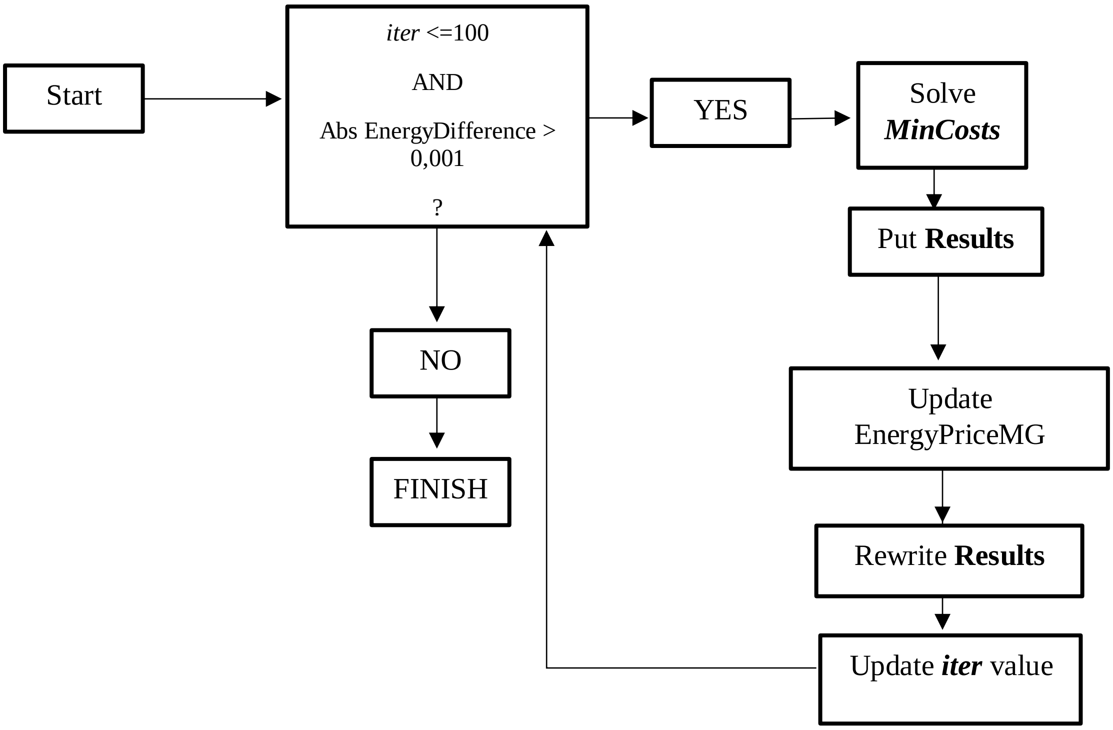


Figure 3.1 – Main execution loop procedure in the Decentralized model

3.2.3 Analysis of the performance

To compare the results obtained from the two models described above, new calculations were made to get the microgrid results in terms of self-consumption on an hourly basis, as in Equation 14, for each one of the assumed four scenarios (winter week-day, winter weekend-day, summer week-day, and summer weekend-day), allowing for a clearer perception of the differences. These results will be compared to a base scenario for the same exact energy system configuration but where no energy exchange occurs, which will be called from this part on of 'No-Exchange scenario'.

$$HourlyTotalSelfConsumptionMG_t = \sum_i (EDemand_{t,i} - EBoughtNetwork_{t,i}) \tag{3.13}$$

To further examine the differences between the centralized and decentralized models, daily self-consumption results for each day-type were calculated, according to the equation below.

$$DailyTotalSelfConsumptionMG = \sum_{t,i} (EDemand_{t,i} - EBoughtNetwork_{t,i}) \qquad (3.14)$$

Financial balances were calculated using Equation 3.15.1 for the No-Exchange scenario in the MG, and Equation 3.15.2 for the Decentralized scenario.

$$\begin{aligned} & HourlyFinancialBalanceMG\ _{t} \\ & = \sum_{i} (EBoughtNetwork_{t,i} * PriceBNetwork_{t,i} - ESoldNetwork_{t,i} \\ & * PriceSNetwork\quad) \end{aligned} \qquad (3.15.1)$$

$$\begin{aligned} & HourlyFinancialBalanceMG\ _{t} \\ & = \sum_{i} (EBoughtNetwork_{t,i} * PriceBNetwork_{t,i} \\ & + \sum_{i} (EBoughtMG_{t,i,j} * PriceMG_{t,j}) - ESoldNetwork_{t,i} \\ & * PriceSNetwork\quad - ESoldMG_{t,i} * PriceMG_{t,i}) \end{aligned} \qquad (3.15.2)$$

For each type of day, the energy flows of the microgrid for both models were demonstrated and compared in arrangements, to allow for a better visualization of the differences in the outcomes.

Finally, an estimation for the possible weekly savings obtained for the whole microgrid is made, according to the Equation 3.16 below.

$$\begin{aligned} & WeeklyTotalMGsaving \\ & = \sum_{t,i} Savings\ for\ a\ week - day * 5 \\ & + \sum_{t,i} Savings\ for\ a\ weekend - day * 2 \end{aligned} \qquad (3.16)$$

3.2.4 PV system's sizing and performance

The equation below was used for the PV systems' sizing:

$$P_{PV} = \frac{Dailyload}{P_{nom} * PSH} \tag{3.17}$$

In Equation 3.17, P_{pv} corresponds to the required number of PV modules, and it is calculated based on the quotient between the daily average load of each prosumer, *Dailyload*, and the nominal power, P_{nom}, of the PV panels times the peak sun hours, *PSH*. These parameters are displayed on Table 3.2 below.

Table 3.2 - Data used for the PV systems' sizing calculations

Data input	
Peak Sun Hours (PSH)	4,84
Nominal Power of the solar panel, kW (P_{nom})	0,315
PV panel's efficiency	0,193
PV module area (m^2)	1,63

A reasonable area of rooftop space was attributed to each one of the 6 loads, as a way of quantifying the availability for installation of PV panels on rooftops. The considered areas were based on real life examples for each type of building (residential, commercial or other), and measured with resource of the Google Maps tool. From those available area, 60% was considered to be suitable for PV panels' installation [55], taking already into account the effects of existing building elements on the rooftop and shading. Table 3.3 shows the resulting area required for the PV panels' installation, compared with the usable areas, and resulting installed capacity. The area needed for the PV panels was calculated by multiplying the results from Equation 3.17 by the area of each module. For all prosumers it was considered the same PV panel model, the SunPower 315 (for which the factsheet can be found in the Annex). As some of these loads, like the bank or offices, frequently occupy the lower levels, or some floors, of buildings with other occupants, it was considered that for those situations total access to the rooftop space would be granted for PV panels installation.

Table 3.3 - Roof space considerations, as in available, suited and required areas, and resulting PV arrays, for each prosumer

Prosumer	Office	Bank	R1	R2	School	Restaurant
Areas (m^2)	400	200	350	350	1100	250
PV usable area (60%) (m^2)	240	120	210	210	660	150
Area needed for panels (m^2)	199,5	93,2	581,6	491,7	726,8	510,1
Considered area for simulation (m^2)	200	94	210	210	660	150
Number of panels	121	48	129	129	405	92
Installed capacity (kW)	38,1	15,1	40,6	40,6	127,5	29

As can be observed for some cases the usable are is lower than the needed area. For those situations the maximum usable area of roof-space was considered in the simulations.

The PV arrays' output, as used for the simulations, is defined according to following formula:

$$PVoutput_{t,i} = PVeff * PVArea_i * Irradiance_t * PR \tag{3.18}$$

This is a simplified calculation in which all components are parameters whose values are directly read from the data file. The produced energy is then defined as the product of the energy efficiency of the PV system (considered to be 19%) by the area of installed PV panels (m^2) for each prosumer *i*, by the normal solar irradiance (kW/m^2) and the performance ratio (PR), considered as 85%. The efficiency of the panels was assumed to be the same for all, since it is considered that all of them use the same PV panel model. No other losses were considered for the calculations. Some of these prosumers are considered to be inserted in shared buildings, like the bank and office, normally occupying only one portion of the building, with the rest belonging to residential occupants or in a shared-office manner. For these cases, it was considered that they would have permission to use the desired roof space.

The solar irradiation values were taken from the Photovoltaic Geographical Information System, a free online tool [54], with location defined as Lisbon, Portugal, and tilt angle of the hypothetical solar arrays corresponding to the optimal year-round value, 34º. Two different daily irradiance profiles were used, one for winter days and another for summer. The values can be seen in Figure 3.2.

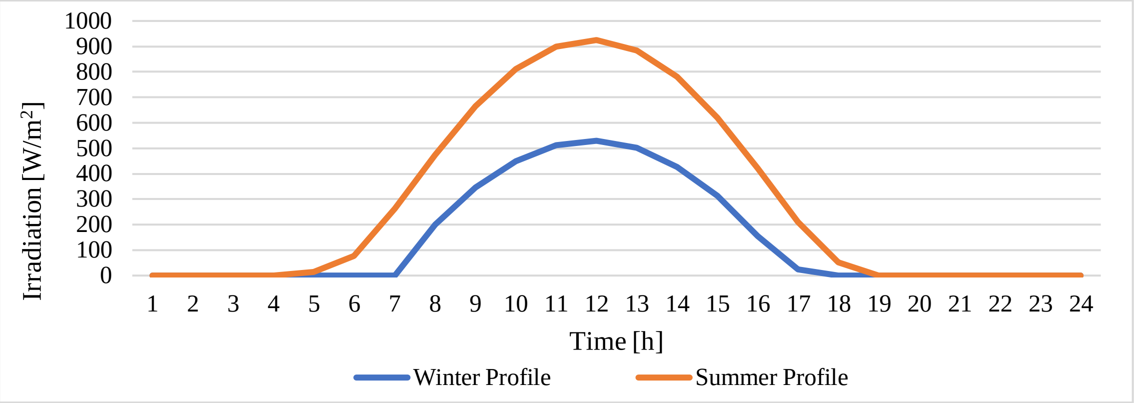


Figure 3.2 - Daily Solar Irradiation(W/m^2) for summer and winter seasons

3.3 Data

The envisioned context for the simulated microgrid is a residential neighborhood, an area mainly occupied by residential buildings, with education facilities, local commerce and some business facilities. The loads incorporated in the proposed energy system are the ones of two residential buildings, a school, a bank and a restaurant.

These buildings were chosen because they provide a considerable amount of roof area allowing for the installation of solar panels for electricity production. Another goal of this thesis would be to illustrate a microgrid which couples loads from different sectors, and hence diverse energy consumption profiles, since this strategy is expected to bring benefits to the whole energy system.

Another benefit that may come from this model type is that the users of the solar panels would benefit from economies of scale, since the PV arrays would be sized for the entire building, which can make a considerable difference compared to individual investments, especially when it comes to residential buildings, because the costs are shared among many buyers.

This setting intends to demonstrate how the exchange of energy between prosumers, without an energy storage unit for keeping the surplus energy, bring benefits to those involved in terms of electricity cost's reduction and rise of the self-consumption level.

3.3.1 Energy demand profiles

The data used for this project came from different sources and with different formats, some with hourly values for the whole year (which is the case for the restaurant, school and office) and others with 15-minute data (residential buildings and bank). The residential and bank power consumption data came from ISA (Intelligent Sensing Anywhere), corresponding to Lisbon loads, and the remaining were picked from a database created by the United Stated Department of Energy with a number of different commercial building benchmark models. In this section, the weekly profiles are presented with their original time format (15 min or hour intervals). As for the daily profiles for the representative days of each season, they are presented in an hourly basis, as used in the data input for the simulations.

For all prosumers one Summer and Winter representative weeks (Monday to Sunday) were gathered from the data files, in order to get a better sense their normal behaviors. Those weeks were chosen based on a whole season analysis, that allowed to pick the most representative weeks, being those the ones with less or no irregularities (associated with holidays, missing data or outliers). From these specific weeks, four day-types were picked for the simulations in the AIMMS software, two for each season (Winter and Summer), two week-days and two weekend-days. As the data was not all from the same year, it was considered irrelevant to pick the precise same dates for the weeks and days chosen for examination.

The simulations are hourly based since the data available was mostly on this format. Although this time-step is common in the literature, as mentioned in Chapter 2.6, it may also be considered less reliable when more realistic results are intended. However, since the energy system considered for the simulations is a hypothetical one, it was considered reasonable for the purpose of behavior demonstration.

Residential Building 1

It is possible to observe daily patterns having load peaks presumably associated with higher occupancy of the houses and, thus, use of electrical appliances: in the morning before work/school, late afternoon when people return home, cook and have dinner, and after dinner, when people have leisure time. The Winter and Summer profiles do not diverge very significantly in terms of base load, which is around 10 kW with daily peaks that go from 20 kW to 90 kW.

From the daily load profiles, it can be concluded that there is a tendency for higher power consumption in the Winter season, which might be associated with the use of electrical heating devices, and higher during the weekend, which might be due to more hours spent at home on those days, and hence more consumption.

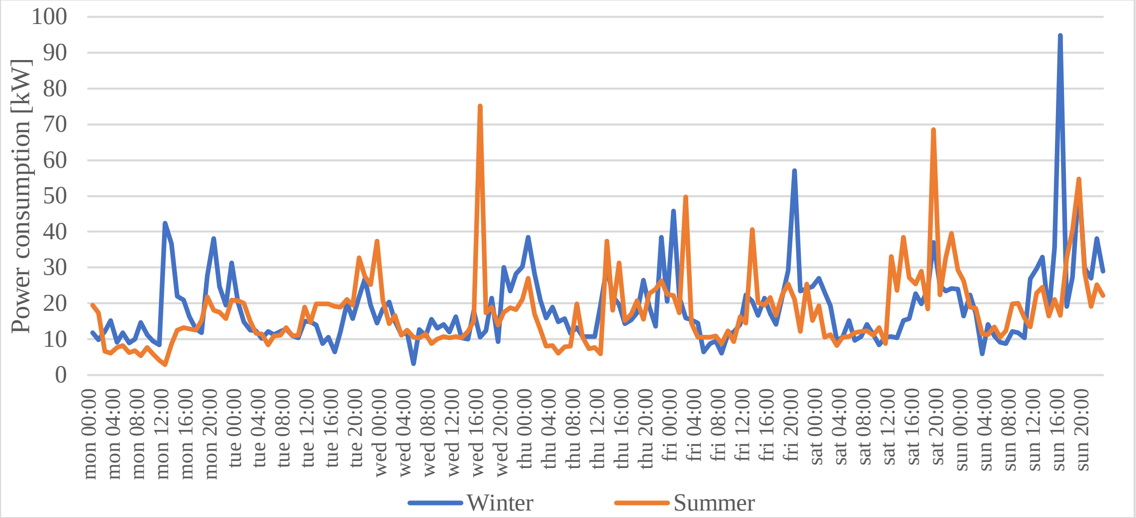


Figure 3.3 – Power consumption in kW of Residential building 1 (R1), for a representative Winter and Summer week

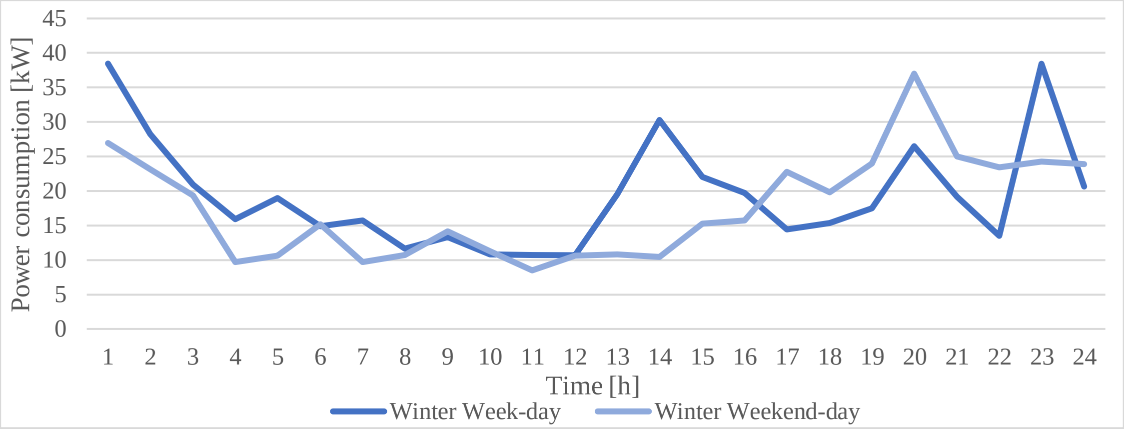


Figure 3.4 - Residential building 1 (R1): daily power consumption profiles for a representative Winter week- and weekend-days, as used for the simulations in the AIMMS software

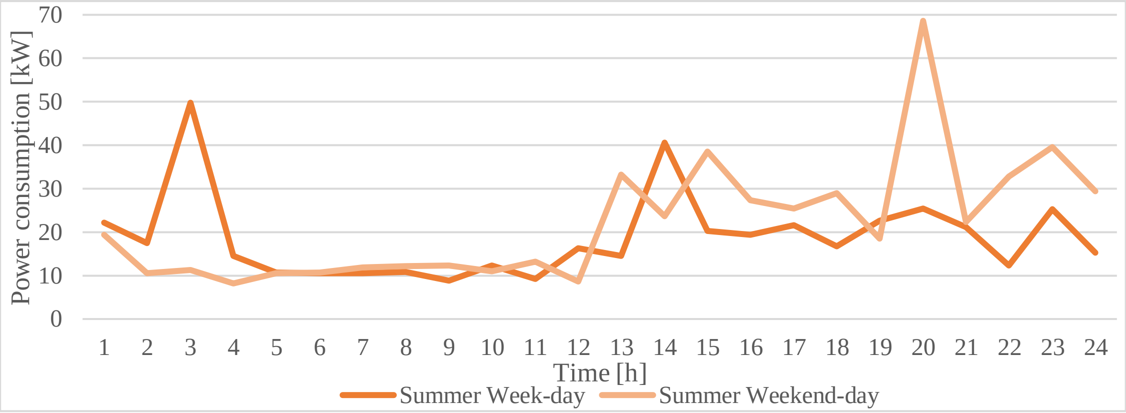


Figure 3.5 - Residential building 1 (R1): daily power consumption profiles for a representative Summer week- and weekend-days, as used for the simulations in the AIMMS software

Residential building 2

There are no clear differences in the weekly profiles as to which season displays higher power consumption. The base load in both cases is approximately 10 kW, peaking from 20 kW to 75 kW, in the winter, and 60 kW in the summer.

There is no evident pattern for the consumption peaks, as opposed to the residential building 1, which may be explained if this profile is the result of an aggregation of different household profiles, that may have very diverse daily habits regarding house occupancy and electricity needs.

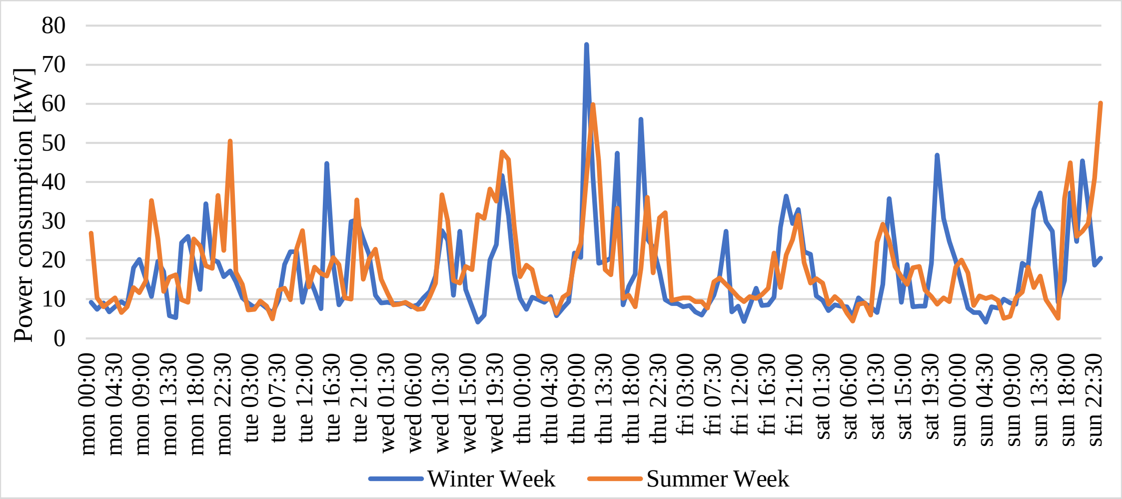


Figure 3.6 - Residential building 2 (R2): Power consumption in kW for a typical summer and winter week

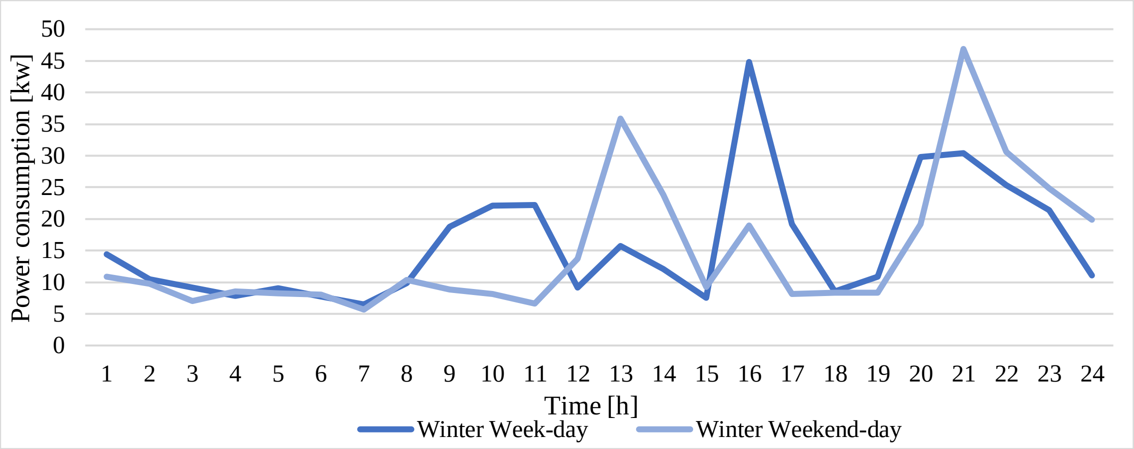


Figure 3.7 - Residential building 2 (R2): daily power consumption profiles for a representative Winter week- and weekend-days, as used for the simulations in the AIMMS software

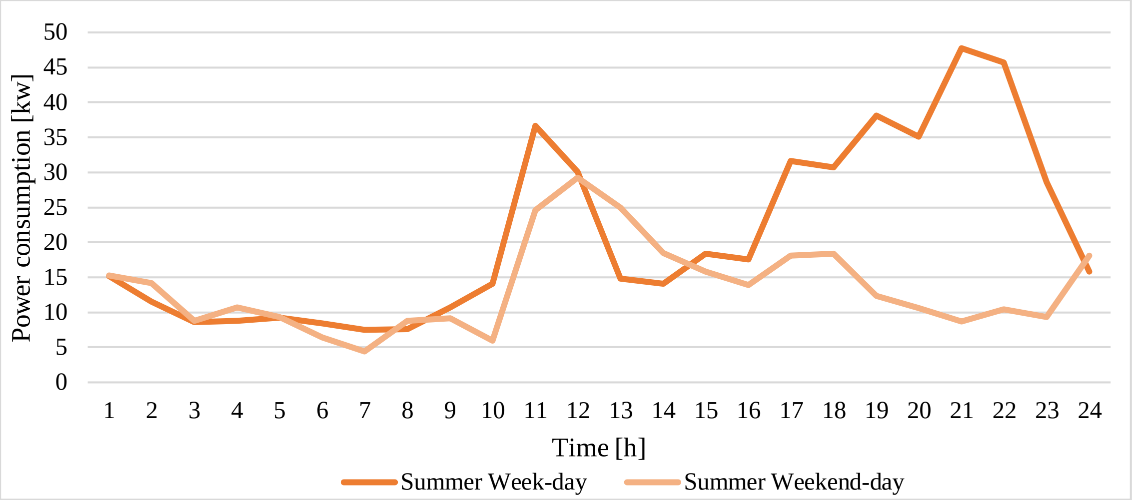


Figure 3.8 - Residential building 2 (R2): daily power consumption profiles for a representative Summer week- and weekend-days, as used for the simulations in the AIMMS software

School

For the School there is a clear daily pattern for all seven days of the week, suggesting a schedule from 8 AM to 6 PM during the winter, and 8 AM to 5 PM during the summer. Throughout the active hours the consumption is relatively constant, decreasing about 10 kW after that, which may be related to after-school activities or cleaning. After this the consumption drops back to the baseline, 20 kW. During the activity hours the load is maintained between 50 and 60 kW during the winter, and around 40 kW during the summer. As it would be expected, the consumption is lower in the summer, since there are no classes. During weekends the consumption corresponds to the base load.

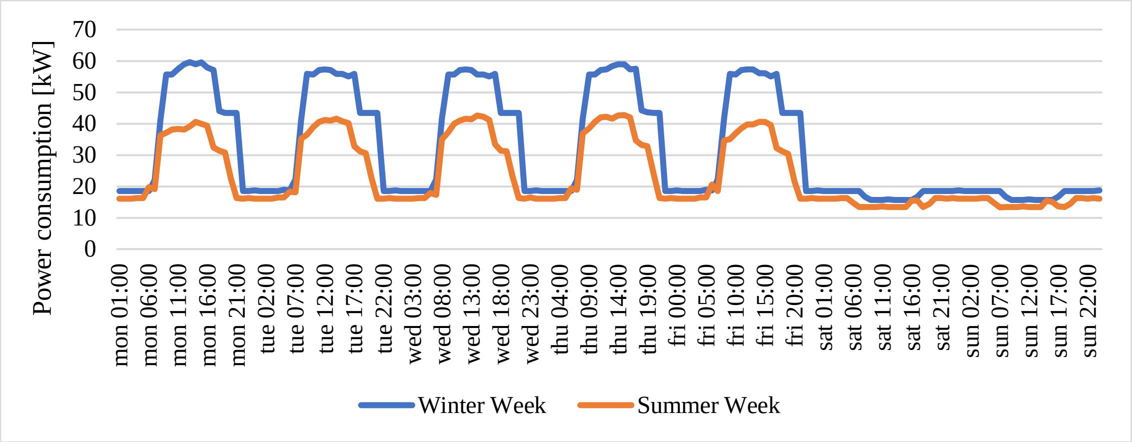


Figure 3.9 – School: Power consumption in kW for a representative Spring and Winter week

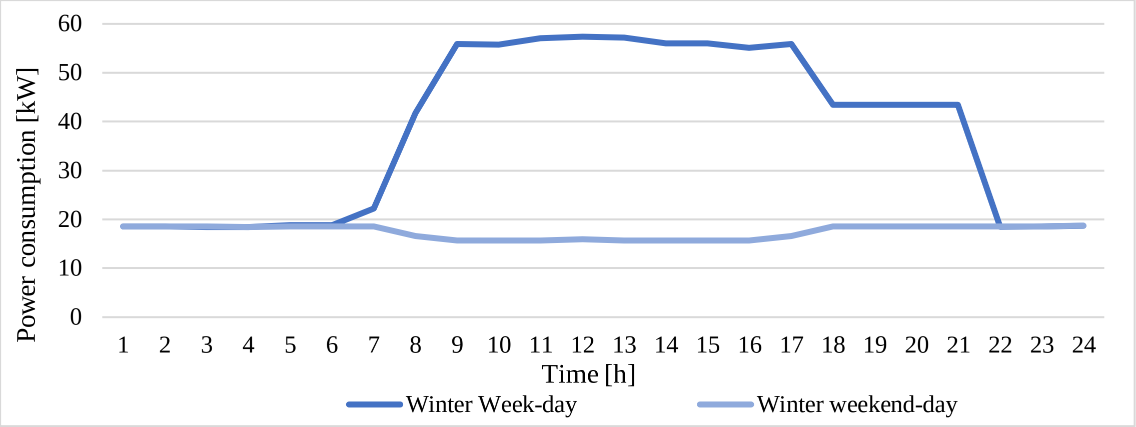


Figure 3.10 – School: Daily power consumption profiles for a representative Winter week and weekend-day in kW, as used for simulations in the AIMMS software

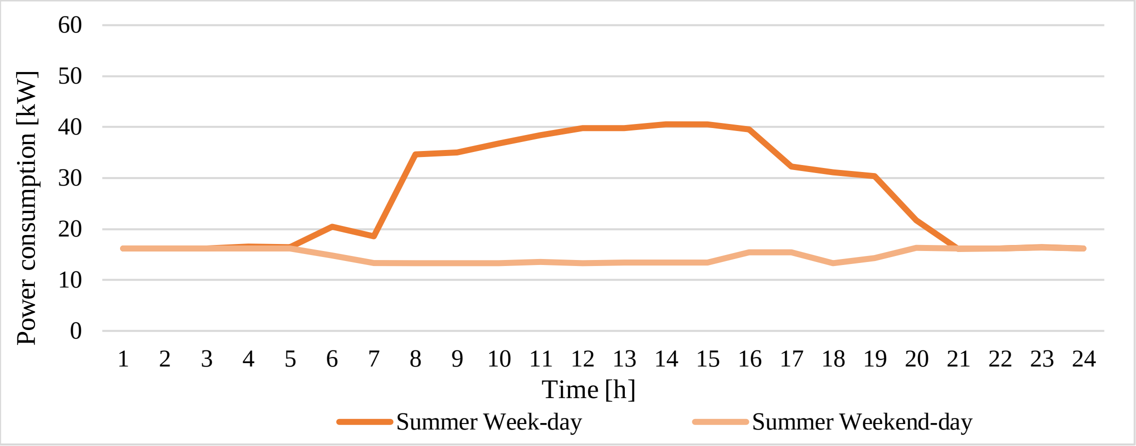


Figure 3.11 - School: Daily power consumption profiles for a representative Summer week and weekend-day in kW, as used for simulations in the AIMMS software

Bank

The weekly curves suggest well-defined daily load patterns for winter days, with five days a week of work activity from 08:45 AM to 8:45 PM, peaking at around 6 kW. After 8:45 PM to the load drops sharply to 2 kW, due to the inexistence of activity. During the night the load stays at 2 kW.

During the summer week the pattern is slightly more irregular, peaking during the period 8:30 AM - 10:45 PM, reaching up to 6 kW after the office hours, which might suggest the use of cooling chiller. During the weekends, when there is no activity, there are peaks of consumption in the winter, small ones, and in the summer, bigger ones, suggesting, again, the working of heating and cooling systems.

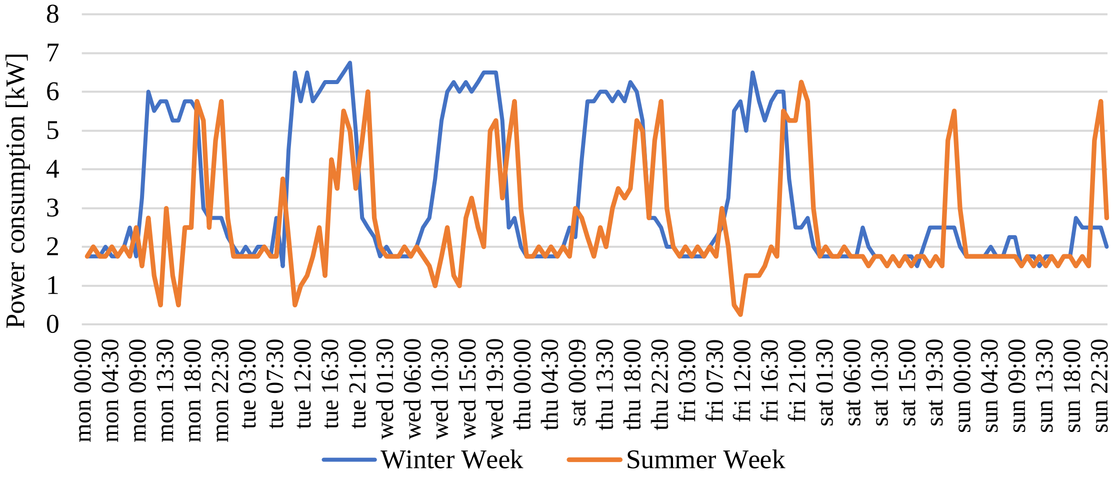


Figure 3.12 – Bank: Power consumption in kW for a representative Summer and Winter week

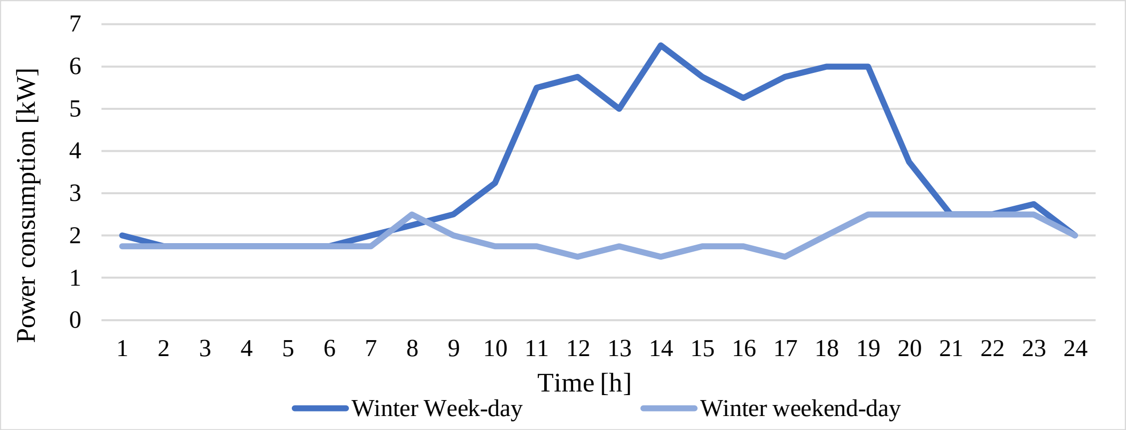


Figure 3.13 - Bank: Daily power consumption profiles for a representative Winter week and weekend-day in kW, as used for simulations in the AIMMS software

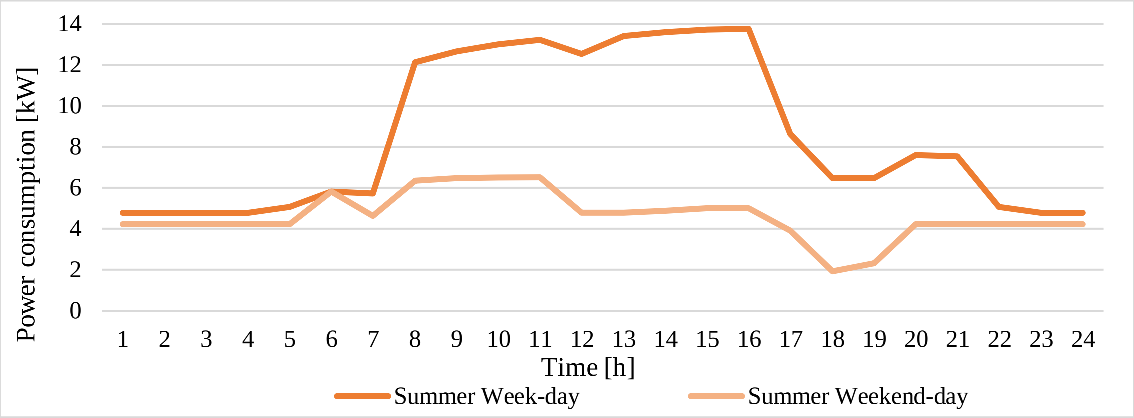


Figure 3.14 - Bank: Daily power consumption profiles for a representative Summer week and weekend-day in kW, as used for simulations in the AIMMS software

Restaurant

For the restaurant, clear patterns can be observed for week days and weekend days for both seasons. The base load is very similar during both weeks (7 kW), although the values suggest that in the summer the closing time is earlier (11 PM) than in the winter (0 PM). The restaurant is open seven days a week, but in the winter, there is a higher load peak, from 6 PM to 7 PM (23 kW), related probably with dinner time.

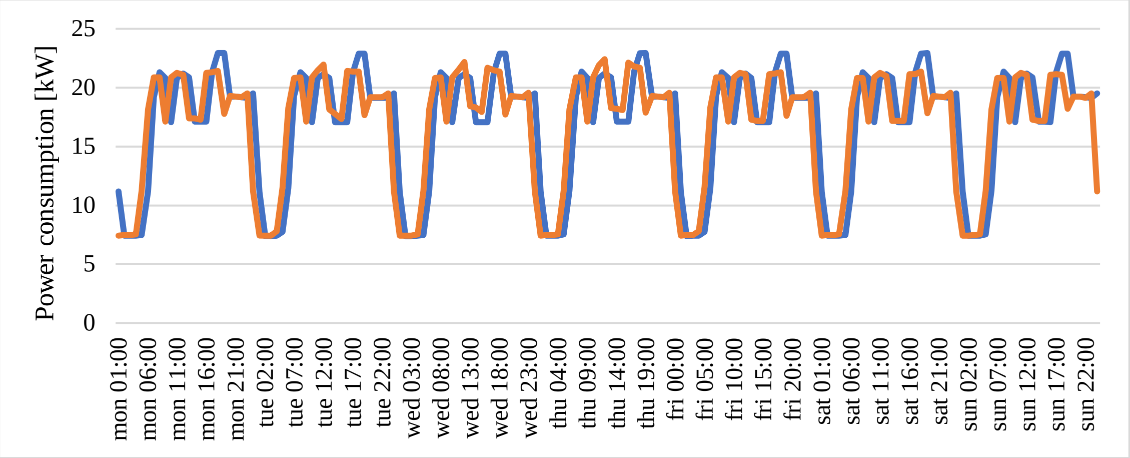


Figure 3.15 – Restaurant: Power consumption in kW, for a representative Summer and Winter week

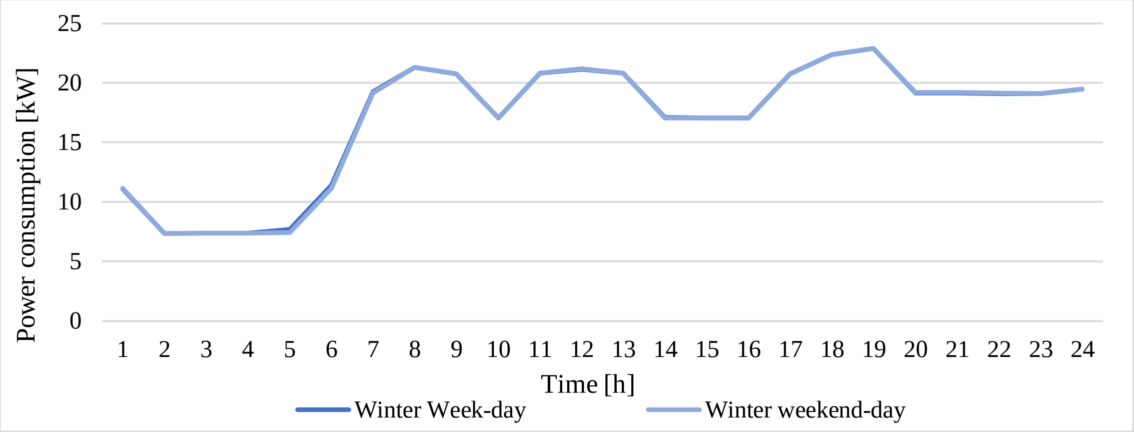


Figure 3.16 – Restaurant: Daily power consumption profiles for a representative Winter week and weekend-day in kW, as used for simulations in the AIMMS software

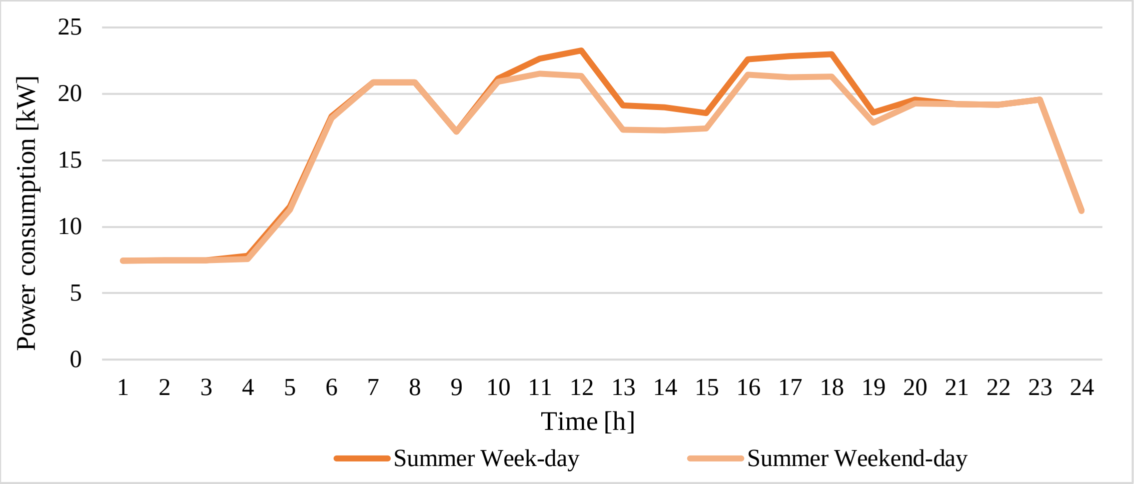


Figure 3.17 - Restaurant: Daily power consumption profiles for a representative Summer week and weekend-day in kW, as used for simulations in the AIMMS software

Office

Finally, for the office the weekly patterns for both summer and winter are evident, having similar base loads (5 kW, for week-days, and 2-4 kW during the weekend). During the weekend it seems to exist some minor occupation of the office on 8 AM to 11AM, and no activity on Sunday, when probably all the computers, screens and other electrical devices are shut down. The power consumption is apparently higher during Summer, probably due to cooling. The working hours for week-days seem to be from 8 AM to 9 PM, after which the consumption drops to its baseline.

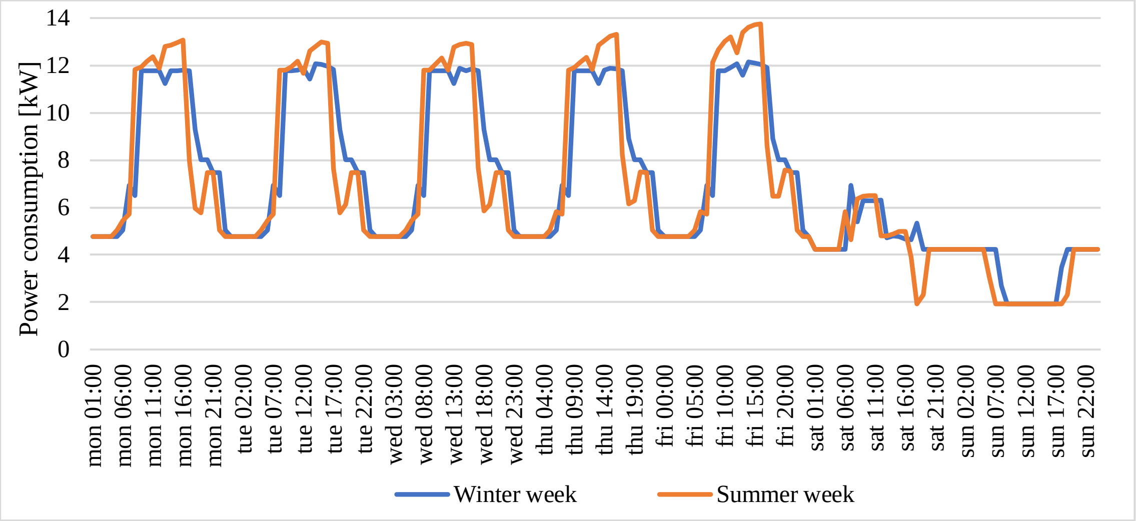


Figure 3.18 - Power consumption in kW of the Office, for a representative Summer and Winter week

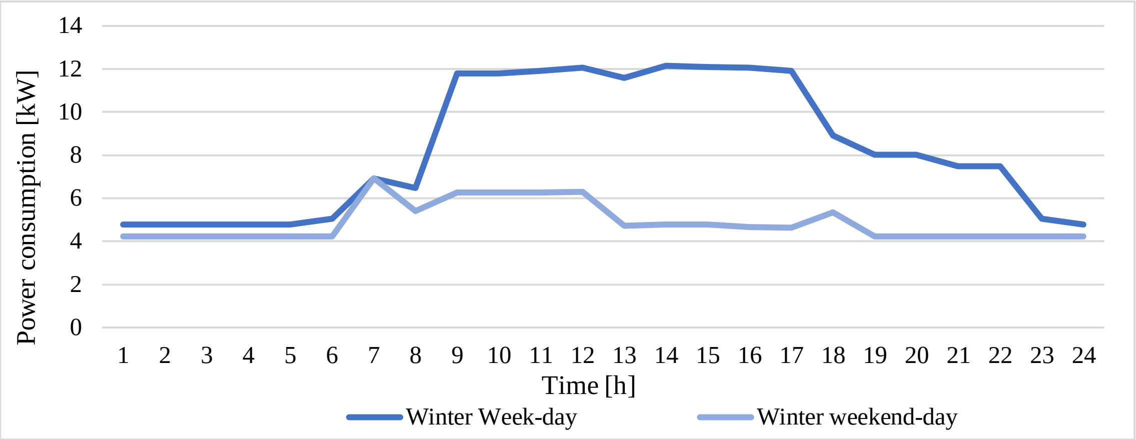


Figure 3.19 – Office: Daily power consumption profiles for a representative Winter week and weekend-day in kW, as used for simulations in the AIMMS software

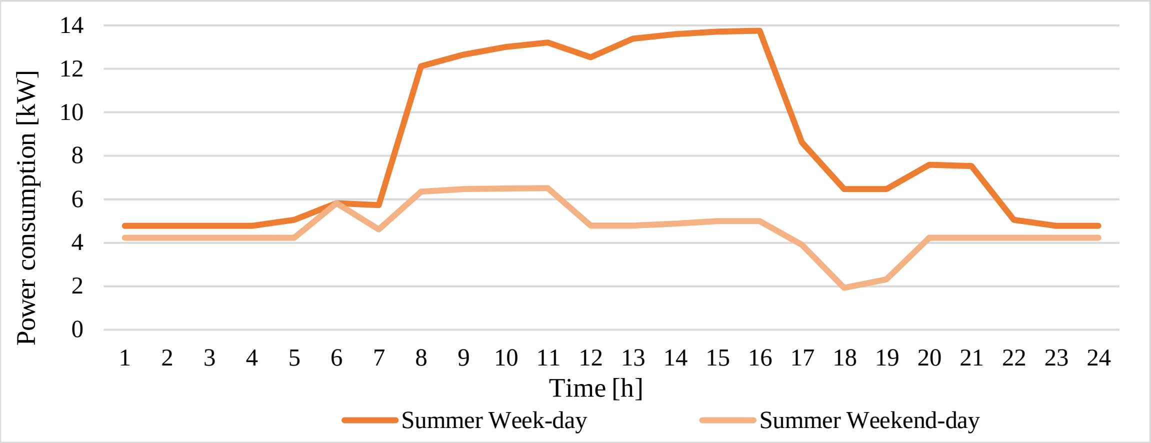


Figure 3.20 - Office: Daily power consumption profiles for a representative Summer week and weekend-day in kW, as used for simulations in the AIMMS software

3.4 Price Structure

According to ERSE [56], the entity responsible for the Portuguese energy market regulation, the tariff structure is based on a differentiation by voltage level, which translates into three types of tariffs: high and medium voltage (AT/MT), special low voltage (BTE) and normal low voltage (BTN). Each tariff is divided into a fixed term, payed on monthly basis, and an active energy price (euros per kWh). As for electricity retailers, EDP Comercial represents around 83% of the energy consumed [57]. For that reason, it was assumed that all consumers in the simulated microgrid are EDP customers, and the prices considered where stablished accordingly [58].

For simulation purposes, it is also assumed that, from the six prosumers considered, the residential ones have contracted the electricity tariff type BTN, and the others (restaurant, bank, school and office) the BTE tariff.

From the document “Caracterização da Procura de Energia Elétrica em 2018” [59], the majority of the BTE clients adopts the MU (medium utilization) option. The corresponding prices can be seen in Figure 7.1 in chapter 7, wherein values of periods I and IV were assumed for the winter season prices and values of periods II and III for the summer season.

Regarding the BTN clients, the voltage option chosen was 6.9 kVA, and the tariff was the simple, since it is what the large majority of these clients choose [56], meaning that it was assumed the same energy price regardless of the time of day, fixed at 0,165 €/kWh for the year of 2018.

In Portugal’s power sector the charging of the active energy consumed by the users is calculated based on a time-of-use scheme, meaning that different prices are defined according to the time of the day, making a distinction between peak load hours, full hours e no-load hours. Table 7.1 in chapter 7 shows the prices used for the simulations for the winter and summer seasons.

As mentioned in Chapter 2.3.2, the remuneration for energy produced in surplus by self-consumption units is calculated based on the closing monthly average market price for the Iberic market operator. The value attributed per unit of surplus energy fed into the grid corresponds to 90% of that price.

Based on the most recent available values [60], shown in Figure 3.21, an average for the winter and summer months was adopted for defining such price. For the winter season simulations, the price was considered to be 5,5 cent/kWh and for the summer season 6,2 cent/kWh.

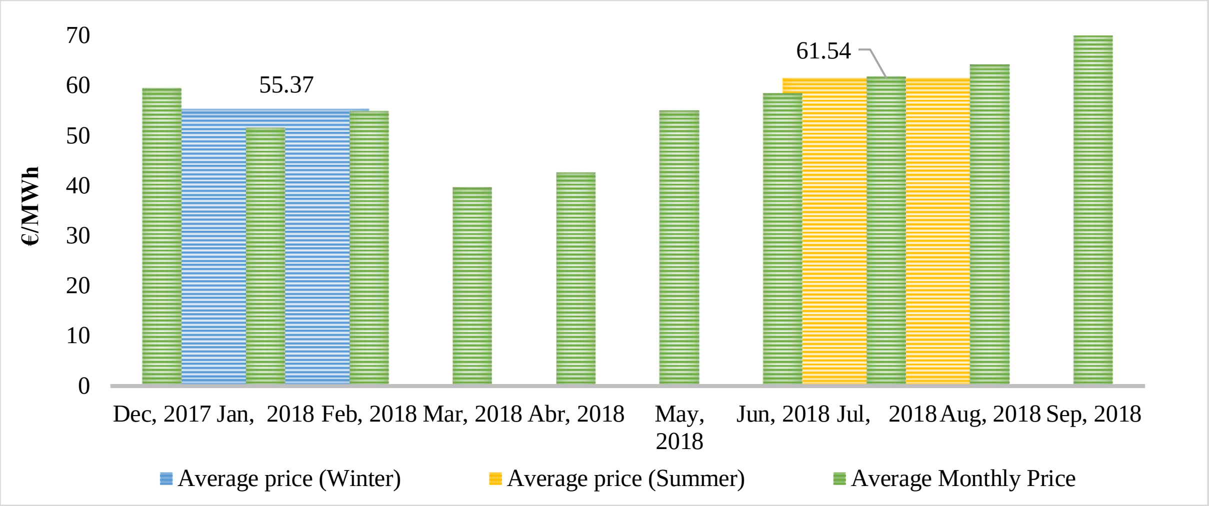


Figure 3.21 – Average monthly closing market price as defined by the Iberian Energy Market Operator, and average prices for the winter and summer months, as considered in the simulations

4. Results and Discussion

This section presents an analytical overview on the results obtained from the simulations of the two energy exchange management models and the base scenario. The results are compared, firstly, based on self-consumption and local energy market behavior and outcomes. Secondly, a financial analysis is presented, comparing costs and revenues of the decentralized management model with the base scenario. As the centralized model does not allow for a complete examination on the financial outcomes, since it was built in a way that keeps some information imperceptible (e.g. the prices practiced in the local energy market), it was not considered in the financial analysis. Finally, a contextualization of the results in the current Portuguese legal constraints is made, according to what is planned in the already mentioned Decree-Law nº 153/2014.

For each season, Figure 4.1 shows the microgrid's load diagram in terms of demand and production.

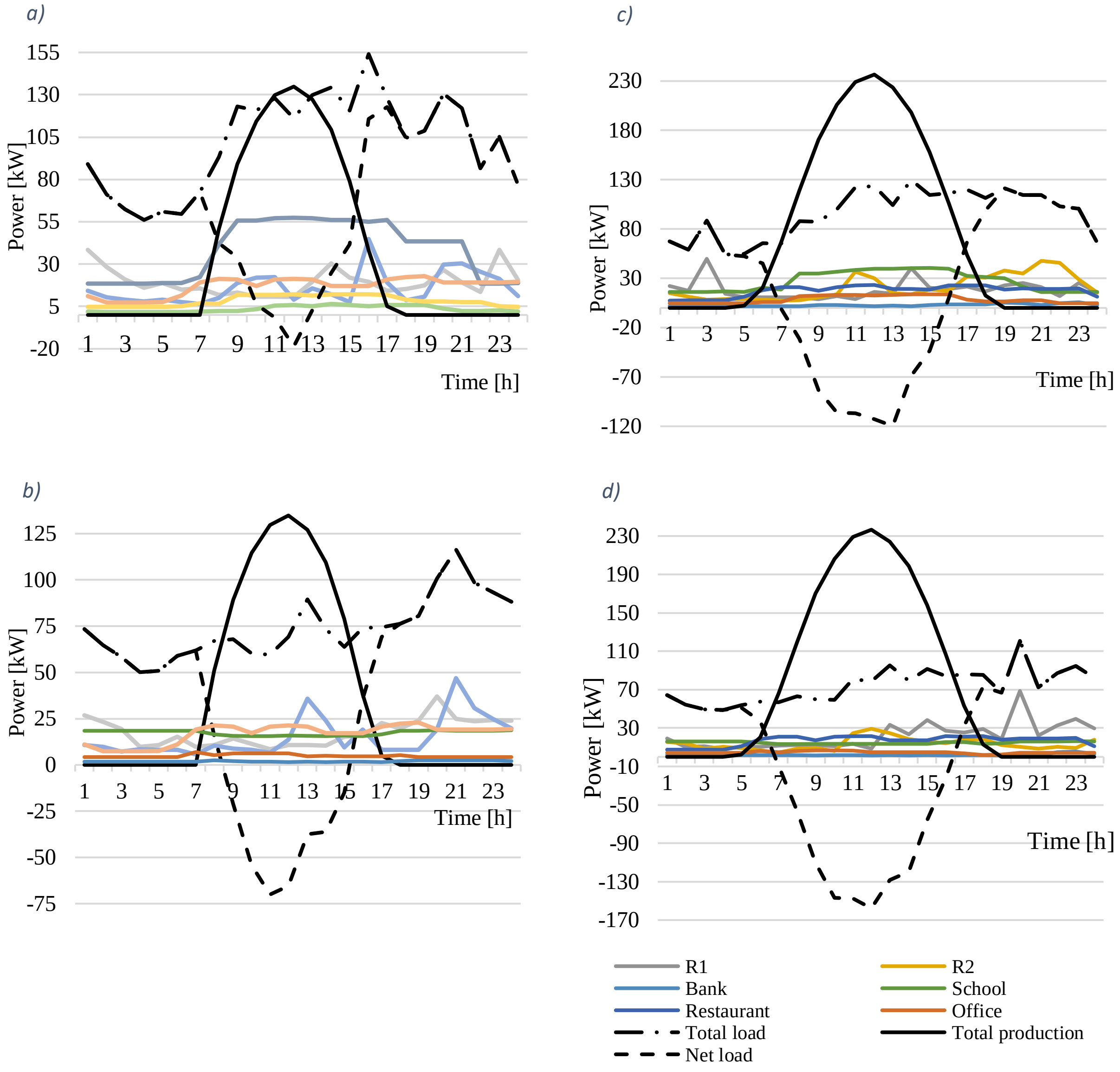
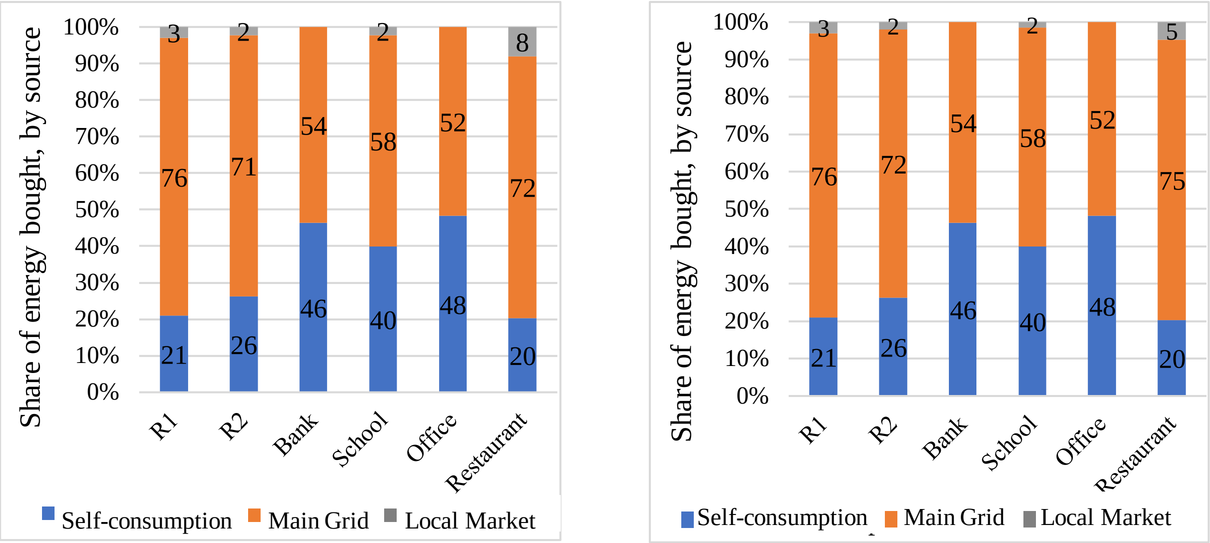


Figure 4.1- Daily load and production profiles for the microgrid, individual loads and net load, for a) winter week-day,b) winter weekend-day,c) summer week-day and d) summer weekend-day

A discriminated analysis by prosumer was made, for each model, in order to realize in greater detail where the differences occur between them. The graphs below show for each prosumer in the MG, for each model type, the shares of energy bought from the grid, bought from the MG local energy market and self-consumed PV energy from each one's own production unit. The summation of these three values represent the prosumer's individual energy demand.

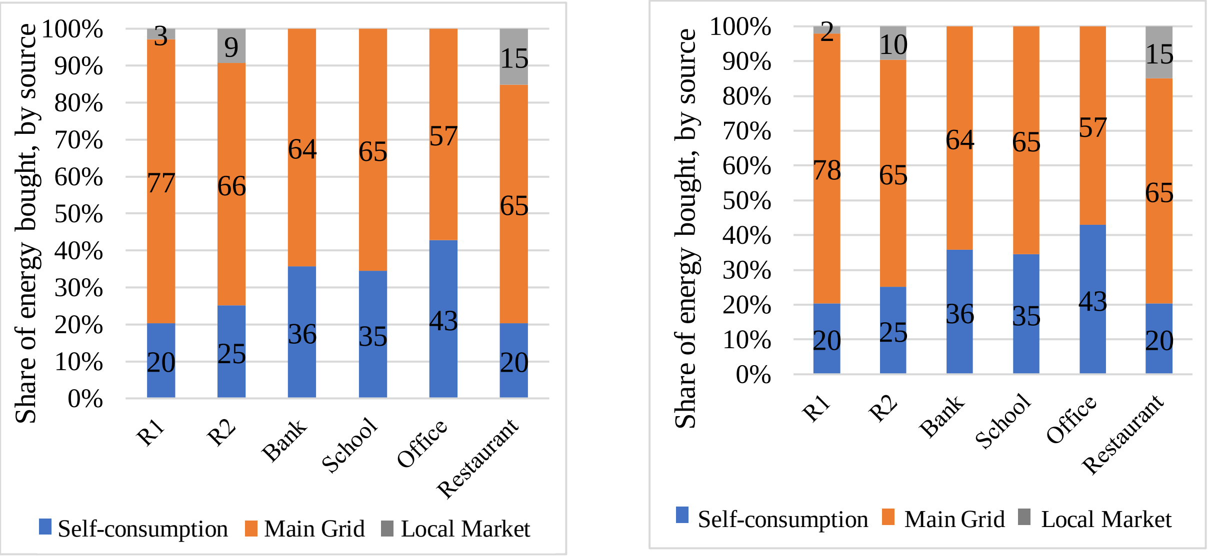


(a) Centralized Model *(b) Decentralized Model*

Figure 4.2- Winter week-day: Share of energy consumed daily by each prosumer, by source (self-produced PV energy, energy from the main grid or energy from the local energy market), for the centralized (a) and decentralized (b) models

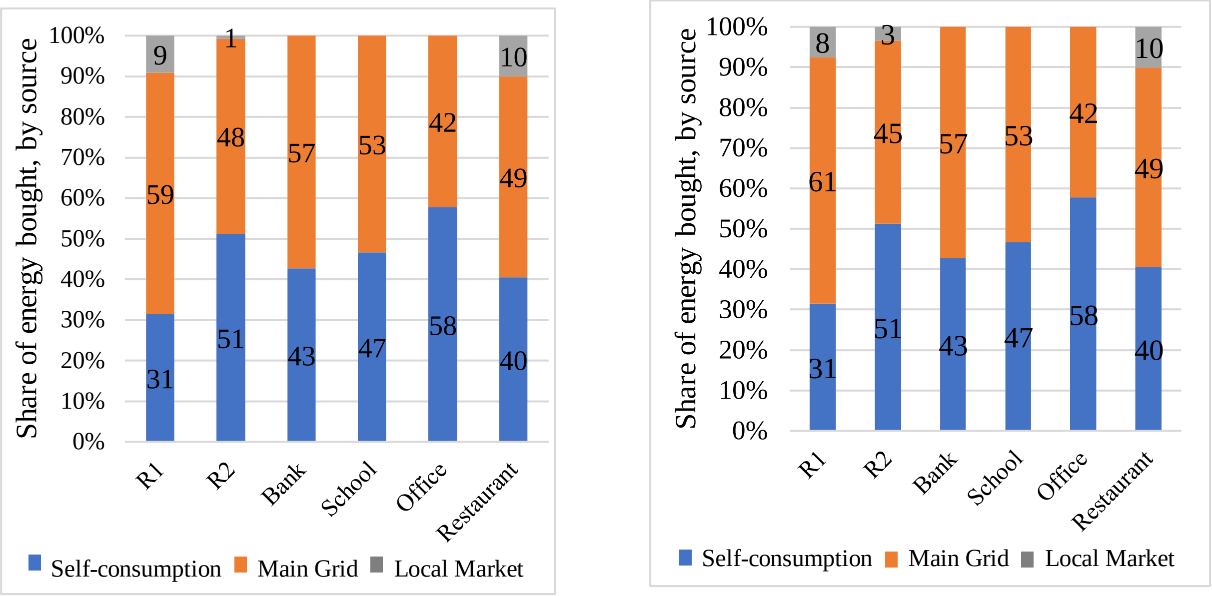
From this first graphs, it is possible to see that in the centralized model the restaurant chooses to buy more energy from the local energy market. As mentioned already, this was simulated under a financial optimization optic, and so it can be assumed that the justification for this difference is in the costs.

The figures below allow for a better visualization of the differences between the centralized and decentralized models, and individual prosumer buying choices for the rest day-types simulated.



(a) Centralized Model *(b) Decentralized Model*

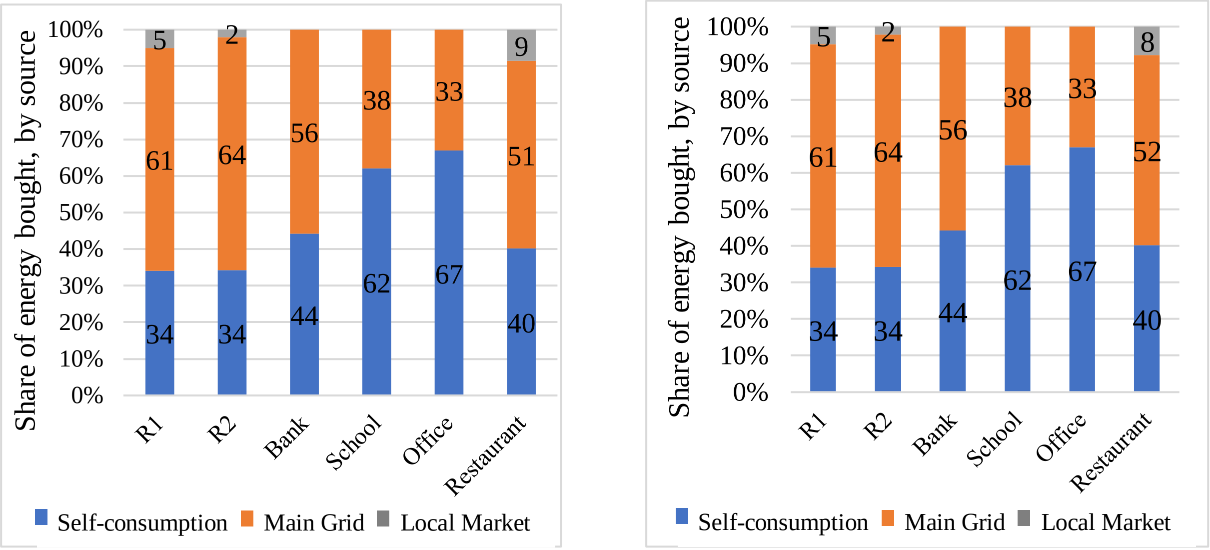
Figure 4.3 – Winter weekend-day: Share of energy consumed daily by each prosumer, by source (self-produced PV energy, energy from the main grid or energy from the local energy market), for the centralized (a) and decentralized (b) models



(a) Centralized Model

(b) Decentralized Model

Figure 4.4 – Summer week-day: Share of energy consumed daily by each prosumer, by source (self-produced PV energy, energy from the main grid or energy from the local energy market), for the centralized (a) and decentralized (b) models



a) Centralized Model

(b) Decentralized Model

Figure 4.5 - Summer weekend-day: Share of energy consumed daily by each prosumer, by source (self-produced PV energy, energy from the main grid or energy from the local energy market), for the centralized (a) and decentralized (b) models

In summary, the highest amount of self-produced energy consumption per prosumer obtained is 67%, in the summer weekend-day case, for both models studied. specifically, in this case, by the office. This can be explained by the good match between this prosumer's production and consumption profiles. Regarding the share of energy consumed from the local energy trade system, the highest value obtained in the simulations was 15%, by the restaurant, in the winter weekend-day.

4.1 Self-Consumption results comparison

As mentioned before, two different days from two seasons were analyzed, in a total of four scenarios: a summer and winter week-day and weekend-day. Both the centralized and decentralized management models were simulated for each type of day. This section compares the results from the two models with each other, and with the base scenario, in order to draw conclusions on the hypothetical benefits of the optimized management models. Figures 4.6 to 4.9 allow a comparison between the level of self-consumption obtained for each management model, and for the base-scenario.

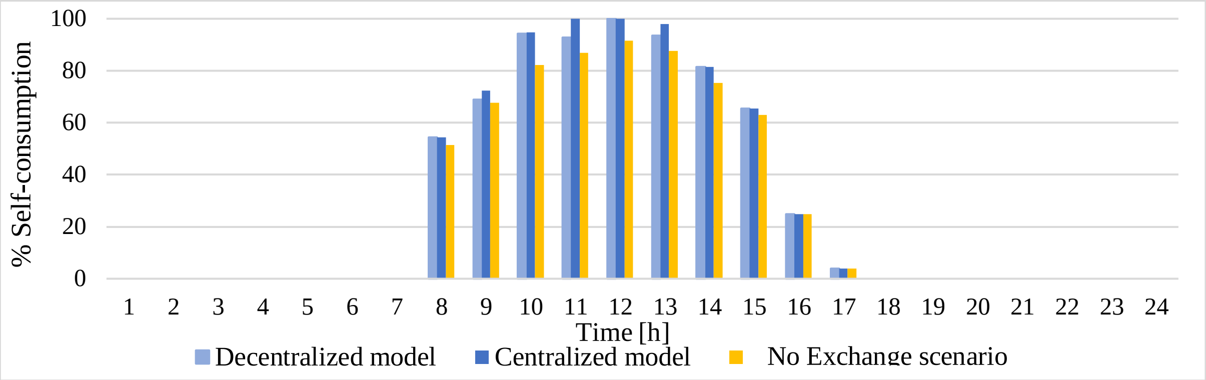


Figure 4.6 – Winter week-day: Self-Consumption, in %, of the whole microgrid, for the centralized and decentralized management model and base scenario with no exchange between prosumers

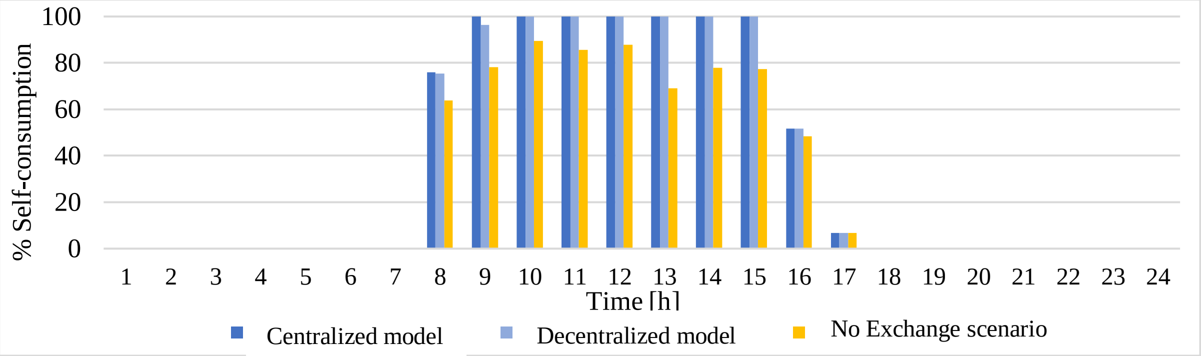


Figure 4.7 – Winter weekend-day: Self-Consumption, in %, of the whole microgrid, for the centralized and decentralized management model and base scenario with no exchange between prosumers

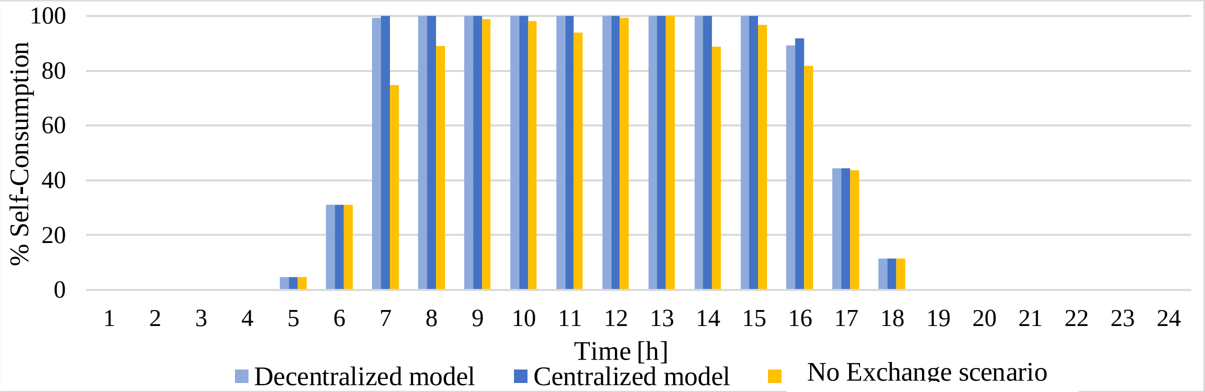


Figure 4.8 – Summer week-day: Self-Consumption, in %, of the whole microgrid, for the centralized and decentralized management model and base scenario with no exchange between prosumers

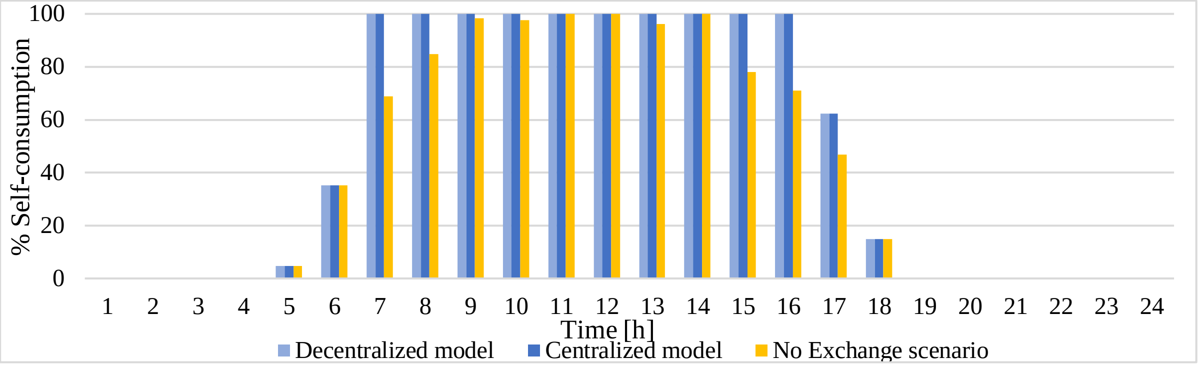


Figure 4.9 – Summer weekend-day: Self-Consumption, in %, of the whole microgrid, for the centralized and decentralized management model and base scenario with no exchange between prosumers

The results show that, as expected, the no exchange scenario is the one with lower values of self-consumption, for both week and weekend days, winter and summer. This difference is particularly noticeable on the weekend. It is also possible to observe that, for some hours of the day, the decentralized model results are worse than the centralized model ones, namely in the extremes of the photovoltaic production period. In order to better understand the models' differences further analysis were made, based on costs and energy availability.

From the comparisons between self-consumption values, it is noticeable that as much as 30% extra self-consumed power is reached on an hourly basis by the energy exchange models in comparison with the base scenario.

Figure 4.10 shows the average values for the whole four types of days, in terms of comparative self-consumption reached for the three cases studied.

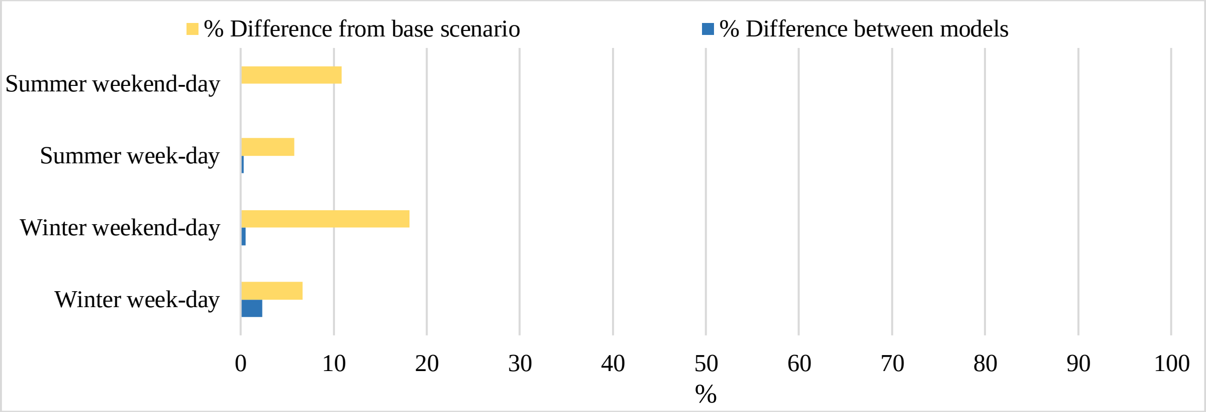


Figure 4.10 - Differences in % between the two management models and between the model's self-consumption and the base scenario for the whole microgrid, for each day type

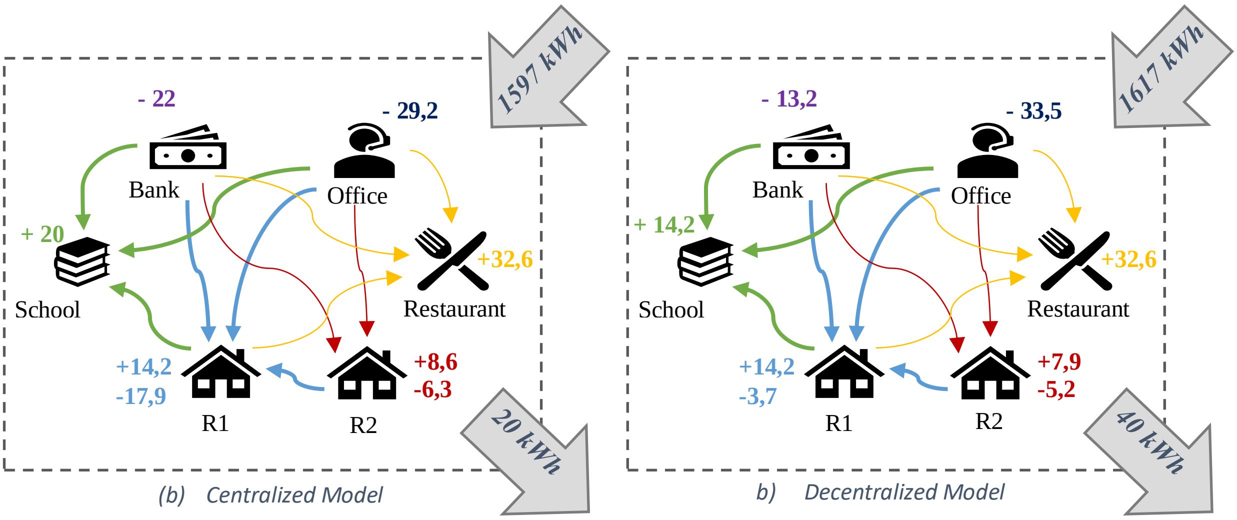
The most expressive divergence, 2,3%, occurs on the winter week-day. For the summer weekend day there is no difference at all between the models. As for the comparison between the models with local energy market and the base scenario, results show that for all studied day-types there are considerable increases on the self-consumed values, on average 10,3%.

It can be concluded by this comparison that differences in self-consumption obtained between the management models are residual, although for the winter season the centralized management approach reaches better results.

From the above results, it seems appropriate to make a connection between the differences observed between the management models and the availability of energy in the local microgrid market in the winter, particularly during the week in the early morning or late afternoon, when there is less energy available to trade since the production matches the demand more closely. By the general rules of a market, when there is high demand and offer is little, the prices rise, which is supposed to happen in the decentralized model. This goes accordingly to the intended behavior, since in this model there is no knowledge in advance of the daily production profile of oneself and the others. Therefore, when there is less available energy in the market, the prices rise, making a less attractive option to buy energy locally instead of from the main grid.

4.2 Energy flows analysis

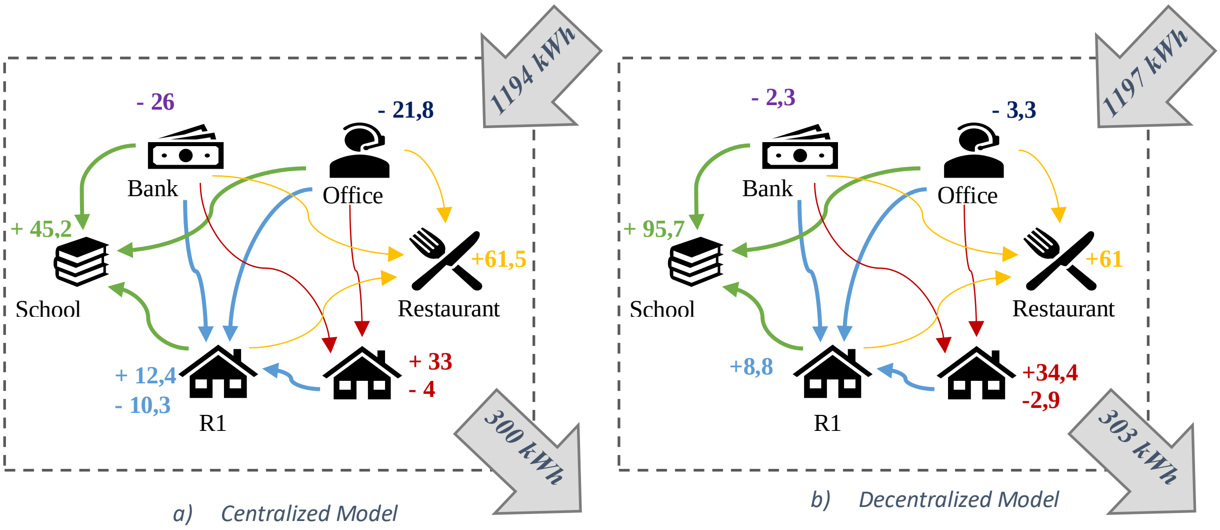
Figures 4.11 to 4.14 represent for each day type, the energy flows within the microgrid for both the centralized and decentralized models. Each color represents the energy bought by one specific prosumer, pointing towards him. The values with a '+' sign indicate the total daily energy bought by each prosumer from the local energy market, and the '-' sign indicates the energy sold. The grey arrows pointing in the right corner to inside the microgrid's boundaries represent the whole energy bought from the main grid, and the ones below, pointing outside, the energy injected into the main grid.



(b) Centralized Model

b) Decentralized Model

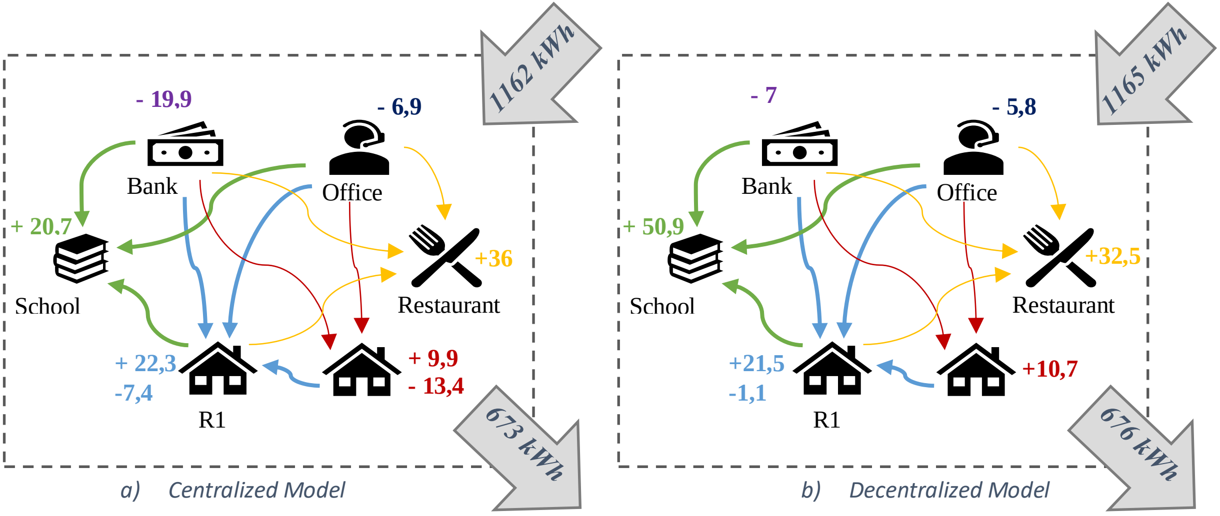
Figure 4.11 - Winter week-day: Energy flows, in kWh, of the microgrid for the centralized (a) and decentralized (b) models



a) Centralized Model

b) Decentralized Model

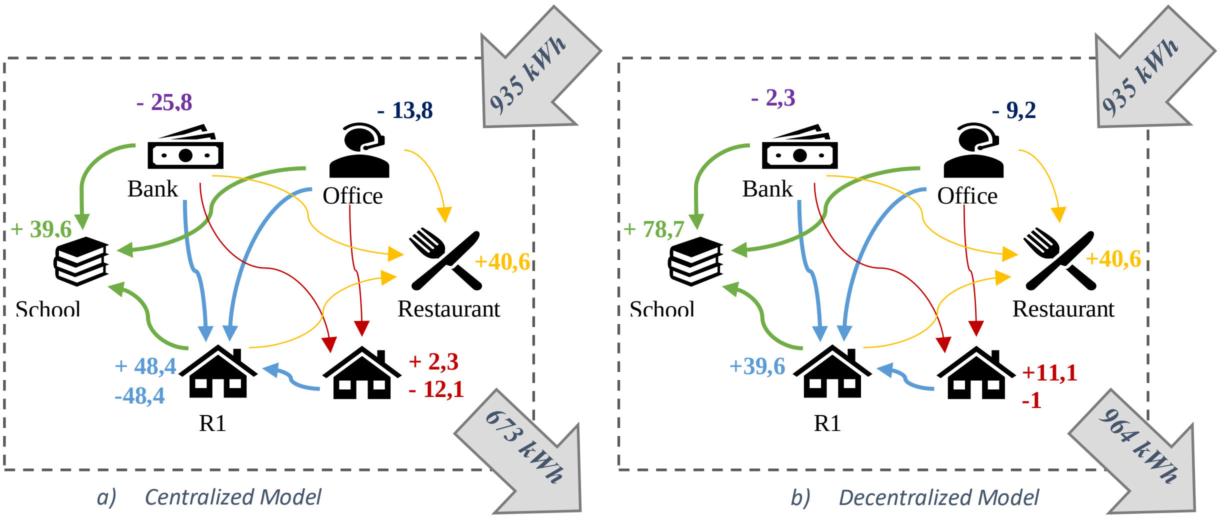
Figure 4.12 - Winter weekend-day: Energy flows, in kWh, of the microgrid for the centralized (a) and decentralized (b) models



a) Centralized Model

b) Decentralized Model

Figure 4.13 - Summer week-day: Energy flows, in kWh, of the microgrid for the centralized (a) and decentralized (b) models



a) Centralized Model

b) Decentralized Model

Figure 4.14 - Summer weekend-day: Energy flows, in kWh, of the microgrid for the centralized (a) and decentralized (b) models

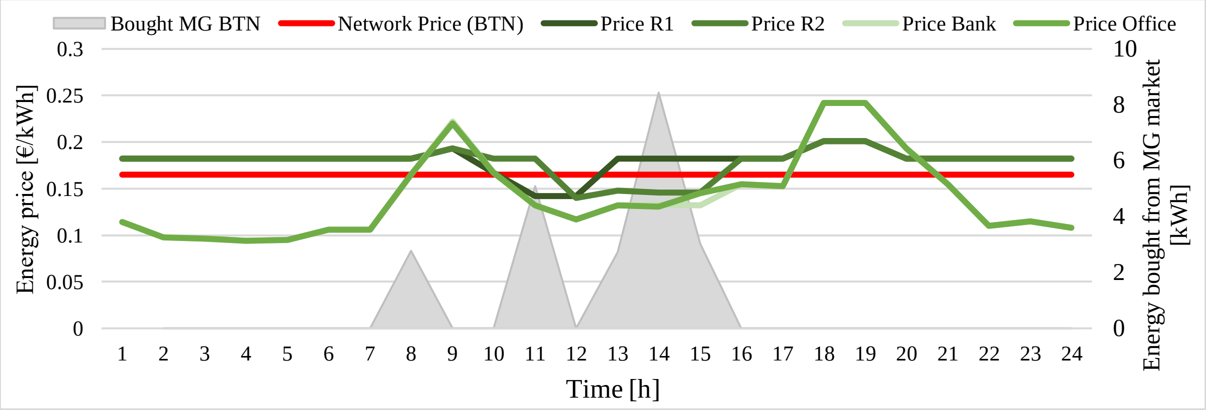
As seen before, in all scenarios the self-consumption is sometimes lower in the decentralized management model, particularly in the winter, as is better observed from Figure 4.11. This can be concluded by comparison between the energy amounts bought between prosumers, but also by the total daily amount of energy bought from the main grid, which is higher for the decentralized model.

It can also be observed from these representations, that the restaurant is the biggest consumer in the local energy market, buying from all the other prosumers, followed by the residential building 1 (R1) and residential building 2 (R2). It is also interesting to point out that for instance, for the summer weekend-day, for which the difference between the models was shown to be non-existent, there are differences in the local MG tradings, exemplifying how the mathematical program is able to find more than one optimal solution for the same problem.

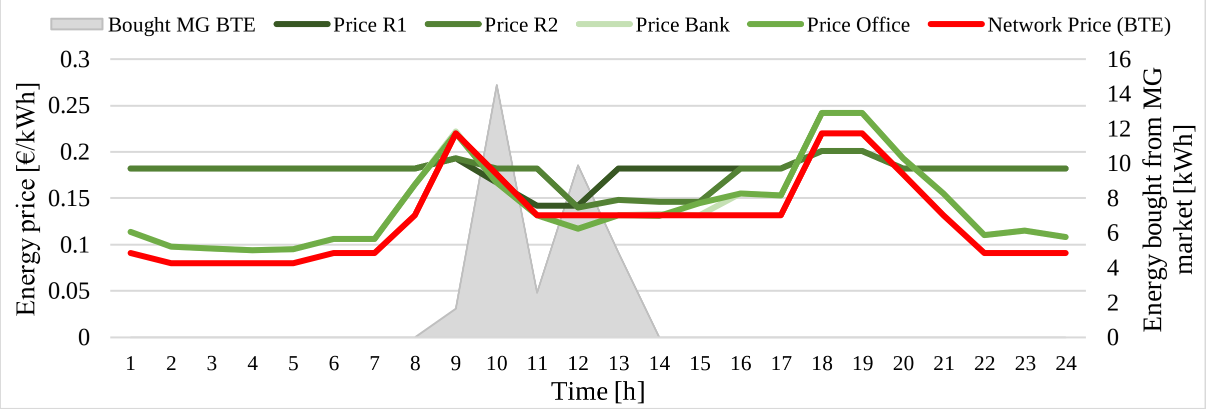
In Figure 4.15 it is visible the behavior of the prosumers regarding their buying choices in response to the price variations. The red line represents the cost of buying energy from the main grid, and the green lines refer to the prices in the local market. The figure refers to the results of the winter week day for exemplification purposes, and the rest can be found in the Annex.

When, after time-step 8, the green line matches the red line or goes over it, it is no longer profitable to buy energy from the local market, and so it can be observed a sudden drop in the energy bought by BTN clients. The same happens for BTE clients in *t*=8. Between *t*=10h and *t*=16h, the prices from the local market lines are again below the grid price in the BTN profile, and the consumption of R1 and R2 increase. For the BTE clients after the *t*= 14h it is no longer profitable to buy from the local market, and so the purchases (grey area) stop.

In Figure 4.16, energy surplus prices available for the prosumers are displayed, focusing on the time period when surplus energy is available. As shown, the surplus energy is worth significantly more, with an overall average worth of 0,13 €/kWh, or 135% valorization comparing to its value as in DL 153/2014.



a) BTN (normal low voltage) clients



b) BTE (special low voltage) clients

Figure 4.15 - Prosumers buying choices according to local energy market price variation in comparison to the network price, for a) BTN clients and b) BTE clients in the Decentralized model for a winter week-day

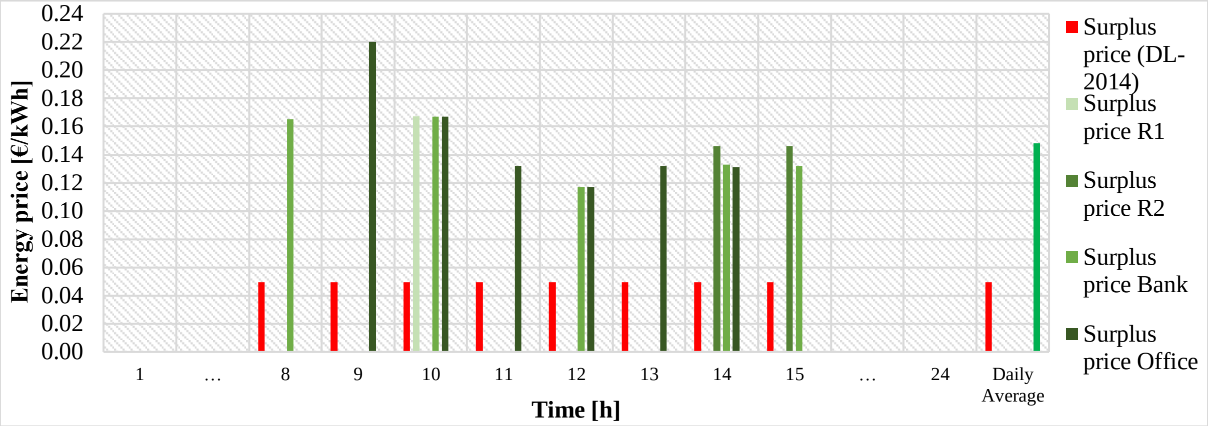


Figure 4.16 - Surplus energy value as established by the DL 153/2014 compared with the value obtained from trades on the local energy market, on an hourly basis

4.3 Financial Analysis

Figures 4.17 and 4.18 below presents the breakdown of the costs' reduction and revenues' increase by prosumer, for each day type, accomplished by the addition of a local energy market optimally managed. The results are presented in percentage, in comparison with the base scenario.

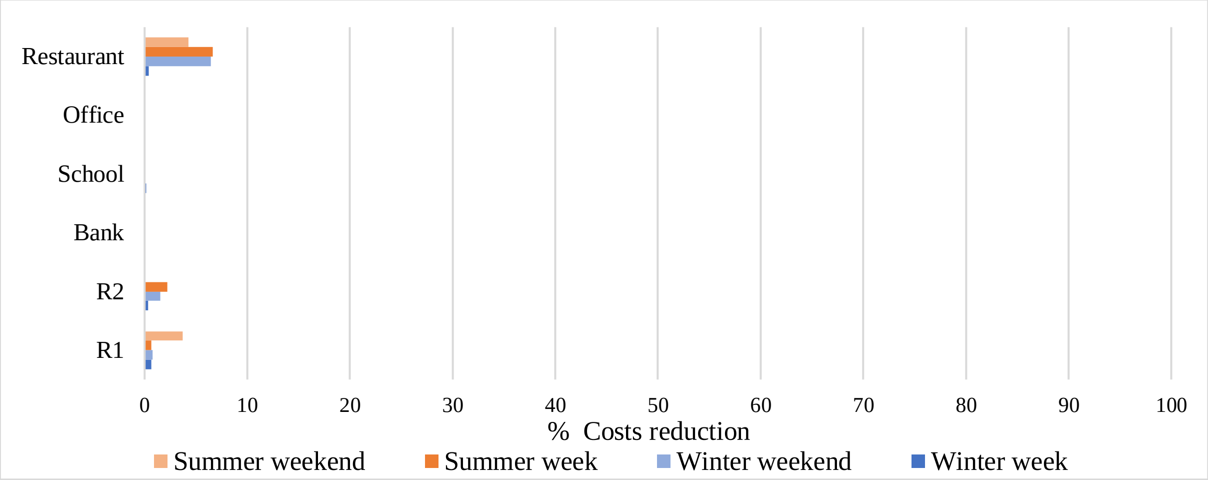


Figure 4.17 – Individual daily costs' reduction originated by using an optimization model in comparison with a base scenario of no-exchange

The biggest relative reductions are accomplished by the restaurant and residential buildings, already identified as the biggest buyers of the local energy market. On average the individual costs' reduction is 1,2%, mostly due to savings during the summer. Where the reductions are zero, for instance for the office and bank no reductions where accomplished for any day type, this means that neither fulfills their energy needs at a cheaper price than on the base scenario. As seen before, these two prosumers in particular produce sufficient energy during some hours to be self-sufficient.

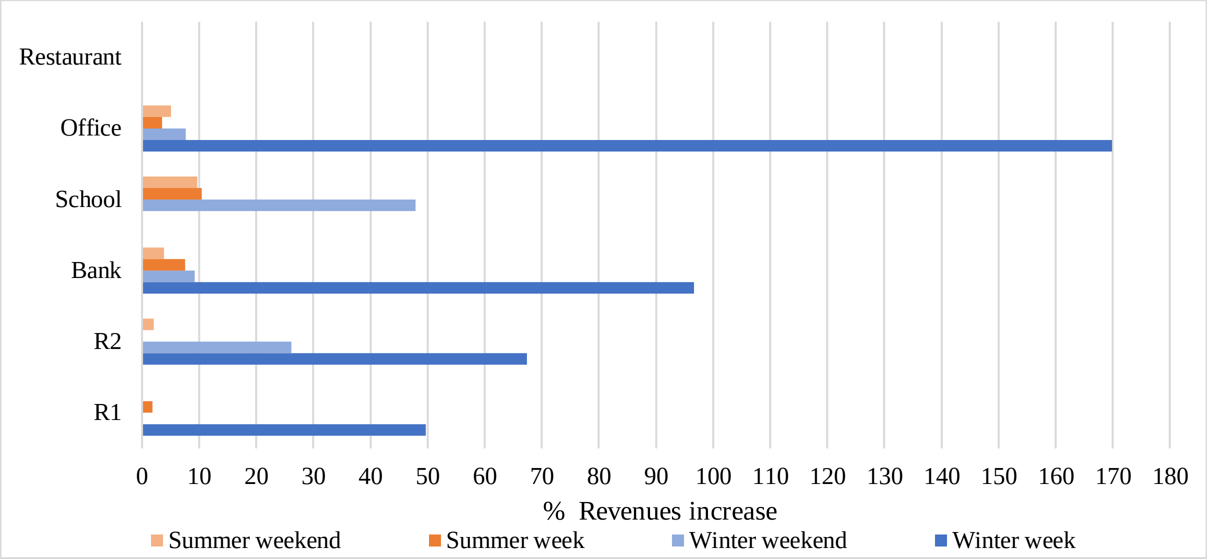


Figure 4.18 - Individual daily revenue's increase originated by using an optimization model in comparison with a base scenario of no-exchange

As for the revenue's increase, overall very positive results were obtained in the microgrid, except for the restaurant since it doesn't produce enough energy to sell on the local market. The highest increases on the revenues are verified in the winter week-day scenario, in particular for the office. An average of 21,6% increase on the revenues for each prosumer was reached over the base scenario.

The Table 4.1 shows estimated weekly savings, obtained from on Equation 3.17, compared with the no-exchange scenario in absolute and relative terms. Results show that the final weekly bill reduction is higher for the summer week simulated, in relative terms, although this doesn't translate into higher bill reductions in terms of actual payment. It can be concluded that, when considering the whole microgrid, the overall economic benefits in terms of actual savings are not so relevant for this particular case-study

Table 4.1 - Estimated Week savings for each prosumer of the microgrid, and for the total energy system

	Weekly reduction on the electricity bill			
	Winter Week		Summer Week	
	In €	In %	In €	In %
Residential 1	5,03	1,23	6,27	1,89
Residential 2	5,3	1,68	6,19	2,05
Bank	6,79	24,53	2,73	123,36
School	10,9	2,61	16,4	41,75
Office	15,88	24,84	2,5	126,70
Restaurant	6,16	2,03	12,5	5,66
Total Microgrid	50,06	3,26	46,59	5,34

4.4 Portuguese context

According to the DL nº 153/2014, for self-consumption units to be considered fit to connect to the main distribution grid:

- The nominal power of connection, meaning the maximum injected power, of the unit must be inferior to the contracted power of the consumption unit;
- The installed power of the self-consumption unit must be inferior to twice the connection power of that unit.

For the totality of the results obtained for local energy market scenarios, the maximum injected power was selected in order to conclude whether the individual production units comply with the national legislation specifications. The results can be found below on Table 4.2. The contracted power values considered for these comparisons were defined according to the maximum consumed power for the days considered in the simulations. The connection power used for the comparisons represented the maximum injected power for the whole simulations results.

Table 4.2 - Power specifications for the prosumers regarding connected, contracted and installed power

Power specifications	Office	Bank	R1	R2	School	Restaurant
Max. Connection Power	30,9	16,4	22,5	21,2	84,9	3,8
Contracted Power	13,8	6,5	68,6	47,7	57,4	23,3
Installed capacity	38,1	15,1	40,6	40,6	127,6	29

Table 4.3 below shows which of the prosumers in the simulated microgrid comply with the national regulations for self-consumption units. As can be observed, three of the prosumers do not comply with the imposed measures, revealing both oversized installed capacities, and excessive energy injected into the main grid.

Table 4.3 - National specifications regarding self-consumption: compliance check for the microgrid prosumers

DL 2014 specifications	Office	Bank	R1	R2	School	Restaurant
P_connection < P_contracted	FALSE	FALSE	TRUE	TRUE	FALSE	TRUE
P_installed < 2 x P_connection	TRUE	TRUE	TRUE	TRUE	TRUE	FALSE
Oversizing (%) *	39	16	0	0	11	0
Excess energy injected into the main grid (%)	125	152	0	0	48	0

*relatively to the installed capacity

5. Conclusions

The aim of this dissertation was to test the benefits of an energy exchange system between prosumers of a microgrid in an urban context. For that purpose, two management models were implemented in the AIMMS software environment, for a same energy system configuration: one of centralized, where a central agent has in advance all information about the daily demand and production, and other of decentralized management, where optimizations are performed individually at each time-step, based on personal preferences. Both models are based on mathematical programming having as objective function the minimization of costs. For both the management models, the simulations were performed for four types of day, representing summer or winter week and weekend days.

It was considered that the microgrid consisted of six different entities with different daily demand patterns: two residential buildings, a bank, a small office, a school and a restaurant. Each one of the consumers was considered to have their own renewable energy generation units, qualifying them as prosumers.

The self-generation units of all prosumers were considered to be photovoltaics, due to its low cost, low maintenance requirements and plenty of solar resource. The panels were considered to be installed in the available roof-top area of the buildings. The resulting self-consumption levels of each prosumer, as well as of the entire microgrid under the two management types, were compared. The results were also compared against a base case scenario without energy exchange between the parts, the No-Exchange scenario. For the decentralized model, the system's financial balance was calculated, and compared with the No-Exchange scenario's financial balance, for quantification of the economic benefits,

Results show that, for all tested day-types, the proposed models of energy exchange lead to self-consumption increases, with an average increase of 10,3% compared to the base scenario. The differences are particularly noticeable during the weekend, when the load is lower, which leads to a higher availability of energy in the local market to trade. For the winter season, in particular for the week-day studied, the differences are minor (2,3%), presumably because there is less energy available to trade in the local market, which contributes to higher prices of the energy available.

Based on these results it is possible to conclude that the centralized model, where a single agent holds ahead of the day all the information for production and consumption, is achieving the best results in terms of self-consumption. However, the decentralized model has several advantages, as it avoids the sharing of data of each prosumer with the coordinating agent avoiding private data related issues.

It was concluded that the restaurant is the biggest purchaser in the microgrid energy market, buying from many prosumers on a daily basis, followed by the residential buildings. This can be explained by the fact that the production and consumption daily profiles of these prosumers do not match, or the production is simply not enough to cover the consumption, as it happens also with the restaurant, causing them to buy from the local market as it suits the economic optimization,

An analysis on the response to price changes by the prosumers show that, as intended, the buyers choose the cheapest supplier available at each time-step, whether this is the main grid or on the local energy market. One of the most positive results from this dissertation was the attained valorization of the energy surplus from the prosumers, worth on average 0.13 €/kWh, translatable in a 135% average valorization comparing with the value expressed on the Decree-Law nº 153/2014.

Results show that the both revenues' increase and costs' decrease are accomplished. On average the individual costs' reduction is 1,2%, although there are some differences between seasons, with the summer being associated with higher savings. The highest increases on the revenues are verified in the winter week-day scenario, in particular for the office. It was observed average of 21,6% increase on the revenues over the base scenario.

An overall economic analysis on the expected electricity bill of each prosumer and for the microgrid as a whole, revealed that the local energy market can cause a bill reduction of 3,3% for the winter week, and 5,3% for the summer. It can be concluded that, when considering the whole microgrid, the overall economic benefits in terms of economic savings are not so relevant as the results obtained in terms of self-consumed energy, for this particular case-study.

In summary, both management models for energy exchange were successful in allowing for increased amount of self-consumed energy and decreased electricity bills.

According to the DL-2014, some of the prosumers in the proposed microgrid would not qualify in neither one of the actual categories (producers for self-consumption or small producers), since the production units were oversized (for the bank, office and school) nor the production is entirely fed into the grid, which are the main conditions for each category.

Nevertheless, it would be reasonable to assume that this type of solution would bring benefits for self-production units' owners because, under the current Portuguese legislation, the surplus energy coming from these units is highly devalued, making it a less attractive option for investment. As showed in the results, for this system configuration, relevant increases for the surplus energy value in the market were obtained, benefiting both sellers, who are able to get a better return for their production, and buyers, who have a broader choice of supply.

Limitations and future work

Although these results are aligned with the results obtained in related experiments, it has to be taken into consideration several simplifying assumptions that were made and some simplifications, such as:

- ideal distribution grid, with 100% efficiency and exempt from transmission losses;
- no losses were considered for the PV systems other than the ones related with the panels efficiency;
- the time-steps of one-hour gaps force unrealistic variations in the production and consumption profiles, compromising to a certain extent the accuracy of these results,

Another important note on the hypothesis here tested is that currently it is not possible to implement such a system of direct energy trade in Portugal, due to infrastructural, legal and technical impediments.

As future work, it is left as suggestion the address of these results. Furthermore, it would be interesting to perform an overall economic analysis considering investments in the PV units in order to conclude on the investment's feasibility. It would also be pertinent to perform a sensitive analysis for the installed capacity in order to determine the maximum capacity that does not exceed the limit amount of power injected into the grid, for the system to comply with national regulations on self-consumption.

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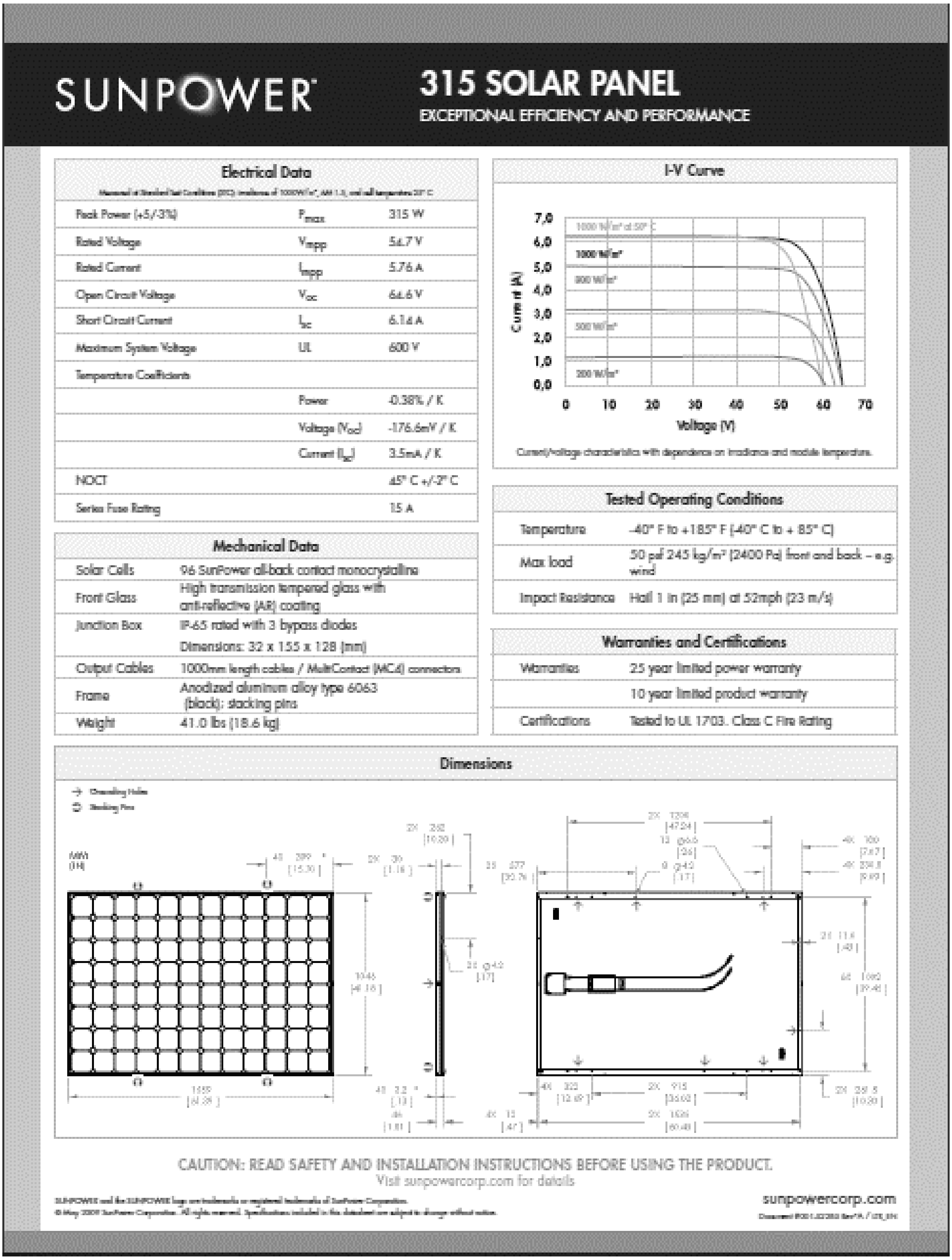
7. Annex

Annex 1: Solar photovoltaic panel datasheet



SUNPOWER

315 SOLAR PANEL

EXCEPTIONAL EFFICIENCY AND PERFORMANCE

Electrical Data		
Peak Power (+5/-3%)	P_{max}	315 W
Rated Voltage	V_{mpp}	54.7 V
Rated Current	I_{mpp}	5.76 A
Open Circuit Voltage	V_{oc}	64.6 V
Short Circuit Current	I_{sc}	6.14 A
Maximum System Voltage	UL	600 V
Temperature Coefficients		
	Power	-0.38% / K
	Voltage (V_{oc})	-176.6mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C
Series Fuse Rating		15 A

Mechanical Data	
Solar Cells	96 SunPower all-back contact monocrystalline
Front Glass	High transmission tempered glass with anti-reflective (AR) coating
Junction Box	IP-65 rated with 3 bypass diodes Dimensions: 32 x 155 x 128 (mm)
Output Cables	1000mm length cables / MultiContact (MC4) connectors
Frame	Anodized aluminum alloy type 6063 (black): stacking pins
Weight	41.0 lbs (18.6 kg)

I-V Curve

Current/voltage characteristics with dependence on irradiance and module temperature.

Tested Operating Conditions	
Temperature	-40° F to +185° F (-40° C to + 85° C)
Max load	50 psf 245 kg/m² (2400 Pa) front and back – e.g. wind
Impact Resistance	Hail 1 in (25 mm) at 52mph (23 m/s)

Warranties and Certifications	
Warranties	25 year limited power warranty
	10 year limited product warranty
Certifications	Tested to UL 1703. Class C Fire Rating

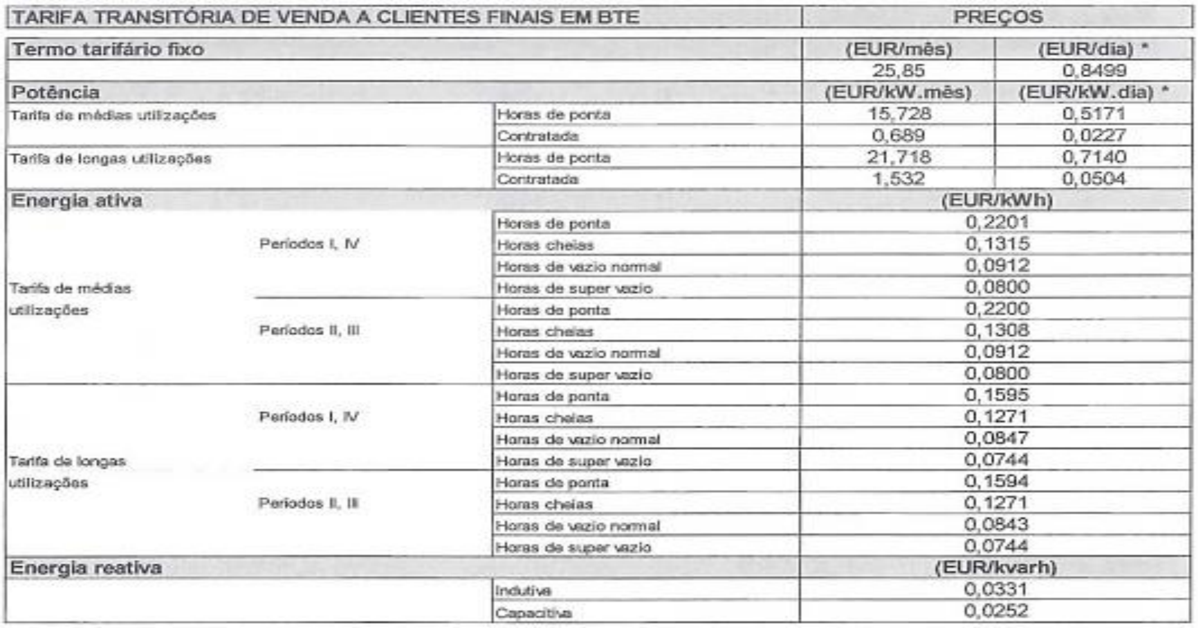
Dimensions

CAUTION: READ SAFETY AND INSTALLATION INSTRUCTIONS BEFORE USING THE PRODUCT.
Visit sunpowercorp.com for details

sunpowercorp.com

Figure 7.1 - Datasheet of the solar photovoltaic panel model considered for the simulations

Annex 2: Price structure



TARIFA TRANSITÓRIA DE VENDA A CLIENTES FINAIS EM BTE			PREÇOS	
Termo tarifário fixo			(EUR/mês)	(EUR/dia) *
			25,85	0,8499
Potência			(EUR/kW.mês)	(EUR/kW.dia) *
Tarifa de médias utilizações		Horas de ponta	15,728	0,5171
		Contratada	0,689	0,0227
Tarifa de longas utilizações		Horas de ponta	21,718	0,7140
		Contratada	1,532	0,0504
Energia ativa			(EUR/kWh)	
Tarifa de médias utilizações	Periodos I, IV	Horas de ponta	0,2201	
		Horas cheias	0,1315	
		Horas de vazio normal	0,0912	
		Horas de super vazio	0,0800	
	Periodos II, III	Horas de ponta	0,2200	
		Horas cheias	0,1308	
		Horas de vazio normal	0,0912	
		Horas de super vazio	0,0800	
Tarifa de longas utilizações	Periodos I, IV	Horas de ponta	0,1595	
		Horas cheias	0,1271	
		Horas de vazio normal	0,0847	
		Horas de super vazio	0,0744	
	Periodos II, III	Horas de ponta	0,1594	
		Horas cheias	0,1271	
		Horas de vazio normal	0,0843	
		Horas de super vazio	0,0744	
Energia reativa			(EUR/kvarh)	
		Indutiva	0,0331	
		Capacitiva	0,0252	

Figure 7.2 - Price structure for BTE clients as used for the simulations

Table 7.1 - Prices for BTN and BTE clients as used for the simulations, by season

	Winter Season		Summer Season	
Time (h)	BTN	BTE	BTN	BTE
01:00	0,1652	0,0912	0,1652	0,0912
02:00	0,1652	0,0800	0,1652	0,0800
03:00	0,1652	0,0800	0,1652	0,0800
04:00	0,1652	0,0800	0,1652	0,0800
05:00	0,1652	0,0800	0,1652	0,0800
06:00	0,1652	0,0912	0,1652	0,0912
07:00	0,1652	0,0912	0,1652	0,0912
08:00	0,1652	0,1315	0,1652	0,1308
09:00	0,1652	0,2201	0,1652	0,2200
10:00	0,1652	0,1758	0,1652	0,1754
11:00	0,1652	0,1315	0,1652	0,1308
12:00	0,1652	0,1315	0,1652	0,1308
13:00	0,1652	0,1315	0,1652	0,1308
14:00	0,1652	0,1315	0,1652	0,1308
15:00	0,1652	0,1315	0,1652	0,1308
16:00	0,1652	0,1315	0,1652	0,1308
17:00	0,1652	0,1315	0,1652	0,1308
18:00	0,1652	0,2201	0,1652	0,2200
19:00	0,1652	0,2201	0,1652	0,2200
20:00	0,1652	0,1758	0,1652	0,1754
21:00	0,1652	0,1315	0,1652	0,1308
22:00	0,1652	0,0912	0,1652	0,0912
23:00	0,1652	0,0912	0,1652	0,0912
00:00	0,1652	0,0912	0,1652	0,0912

Annex 3: Surplus energy prices

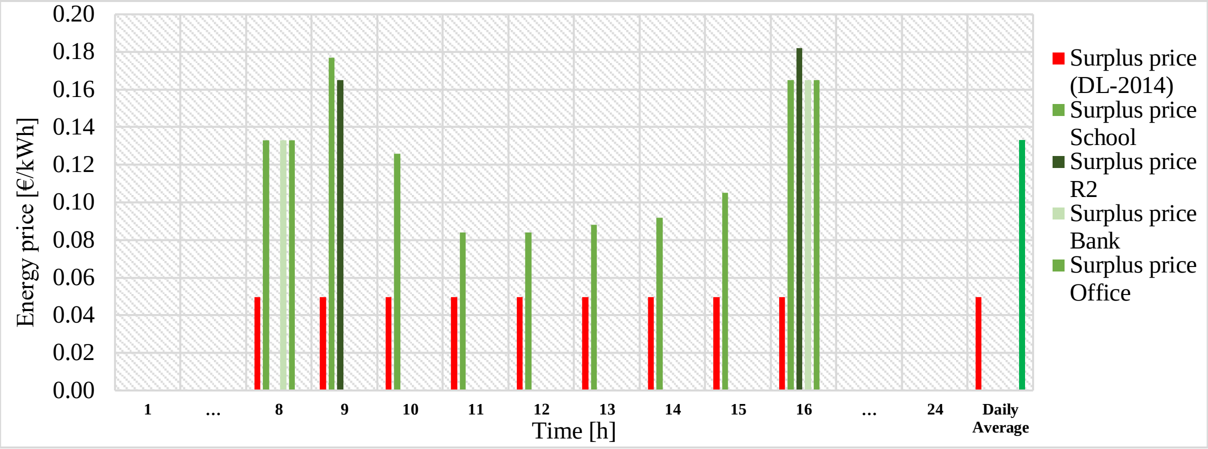


Figure 7.3 – Winter weekend-day: Comparison between the prices of the surplus energy sold in the local market (LM) with the value of energy sold to the main grid, and daily average

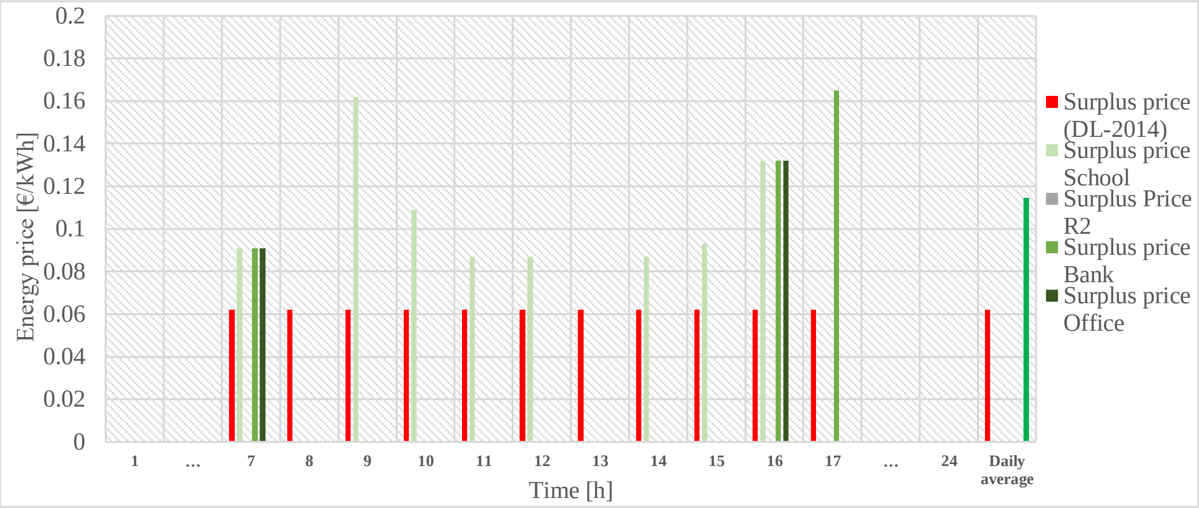


Figure 7.4 – Summer week-day: Comparison between the prices of the surplus energy sold in the local market (LM) with the value of energy sold to the main grid, and daily average

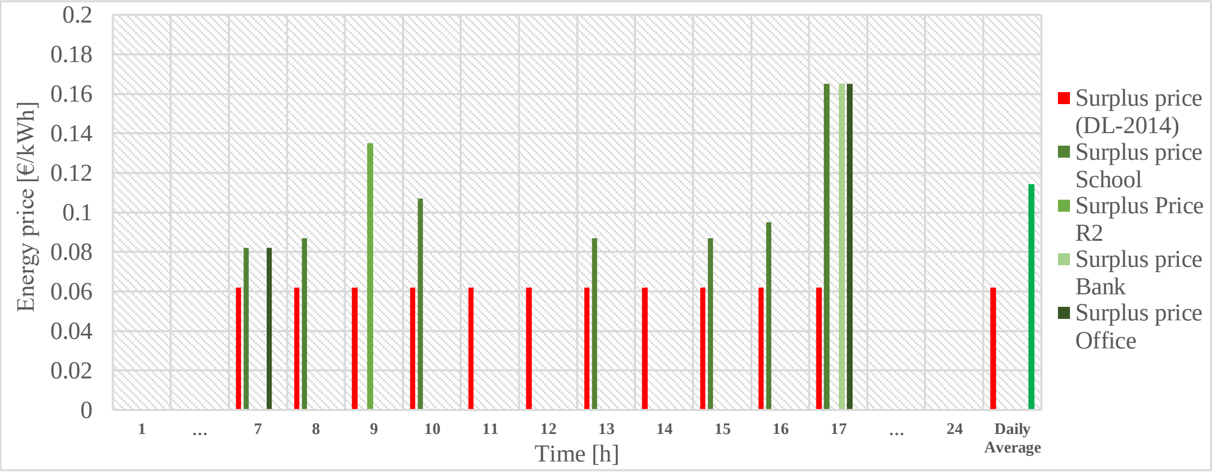


Figure 7.5 – Summer week-day: Comparison between the prices of the surplus energy sold in the local market (LM) with the value of energy sold to the main grid, and daily average