Assessing the value proposition of P2P energy markets for decarbonization by 2050

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Abstract

Energy communities are seen as a new decentralization paradigm that will allow the energy transition at local scale. Peer-to-peer (P2P) energy markets can be used as a mean of inciting community members to increase local renewable self-consumption by allowing trading among peers and increasing synchronization of supply and demand. Consequently, it is important to evaluate how these markets contribute to decarbonization goals, at national level.

In this work, a P2P optimization market model was developed at municipality level, to assess the dynamics of P2P trading, in the 2050 horizon, accounting with the different economic sectors as participants and proportional corresponding solar PV systems. The model was applied to all municipalities in Portugal, which were analysed in clusters, in terms of energy traded, self-sufficiency shares, P2P clearance price, total costs, and CO_2 emissions reductions, then being extrapolated to national scale. To assess the model results, three scenarios were designed: Present Scenario (PS), without PV systems, collective self-consumption community (CSC), and lastly one with P2P implementation.

Relatively to PS, both CSC and P2P resulted in reductions of total system costs (31.48% and 31.49%, respectively) and CO_2 emissions (26.34% and 26.33%). P2P implementation had slightly lower costs than CSC, even though CSC ended up with lower emissions. The services sector revealed a generalized participation in the P2P market, contrarily to the industrial sector. Single family houses (SFH) and multi apartment buildings (MAB) demonstrated a clear *buyer and seller* behaviour, depending on the type of municipality (urban or rural).

Keywords: Peer-to-Peer; Energy markets; Energy systems modelling; Decentralised energy production; Self-consumption.

Resumo

As comunidades de energia são encaradas como um novo paradigma de descentralização, que irá permitir transição energética na escala local. Os mercados *peer-to-peer* (P2P) podem ser usados de forma a incitar os membros de uma comunidade a aumentar o autoconsumo de energia renovável através da troca de energia e aumento da sincronização de procura e fornecimento de eletricidade. Consequentemente, é importante avaliar como podem contribuir para os objetivos de descarbonização, ao nível nacional.

Neste trabalho, foi desenvolvido um modelo de mercado P2P a nível municipal, para estudar as dinâmicas de troca no horizonte 2050, contabilizando os diferentes sectores económicos como participantes e com sistemas solar PV proporcionais. O modelo foi aplicado a todos os municípios de Portugal, analisados, por *clusters*, em termos de energia trocada, autossuficiência, preço P2P, custos totais e reduções de emissões de CO_2, sendo depois extrapolados resultados nacionais. São desenhados três cenários – sem sistemas PV (PS), comunidades de autoconsumo coletivo (CSC) e implementação de P2P.

Relativamente ao PS, quer o CSC, quer o P2P resultaram numa redução do custo total do sistema (31.48% e 31.49%, respetivamente) e das emissões de CO_2 (26.34% e 26.33%). A implementação de P2P levou a custos ligeiramente inferiores aos de CSC, sendo que neste cenário as emissões foram também ligeiramente menores. O sector dos serviços revelou uma participação generalizada no mercado P2P, contrariamente ao sector da indústria. As casas unifamiliares (SFH) e os apartamentos multifamiliares (MAB) demonstraram participação como comprador ou vendedor, consoante o município correspondente é rural ou urbano.

Palavras-chave: *Peer-to-Peer*; Mercados de energia; Modelação de sistemas de energia; Produção descentralizada de energia; Auto-consumo

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Nomenclature

$\%_{\text{decentralized PV}}^{\text{electricity production sector}}$	Fraction of decentralized PV production existent in the electricity power sector
$\overline{\text{A\_accom}}$	Average area for an accommodation
A_{floor}	Total floor area
A_{roof}	Total roof area
$\frac{\text{C}}{\text{A}}$	Electricity intensity per unit area
C_{annual}	Annual electricity consumption
C_{j}	Hourly energy consumption
C^{norm}	Normalised load
$\text{C}_{\text{PV,j}}$	Fraction of the total consumption provided by decentralized PV
CF	Annual average capacity factor
CR	Electricity Consumption Ratio
CSC	Collective self-consumption
$\text{E}_{\text{excess}}^{\text{i}}$	Total energy received by member *i* from other members in the EC
EC	Energy community
E_{prod}	Hourly PV generation
i	EC Member
j	Municipality
MAB	Multi appartment buildings
$\overline{\text{N\_accom\_build}}$	Average number of accommodations per building
$\overline{\text{N\_accom\_floor}}$	Number of accommodations per floor
$\overline{\text{N\_floors}}$	Average number of floors per building
P	Energy trade matrix
$\text{p}_{\text{i/EC}}$	Self-consumption of member *i*
$\text{p}_{\text{i/grid}}$	Grid consumption of member *i*
$\text{P}_{\text{j}}^{\text{1kW}}$	Hourly power output
$\text{P}_{\text{PV,j}}$	Installed nominal power
P2P	Peer-to-peer
PS	Present Scenario
PV	Photovoltaic
SFH	Single family houses
$\Sigma_{\text{h=1}}^{8760}\text{E}_{\text{prod}}(\text{h})$	Annual PV production
Ω_{deficit}	Group of members in deficit
Ω_{excess}	Group of members in excess
ω_{n}	Set of peers of member *n*
γ	Network charge
λ	Trading price

1. Introduction

1.1. Motivation

Climate change mitigation is one of the greatest challenges faced by humanity in the 21st century. The problem has been, for decades, in the public agenda, but since the Paris Agreement in 2015, countries have been greatly increasing their efforts to reduce their greenhouse gas (GHG) emissions, namely by committing to keep a global temperature rise below 2ºC above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1,5ºC. This, alongside the desire to achieve a more sustainable future, has triggered the European Union's (EU) response to promote an energy transition, by committing to achieve net-zero GHG emissions by 2050. Accordingly, the EU targeted the objectives of, until 2030, cutting at least 55% in GHG emissions and having no less than 40% of renewable energy sources in its energy mix. (European Comission, 2021). As of 2019, renewable energy represented only 19.7% of the energy consumed in the EU-27, although it represented 34.1% of electricity consumption (Eurostat, 2020).

The strategy to accomplish the energy transition is complex and has many lines of action, which can be summarised in seven main ideas (European Commission, 2018):

- Maximise the benefits from energy efficiency, including zero emission buildings:
- Maximise the deployment of renewables and the use of electricity to fully decarbonise Europe's energy supply;
- Embrace clean, safe and connected mobility;
- A competitive EU industry and the circular economy as a key enabler to reduce greenhouse gas emissions;
- Develop an adequate smart network infrastructure and inter-connections;
- Reap the full benefits of bio-economy and create essential carbon sinks;
- Tackle remaining CO_2 emissions with carbon capture and storage.

These ideas compelled the EU to develop the "Clean energy for all Europeans Package" (CEP), with more concrete measures and targets to be established in the more near future (2020-2030), to pave the way to a long-term scenario of carbon-neutrality in 2050. The CEP is divided in eight legislative acts:

- "Energy Performance of Buildings Directive 2018/844",
- "The recast Renewable Energy Directive (EU) 2018/2001",
- "The revised Energy Efficiency Directive (EU) 2018/2002",
- "Governance of the Energy Union and Climate Action (EU) Regulation 2018/1999",
- "Regulation on risk-preparedness in the electricity sector (EU) 2019/941",
- "Regulation establishing a European Union Agency for the Cooperation of Energy Regulators (EU) 2019/942",
- "Regulation on the internal market for electricity (EU) 2019/943",

- "Directive on common rules for the internal market for electricity (EU) 2019/944")

These directives, published between 2018 and 2019, incorporate the EU's vision on the energy transition, and were intended to legislate common ground in diverse energy areas, such as building performance, renewable energy, energy efficiency, governance regulation and electricity market design, for the Member States to translate into national law. These encompass a vision of increased efficiency, renewables integration, energy security increase, citizen participation and cooperation and country interconnection and solidarity, as shown in Figure 1.

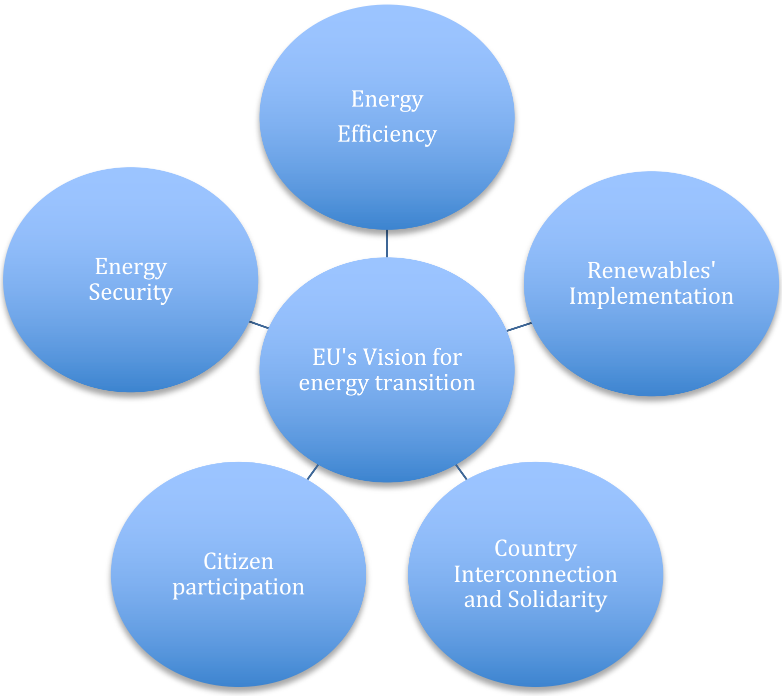


Figure 1 – EU's Vision for Energy Transition

There is a clear emphasis on the take-up of *renewables*. Once again a goal is proposed - no less than 32% of renewable energy sources in its energy mix until 2030. (European Parliament, 2018) This value was also updated into 40% in the Fit for 55 package, more specifically in the "Amendment to the Renewable Energy Directive to implement the ambition of the new 2030 climate target" (Rofifah, 2021). The increase of renewables has more benefits besides the reduction of GHG emissions, since it increases the *energy security* of the EU, by enabling more energy generation without the need of fuel imports. Due to the unstable nature of renewable energy generation, there might be challenges matching demand and supply, hence, demand response, energy storage or cross-border trade might be important. Moreover, this kind of trade may also increase efficiency, competitive prices or higher standards of service (The European Parliament and the Council of the European Union, 2019). For that, *country interconnection and solidarity* is necessary.

Additionally, *citizen participation* is encouraged, since it will provide more flexibility, by allowing them to decide how and when to consume, produce, store, sell or share their own energy. This democratisation of energy will give more rights to citizens and result in higher savings and transparency in their electricity bills, while also reducing energy poverty, as no citizen should be hindered from having an active participation, independently from his income or capital (European Parliament, 2019).

Finally, it should be stated that these concepts of the EU's vision are not independent; contrarily, they frequently act together. For instance, the rise of renewables is dependent on the growing participation of citizens and communities and vice-versa. Another example is that security and efficiency may be dependent on cross-border trade in some situations, as previously stated. To sum up, the energy transition's vision involves scientific knowledge and technology replacement, but also full cooperation between Member States and a sense of togetherness of the EU in energy matters.

Additionally, the EU directives, specifically "*The recast Renewable Energy Directive*" (RED II) and the "*Directive on common rules for the internal market for electricity*" (EMD), emphasize that citizen participation - individually and/or through collective forms, either by participating in individual or collective self-consumption, or by creating energy communities (ECs) -, will play a very prominent role in the future of the energy system being crucial to the energy transition. In the EU's view, these energy communities will be essential, not only because they can stimulate the growth of renewable energy, but also because they can promote decentralisation of energy generation, which in turn will create more flexibility in electricity usage and more efficiency, whilst also increasing quality of service and, consequently, social well-being. (Caramizaru & Uihlein, 2019). Thus, energy communities appear as another instrument to enable this energy transition. However, they have a wide variety of activities, legal structures, organisational forms and markets. Being a possible market, a peer-to-peer (P2P) energy market implementation and its real contribution for decarbonization should be further studied, since the knowledge regarding its implementation and the role it could play in the future European (and Portuguese) energy system is still unsure.

1.2. Research questions and Objectives

In this context, the main goal of this thesis is to perform an analysis of the impact of a widespread dissemination of P2P market-based energy communities in the Portuguese energy system, at municipal and national level, for the decarbonization targets in 2050, assessing economic and environmental indicators, by answering two research questions:

- "What would be the reduction of emissions of CO_2 in the scenario of the dissemination of P2P energy communities in Portugal in 2050?"
- "What would be the costs or earnings of this implementation?"

To answer these questions, the following goals were defined:

- Collect data on renewable energy generation and electricity demand by 2050, according to national decarbonization strategy;
- Characterize economic sectors as potential participants to integrate P2P energy communities;

- Develop a P2P market model optimization, to understand P2P market behaviour, energy exchanges and prices' dynamics, according to community typology;
- Implement a P2P energy trading model at municipal level and extrapolate for national scale to find overall results.

1.3. Structure of the thesis

The thesis is organized as follows:

- In Chapter 2, a literature review on ECs, the Portuguese decarbonisation context, P2P energy markets, energy modelling and P2P and EC studies is presented;
- Chapter 3 reports the methodology used in the thesis: the first part focuses on the EC modelling, the second on the clustering approach and the third displays key performance indicators;
- Chapter 4 presents the case study, including all the data and assumptions gathered;
- In Chapter 5 the results are presented alongside a correspondent analysis, with scenarios' comparison;
- Finally, in Chapter 6 the main conclusions of the study are stated, besides thoughts on the study's limitations and future work.

2. Literature Review

2.1. Energy communities

The idea of citizen participation is greatly leveraged in decentralised energy generation, in the form of individual or collective self-consumption, as well as energy communities. The importance of decentralisation is mainly due to higher efficiencies on energy supply and its increase on energy security. Renewable energy, such as wind (with the creation, for example, of community owned wind farms) and solar (photovoltaic panels can be placed on the rooftops of residential, industrial and service buildings) are thus greatly compatible with this concept.

Although some EC projects already existed across Europe, their formal definition was only proposed in December 2018, in ”*The recast Renewable Energy Directive (EU) 2018/2001” (RED II),* in the case of a “Renewable Energy Community” (REC), and in June 2019, in the *“Directive on common rules for the internal market for electricity (EU) 2019/944*” (EMD), concerning “Citizen Energy Community” (CEC). The RED II defined REC as follows:

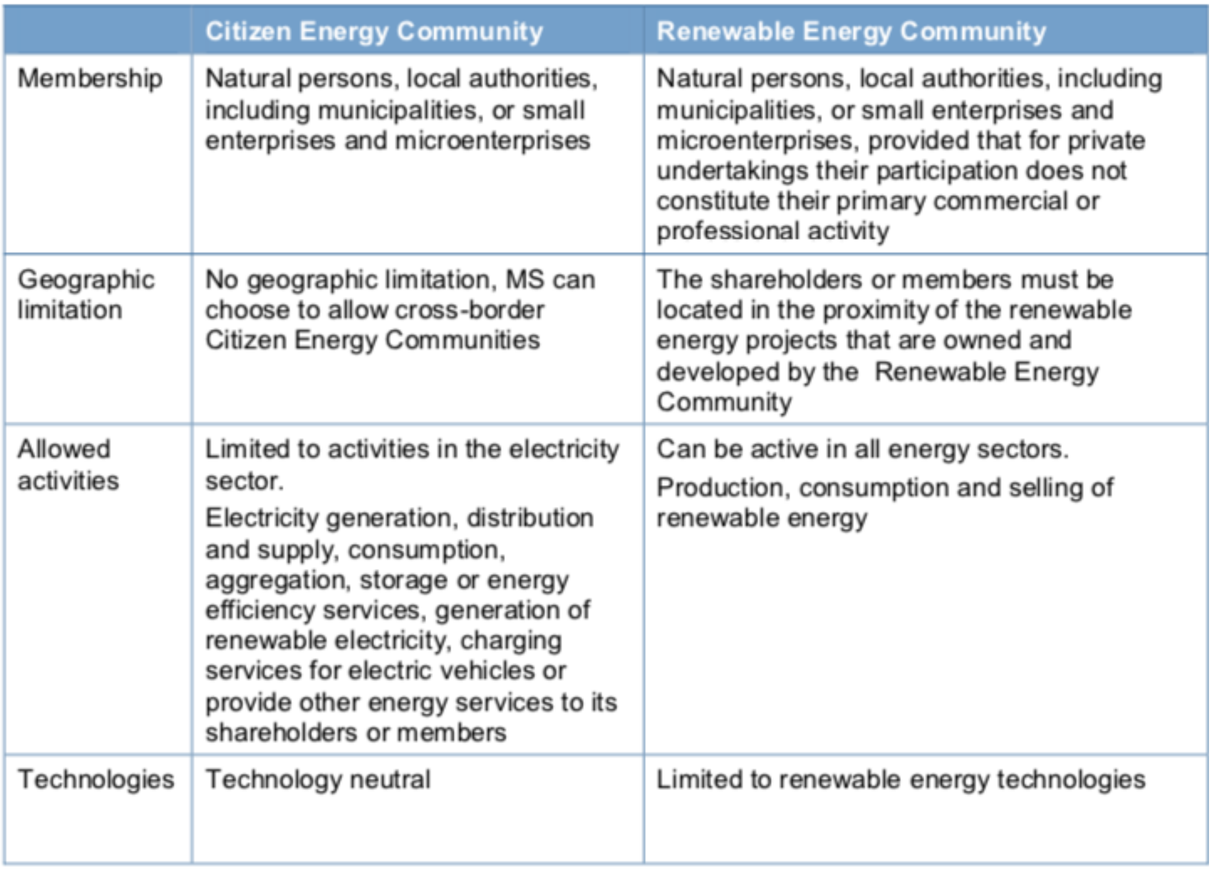
“ ‘*renewable energy community’ means a legal entity: (a) which, in accordance with the applicable national law, is based on open and voluntary participation, is autonomous, and is effectively controlled by shareholders or members that are located in the proximity of the renewable energy projects that are owned and developed by that legal entity; (b) the shareholders or members of which are natural persons, SMEs or local authorities, including municipalities; (c) the primary purpose of which is to provide environmental, economic or social community benefits for its shareholders or members or for the local areas where it operates, rather than financial profits.*” (European Parliament, 2018)

On the other hand, the EMD defined CEC as:

“ *'citizens energy community' means a legal entity that: (a) is based on voluntary and open participation and is effectively controlled by members or shareholders that are natural persons, local authorities, including municipalities, or small enterprises; (b) has for its primary purpose to provide environmental, economic or social community benefits to its members or shareholders or to the local areas where it operates rather than to generate financial profits; and (c) may engage in generation, including from renewable sources, distribution, supply, consumption, aggregation, energy storage, energy efficiency services or charging services for electric vehicles or provide other energy services to its members or shareholders*”. (European Parliament, 2019)

The comparison between energy communities is summarized in the following table (CEER, 2019):

Table 1 – Comparison between Citizen and Renewable Energy Communities



	Citizen Energy Community	Renewable Energy Community
Membership	Natural persons, local authorities, including municipalities, or small enterprises and microenterprises	Natural persons, local authorities, including municipalities, or small enterprises and microenterprises, provided that for private undertakings their participation does not constitute their primary commercial or professional activity
Geographic limitation	No geographic limitation, MS can choose to allow cross-border Citizen Energy Communities	The shareholders or members must be located in the proximity of the renewable energy projects that are owned and developed by the Renewable Energy Community
Allowed activities	Limited to activities in the electricity sector. Electricity generation, distribution and supply, consumption, aggregation, storage or energy efficiency services, generation of renewable electricity, charging services for electric vehicles or provide other energy services to its shareholders or members	Can be active in all energy sectors. Production, consumption and selling of renewable energy
Technologies	Technology neutral	Limited to renewable energy technologies

Despite their differences, ECs share many benefits. First of all, they facilitate decentralisation with the implementation of renewables (in doing so, they also foment their social acceptance). Besides, they can also ease the local optimisation of power flows and the reduction in energy losses, thus boosting efficiency (Caramizaru & Uihlein, 2019). They have the ability to create local value, by creating jobs, avoiding the outflow of financial resources from the region and reducing fuel poverty and carbon emissions (Kunze & Becker, 2014). Lastly, they can provide their members with savings due to reduced grid fees and potentially, higher PV grid injection tariffs in addition to improving local energy security (European Parliament, 2018).

Nevertheless, it should be stated that some difficulties may arise with the development of ECs and that regulation is necessary to help their evolution. Individually, an EC may prefer to keep costs low for their members instead of building up financial reserves to have the capacity to answer to a sudden need of investment (such as the replacement of a transformer), which can lead to an inability to react properly, even more if the community is small and its members decide to leave. Besides, the coordination between communities and the supplier may be challenging if the community only partially powers itself, i.e., a backup supplier (normally the grid) exists. In this case, it is likely that there will be higher market prices (CEER, 2019). Looking at the system as a whole, whilst there may be savings within the communities, these may result in costs for consumers elsewhere, i.e., there is no resulting cost-efficiency on the system. This is also true if ECs deploy local grids in areas where a DSO already exists (CEER, 2019).

2.2. The Portuguese decarbonization context

Aligned with the EU's vision, Portugal has developed its national strategy for long-term low-GHG development in the "2050 Carbon Neutrality Roadmap" document ("Roteiro para a Neutralidade Carbónica" - RNC2050). This document describes a transversal revolution in the Portuguese economy, by planning structural changes in sectors such as power generation, mobility, industry, buildings, agriculture, forestry and water and waste management.

From the point of view of this thesis, the most relevant aspects to be mentioned are the projected goals (Portuguese government, 2019):

- Energy system: reductions in GHG emissions of around 60% by 2030 and 90% by 2050, compared to 2005
- Power generation: 99% reduction in GHG emissions by 2050, compared to 2005
- Renewables: two thirds are wind and solar; 80% of primary consumption in 2050
- Electricity: 100% from renewables in 2050
- Final Energy consumption: 66% to 68% from electricity; over 85% from renewables in 2050

The RNC2050 also mentions the future prominence of decentralization and eventually energy communities: "*the increase in installed capacity of decentralised solar to 2.3 GW by 2030 and 12 to 13 GW by 2050 demonstrates the cost-effectiveness of decentralisation in solar electricity generation, allowing one to envisage the important role of producers/ consumers in the future*." (Portuguese government, 2019).

Nonetheless, renewable energy self-consumption was not regulated in Portugal until the 2014 decree-law (DL 153/2014) introduced the definition of 'Small Production Units for Self-consumption', that were limited to individual or collective persons, with each production unit being associated only to one single meter, which made impossible any form of collective prosumerism (Campos et al., 2020). It was only with the 2019 decree-law (DL 162/2019) that direct exchange between two or more prosumers (including peer-to-peer arrangements) were envisioned. DL 162/2019 also states that there should be remuneration for collective self-consumption and RECs whenever they supply excess energy to the grid and that this should reflect the market value of that electricity, as it can be commercialised by an utility company (Presidência do Conselho de Ministros, 2019). This new regulation can incentivize the growth of energy communities in Portugal.

2.3. P2P Markets

One of the possible ECs business models is P2P energy trading. The P2P trading approach represents an open model, allowing trading among customers on a local energy market and is best suited to operate within a single distribution network to fully benefit localized supply and consumption (Hall & Roelich, 2016). The key motivation of this type of model is to have better asset utilization and reduced energy bills (Gui & MacGill, 2018).

Still, P2P energy communities can be virtual and not necessarily enable the physical local exchange of electricity; instead, they may connect electricity consumers and producers on a market and financial level. Besides converging supply and demand locally, P2P energy communities might also incite community members to increase local self-consumption by synchronizing supply and demand in terms of time. To do so, multiple technologies can be used, such as time-dependent tariffs, smart meters, and gateway technologies to display or automatically adapt consumption patterns (for instance, through the use of battery storage, according to the locally available supply) (Plewnia & Guenther, 2020).

2.4. Energy Modelling

The existing panorama of energy modelling has a subdivision of this activity in two main methodologies: bottom-up, linked with technical studies, and top-down, related to macroeconomic ones.

The goal of top-down energy models is to portray the economy on a national or regional level and to evaluate the monetary impacts of energy and/or climate change policies. Therefore, they intend to simulate economic development, with its consequent energy demand and supply, as well as employment and other social welfare factors. Accordingly, they are generally executed by economists and public administrations. These models normally do not address matters such as energy efficiency or technological details; instead, they are applied as a macroeconomic tool, for instance, to forecast the price elasticity of a good, or an investment's rate of return. (Herbst et al., 2012)

On the other hand, bottom-up models, while also aiming at simulating future energy demand and supply, incorporate a high level of technological detail and disregard macroeconomic impacts of investments and energy and climate policies. They also try to calculate external benefits, such as environmental, resulting from energy efficiency measures, by identifying synergy-effects between sectors, and sectorial costs and surpluses. Correspondingly, engineers and scientists usually develop these. Bottom-up models are divided into four categories: partial-equilibrium, optimisation, multi-agent and simulation models. Moreover, these approaches have the characteristic of needing intensive input data, such as technologies specifications, forecasts of demand and supply maps, in addition to the systems overall cost and weather related data. Depending on data availability, this fact can pose great challenges, when trying to achieve trustworthy results (Herbst et al., 2012).

Due to the technical nature of this thesis, bottom-up approach models are more relevant. Hence, a more detailed look at significant publications is taken on the next chapter, more precisely to the ones using the optimisation sub-category, as it is present in this work's methodology.

2.5. EC and P2P Studies

Countless works using optimisation algorithms in energy systems modelling have been published, with an enormous scope of domain sizes (national level, regional, local, etc.), technologies (fossil fuel based, renewables based, multiple/single energy source), agents (residential buildings – small houses, apartment blocks -, industry, commerce, services), locations (developed/undeveloped countries, urban/rural environment) and technical feasibility (for example, grid analysis). However, as shown in the Introduction, both ECs and P2P markets are still relatively growing concepts and many of their studies have only been published in the recent years. Therefore, some recent studies, closely related to the purpose of this thesis are shown next.

Fina et al. (2020) developed a model to estimate the cost-optimal large-scale economic potential of shared rooftop PV systems based on neighbourhood ECs and applied it to Austria. They created 4 types of settlement patterns (city, town, mixed and rural) and also divided buildings into 3 categories (single-family houses, large multi-apartment buildings and small multi-apartment buildings). After defining energy communities (one for each pattern) by assigning them the amount of building types, the number of ECs was estimated on district and national level, based on statistics. The optimal PV system size for each EC was modelled by maximising the net present value over a 20-year time horizon. Afterwards, an upscaling was performed based on the number of ECs, resulting in optimal capacities for each settlement pattern for whole Austria, which was compared with the geographic potential, i.e. the maximum installable PV capacity, based on the total rooftop area. Nevertheless, this study only addresses residential buildings and does not evaluate emissions.

Karunathilake et al. (2018) established a way of selecting the most viable renewable energy technologies during the pre-project planning stage of an EC. This was done by, first of all, establishing the technologies' technical viability, and then using multi-attribute decision making to compare them with regard to economic, environmental and social criteria. The study concluded that, weighting the criteria differently according to the desired scenario (pro-economic, pro-environmental or neutral), the order of the technologies in the obtained rankings could swap, i.e., technologies may not be considered optimal in both objectives.

Riva et al. (2019) studied energy demand in rural India and linked it with optimisation models to plan long-term electrification. After defining their system, consisting of 12 households, and retrieving data such as income and household size, based on local surveys, they predicted the diffusion and ownership of electric appliances in overall population along a 20-year scenario. Afterwards, they randomly distributed these appliances among the 12 houses and generated many daily load profiles. Of these, the ones with minimum, mean and maximum daily variability were selected and used as input for OSeMOSYS modelling software in order to identify the least cost long-term energy supply mix in the community. The study concluded that long-term variations of electricity demand have a higher impact on the costs of systems than the daily variations of the load profiles.

Fleischhacker et al. (2019) applied multi-objective optimisation in order to quantify an EC's trade-off curve (Pareto front) of costs and emissions, thus determining the optimal energy system in terms of environment and economy. They found that a decrease of costs cannot be achieved without an increase in emissions and vice-versa. The changes along the curve allow the quantification of emissions' reduction costs or the correspondent cost savings due to emissions' increase. This work models an entire Austrian city as an EC, divided in city blocks (of different residential typologies) and as a multi-energy system. Such an approach requires time-series data, such as energy consumption (electricity, heat, cooling) and solar radiation, geographical data, such as building area, technical (energy and emission conversion efficiency, technical limits) and economic parameters (investment, maintenance, and fuel costs).

Perger et al. (2021) developed a linear program intended to optimize P2P trading between prosumers of a local energy community with PV and battery energy storage systems, with the innovative concept of adding the characterization of the individual members' willingness to pay. This was defined as the sum of the retailer's electricity price with an individual weighting factor (in EUR/ton CO_2) multiplied by the marginal emissions emitted when producing a unit of electricity in the wider electricity system (in ton CO_2/kWh), thus representing how much above the retailer's price the consumer is willing to pay when consuming locally produced energy. With this method, prosumers can calculate their environmental impact, since they know the avoided tons of CO_2 emitted. The authors concluded that battery energy storage systems could decrease imports from the grid by 15% due to flexibilities and that the willingness-to-pay could save marginal emissions from the grid, with up to 38% of annual savings.

Long, Wu, Zhou, et al. (2018) investigated the aggregated control of small-scale batteries in P2P sharing within a community microgrid as an alternative to power-to-grid (P2G) due to decrease in grid injection tariffs. They observed that P2P energy sharing resulted in higher self-consumption (10-30% increase) in comparison with the conventional P2G trading and that the average annual costs were less (30%). Besides, they concluded that, for the same number of participants in the P2P scheme, an increase in individual battery capacities (assuming all participants have similar batteries) would result in higher community self-consumption and smaller community average annual energy cost.

Nguyen et al. (2018) proposed an optimization model to maximize the economic benefits for rooftop PV-battery distributed generation in a P2P energy trading environment and illustrated it in a simulation framework for a local community with 500 households under real-world constraints, encompassing PV systems, battery storage, customer demand profiles and market signals including the retail price, grid injection tariff and P2P energy trading mechanism. The authors identified the scale of PV systems, the PV penetration, the P2P trading margins, the presence of battery storage and energy trading time as the factors affecting household energy savings. The model showed that maximal savings up to 28% could be achieved by households equipped with larger PV systems and battery storages during weekdays from the exemplified case study.

Baroche et al. (2019) proposed a formulation to describe a decentralised P2P market without a limit to the number of community agents. In this paper, agents always objectively make the most beneficial decisions, do not anticipate actions and reactions of other agents and can be consumers, generators or prosumers. The goal is, once again, to minimize the community's total cost, which is equal to the sum of each agent's individual cost. The amounts traded have limitations due to the networks' physical constraints and to the necessary power balance of the grid. This formulation includes an algorithm to simulate the negotiation mechanism between agents, which results in accorded trading prices. Furthermore, besides the trading prices, network charges, which are considered exogenous costs, are provided *a priori* by a system operator. These have two purposes: they allow the system operator to reach cost recovery and may be used to reduce congestion risks. Finally, 3 exogenous cost allocation policies are suggested, namely unique cost, electrical distance cost and uniform zonal cost.

Wang et al. (2021) proposed a P2P energy trading strategy for energy balance service provider (EBSP) considering market elasticity in a community microgrid. This was achieved by, firstly, establishing a market equilibrium model for the community microgrid with EBSP and solving the parameters with the historical trading information of typical scenario sets, and then by creating and solving an optimized pricing model and trading strategy to maximize the economic revenue of EBSP. The study concluded that this revenue increased by 13.57% and 9.52% in sunny and cloudy scenarios, respectively, without harming the overall benefit of the community microgrid.

Kusakana (2020) developed a model to optimize the operation of two grid-connected prosumers (one residential and one commercial) in a P2P energy sharing scheme. The developed model minimized both prosumers' operation costs by maximizing the use of the power from the renewable energy sources, optimally managing the internal power sharing between the prosumers, and minimizing the use of the electrical supplying energy under the Time-of-Use rates. A case study was selected in South Africa where the residential prosumer is using a photovoltaic system with battery energy storage while the commercial prosumer uses a dual-tracking photovoltaic system. The results have verified that the P2P scheme assists both to benefit from their own generated energy and substantial cost can be saved, compared to using the grid as sole power source, concretely a total daily cost reduction of 62.71% in summer and 68.99% in winter for the residential prosumer and 81.31% in summer and 31.69% in winter for the commercial prosumer.

Long, Wu, Zhang, et al. (2018) investigated the feasibility of applying P2P energy trading to reduce costs for energy consumers, and to increase income for distributed energy resources producers in a community microgrid. Three representative market paradigms were proposed, concretely bill sharing, mid-market rate and an auction-based pricing strategy. They found that with a moderate level of PV penetration, P2P energy trading resulted in a reduction of community energy costs by ~30%.

Summing up, the studies' results show great variance on the results, due to different approaches and assumptions, and being too case study based. However, one can conclude that the main drivers influencing P2P outputs are the type of prosumers, inclusion and size of batteries, level of PV penetration, EC location (directly influences PV electricity generation) and number of participants. Pricing is modelled in many different ways (with/without grid costs, averaged, computed or exogenous) without a clear market model consensus.

3. Methodology

With the goal of assessing the decarbonization potential of energy communities with P2P electricity trading by 2050, for mainland Portugal, a combined top-down and bottom-up modelling approach was taken. First, the scale of EC implementation was defined as municipal level, and, through a top-down modelling, local renewable energy production potential and main energy consumers/traders (with respective demands) were determined. For each EC, a P2P market was defined through an optimization of traded energy and prices, given the traders' constraints. Finally, through clustering methods of similar ECs, and using a bottom-up approach from the representativeness of typical EC results, national results were computed.

Figure 2 presents graphically how the different steps of the methodology interact.

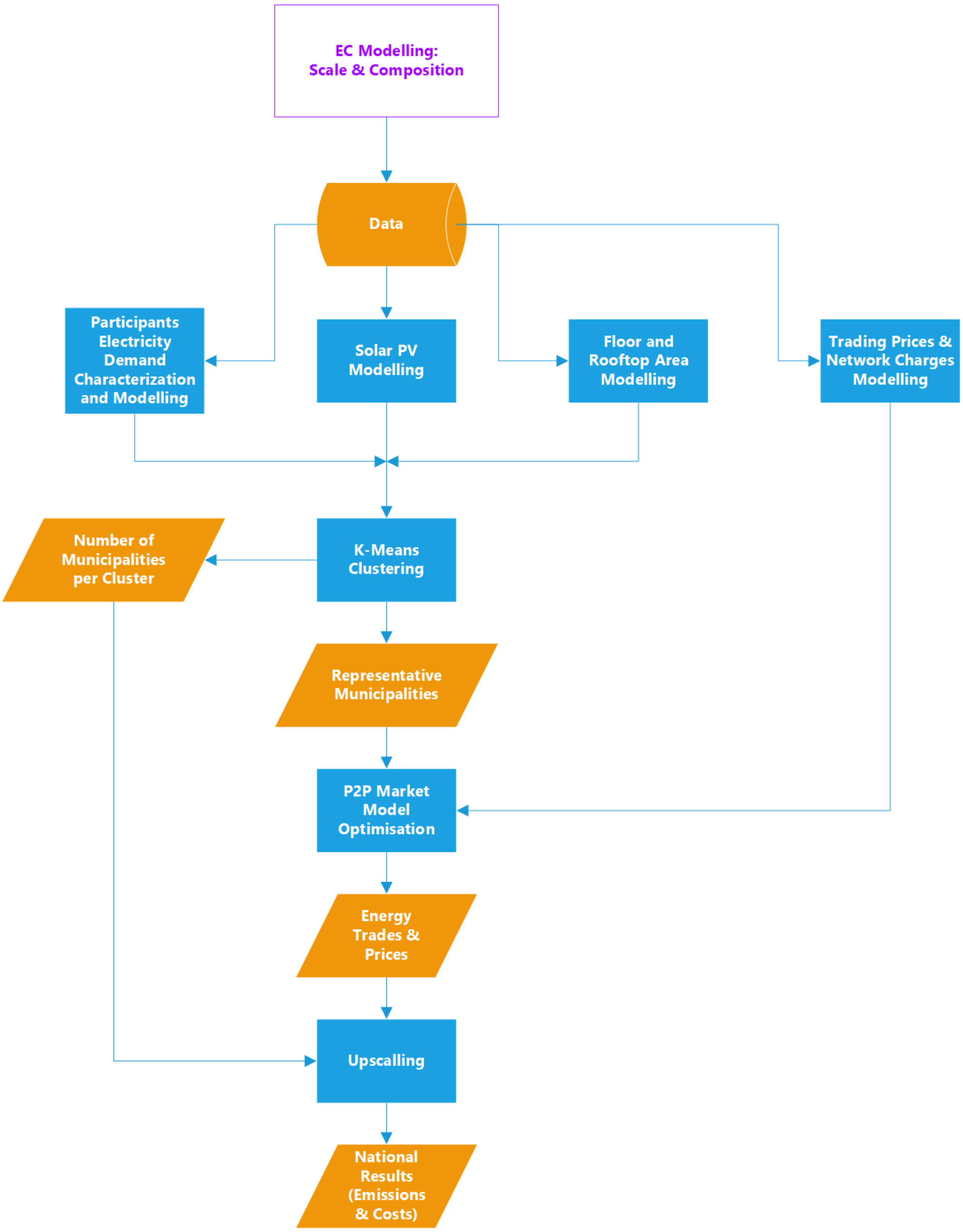


Figure 2 – Methodology's Flow Diagram

3.1. Energy communities modelling

Even though Portugal is a small country, there is still significant differentiation in the energy paradigm between districts and, frequently, even between the municipalities inside each district. Although, in the future, many energy communities will, most likely, spread on a local basis, such as buildings, streets, neighbourhoods or city districts, in this work, due to lack of more detailed data and the huge computational effort of further subdividing and analysing ECs at parish level, it was considered that each municipality forms an EC, which results in a total of 278 ECs spread across mainland Portugal.

Regarding the local renewable generation, the focus was placed in assessing the potential of photovoltaic (PV) electricity generation in mainland Portugal, since it is the renewable technology with highest deployment potential at local level (considering building's rooftops) and thus for energy communities' implementation.

Using a top-down approach, the agents involved in the energy trading market were determined by demanding economic sectors, as residential, industry and services (tertiary) sectors, considering each one as a member, and coupling them with solar PV production. Nevertheless, given the different rooftop availability in the residential sector according to type of buildings, this was subdivided into single-family houses (SFH) and multi-apartment buildings (MAB) (Fina et al., 2020). Furthermore, having the different sectors as members also allows differentiating EC results, as some zones of the country are more industrialised, or have more services than others, leading to different EC outputs in comparison with the typical only residential ECs.

As such, we allow for the formation of energy communities, one per municipality, with 4 traders each, as represented in Figure 3. Energy communities are expected to ignite the energy generation decentralization, allowing to aggregate complementary consumers and increasing self-consumption of locally generated renewable energy.

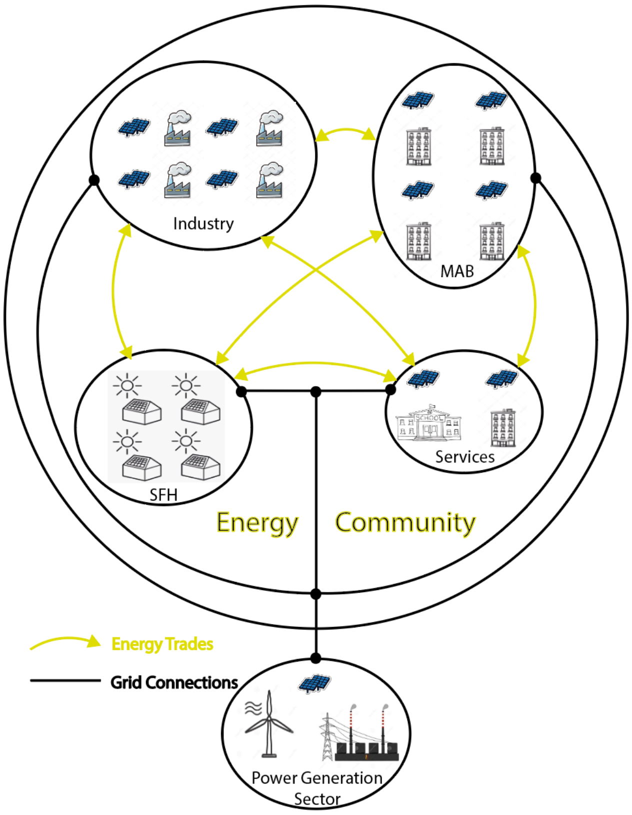
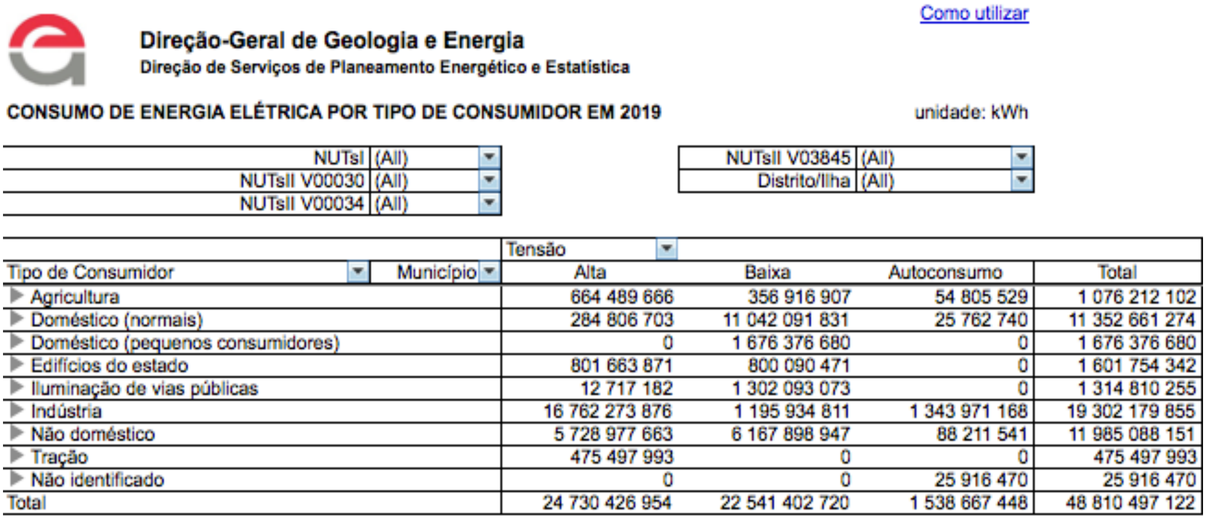


Figure 3 – Energy community model

3.1.1. Electricity demand modelling

In order to achieve the propositioned goal, electricity consumption and PV generation modelling is required. For each municipality, a characterisation of the residential, industry and services sectors was made. The consumption data was retrieved from Direção-Geral de Energia e Geologia (DGEG) for the year 2019, (DGEG, 2019), not only because that is the most recent available year, but also because it presents more representative demand data, when compared to 2020, which was influenced by the outbreak of the COVID-19 pandemic. Figure 4 shows the DGEG interface for the national electricity consumption, i.e., the sum of all municipalities' consumption, per type of consumer (left column) and voltage type, for that year.



Como utilizar

Direção-Geral de Geologia e Energia
Direção de Serviços de Planeamento Energético e Estatística

CONSUMO DE ENERGIA ELÉTRICA POR TIPO DE CONSUMIDOR EM 2019

unidade: kWh

NUTsI (All)
NUTsII V00030 (All)
NUTsII V00034 (All)
NUTsII V03845 (All)
Distrito/Ilha (All)

Tipo de Consumidor	Município	Tensão Alta	 Baixa	 Autoconsumo	 Total
Agricultura		664 489 666	356 916 907	54 805 529	1 076 212 102
Doméstico (normais)		284 806 703	11 042 091 831	25 762 740	11 352 661 274
Doméstico (pequenos consumidores)		0	1 676 376 680	0	1 676 376 680
Edifícios do estado		801 663 871	800 090 471	0	1 601 754 342
Iluminação de vias públicas		12 717 182	1 302 093 073	0	1 314 810 255
Indústria		16 762 273 876	1 195 934 811	1 343 971 168	19 302 179 855
Não doméstico		5 728 977 663	6 167 898 947	88 211 541	11 985 088 151
Tração		475 497 993	0	0	475 497 993
Não identificado		0	0	25 916 470	25 916 470
Total		24 730 426 954	22 541 402 720	1 538 667 448	48 810 497 122

Figure 4 – Electricity consumption per type of consumer (2019)

For the residential sector, the annual electricity consumption ($C_{annual,j}^{residential}$) was considered as the sum of the "Domestic - Normal" and "Domestic - Small Consumers" values. Concerning the industrial sector, its annual consumption was calculated as the sum of high ($C_{annual,HV,j}^{industry}$) and low voltage ($C_{annual,LV,j}^{industry}$). The services sector is not described in DGEG data, as the information available is related either to "Non Domestic" or "State Buildings" types of consumer. Nevertheless, their percentage of high and low voltage consumers, as well as the percentage of high and low voltage consumption, is very similar and, therefore, these types were joined as a single sector. Consequently, its consumption is pondered as the sum of high ($C_{annual,HV,j}^{services}$) and low voltage ($C_{annual,LV,j}^{services}$) values of both types. This association is summarised in Table 2.

Table 2 – Association of DGEG consumers with economic sectors

Type of Consumer (DGEG nomenclature)	**Economic Sector**
Agricultura	Not considered
Doméstico (normais)	Residential
Doméstico (pequenos consumidores)	
Edifícios do Estado	Services
Não Doméstico	
Iluminação de vias públicas	Not considered
Indústria	Industry
Tração	Not considered
Não Identificado	Not considered

Nonetheless, the Portuguese Census (INE, 2011) provides more detailed information about the residential sector, namely the number of buildings by number of floors. Since the consumption is not exactly the same for low-rise houses in comparison with high-rise buildings, the residential sector was, as previously mentioned, subdivided in single-family houses (SFHs), consisting in buildings with 1-2 floors, and multi apartment buildings (MABs), with 3 or more floors. With the purpose of deriving more building-dependent electricity demand values, the following formula is used:

$$C_{annual,j}^{residential} = \left(\frac{C}{A}\right)_j^{SFH} \times A_{floor,j}^{SFH} + \left(\frac{C}{A}\right)_j^{MAB} \times A_{floor,j}^{MAB}$$

$$for \quad j \in \{Abrantes, \dots, Vouzela\} \qquad \text{Eq. 1}$$

With

- $C_{annual,j}^{residential}$ - Annual electricity consumption value for the entire residential sector $[kWh]$;
- $\frac{C}{A}$ - Electricity intensity per unit area $[\frac{kWh}{m^2}]$;
- A_{floor} - Total floor area $[m^2]$.

However, in the absence of specific energy intensities for the case study, the ones found on the USA's Census (U.S. Energy Information Administration (EIA), 2018) were used, where the electricity intensity are not absolute, rather relative between SFH and MAB. Thus, estimating that $(\frac{C}{A})_j^{SFH} = 1{,}96 \times (\frac{C}{A})_j^{MAB}$, and replacing in previous Eq. 2, results in the following set of Equations:

$$(\frac{C}{A})_j^{MAB} = \frac{C_{annual,j}^{residential}}{1.96 \times A_{floor,j}^{SFH} + A_{floor,j}^{MAB}} \qquad \text{Eq. 3}$$

$$C_{annual,j}^{MAB} = (\frac{C}{A})_j^{MAB} \times A_{floor,j}^{MAB} \qquad \text{Eq. 4}$$

$$C_{annual,j}^{SFH} = C_{annual,j}^{residential} - C_{annual,j}^{MAB} \qquad \text{Eq. 5}$$

$$for \; j \in \{Abrantes, \dots, Vouzela\}$$

With

- $C_{annual,j}^{SFH}$,$C_{annual,j}^{MAB}$ and $C_{annual,j}^{residential}$ - Annual electricity consumption values for SFH, MAB and the entire residential sector, respectively $[kWh]$;

In order to obtain the electricity load with an hourly basis, national load profiles, retrieved from (E-Redes, 2020), were normalized. These profiles report the energy consumption each 15 minutes for the whole year and are divided in 5 types: MAT ("Very High Voltage"), AT ("High Voltage"), MT ("Medium Voltage"), BTE ("Special Low Voltage") and BTN ("Normal Low Voltage"). An association between the different voltage type profiles and economic sectors was proposed and is present in Table 3: MAT and

AT are usually present in industry, MT in services, BTN in the domestic sector, and BTE can be found when there are low voltage applications in services or industries.

Table 3 – Association between voltage type profiles and economic sectors

Type of demand (DGEG nomenclature)	**Economic Sector**	**High voltage (DGEG)**	**Low voltage (DGEG)**
		Type of voltage hourly profile applied (from EDP)	
Doméstico (pequenos consumidores)	Residential: SFH MAB	BTN	
Doméstico (normais)			
Edifícios do Estado	Services	MT	BTE
Não Doméstico			
Indústria	Industry	Average (MAT, AT)	BTE

Thus, the hourly energy consumption, for each sector of each municipality was calculated as follows:

$$C_j^{SFH}(h) = C_{BTN}^{norm}(h) \times C_{annual,j}^{SFH} \tag{Eq. 6}$$

$$C_j^{MAB}(h) = C_{BTN}^{norm}(h) \times C_{annual,j}^{MAB} \tag{Eq. 7}$$

$$C_j^{industrial}(h) = \frac{C_{MAT}^{norm}(h) + C_{AT}^{norm}(h)}{2} \times C_{annual,HV,j}^{industry} + C_{BTE}^{norm}(h) \times C_{annual,LV,j}^{industry} \tag{Eq. 8}$$

$$C_j^{services}(h) = C_{MT}^{norm}(h) \times C_{annual,HV,j}^{services} + C_{BTE}^{norm}(h) \times C_{annual,LV,j}^{services} \tag{Eq. 9}$$

$$for\ j \in \{Abrantes, \dots, Vouzela\}, h \in \{1, \dots, 8760\}$$

With

- C_j - Hourly energy consumption $[kWh]$;
- C^{norm} - Normalised loads (adimensional);

Hence, BTE consumption is included in industry and service sectors, and its inclusion is attributed to low voltage consumption referenced in DGEG data. Besides, high voltage in industry was averaged between MAT and AT profiles.

3.1.2. Solar PV modelling

Afterwards, the installed nominal power ${P^i}_{PV,j}$ for each EC member, was computed based on the share of decentralized PV power in the electricity production sector, as follows:

$$C^i_{PV,j} = C^i_{annual,j} \times \%^{electricity\ production\ sector}_{decentralized\ PV} \quad \text{Eq. 10}$$

$${P^i}_{PV,j} = \frac{C^i_{PV,j}}{365 \times 24 \times CF_j} \quad \text{Eq. 11}$$

$$i \in \{residential, industrial, services\}$$

With

- $C_{PV,j}$ - Fraction of the total consumption provided by decentralized PV $[MWh]$, from decarbonization strategy (RNC 2050);
- $\%^{electricity\ production\ sector}_{decentralized\ PV}$ - Fraction of decentralized PV production existent in the electricity power sector (adimensional);
- $P_{PV,j}$ - Installed nominal power $[MW]$;
- CF - The annual average capacity factor (adimensional), calculated from 2019 generation data.

The previous formula calculated the installed nominal power for the totality of each EC member. Given that for the industry and services' sectors there is no further information about number of buildings or available areas for PV deployment, it was assumed that these PV power calculated by Eq. 11 was possible to be installed. However, given that for the residential sector there is more available information regarding the number, types, areas and number of floors of residential buildings, the approach to find the PV installed nominal power was further refined.

For residential buildings, MABs, due to their multiple floors and families, typically have a lower ratio between available rooftop area and electricity demand, when compared to SFHs, since PV generation is mainly dependent on the rooftop area available for installation. Therefore, the PV power to be installed in SFH and MAB was computed by multiplying the entire residential sector's installed power by each member's ratio between respective roof area and the total residential sector's roof area (Eq. 12). This way, if, for instance, a municipality's residential sector has more rooftop area in SFHs, then these will have more installed PV power than MABs.

$${P^i}_{PV,j} = P^{residential}_{PV,j} \times \frac{A^i_{roof,j}}{A^{SFH}_{roof,j} + A^{MAB}_{roof,j}} \quad \text{Eq. 12}$$

$$for \quad i \in \{SFH, MAB\}, j \in \{Abrantes, \dots, Vouzela\}$$

With A_{roof} as the total roof area $[m^2]$.

How to estimate the available rooftop area will be further explained in subsection 3.1.2.1.

Finally, hourly solar PV production diagrams were made for each municipality and sector, by multiplying ${P^i}_{PV,j}$ by the hourly power output representative of a 1 kW standard capacity ($P_j^{1kW}(h)$) for the geographic location of each municipality:

$$E_{prod,j}^{i}(h) = P_j^{1kW}(h) \times {P^i}_{PV,j}$$
$$i \in \{residential_{SFH}, residential_{MAB}, industrial, services\}, j \in \{Abrantes, \dots, Vouzela\},$$
$$h \in \{1, \dots, 8760\} \qquad \text{Eq. 13}$$

With

- $E_{prod,j}$ - Hourly PV generation $[kWh]$
- P_j^{1kW} - Hourly power output (adimensional).

3.1.2.1. Residential floor area and rooftop available area modelling

In order to estimate the available roof area to install PV panels in the residential sector, as well as its floor area, data from INE was used (INE, 2011).

Knowing the distribution of accommodations with the number of floors (available in the document "*Edifícios (N.º) por Localização geográfica (à data dos Censos 2011), Dimensão de pisos, Tipo de utilização e Escalão de dimensão de alojamentos; Decenal*"), an average number of accommodations per building ($\overline{N\_accom\_build}$), as well as an average number of floors per building ($\overline{N\_floors}$) were computed for each municipality, for both types of buildings (SFH and MAB). The document "*Alojamentos familiares clássicos de residência habitual (N.º) por Localização geográfica (à data dos Censos 2011), Escalão de divisões e Escalão de área útil; Decenal*" provides the number of accommodations with a certain range of floor areas as well as its distribution with their number of divisions; however, there is no data relating the number of divisions with the number of floors and, therefore, no way to find an average area for each type of buildings. This way, the average area for an accommodation ($\overline{A\_accom}$) was calculated for each municipality, which means that the model assumes that an accommodation has the same area whether it belongs to a SFH or a MAB.

Finally, the number of accommodations per floor ($\overline{N\_accom\_floor}$) was also based on an assumption:

$$\overline{N\_accom\_floor}^{bt} = \begin{cases} 4 \ , \overline{N\_accom\_build}^{bt} \geq 3{,}5 \\ 3 \ , \overline{N\_accom\_build}^{bt} \geq 2{,}5 \\ 2 \ , \overline{N\_accom\_build}^{bt} \geq 1{,}5 \\ 1 \ , \overline{N\_accom\_build}^{bt} \quad c.c. \end{cases}, \quad bt \in \{SFH, MAB\} \qquad \text{Eq. 14}$$

Having established these assumptions, the available roof area for residential buildings of each type was approximated as

$$A_{roof,j}^{bt} = \overline{N\_accom\_floor}^{bt} \times \overline{A\_accom} \times N^{bt}$$

$$for \quad bt \in \{SFH, MAB\}, j \in \{Abrantes, \dots, Vouzela\}$$

Eq. 15

With

- $\overline{A\_accom}$ - Average accommodation area $[m^2]$;
- N^{bt} – Number of buildings (adimensional).

The floor area, used in the SFH and MAB consumption calculations through energy intensity index, was computed simply by multiplying the roof area by the average number of floors:

$$A_{floor,j}^{bt} = A_{roof,j}^{bt} \times \overline{N\_floors}^{bt}$$

$$for \quad bt \in \{SFH, MAB\}, j \in \{Abrantes, \dots, Vouzela\}$$

Eq. 16

With

- $\overline{N\_floors}$ - Average number of floors (adimensional);

Afterwards, the correspondent areas of PV panels were calculated, in order to compare them with the rooftop areas:

$$A_{panel,j}^{i} = \frac{{P^{i}}_{PV,j}}{I * \eta}$$

$$for \quad i \, \epsilon \, \{SFH, MAB, industrial, services\}\,, j \in \{Abrantes, \dots, Vouzela\}$$

Eq. 17

In this formula, *I* is the irradiance, which is equal to 1000W/m^2, according to the standard test conditions for nominal PV power calculations and η is the solar panel efficiency, considered as 20% (U.S. Energy Information Administration (EIA), 2021) for all installations.

3.1.3. P2P market model optimisation

As previously mentioned, although ECs aim to promote environmental wellbeing, they also intend to create local value and avoid the outflow of financial resources. P2P models, in particular, claim to be effective in reducing electricity bills. Therefore, the designed P2P market model performs an optimization, which minimizes the communities' total costs, by finding a compromise that benefits all members. The proposed model allows each member to buy from and sell to any other member and the grid. The main goal was to compute a matrix *P* for each EC and each hour of the year, with energy exchanges as its components:

$$P[kWh](h) = \begin{bmatrix} 0 & p_{SFH/MAB} & p_{SFH/IND} & p_{SFH/TERC} & p_{SFH/GRID} \\ p_{MAB/SFH} & 0 & p_{MAB/IND} & p_{MAB/TERC} & p_{MAB/GRID} \\ p_{IND/SFH} & p_{IND/MAB} & 0 & p_{IND/TERC} & p_{IND/GRID} \\ p_{TERC/SFH} & p_{TERC/MAB} & p_{TERC/IND} & 0 & p_{TERC/GRID} \end{bmatrix} \qquad \text{Eq. 18}$$

$$h \in \{1, \dots, 8760\}$$

The way that this matrix is shown presents a convention used in this entire thesis: SFH, MAB, industry and services have indexes 1, 2, 3 and 4, respectively.

The problem formulation was grounded on the proposal made by (Baroche et al., 2019):

$$\begin{aligned} & min_{P, p_n \epsilon \Omega} && \Sigma_{n \epsilon \Omega} [f_n(p_n) + \gamma_n^0 + \Sigma_{m \epsilon \omega_n} \gamma_{nm} p_{nm}] \\ & s.t. && P = -P^T \\ & && p_n = \Sigma_{m \epsilon \omega_n} \, p_{nm} \end{aligned} \qquad \text{Eq. 19}$$

With

- Ω - P2P community;
- ω_n - Set of partners of member *n*;
- *m* - A particular peer;
- f_n – Costs dependent of the power traded (collected by other agents) [€];
- γ_n^0 – Costs independent of the power traded, such as power line investment and maintenance (collected by the system operator)[€];
- γ_{nm} – Network charges, (collected by the system operator) $[\frac{€}{kWh}]$;
- p_{nm} – Energy exchanges $[kWh]$;

The formulation shows that the *P* matrix must be skew-symmetric, because the amount of energy sold by member *n* to member *m* must be the same as the amount bought by member *m* from member *n*. This also denotes the used convention of having positives or negatives according to the direction of the energy transactions. As reported by (Baroche et al., 2019), positive values are used for sales (($p_{nm} \geq 0$) and negatives ($p_{nm} \leq 0$) for purchases. Some adjustments were made here, such as not including γ_n^0 and reducing f_n only to trading prices, which will be explained in market optimization. Also, the minimization function was also subjected to additional constraints that limit sales and purchases to what each consumer is producing in excess or demanding in that specific moment, avoiding speculative behaviours.

These constraints imply that a member, when in excess, i.e., when it produces more energy than it consumes, cannot buy more energy ($p_{nm} \geq 0$) and cannot sell more than this difference, which means that, before selling, it satisfies its individual consumption needs from local production first. Similarly, when a member has an energy deficit, i.e., when it produces less than it consumes, it cannot sell energy ($p_{nm} \leq 0$) and can not buy more than the difference so that all its production ensures as much of the consumption needs as it can. In other words, in both cases, self-consumption is prioritised. Self-consumption also explains the zeros on matrix *P*, assuring there is no trading of a member with itself.

This problem was also solved with an iterative process present in (Baroche et al., 2019) (with the mentioned approximations and restrictions), that simulates a decentralised negotiation mechanism for a P2P market:

$$P_n^{k+1} = argmin_{P_n} \quad \Sigma_{m\epsilon\omega_n} \left[\gamma_{nm}\mathrm{p}_{nm} + \lambda_{nm}^k\left(\frac{p_{nm}^k - p_{mn}^k}{2} - p_{nm}\right) + \frac{\rho}{2}\left(\frac{p_{nm}^k - p_{mn}^k}{2} - p_{nm}\right)^2\right] \qquad \text{Eq. 20}$$

$$\lambda_{nm}^{k+1} = \lambda_{nm}^k - \frac{\rho}{2}(p_{nm}^{k+1} - p_{mn}^{k+1}) \qquad \text{Eq. 21}$$

With

- *P* – Energy trade matrix;
- *k* – iteration index
- ω_n - the set of peers of member *n*;
- *m* as a particular peer;
- γ_{nm} - Network charges [$\frac{€}{kWh}$];
- p_{nm} - Traded energy between *n* and *m* [kWh];
- λ_{nm} - Trading price of electricity per energy unit [$\frac{€}{kWh}$];
- ρ - Penalty factor ($\rho > 0$) [$\frac{€}{kWh^2}$].

The first equation estimates the energy exchanges, i.e. p_{nm}, using a minimization function (concretely, *fmincon* on *Matlab*), that minimizes costs. Then, the second equation calculates new values for the trading prices based on the newly calculated energy exchanges and a penalty factor, that penalizes differences on symmetric entries on matrix *P*. This process is repeated iteratively until the following stopping criteria is met:

$$\Sigma_{n\epsilon\Omega}\ r_n^{k+1} \leq \epsilon^{primal^2} \qquad \text{Eq. 22}$$

$$\Sigma_{n\epsilon\Omega}\ s_n^{k+1} \leq \epsilon^{dual^2} \qquad \text{Eq. 23}$$

With Ω as the P2P community, ϵ^{primal} and ϵ^{dual} as primal and dual global feasibility tolerances, respectively, and r_n^{k+1} and s_n^{k+1} denoting primal and dual local residuals:

$$r_n^{k+1} = \Sigma_{m\epsilon\omega_n}\ (p_{nm}^{k+1} + p_{mn}^{k+1})^2 \qquad \text{Eq. 24}$$

$$s_n^{k+1} = \Sigma_{m\epsilon\omega_n}\ (p_{nm}^{k+1} - p_{nm}^{k})^2 \qquad \text{Eq. 25}$$

Eq. 22 and Eq. 24 certify residual (as large as allowed by the primal global feasibility tolerance) differences between the values bought and sold in energy trades. In other words, they assure that *P* is skew-symmetric. Eq. 23 and Eq. 25 make sure that the solution has converged, i.e., that the difference between each entry on *P* and its previous iteration is residual (controlled by the dual global feasibility tolerance).

Therefore, the penalty factor is the parameter that drives the algorithm forward, since it is directly related to the update of trading prices, that will influence the calculation of energy exchanges in the next iteration. However, it does not represent a real cost. In fact, upon the process' stoppage, the term that multiplies by ρ on Eq. 20 ($\frac{p_{nm}^k - p_{mn}^k}{2} - p_{nm}$) tends to 0, due to skew-symmetry.

In order to initialise the process, the matrixes with the trading prices and network charges must have initial guesses. Concerning the network charges, constant values were used, according to the collected data. However, the trading prices were obviously unknown, as they are objectives of the minimization problem. Ideally, when selling, a member wants to sell at the highest price, while a buyer is interested in performing that transaction paying the lowest price. Thus, in this case, the highest selling price would be limited by the "buying-from-grid" price (λ_{grid}), because with a price higher than that, the buyer would prefer to buy from the grid instead. On the other hand, the lowest buying price would converge to the "selling-to-grid" price ($\lambda_{grid,out}$), since, once again, if asked to sell to a member for a lower value, the seller would prefer to sell to the grid. Therefore, before initiating the algorithm, the energy state of each member (i.e. deficit – D - or excess – E - of energy) is checked, to be able to tell if it is interested in buying or selling energy and to compute an initial guess for λ^1. Since there are 4 members and 2 states, a total of 2^4=16 combinations are possible. For example, a case with deficit for SFH, MAB and industry, and excess for services (DDDE) implies:

$$\lambda^1[\frac{€}{kWh}] = \begin{bmatrix} 0 & 0 & 0 & \lambda_{grid,out} \\ 0 & 0 & 0 & \lambda_{grid,out} \\ 0 & 0 & 0 & \lambda_{grid,out} \\ \lambda_{grid}^{SFH} & \lambda_{grid}^{MAB} & \lambda_{grid,j}^{industry} & 0 \end{bmatrix} \qquad \text{Eq. 26}$$

$$for \quad j \in \{Abrantes, \dots, Vouzela\}$$

The variation of $pGin$ and the constant values of $pGout$ will be explained in the next chapter.

3.2. Clustering

Due to the high number of municipalities (278) and computing time for each one (approximately half a day), for the purpose of this thesis, it was not feasible to simulate each one individually. Thus, clustering is a good choice to aggregate the ones with similar characteristics *a priori* in order to present results.

With this objective in mind, *k*-means clustering was run in *Matlab*, using 9 variables shown in Table 4:

Table 4 – Clustering Variables

Annual PV Production (SFH)	$\Sigma_{h=1}^{8760} E_{prod,j}^{SFH}(h)$
Annual PV Production (MAB)	$\Sigma_{h=1}^{8760} E_{prod,j}^{MAB}(h)$
Annual PV Production (Industry)	$\Sigma_{h=1}^{8760} E_{prod,j}^{Industry}(h)$
Annual PV Production (Services)	$\Sigma_{h=1}^{8760} E_{prod,j}^{Services}(h)$
Consumption Ratio SFH/Industry	$\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{industry}}$
Consumption Ratio SFH/Services	$\frac{C_{annual,j}^{MAB}}{C_{annual,j}^{industry}}$
Consumption Ratio MAB/Industry	$\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{services}}$
Consumption Ratio MAB/Services	$\frac{C_{annual,j}^{MAB}}{C_{annual,j}^{services}}$
Number of accommodations per MAB	$\overline{N\_accom\_MAB}$
$j \in \{Abrantes, \dots, Vouzela\}$	

The first 4 variables (Annual PV Production) differentiate municipalities when setting them apart by their solar electricity production potential, whereas the following 4 (Consumption Ratios) discern them by dividing residential by industry and services' consumptions. These are meaningful, since the availabilities and needs of these sectors are, as mentioned before, the main drivers of energy exchanges. Finally, the last variable, the number of accommodations per MAB, aims at further distinguishing rural (with less MABs) and urbanized areas since the consumption of MABs regarding the available rooftop area tends to be larger in the latter, due to a higher number of floors and accommodations.

Besides aggregating municipalities in clusters, *k-means* also provides a centroid for each cluster, which serves as its representation. Nevertheless, the centroids are not directly used to compute the results because the data used for clustering is not sufficient to model the P2P EC (for instance, the CF depends on the municipality's location, which does not exist for the centroid). Subsequently, the municipalities closest to the centroid were used as representative for their clusters, whilst to evaluate a cluster's dispersion, the ones furthest from the centroid were also modelled.

3.3. Key Performance Indicators

The results were evaluated through energy, environmental and economic key performance indicators (KPI). Self-sufficiency assesses the fraction of consumption supplied by locally produced electricity. The surplus indicates the portion of produced energy available to sell.

$$Self\ Sufficiency_j^i\ [\%] = 1 - \frac{\Sigma_{h=1}^{8760}\left(C_j^i(h) - E_{prod,j}^i(h)\right) > 0}{C_{annual,j}^i} \qquad \text{Eq. 27}$$

$$Surplus_j^i[\%] = \frac{\Sigma_{h=1}^{8760}\left(E_{prod,j}^i(h) - C_j^i(h)\right) > 0}{\Sigma_{h=1}^{8760} E_{prod,j}^i(h)} \qquad \text{Eq. 28}$$

$$for\ i\ \epsilon\ \{SFH, MAB, industrial, services\}, j \in \{Abrantes, \dots, Vouzela\}$$

The environmental KPI is the total CO_2, which is proportional to total grid consumption.

$$Total\ Grid\ Consumption_j\ [GWh] = \Sigma_m \Sigma_{h=1}^{8760} p_{m/GRID}[GWh] \qquad \text{Eq. 29}$$

$$\begin{aligned} &Total\ CO_2\ Emissions_j\ [kton] \\ &= Total\ Grid\ Consumption_j\ [GWh]\ \times\ CO_2\ Emissions\ Factor\ [{}^{kton}/_{GWh}] \end{aligned} \qquad \text{Eq. 30}$$

$$for\ m\ \epsilon\ \{SFH, MAB, industrial, services\}, j \in \{Abrantes, \dots, Vouzela\}$$

Regarding the economic KPI, total costs indicate how much the EC spends on its electricity bill, deducting the amount of income it generates.

$$Expenses_j[M€] = \Sigma_{h=1}^{8760}\ (\Sigma_m\, \Sigma_n(\gamma_{nm} \mathrm{p}_{nm} + \lambda_{nm} \mathrm{p}_{nm})\ +\ \Sigma_m\, \lambda_{grid}^m \times p_{i/GRID}), \qquad \mathrm{p}_{nm} < 0 \qquad \text{Eq. 31}$$

$$Income_j[M€] = \Sigma_{h=1}^{8760}(\Sigma_m\, \Sigma_n\, \lambda_{mn} \mathrm{p}_{nm} +\ \Sigma_m\, \lambda_{grid,out} \times p_{i/GRID}), \qquad \mathrm{p}_{nm} > 0 \qquad \text{Eq. 32}$$

$$Total\ Costs_j\ [M€] = Income_j + Expenses_j \qquad \text{Eq. 33}$$

$$for\ m, n \epsilon \{SFH, MAB, industrial, services\}, j \in \{Abrantes, \dots, Vouzela\}$$

4. Case Study Definition

In order to operate the previously described model, sets of data are needed, concerning electricity demand, solar PV electricity production, buildings' dimensions and electricity prices. In this chapter, it is presented how these sets were obtained for mainland Portugal in 2050. Afterwards, three scenarios for that year are described.

4.1. Data acquisition

With the purpose of estimating electricity demand, normalised load profiles and annual demand are required, according to equations Eq. 6 -Eq. 9. Normalised load profiles reflect consumption behaviours and thus are assumed to remain the same in 2050.

Contrarily, annual consumptions can change, so, for their calculation, simple ratios (CR) are computed by dividing the predicted electricity consumption values for 2050 by their 2020 counterparts, for residential, industry and services, retrieved from the RNC2050 (Portuguese government, 2019). This document has predictions for 2020, assumed to match 2019 consumption. These ratios, displayed on Table 5, are then multiplied by each member's annual consumption data (DGEG, 2019). The ratio is the same for the residential and services sectors, as these are both included in a "buildings" category.

Table 5 - Electricity Consumption Ratios

Economic Sector	Electricity Consumption Ratio (CR) (2050/2020) (%)
Residential (SFH, MAB)	118.2
Industry	215.3
Services	118.2

$$C_{annual,j}^{residential}[kWh] = CR^{residential} \times C_{annual,DGEG\,,j}^{residential}[kWh] \quad \text{Eq. 34}$$

$$C_{annual,vt,j}^{industry}[kWh] = CR^{industry} \times C_{annual,DGEG\,,j}^{industry}[kWh] \quad \text{Eq. 35}$$

$$C_{annual,vt,j}^{services}[kWh] = CR^{services} \times C_{annual,DGEG\,,j}^{services}[kWh] \quad \text{Eq. 36}$$

$$for\ j \in \{Abrantes, \dots, Vouzela\}, vt \in \{HV, LV\}$$

Considering solar PV electricity production (see Eq. 13), hourly power outputs and PV installed capacities (which are dependent on capacity factors and the fraction of decentralized PV production existent in the electricity power sector - see Eq. 10 and Eq. 11) are needed.

The hourly power outputs and the capacity factors were retrieved, for all municipalities, from the "Renewables Ninja" website (*Renewables.Ninja*, 2019), by selecting a standard capacity of 1 kW, as well as a system loss of 10%, an azimuth angle of 180º (i.e. south-facing panels), no tracking systems for the panels and an optimal tilt angle for each location, which was calculated using the European

Union's JRC Photovoltaic Geographical Information System (European Commission, 2021). With these constraints, the obtained inputs are only determined by the municipalities' locations, and, subsequently, are assumed to be valid for 2050.

The future fraction of decentralized PV production existent in the electricity power sector is estimated as 27.6%, based on the RNC2050 (Portuguese government, 2019).

Regarding the buildings' dimensions, namely the estimation of roof and floor areas of SFH and MAB, necessary for installed nominal power and annual consumption calculations, respectively, the previously mentioned data from INE (INE, 2011) was considered to be valid for the case study, as significant changes in the residential sector are not forecasted for the next decades and any foresight of that sort would be out of the scope of this work.

The functioning of the P2P market is modelled by minimizing the EC's members' costs, which were subdivided in network charges and trading prices. Network charges (γ), independent of the members' negotiations and defined *a priori*, were obtained from ERSE (Entidade Reguladora dos Serviços Energéticos, 2020), and vary according to the voltage level (MAT, AT, MT, BTE and BTN), daily consumption periods (super off-peak, off-peak, shoulder and peak) and the year's trimesters. Concretely, 4-period tariffs were chosen for MAT, AT, MT and BTE, and 2-period tariffs (off-peak and peak) for BTN. While 4-period tariffs are usual for their corresponding voltage levels, in BTN, both 2-period (dual) and 1-period (simple) tariffs are common. Nonetheless, when PV systems are installed, a dual tariff is generally preferred, as self-consumption provides energy during peak hours (at least partially), when it is more costly, and the grid provides during off-peak periods, which is cheaper in comparison with the constant price of simple tariffs. Moreover, in contrast to BTN, whose values do not change between weekdays (daily cycle), for MAT, AT, MT and BTE, weekdays' consumption periods differ from weekends (weekly cycle).

Afterwards, for each EC member, network charges were computed similarly to the way consumptions were, as the members are associated with the same voltage types as before:

$$\gamma^{SFH}(h) = \gamma^{MAB}(h) = \gamma^{BTN}(h) \qquad \text{Eq. 37}$$

$$\gamma_j^{industrial}(h) = \frac{C_{annual,HV,j}^{industry}}{C_{annual,HV,j}^{industry} + C_{annual,LV,j}^{industry}} \times \frac{\gamma^{MAT}(h) + \gamma^{AT}(h)}{2} + \frac{C_{annual,LV,j}^{industry}}{C_{annual,HV,j}^{industry} + C_{annual,LV,j}^{industry}} \times \gamma^{BTE}(h) \qquad \text{Eq. 38}$$

$$\gamma_j^{services}(h) = \frac{C_{annual,HV,j}^{services}}{C_{annual,HV,j}^{services} + C_{annual,LV,j}^{services}} \times \gamma^{MT}(h) + \frac{C_{annual,LV,j}^{services}}{C_{annual,HV,j}^{services} + C_{annual,LV,j}^{services}} \times \gamma^{BTE}(h) \qquad \text{Eq. 39}$$

$$for \quad j \in \{Abrantes, \dots, Vouzela\}, \qquad h \in \{1, \dots, 8760\}$$

With γ in $[\frac{€}{kWh}]$ and $C_{annual,j}$ in $[kWh]$.

It should be noted that these equations are only hourly dependent because each hour has an association with a year's trimester, consumption period and weekday. Also, since residential members all use BTN, their network charges are constant across all country, unlike for industry and services.

Regarding the trading prices, data was also retrieved from (Entidade Reguladora dos Serviços Energéticos, 2020) as well as (OMIE, 2021). The first data source provides the final prices consumers pay to the grid ($pGin$), which change in the same way as network charges, according to voltage level.

However, these prices already include network charges, and thus these were subtracted to obtain the trading prices (λ):

$$\lambda_{grid}^{SFH}(h) = \lambda_{grid}^{MAB}(h) = pGin^{BTN} - \gamma^{BTN} \qquad \text{Eq. 40}$$

$$\begin{aligned} \lambda_{grid,j}^{industry}(h) = {} & \frac{C_{annual,HV,j}^{industry}}{C_{annual,HV,j}^{industry} + C_{annual,LV,j}^{industry}} \times \frac{pGin^{MAT}(h) + pGin^{AT}(h)}{2} \\ & + \frac{C_{annual,LV,j}^{industry}}{C_{annual,HV,j}^{industry} + C_{annual,LV,j}^{industry}} \times pGin^{BTE}(h) - \gamma_j^{industry}(h) \end{aligned} \qquad \text{Eq. 41}$$

$$\begin{aligned} \lambda_{grid,j}^{services}(h) = {} & \frac{C_{annual,HV,j}^{services}}{C_{annual,HV,j}^{services} + C_{annual,LV,j}^{services}} \times pGin^{MT}(h) + \frac{C_{annual,LV,j}^{services}}{C_{annual,HV,j}^{services} + C_{annual,LV,j}^{services}} \times pGin^{BTE}(h) \\ & - \gamma_j^{services}(h) \end{aligned} \qquad \text{Eq. 42}$$

$$for \quad j \in \{Abrantes, \dots, Vouzela\}, \quad h \in \{1, \dots, 8760\}$$

With λ, γ and $pGin$ in $[\frac{€}{kWh}]$ and $C_{annual,j}$ in $[kWh]$.

Based on (European Commission, 2016), it was assumed that the average network charges will increase by 92% whilst the remaining components of electricity prices will have a 15% reduction.

The second source is OMIE, (OMIE, 2021), which regulates the Iberian electricity market and that stipulates electricity prices. According to the current legislation, the "selling-to-grid" price ($\lambda_{grid,out}$) is independent of the selling agent and is equal to 90% of the OMIE price:

$$\lambda_{grid,out}^{SFH} = \lambda_{grid,out}^{MAB} = \lambda_{grid,out}^{industry} = \lambda_{grid,out}^{services} = \lambda_{grid,out} = 0{,}9 \times p^{OMIE} \qquad \text{Eq. 43}$$

With p^{OMIE} in $[\frac{€}{kWh}]$.

Since p^{OMIE} varies daily and even intra-daily, 12 values of p^{OMIE} (one for each month of the year) are generated by averaging.

However, p^{OMIE} has had large fluctuations over the course of recent years. During 2019, it had a maximum value of 62.69 €/MWh and a minimum of 33.68€/MWh, during 2020, coincident with the COVID-19 outbreak, it varied between 17.77€/MWh and 42.09€/MWh and recently, in September

2021, it has reached a record 156.53€/MWh. Therefore, a sensibility analysis is made to see how the variation of p^{OMIE} affects the results, based on its values during 2020 and 2021, as presented in 5.4.

Finally, for the $CO_2\, Emissions\, Factor$, data from 2019 was used (European Environment Agency, 2019).

4.2. Scenarios

To assess the energy community's performance, three scenarios were designed: the present scenario (to which the others are compared), a community self-consumption and P2P.

The first studied scenario is the **Present Scenario (PS)**. In this case, the energy system is modelled similarly to the current situation, without the presence of EC and local production. Accordingly, all energy demand is supplied by the grid at all times, which simplifies the energy exchange matrix (Eq. 18) into:

$$P_{PS}[kWh] = \begin{bmatrix} p_{SFH/grid} \\ p_{MAB/grid} \\ p_{industry/grid} \\ p_{services/grid} \end{bmatrix} \qquad \text{Eq. 44}$$

All the values in this matrix represent purchases, as no sales are possible.

The second scenario involves **Collective Self-Consumption (CSC)**. In this situation, the entire EC's electricity consumption and production is summed. Then, two outcomes are possible: either the consumption is larger than the production or vice-versa. The following matrix, P_{CSC}, represents the origin of consumed energy:

$$P_{CSC}[kWh] = \begin{bmatrix} p_{SFH/EC} & p_{SFH/grid} \\ p_{MAB/EC} & p_{MAB/grid} \\ p_{industry/EC} & p_{industry/grid} \\ p_{services/EC} & p_{services/grid} \end{bmatrix} \qquad \text{Eq. 45}$$

The first column aggregates self-consumption of member *i*, whose energy can be generated, in this case, by member *i* or the remaining community members. The second column corresponds to the energy coming from the grid. The following equations explain how these values are computed.

$$p_{i/EC}(h) = \begin{cases} C_j^i(h), & E_{prod,j}^i(h) - C_j^i(h) > 0 \\ E_{prod,j}^i(h) + E_{excess,j}^i, & E_{prod,j}^i(h) - C_j^i(h) < 0 \end{cases} \qquad \text{Eq. 46}$$

$$p_{i/grid}(h) = \begin{cases} 0, & E_{prod,j}^i(h) - C_j^i(h) > 0 \\ C_j^i(h) - (E_{prod,j}^i(h) + E_{excess,j}^i), & E_{prod,j}^i(h) - C_j^i(h) < 0 \end{cases} \qquad \text{Eq. 47}$$

$$E^{i}_{excess,j}(h) = \frac{C^{i}_{j}(h) - E^{i}_{prod,j}(h)}{\Sigma_{\Omega_{deficit}} \left(C^{i}_{j}(h) - E^{i}_{prod,j}(h) \right)} \times \Sigma_{\Omega_{excess}} (E^{i}_{prod,j}(h) - C^{i}_{j}(h)) \qquad \text{Eq. 48}$$

$$for \quad i \,\epsilon\, \{SFH, MAB, industrial, services\}, \quad j \in \{Abrantes, \dots, Vouzela\}, \quad h \in \{1, \dots, 8760\}$$

With

- $p_{i/EC}$ - Self-consumption of member *i* $[kWh]$;
- $E^{i}_{excess,j}$ - Total energy received by member *i* from other members in the EC $[kWh]$;
- $p_{i/grid}$ - Grid consumption of member *i* $[kWh]$;
- $\Omega_{deficit}$ - Group of members in deficit;
- Ω_{excess} - Group of members in excess.

Eq. 46 states that the energy originated from the EC is equal to the members' consumption if it is in excess or to its production plus its received energy if it is in deficit. The energy originated from the grid is either equal to 0, if the member is in excess, or to the difference between consumption and the sum of production and received energy (Eq. 47).

The amount of energy sold by the EC to the grid ($p^{sold}_{grid/EC}$) is equal to the difference between total production and consumption, i.e., it only occurs when the community is in excess:

$$p^{sold}_{grid/EC}(h) = \Sigma^{i} \left(E^{i}_{prod,j}(h) - C^{i}_{j}(h) \right), \qquad \Sigma^{i} (E^{i}_{prod,j}(h) - C^{i}_{j}(h)) > 0 \qquad \text{Eq. 49}$$

$$for \quad i \,\epsilon\, \{SFH, MAB, industrial, services\}, \quad j \in \{Abrantes, \dots, Vouzela\}, \qquad h \in \{1, \dots, 8760\}$$

With $p^{sold}_{grid/EC}$ as the amount of energy sold by the EC to the grid $[kWh]$.

Regarding the costs, in this scenario, all expenses are paid to the grid, in the form of grid purchases and network charges when redistributing energy. In other words, an energy trading between members is not accompanied by a monetary transaction – only the receiver pays charges.

Lastly, the final scenario is **P2P dissemination**, which was already detailed in chapter 3 - Methodology.

5. Results

In this chapter, the results of the case study are presented. Firstly, the distribution of municipalities, along with an analysis of dispersion in their clusters, is shown. Then, the outcomes of each scenario's representative municipalities for each cluster are displayed. Finally, through upscaling, a national comparison is drawn between the three scenarios.

5.1. Clustering

In order to identify the number of clusters, the two most common approaches are the silhouette analysis and the elbow point method. The latter was chosen in this work and, thus, a plot between the sums of the municipalities' distances to their centroids and the number of centroids was made (Figure 5). The elbow point of this plot occurs for 6 clusters and thus this became the number of clusters used for *k-means*.

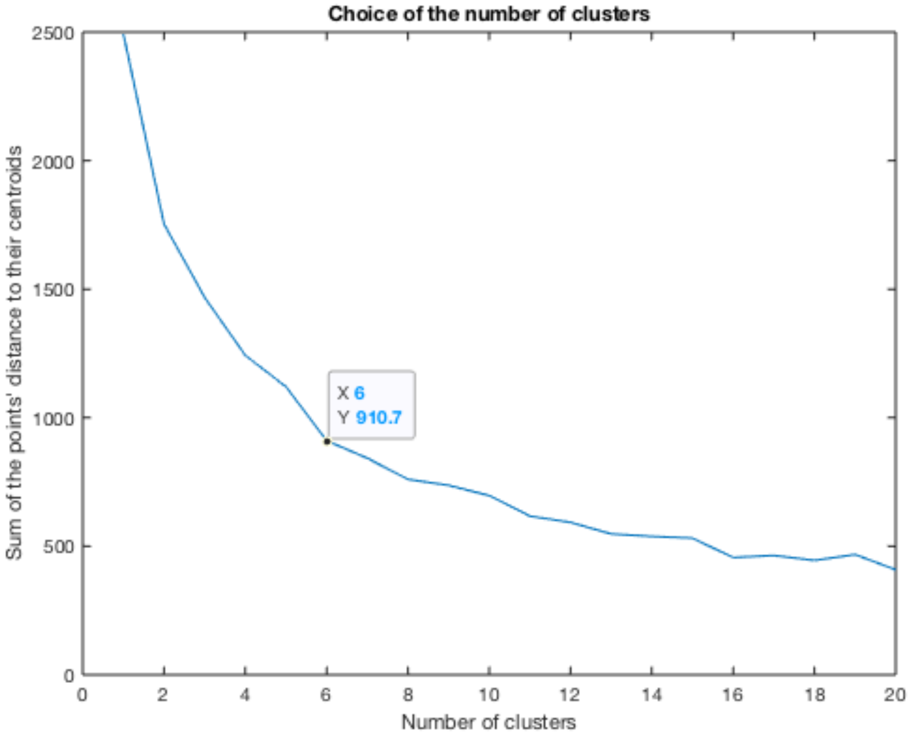


Figure 5 – Choice of the number of clusters

Table 11 (in Annex), displays the municipalities in each cluster. For each cluster, the municipality closest to its centroid is highlighted in green, whereas the one furthest is highlighted in orange.

The more industrialised municipalities compose **Cluster 1**, as seen in Figure 6, where its points, in black, have the highest values of $\Sigma_{h=1}^{8760} E_{prod,j}^{Industry}(h)$. Also, in Figure 8, all points from Cluster 1 have a very low $\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{industry}}$,ratio which indicates a large industrial electricity consumption. Cluster 1 includes 21 municipalities.

The most densely urbanised municipalities, with the highest presence of services, compose **Cluster 2**. Figure 7 clarifies this statement, as its points, in red, have the largest $\Sigma_{h=1}^{8760} E_{prod,j}^{MAB}(h)$ and $\Sigma_{h=1}^{8760} E_{prod,j}^{Services}(h)$ values. This cluster has 5 municipalities, including the biggest cities in the country: Lisbon and Porto.

The municipalities included in **Cluster 3** are very well balanced, as they do not possess a predominant sector, and are mostly suburbs of big cities and/or South-located (Algarve region), with good solar potential. Their lack of predominant characteristics is manifested in some dispersion seen in the yellow points on Figure 6 and Figure 7. It is composed by 22 municipalities.

Cluster 4 groups the most rural municipalities (19), with their residential sectors mainly composed by SFH and almost no industry, as perceived in Figure 8, where its points, in light blue, have the largest $\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{industry}}$, whereas in Figure 6 and Figure 7, the corresponding points have the lowest annual PV production values across all sectors.

Average-sized municipalities (93) compose **Cluster 5**. Generally, these have lower annual PV productions across all sectors than those belonging to Cluster 3, but higher than the ones grouped in Clusters 4 and 6.

Finally, **Cluster 6** is mainly composed by small municipalities, although bigger and more developed than those present in Cluster 4, many of which located in the interior. Their annual PV production values are usually bigger than those belonging to Cluster 4, and industry, in particular, is more developed (smaller $\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{industry}}$ in Figure 8). It is the largest cluster, with 118 municipalities.

For reference, the clusters' representative municipalities are also present in Table 6:

Table 6 – Representative Municipalities

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Closest to centroid	Viana do Castelo	Porto	Póvoa de Varzim	Alfândega da Fé	Lamego	Vouzela
Further from centroid	Setúbal	Lisboa	Odivelas	Penedono	Montijo	Salvaterra de Magos

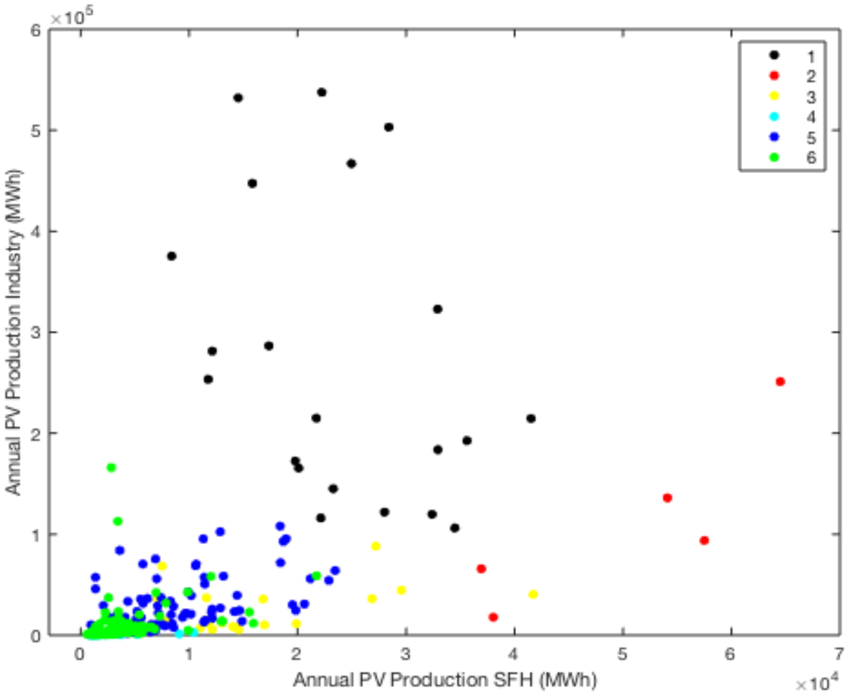


Figure 6 – Clustering: $\Sigma_{h=1}^{8760} E_{prod,j}^{SFH}(h)$ vs $\Sigma_{h=1}^{8760} E_{prod,j}^{Industry}(h)$

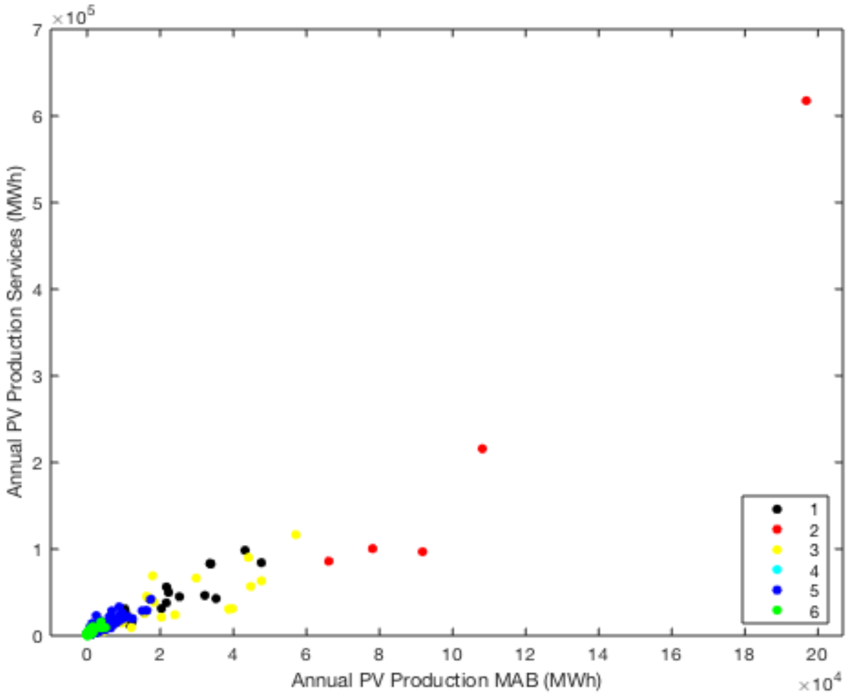


Figure 7 – Clustering: $\Sigma_{h=1}^{8760} E_{prod,j}^{MAB}(h)$ vs $\Sigma_{h=1}^{8760} E_{prod,j}^{Services}(h)$

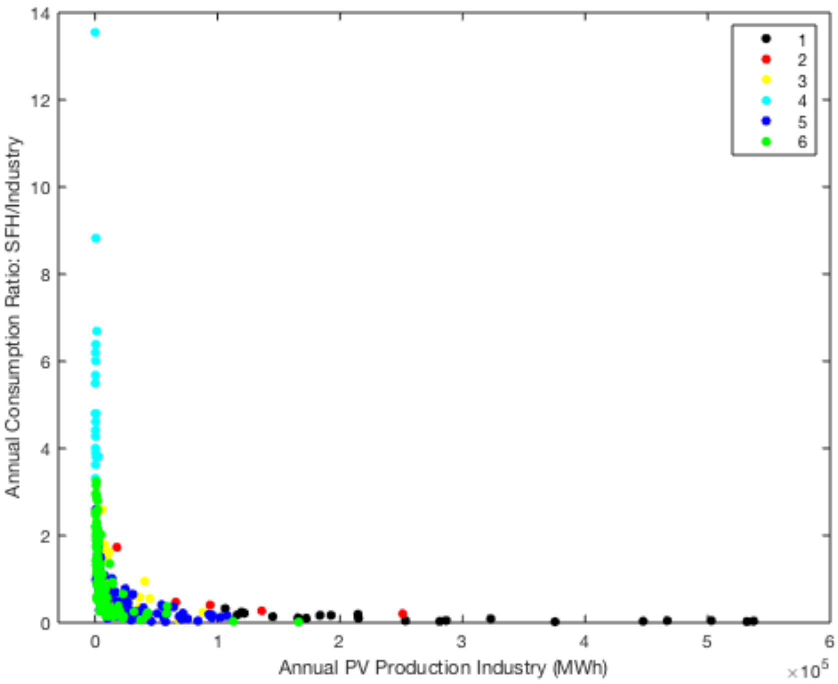


Figure 8 – Clustering: $\Sigma_{h=1}^{8760} E_{prod,j}^{Industry}(h)$ vs $\frac{C_{annual,j}^{SFH}}{C_{annual,j}^{industry}}$

5.2. Scenarios' results

In the following sub-chapters, detailed displays of results are made for Lisbon, followed by more succinct displays for other representative municipalities, which include graphic representations of energy consumption and money fluxes. In these, the colour code use was the following: SFH is represented in green, MAB in light blue, industry in red, services in dark blue, grid in grey and self-consumption in yellow. These circular visualizations are composed by 4 segmented circular bars and inner "bridges". Each bridge represents a purchase and is proportional in size to its magnitude (whether in energy or money units). The bar closest to the centre (with the absolute value scale) symbolises the members, according to each segment's colour. The two ends of each bridge connect a pair of members, with the one in direct contact representing a buyer and the other, with a small gap, representing the seller. Concerning the outer bars and starting from closest to the centre: the first represents purchases, the second is related with sales and the last is equal to the sum of the previous, thus representing the total flux.

5.2.1. Present Scenario

For the Present Scenario, Figure 9 shows the energy trades between grid and EC members, for Lisbon. All 4 bridges connect a member, whether it is SFH, MAB, industry, or services, to the grid, and they are painted in the members' colours, which means that they are the ones purchasing, appropriately to this scenario. Consequently, the grid acts merely as a seller (there are no grey bridges). The size of the blue bridges indicates that the main buyers from the grid are the services (65.27% - dark blue), followed by MAB (20.80% - light blue), which is a fitting result for this municipality, as a member of Cluster 2. SFH (4.02%) and industry (9.91%) are responsible for a smaller share. The total grid consumption is equal to 3.423 TWh.

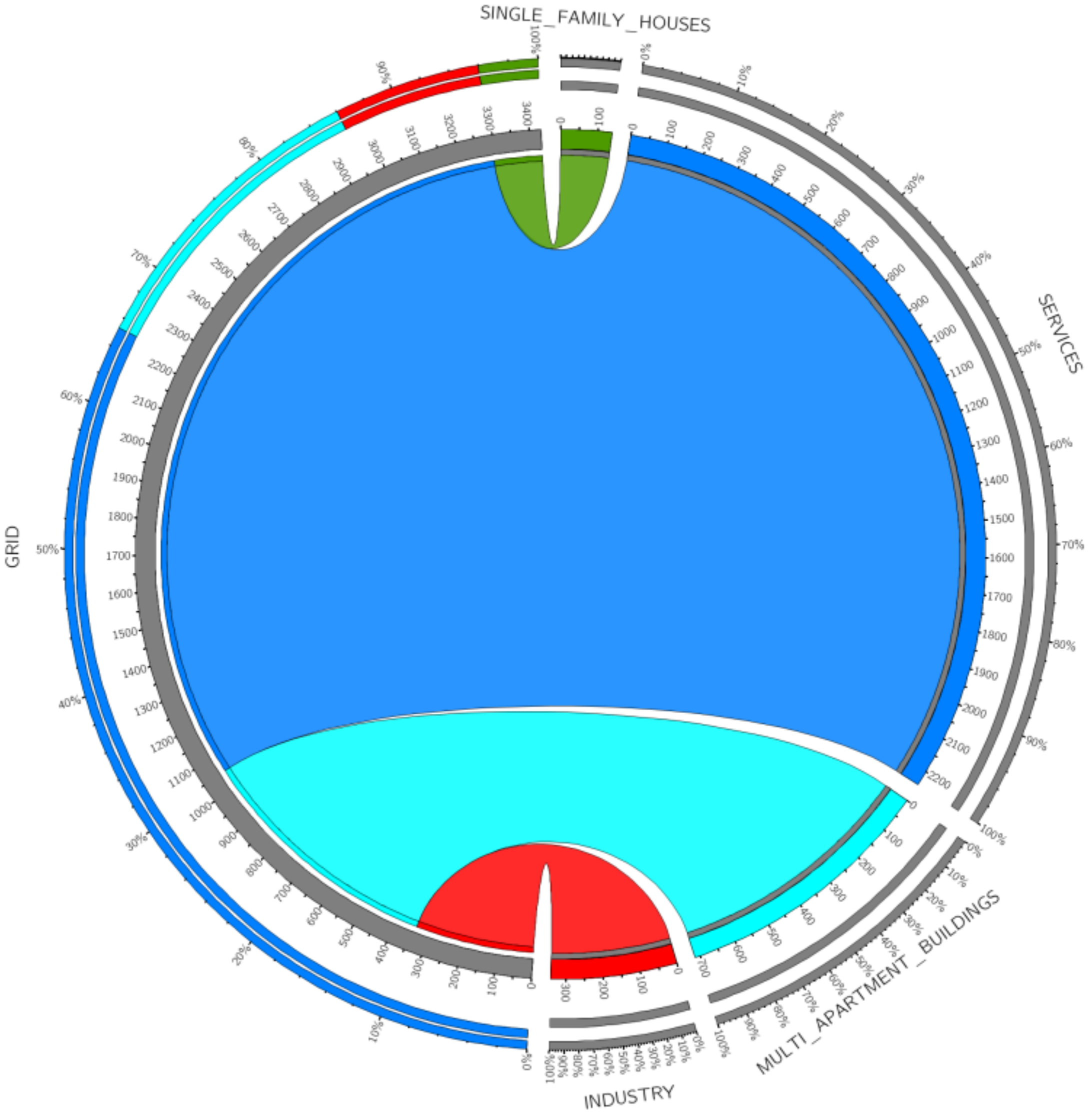


Figure 9 - Energy Consumption for Lisbon (GWh) - Present Scenario

For money fluxes, the bridges also represent purchases. However, since money flows in the opposite direction of energy, the magnitude of blue bridges in Figure 10 means that the most of the grid's sales are with services and MAB. Still, in this case, services represent 58.68% and MAB 28.88% of money fluxes, due to the fact that prices for the residential sector are higher than for services. For the same reason, the share of SFH grows (5.66%) while for industry there is a reduction (6.79%). A total of 529.174 M€ is paid to grid in this scenario.

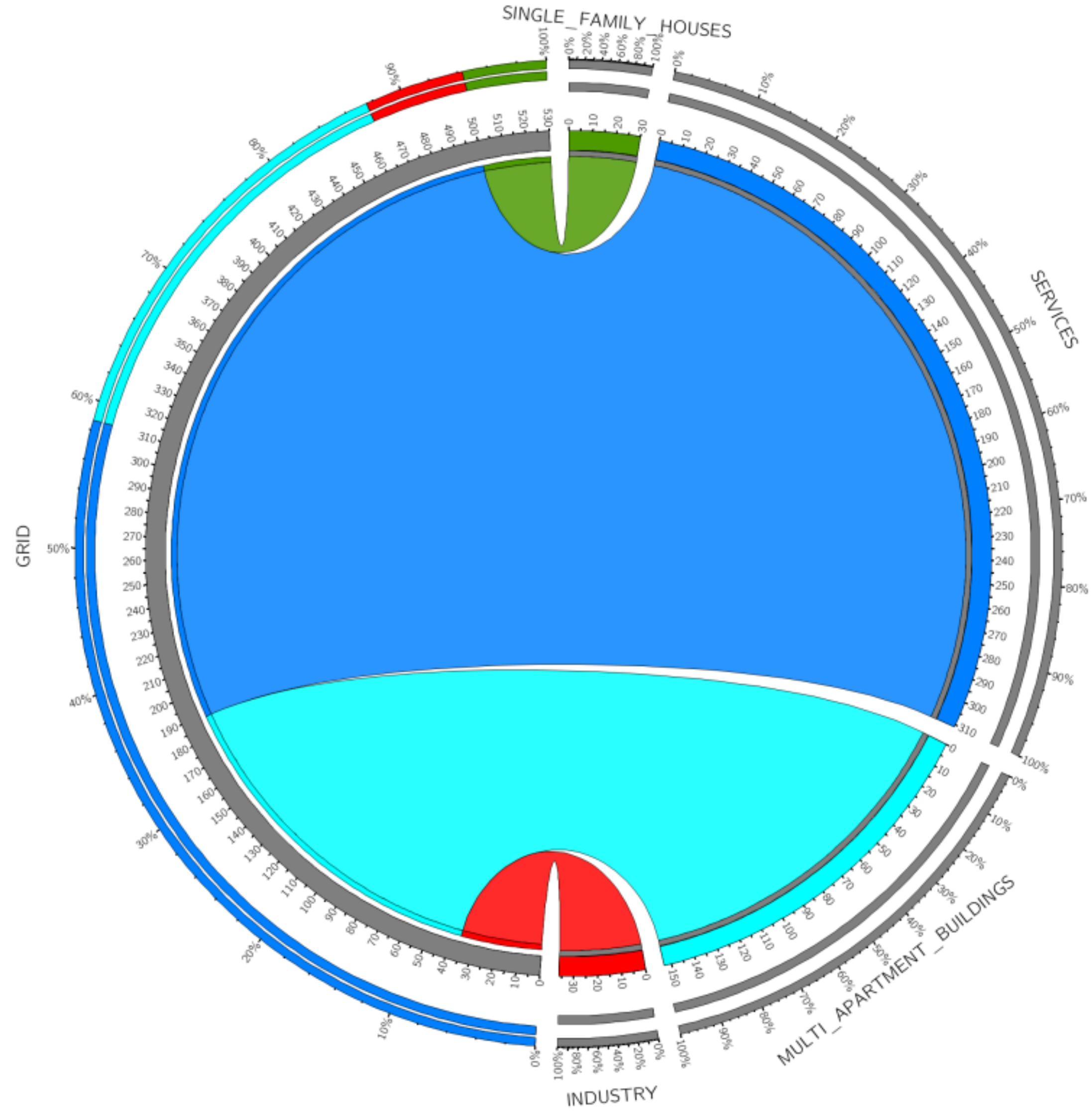
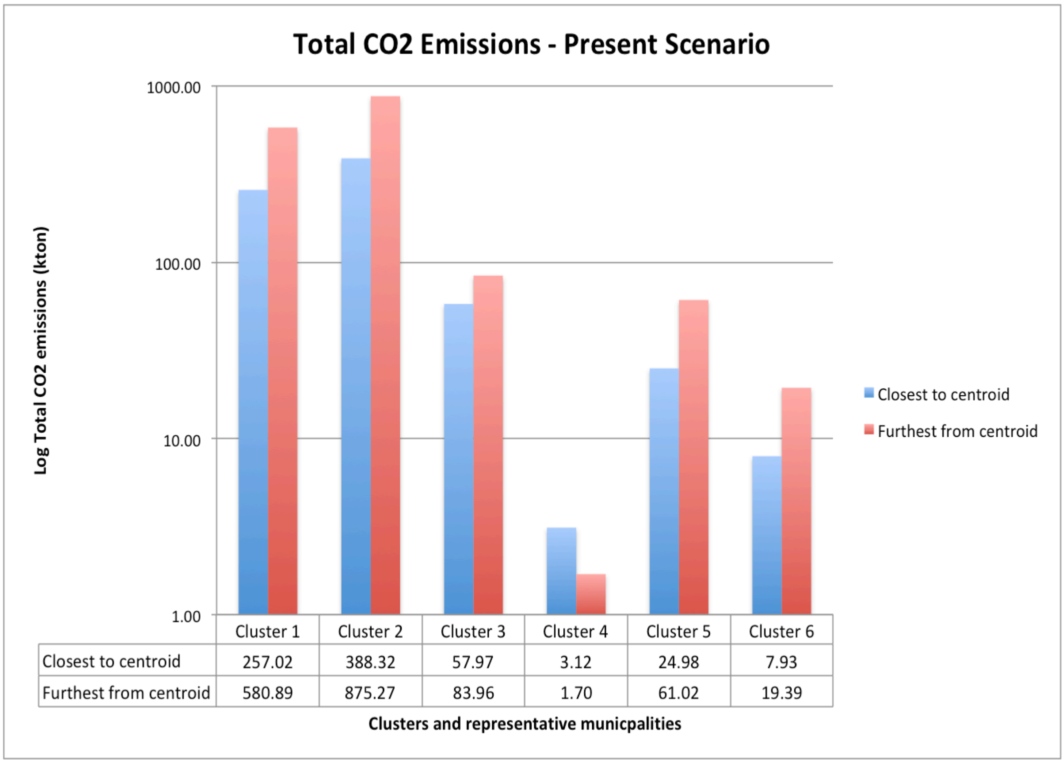


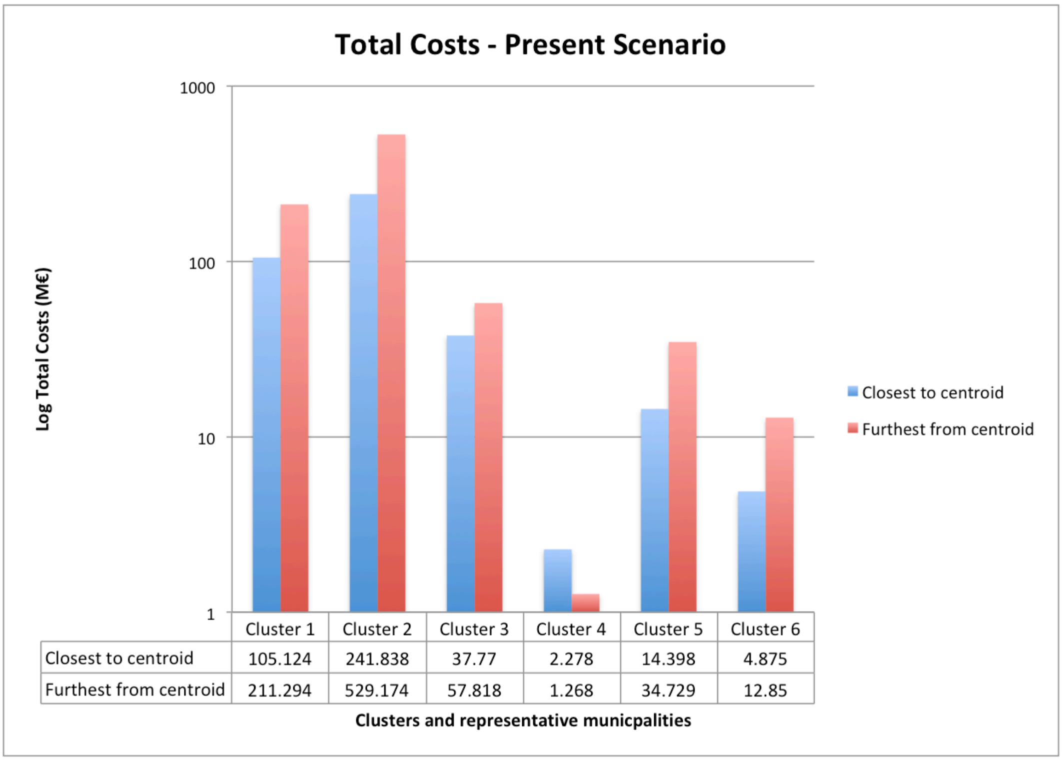
Figure 10 - Money Fluxes (M€) for Lisbon - Present Scenario

Subsequently, a comparison between clusters, through their representative municipalities, is shown in Figure 11 and Figure 12. The description of municipalities in sub-chapter 3.2 matches these figures, because both the biggest emissions (directly proportional to grid consumption) and costs occur for Cluster 2, followed by Cluster 1, 3, 5, 6 and 4. Nevertheless, the CO_2 emissions in Cluster 1's furthest from centroid municipality, Setúbal, surpass those of Cluster 2's representative municipality, Porto, even though Porto has higher costs. The previously mentioned logic applies here as well, as Setúbal has a lot of its electricity consumption coming from industry, whose purchasing prices are smaller than those of MAB and services.



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	257.02	388.32	57.97	3.12	24.98	7.93
Furthest from centroid	580.89	875.27	83.96	1.70	61.02	19.39

Figure 11 – CO_2 emissions in representative municipalities – Present Scenario (See Table 6 for correspondence with municipality)



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	105.124	241.838	37.77	2.278	14.398	4.875
Furthest from centroid	211.294	529.174	57.818	1.268	34.729	12.85

Figure 12 - Costs in representative municipalities – Present Scenario (See Table 6 for correspondence with municipality)

5.2.2. Collective Self-Consumption Scenario

Considering the CSC scenario, we now see bridges connecting members to the grid but also to local production. In Lisbon, the grid accounts for 66.70% of consumption for SFH, 72.84% for MAB, 72.89% for industry and 72.62% for services, which sums for a total of 2.487 TWh. This is subdivided in 91.991 GWh (3.70%) for SFH, 519.882 GWh (20.90%) for MAB, 248.170 GWh (9.98%) for industry and 1627.005 GWh (65.42%) for services. The remaining needs are supplied by EC generated electricity (Figure 14). Moreover, the EC sells 20.462 GWh to the grid, which is represented by a small grey bridge connecting the industry and local production. Figure 13 illustrates these fluxes.

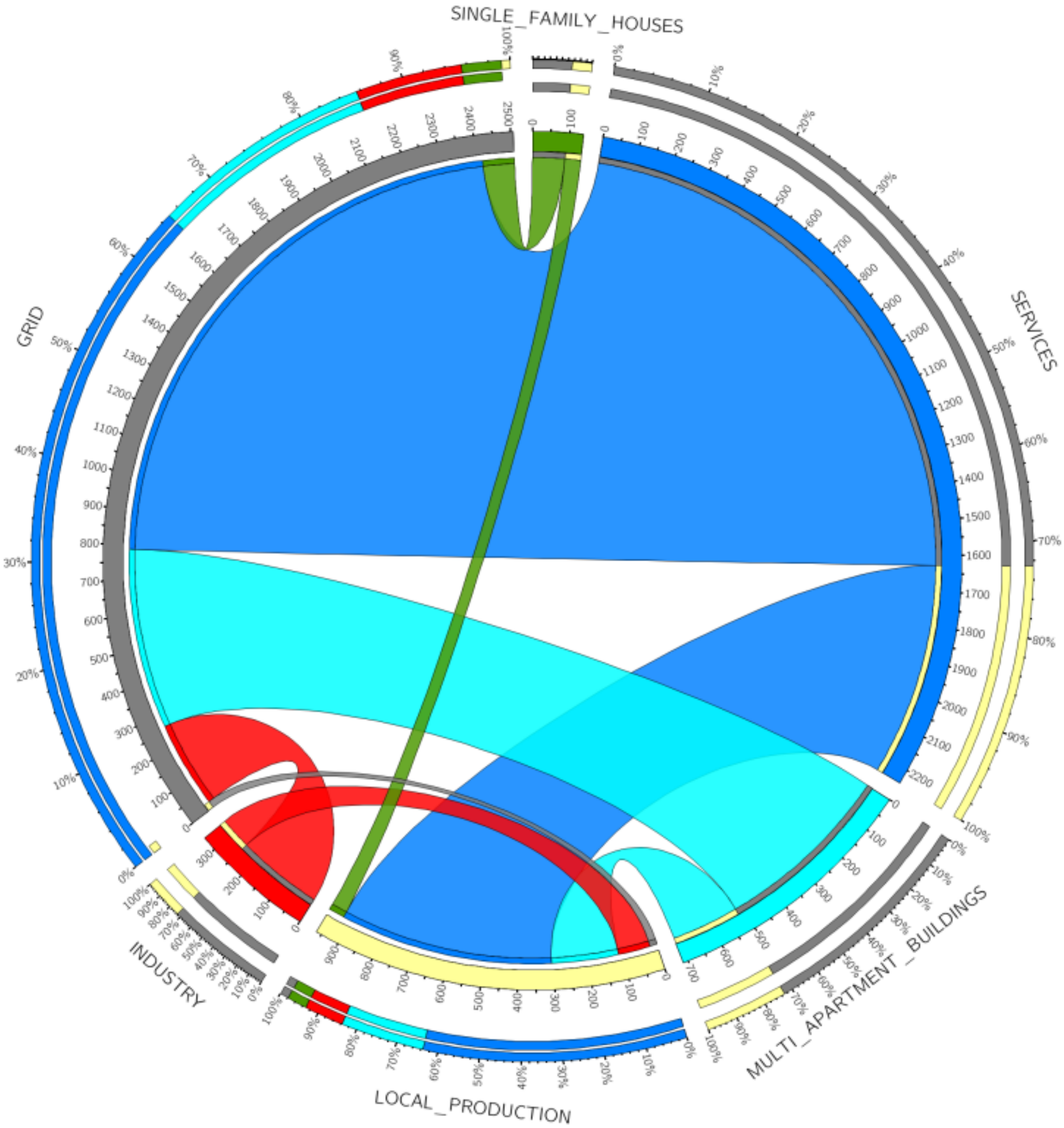


Figure 13 - Energy Consumption (GWh) for Lisbon - CSC Scenario

In Figure 14, it is shown that self-sufficiency is roughly the same for MAB, industry and services, which is coherent with the fact that their grid consumption is also similar. Contrarily, being the member with less grid consumption, it is natural that SFH displays the highest self-sufficiency, because it is the member that consumes less electricity from the grid. Indeed, although SFH's annual electricity consumption represents 16.2% of the total residential sector, its installed PV nominal power is equal to 24.5% (see Eq. 12), which means the ratio between production and demand is more favourable to SFH when comparing to MAB.

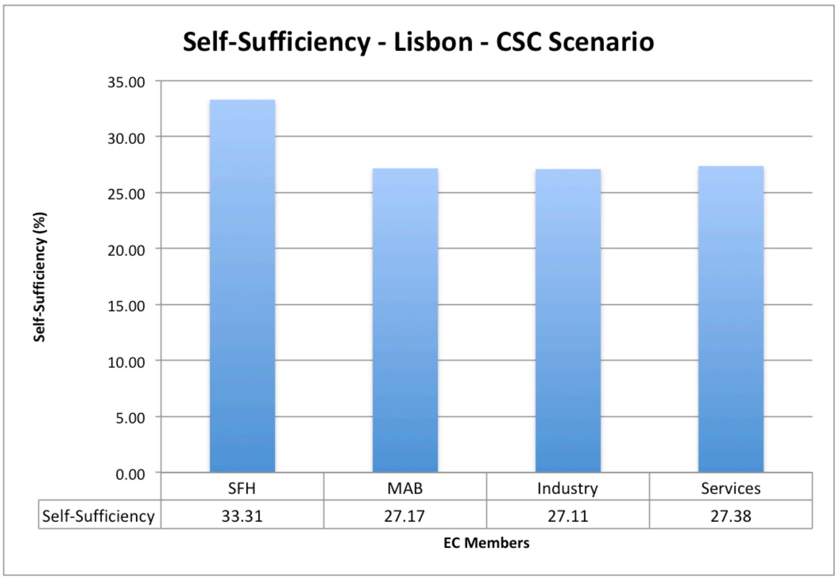


Figure 14 - Self-sufficiency in Lisbon – CSC Scenario

Regarding the costs, Figure 15 is similar to Figure 10, with the exception of the narrow grey bridges involving the members' earnings (0.870 M€, in total). Deducting these, the overall EC costs make up 356.358 M€. Once more, the ratio of grid expenses differs from its consumption counterpart: for services and industry it drops (59.75% and 6.93%, respectively), while for SFH and MAB it increases (4.85% and 28.47%). The reasoning behind this is the same as before: generally, residential grid purchasing prices are higher than those of industry and services.

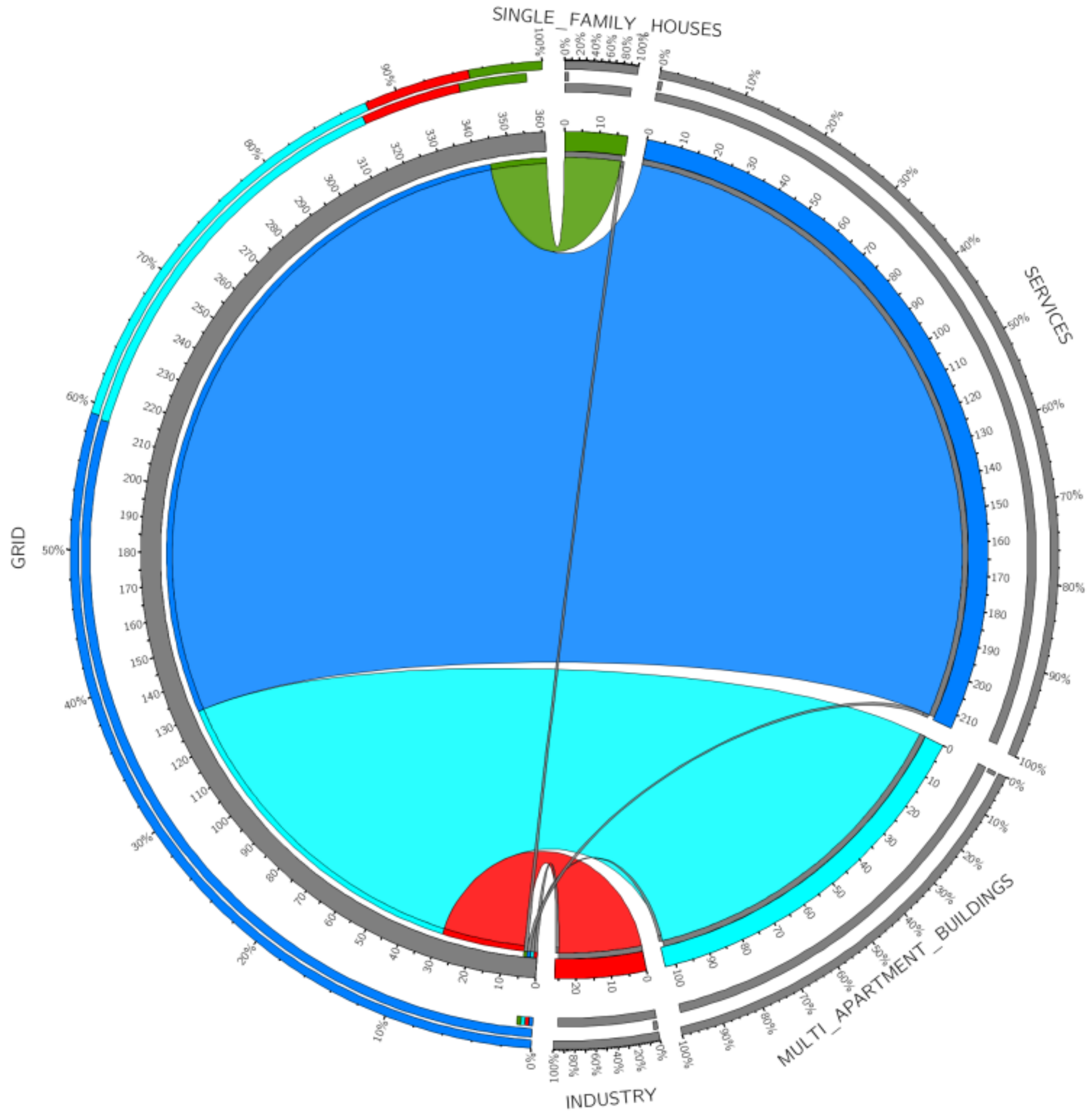
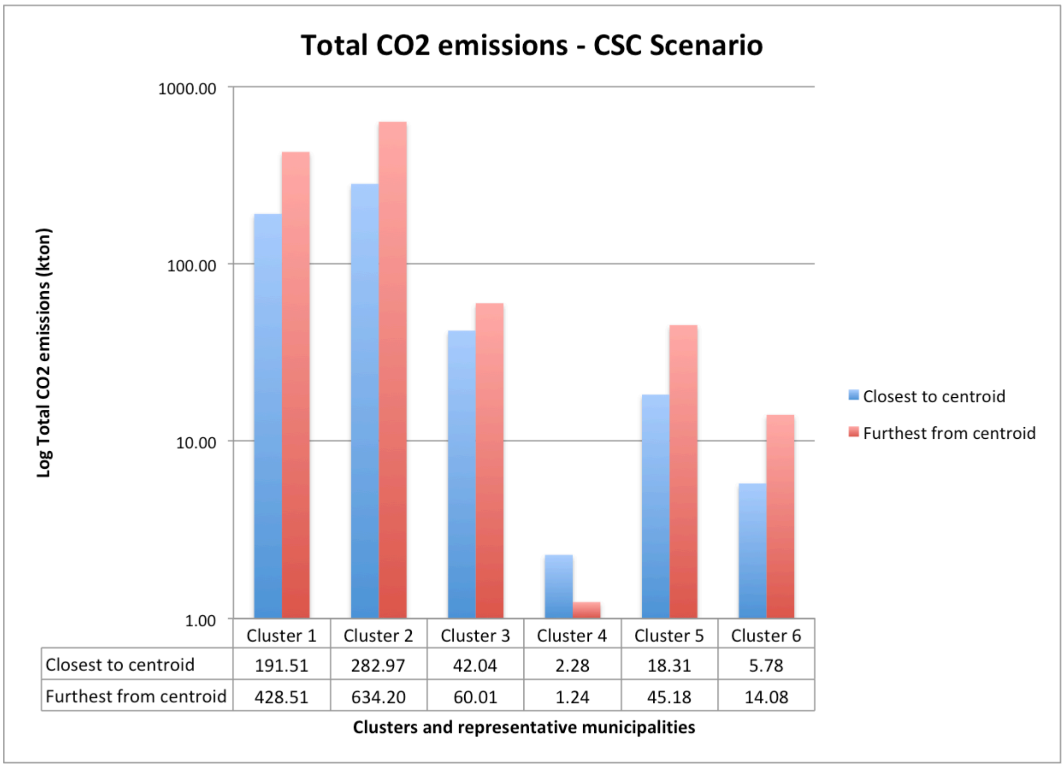


Figure 15 - Money Fluxes (M€) for Lisbon - CSC Scenario

Next, a comparison between representative municipalities is presented. A qualitative analysis similar to the one presented in 5.2.1 can be made here, even though, quantitatively, both emissions and costs are reduced, as shown in Figure 16 and Figure 17, respectively. Additionally, Figure 18 evaluates the same municipalities in terms of self-consumption.

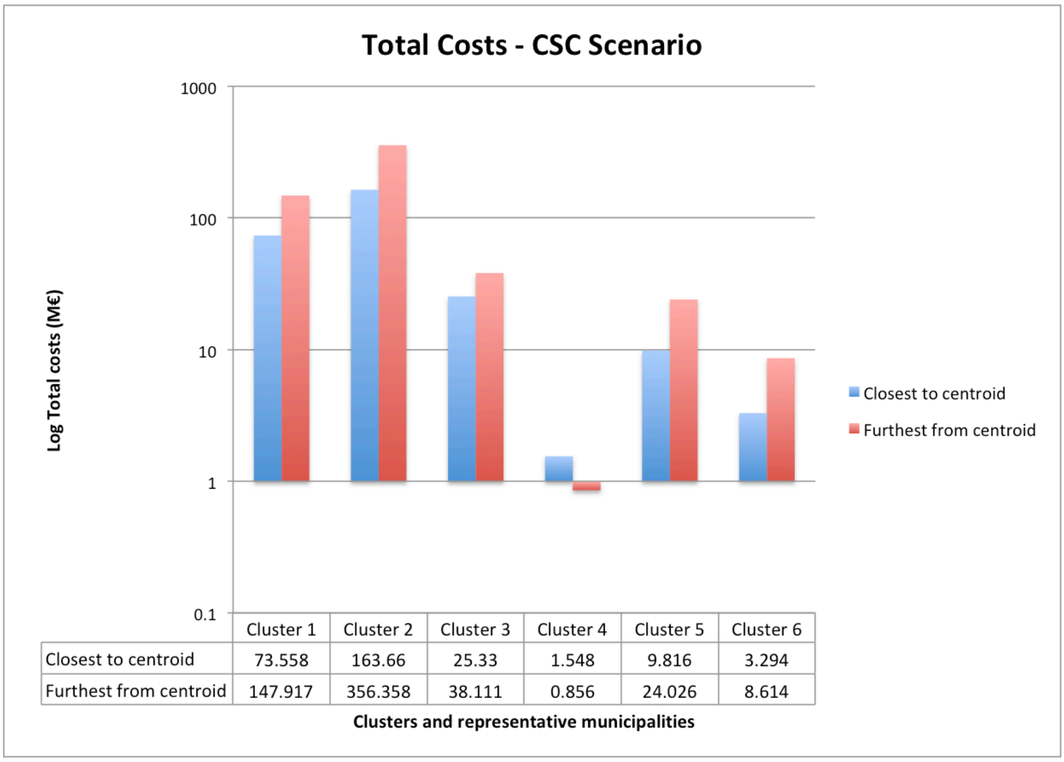
The clusters' hierarchy in terms of costs and emissions remains the same as PS in Figure 16 and Figure 17, because the installed power is proportional to the fraction of the total consumption provided by decentralized PV (see sub-chapter 3.1.2). Nevertheless, considering the municipalities closest to the centroids, the CO_2 emissions are reduced by 25.49% for Cluster 1, 27.13% for Cluster 2, 27.48% for Cluster 3, 26.92% for Cluster 4, 26.70% for Cluster 5 and 27.11% for Cluster 6. Since this reduction is only due to the clean locally generated electricity, these percentages are equal to the ratio between total self-consumption (present in Figure 18) and the total grid consumption in the PS.



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	191.51	282.97	42.04	2.28	18.31	5.78
Furthest from centroid	428.51	634.20	60.01	1.24	45.18	14.08

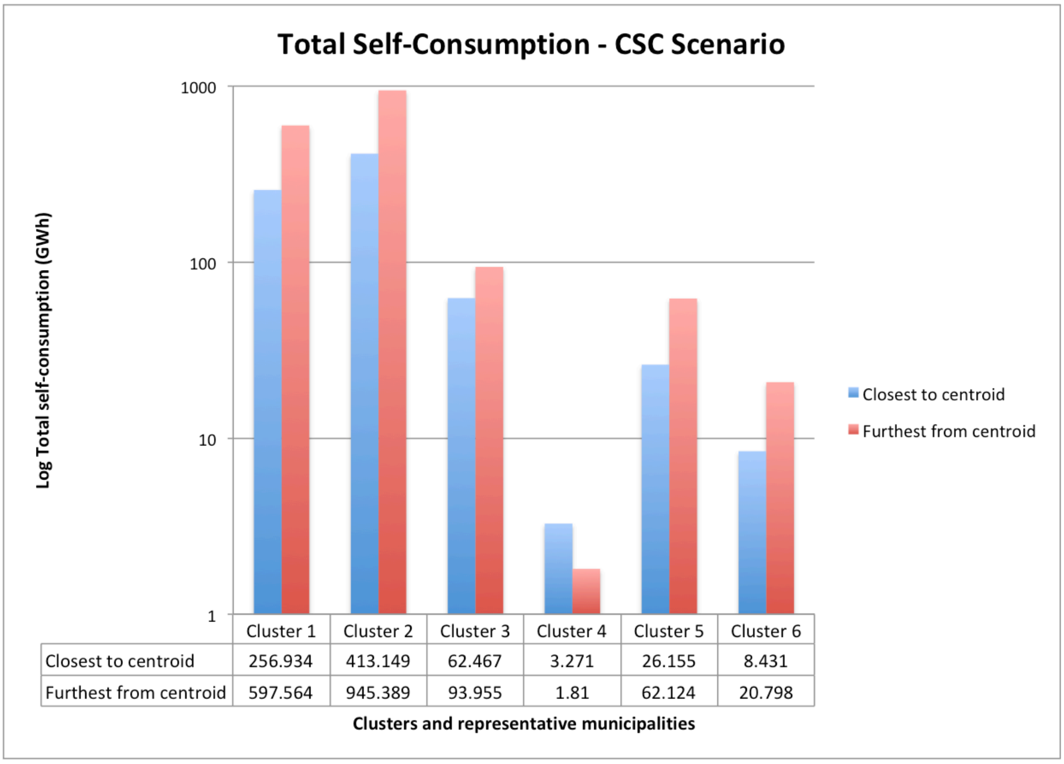
Figure 16 - CO_2 emissions in representative municipalities – CSC Scenario (See Table 6 for correspondence with municipality)

The incorporation of PV systems also allows the ECs to reduce their total costs by 30.03% for Cluster 1, 32.33% for Cluster 2, 32.94% for Cluster 3, 32.05% for Cluster 4, 31.82% for Cluster 5 and 32.43% for Cluster 6 (Figure 17). Due to the large presence of industry, Cluster 1's municipality is the least benefited in terms of cost reduction.



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	73.558	163.66	25.33	1.548	9.816	3.294
Furthest from centroid	147.917	356.358	38.111	0.856	24.026	8.614

Figure 17 - Costs in representative municipalities – CSC Scenario (See Table 6 for correspondence with municipality)



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	256.934	413.149	62.467	3.271	26.155	8.431
Furthest from centroid	597.564	945.389	93.955	1.81	62.124	20.798

Figure 18 – Self-consumption in representative municipalities – CSC Scenario (See Table 6 for correspondence with municipality)

5.2.3. P2P Scenario

For this scenario, a closer look is taken into the functioning of the P2P model on a single day, for Lisbon. Figure 19 shows the demand and production profiles for the Summer Solstice, 21st June. Obviously, all members show no PV electricity generation during night hours. However, being the longest day in the year, generation starts early in the morning, at 7:00h and ends late in the evening, at 20:00h. Furthermore, the services exhibit no surplus during the day, whereas SFH have surplus from 10:00h to 17:00h, MAB from 13:00h to 14:00h and industry from 12:00h to 14:00h. Table 7 displays the energy exchanges in the EC during this day, excluding hours of no generation, when all energy is purchased from the grid. The cells highlighted in red refer to purchases and the ones highlighted in green refer to sales.

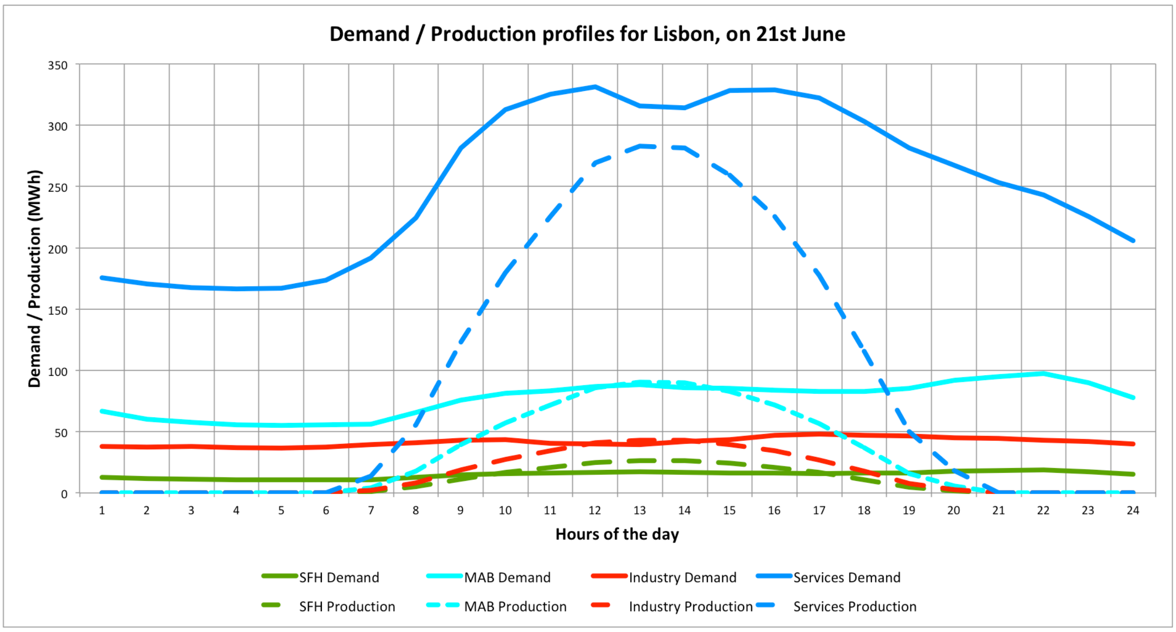


Figure 19 – Demand and Production Profiles for Lisbon on 21st June

Table 7 – Energy Trading for Lisbon, on the 21st June

	hour	7	8	9	10	11	12	13	14	15	16	17	18	19	20
SFH	MAB	0	0	0	0.98	0	0	0	0	2.5	4.8	0.5	0	0	0
	IND	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SER	0	0	0	0	4.9	8.3	9.3	9.6	5.2	0	0	0	0	0
	GRI	9.6	7.5	3.1	0	0	0	0	0	0	0	0	5.3	11.8	16.0
MAB	SFH	0	0	0	0.98	0	0	0	0	2.5	4.8	0.5	0	0	0
	IND	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	SER	0	0	0	0	0	0	1.9	3.9	0	0	0	0	0	0
	GRI	51.9	48.1	36.4	23.3	11.6	0.95	0	0	0	7.0	25.7	46.2	69.4	85.9
IND	SFH	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	MAB	0	0	0	0	0	0	0	0	0	0	0	0	0	0

	SER	0	0	0	0	0	1.0	3.8	0.7	0	0	0	0	0	0
	GRI	37.3	32.7	24.1	16.1	6.1	0	0	0	4.2	12.5	20.8	29.6	39.0	42.4
SER	SFH	0	0	0	0	4.9	8.3	9.3	9.6	5.2	0	0	0	0	0
	MAB	0	0	0	0	0	0	1.9	3.9	0	0	0	0	0	0
	IND	0	0	0	0	0	1.0	3.8	0.7	0	0	0	0	0	0
	GRI	178.2	168.9	158.1	133.1	94.9	53.1	17.5	18.5	63.5	103.5	144.7	187.8	231.6	249.2

As seen in Table 7, no sales happen unless a member is in excess, because energy is being generated during all hours represented on the table and sales only occur between 10:00h (when SFH begins its surplus period) and 17:00h (when this period ends). Moreover, the allocation of surplus energy is related, as mentioned, with minimization of costs and with trading prices. At 10:00h, SFH sells to MAB since $\lambda_{grid}^{MAB} = 61.88 \frac{€}{MWh} > \lambda_{grid}^{services} = 50.95 \frac{€}{MWh} > \lambda_{grid}^{industry} = 44.94 \frac{€}{MWh}$ and, thus, MAB is willing to pay more than its peers. At 11:00h, SFH sells to the services, since $\lambda_{grid}^{services} = 64.70 \frac{€}{MWh} > \lambda_{grid}^{MAB} = 61.88 \frac{€}{MWh} > \lambda_{grid}^{industry} = 52.89 \frac{€}{MWh}$. This order of prices remains the same until 13:00h and, therefore, all members sell their surplus to the services. From 14:00h until 20:00h, $\lambda_{grid}^{MAB} > \lambda_{grid}^{services} > \lambda_{grid}^{industry}$, but, at 14:00h, SFH still sells all its excess to the services because MAB is also in excess. At 15:00h, SFH prioritizes selling to MAB, although, since its excess is enough to supply all MAB's deficit, the remaining is sold to the services. Until SFH itself is in deficit, all sales are attributed to MAB.

Proceeding with the year analysis, in the P2P scenario, the majority of energy exchanges are still grid purchases. For Lisbon, Figure 20 shows that the large bridges either refer to grid purchases or self-consumption, while P2P trades are barely visible as they are orders of magnitude smaller. Concretely, P2P purchases represent 0.01% of consumed energy for SFH, 0.49% for MAB, 0.04% for industry and also 0.49% for services. The grid accounts for 66.69% of consumption for SFH, 72.63% for MAB, 73.08% for industry and 72.67% for services, which sums for a total of 2.487 TWh. The remaining part, equal to self-sufficiency, is plotted in Figure 21. In this plot, self-sufficiency has slightly decreased in comparison with CSC (Figure 14), as expected, since the energy received from peers is accounted in self-consumption in the CSC scenario (see Eq. 45 and Eq. 46).

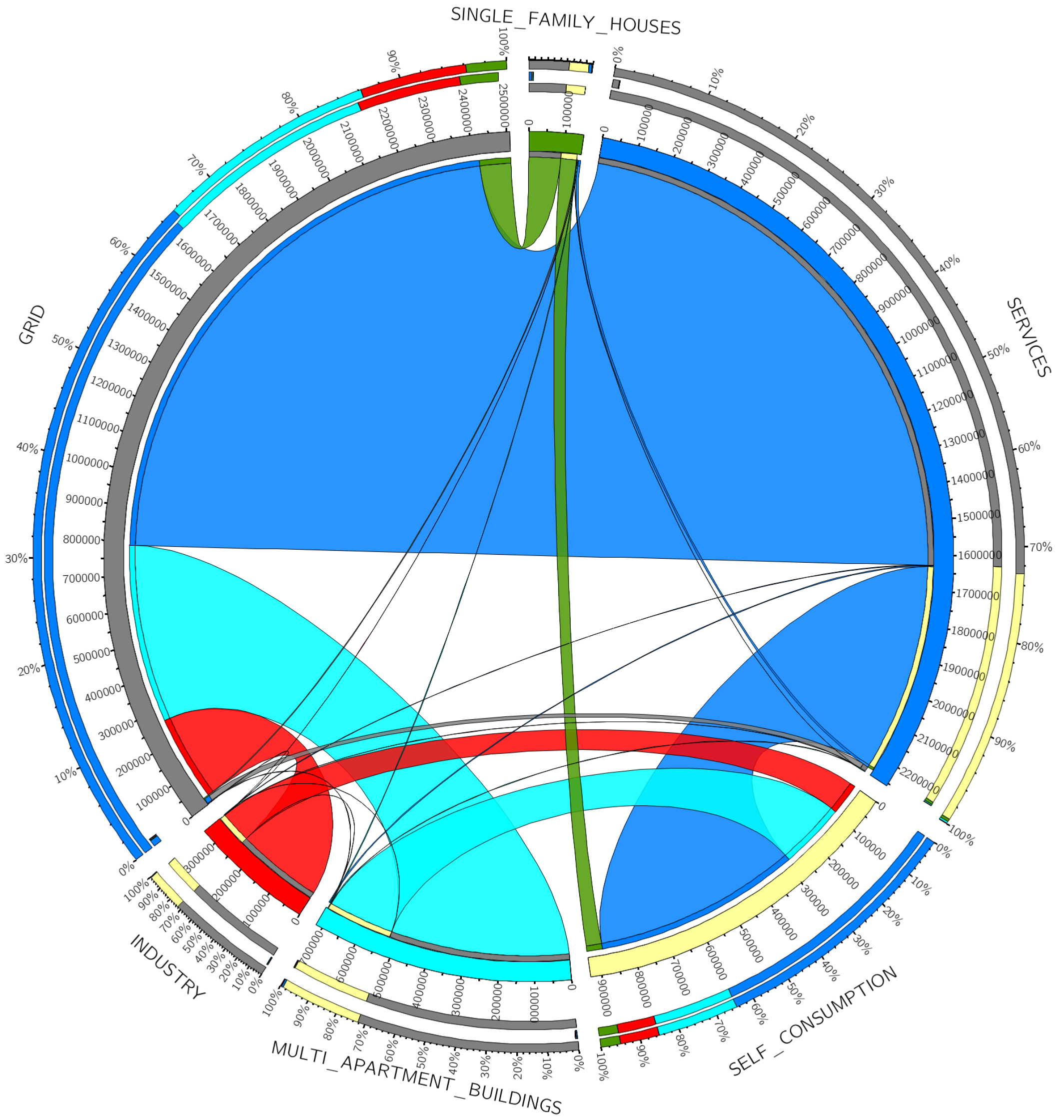
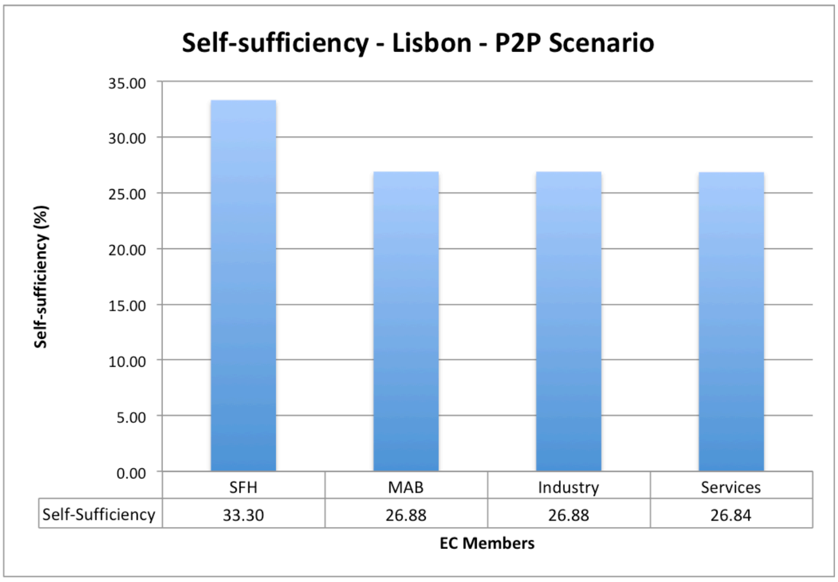


Figure 20 - Energy Consumption (MWh) for Lisbon - P2P Scenario



	SFH	MAB	Industry	Services
Self-Sufficiency	33.30	26.88	26.88	26.84

Figure 21 – Self-sufficiency in Lisbon – P2P Scenario

Similarly, Figure 22 also clarifies the reduced share of P2P trades represented by the thin bridges (almost lines), as 99.48% of all monetary transactions consist of grid sales.

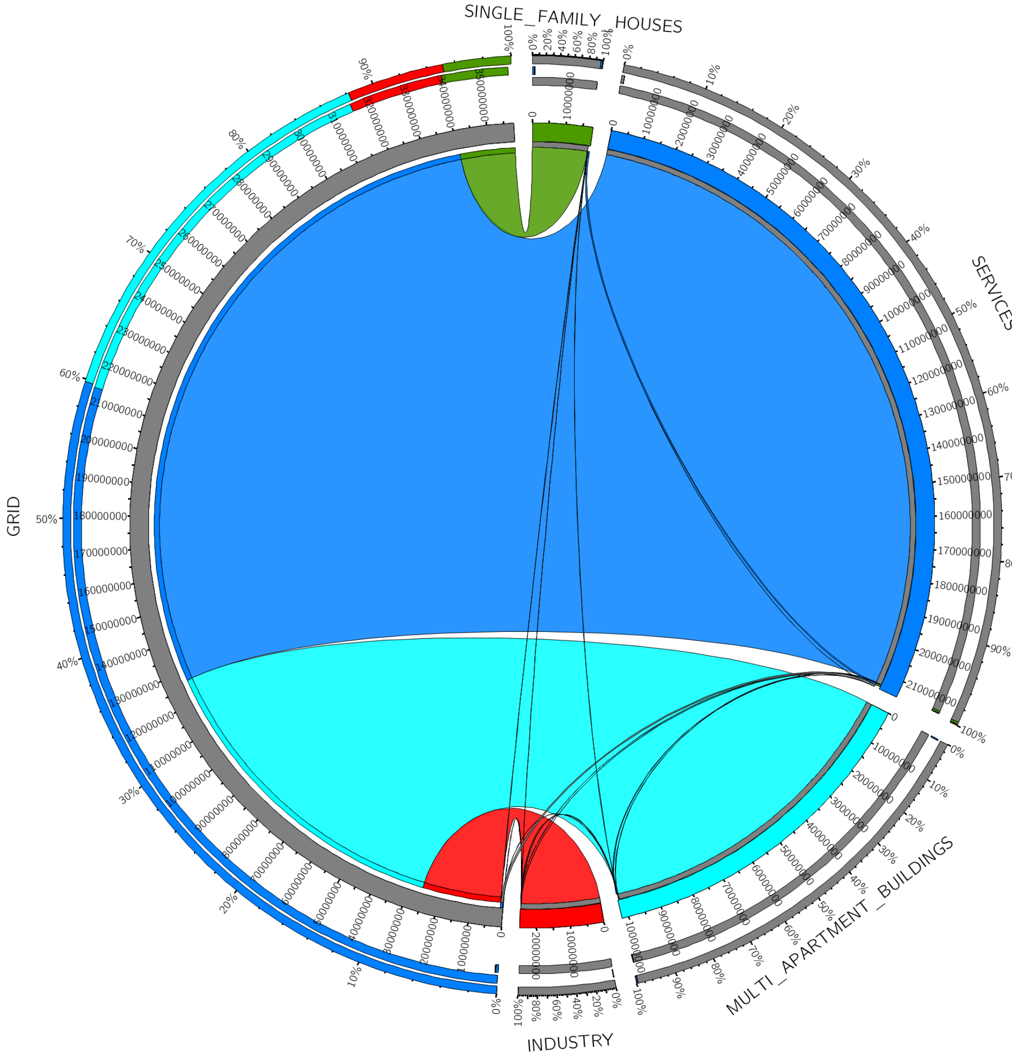


Figure 22 – Money Fluxes for Lisbon - P2P Scenario

Therefore, in order to better understand P2P trading tendencies, Figure 23 and Figure 25 display the same results (energy and money fluxes, respectively), excluding grid purchases. The main consumer, services, acquires 10.898 GWh of P2P energy, 61.52% of which from SFH, 29.03% from MAB and 9.45% from industry, while the second, MAB, buys 3.469 GWh - 59.38% from SFH, 3.92% from industry and 36.70% from services. The absence of significant green and red bridges indicates that SFH and industry practically do not buy energy from their peers.

The biggest seller is also the services (16.362 GWh), although mainly selling to the grid (91.60%), followed by the SFH (11.588 GWh), which is also the member with the highest surplus - Figure 24. In fact, SFH's surplus explains why this member acts mainly as a seller and rarely as a buyer. Industry is the least active participant in the P2P market, as it only sells 2.353 GWh and has little interaction with the residential members (5.66%). One motive for the little interaction is the residential sector's high demand, accompanied by the industry's low surplus (Figure 24).

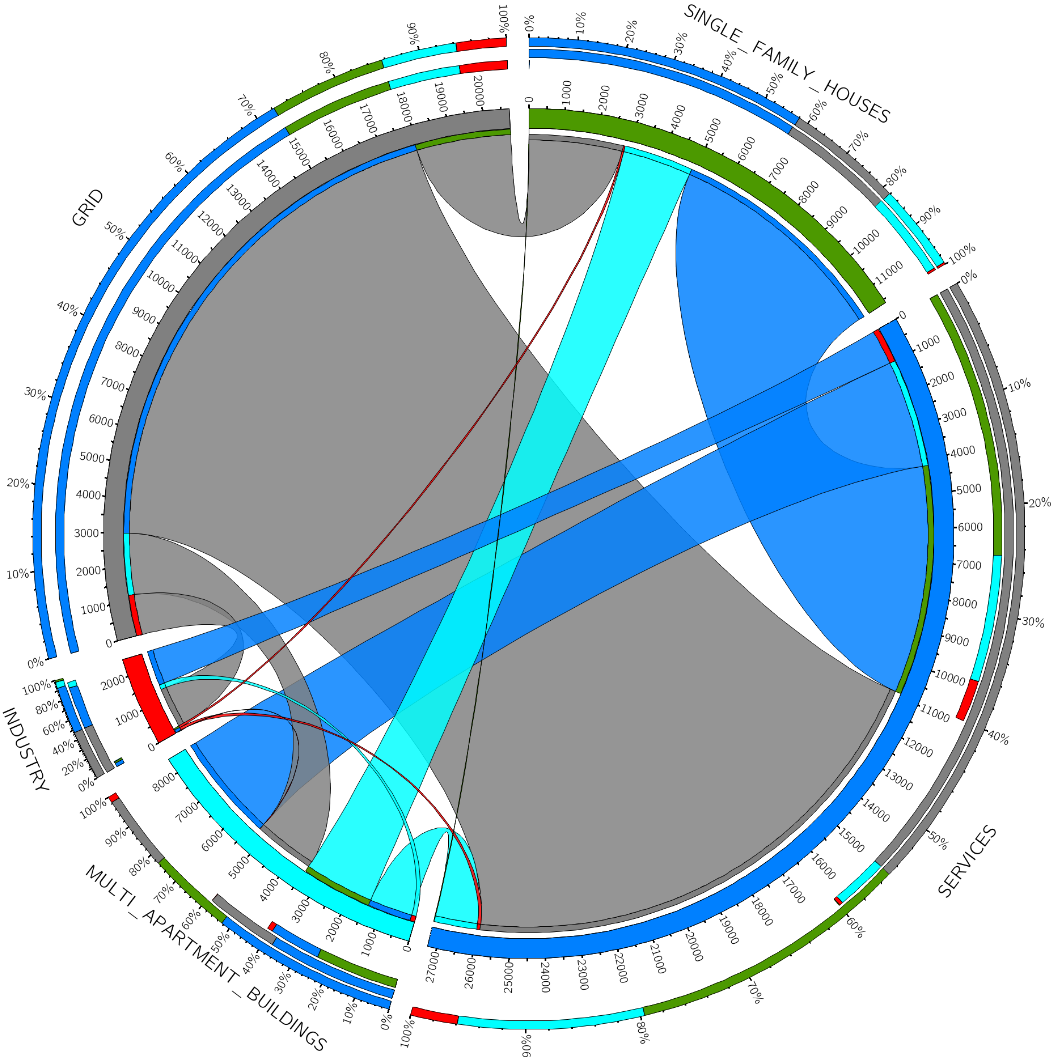


Figure 23 – Energy Consumption (MWh) for Lisbon (no grid purchases) - P2P Scenario

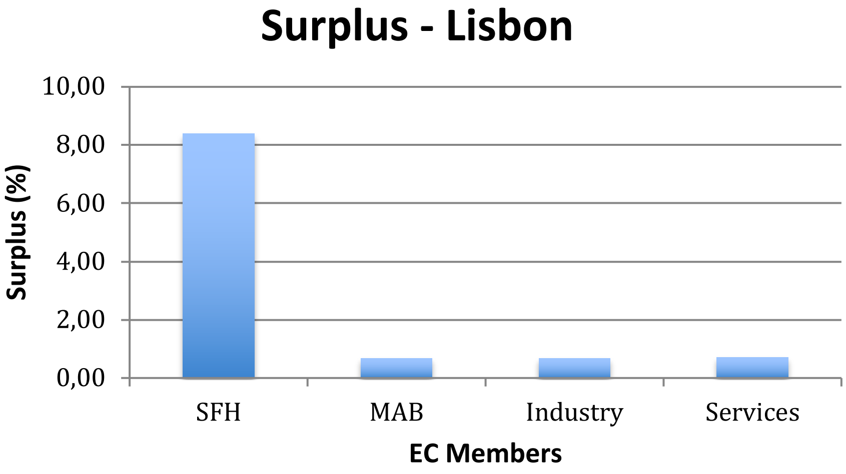


Figure 24 – Surplus – Lisbon – P2P Scenario

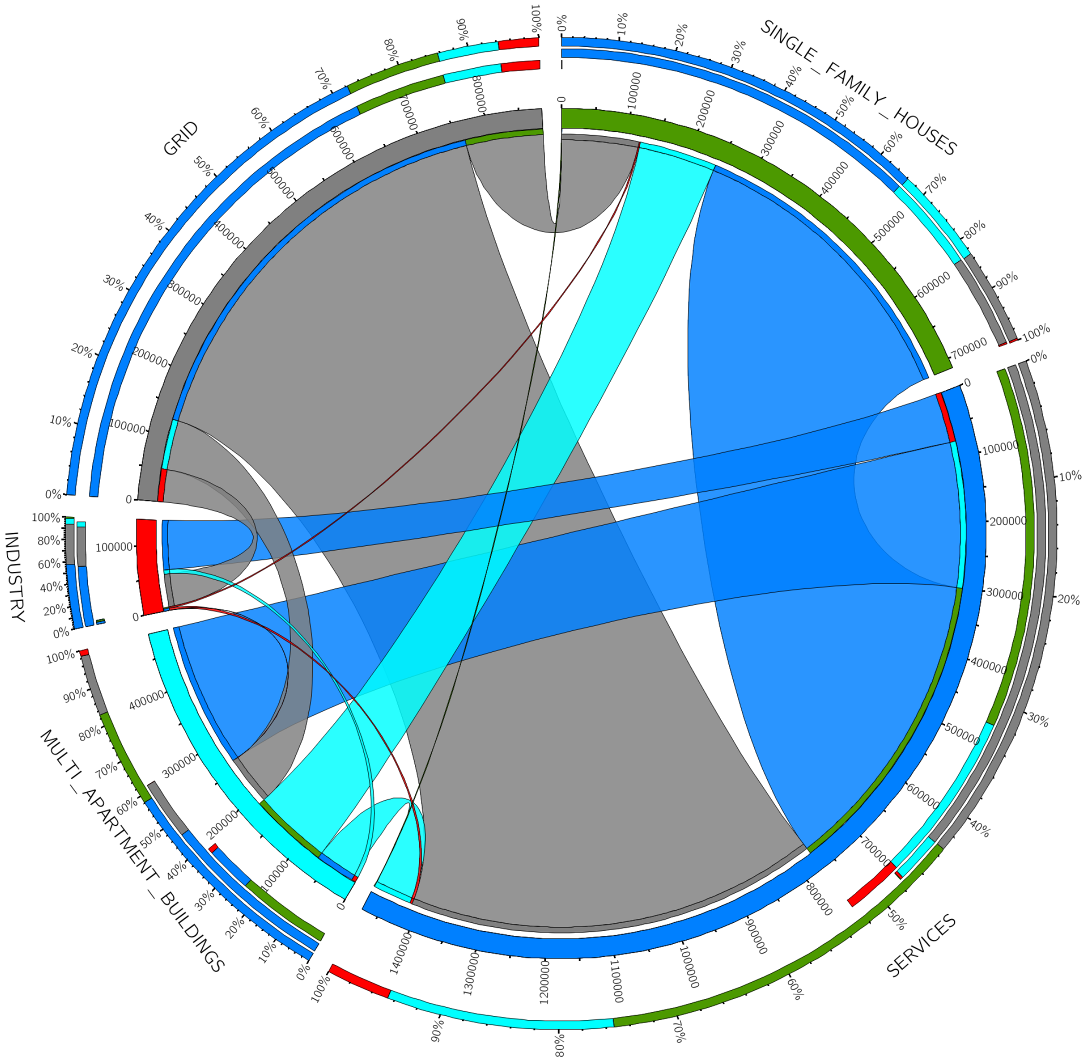


Figure 25 - Money Fluxes for Lisbon (no grid purchases) - P2P Scenario

Table 8 presents the average trading and grid prices for the hours when energy transactions occur, for Lisbon. For example, considering all services' purchases from MAB, an average of 69.65 €/MWh are paid, which is lower than the average of what would have been paid to the grid. Highlighted in green are the best purchase prices for each member. While for SFH there is almost no difference between peer trading and the grid (given being in the majority of the time a seller, with high surplus during solar hours), the industry buys at the lowest prices (otherwise it would not be favourable to purchase from peers), so its peers generate more money by selling to other peers or the grid, which is another motive that justifies its lack of purchases. In fact, this happens even for municipalities belonging to Cluster 1 (Figure 37 through Figure 39 -Annex). SFH do not purchase from MAB, while the services get the best P2P price from SFH.

Table 8 - Purchase Prices – Lisbon P2P

	Avg	Grid	Avg	Grid	Avg	Grid	Avg	Grid
€/MWh	SFH		MAB		Industry		Services	
SFH	-	-	-	-	61.88	61.88	61.85	61.88
MAB	56.49	61.88	-	-	35.81	61.88	35.91	61.88
Industry	42.47	46.52	35.81	47.03	-	-	35.81	47.16
Services	69.08	70.32	69.65	71.20	71.06	74.57	-	-

With the purpose of illustrating P2P dynamics in a different context, another municipality is examined in this sub-chapter. Alfândega da Fé represents Cluster 4 and hence is a rural municipality, which is complemented by the fact that, comparing with Figure 20, Figure 27 has much smaller values in its scale, and the services and MAB lose predominance to SFH. Once more, the large bridges refer to grid purchases or self-consumption, with P2P trading accounting for 0.08% of consumed energy for SFH, 0.07% for MAB, 0.05% for industry and 1.02% for services. The total grid consumption is 8.951 GWh and represents 73.86% of SFH consumption, 73.81% for MAB, 73.20% for industry and 72.31% for services.

SFH, specifically, is less self-sufficient than in Lisbon, and therefore it is more grid dependent (Figure 26). In fact, in this case, and contrarily to Lisbon (see Figure 21), SFH is slightly less self-sufficient than MAB. Indeed, although SFH's annual electricity consumption represents 88.8% of the total residential sector, its installed PV nominal power is equal to 88.5%, which means that the ratio between production and demand is favourable to MAB when comparing to SFH. With this comparison, it can be concluded that the calculation of electricity consumption and installed power for SFH and MAB based on the entire residential sector is one of the motives affecting the self-sufficiency of one member relative to the other.

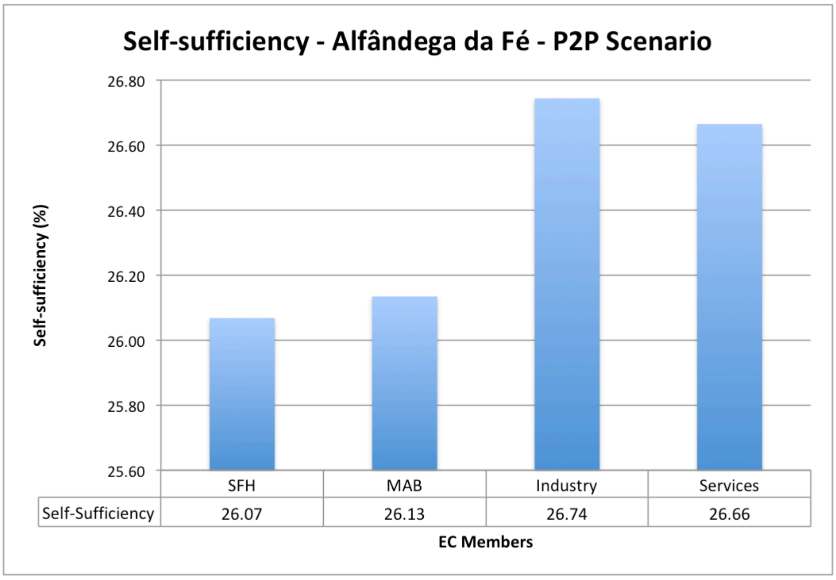


Figure 26 – Self-sufficiency – Alfândega da Fé

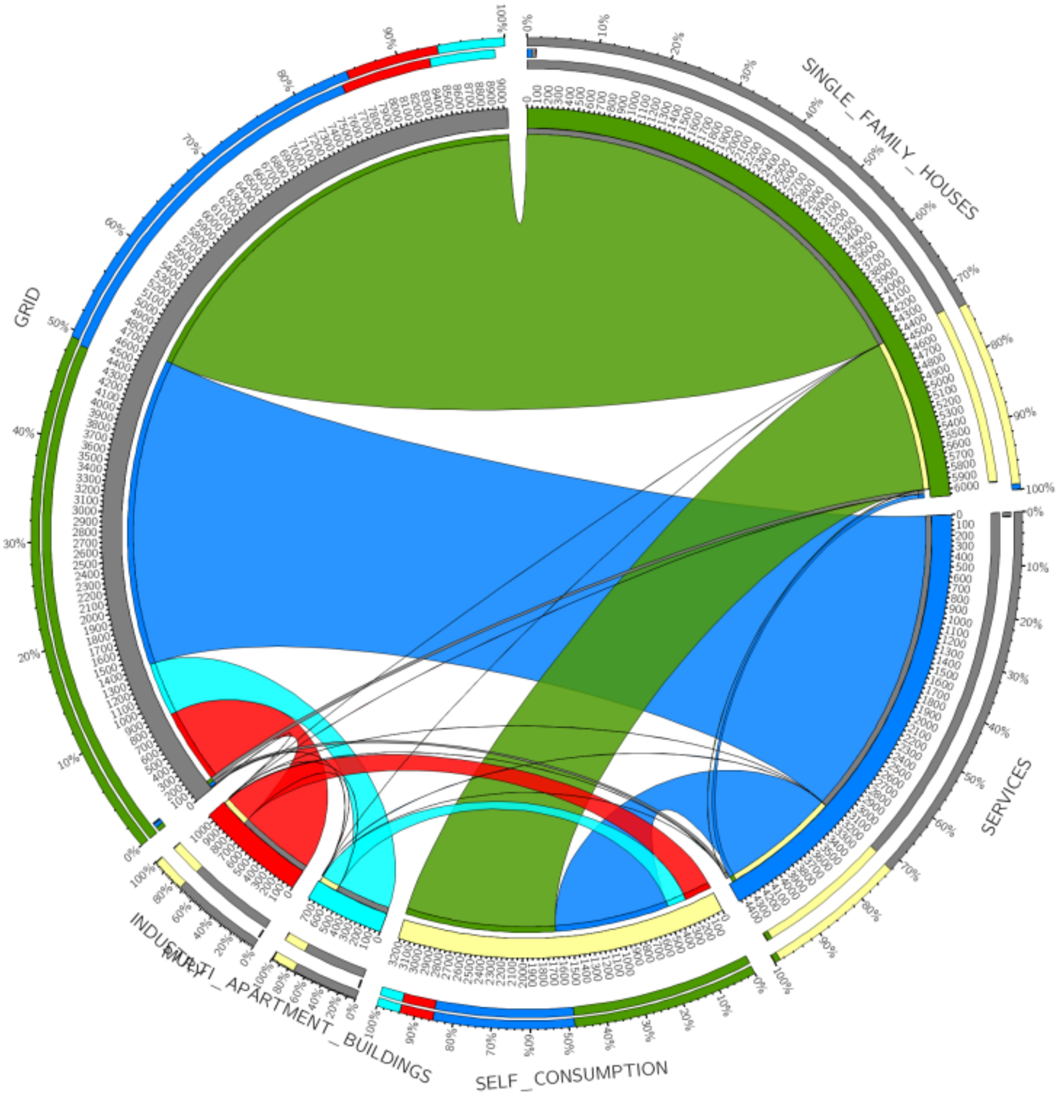


Figure 27 - Energy Consumption (MWh) for Alfândega da Fé - P2P Scenario

Excluding grid purchases, the main consumer, services, acquires 45.516 MWh of P2P energy, 89.56% of which from SFH, 9.57% from MAB and 0.87% from industry, while the second, SFH, buys 4.725 MWH – 0.02% from MAB, 7.78% from industry and 92.20% from services. The absence of significant light blue and red bridges indicates that MAB and industry practically do not buy energy from their peers.

The biggest seller in this case is SFH (81.155 MWh), splitting this amount almost equally between grid (49.42%) and services (50.23%), (with remaining residual sales to industry), followed by the services (38.320 MWh). Industry is once again the least active participant in the P2P market as it only sells 8.280 MWh, of which 88.75% go to the grid. Figure 28 illustrates these considerations.

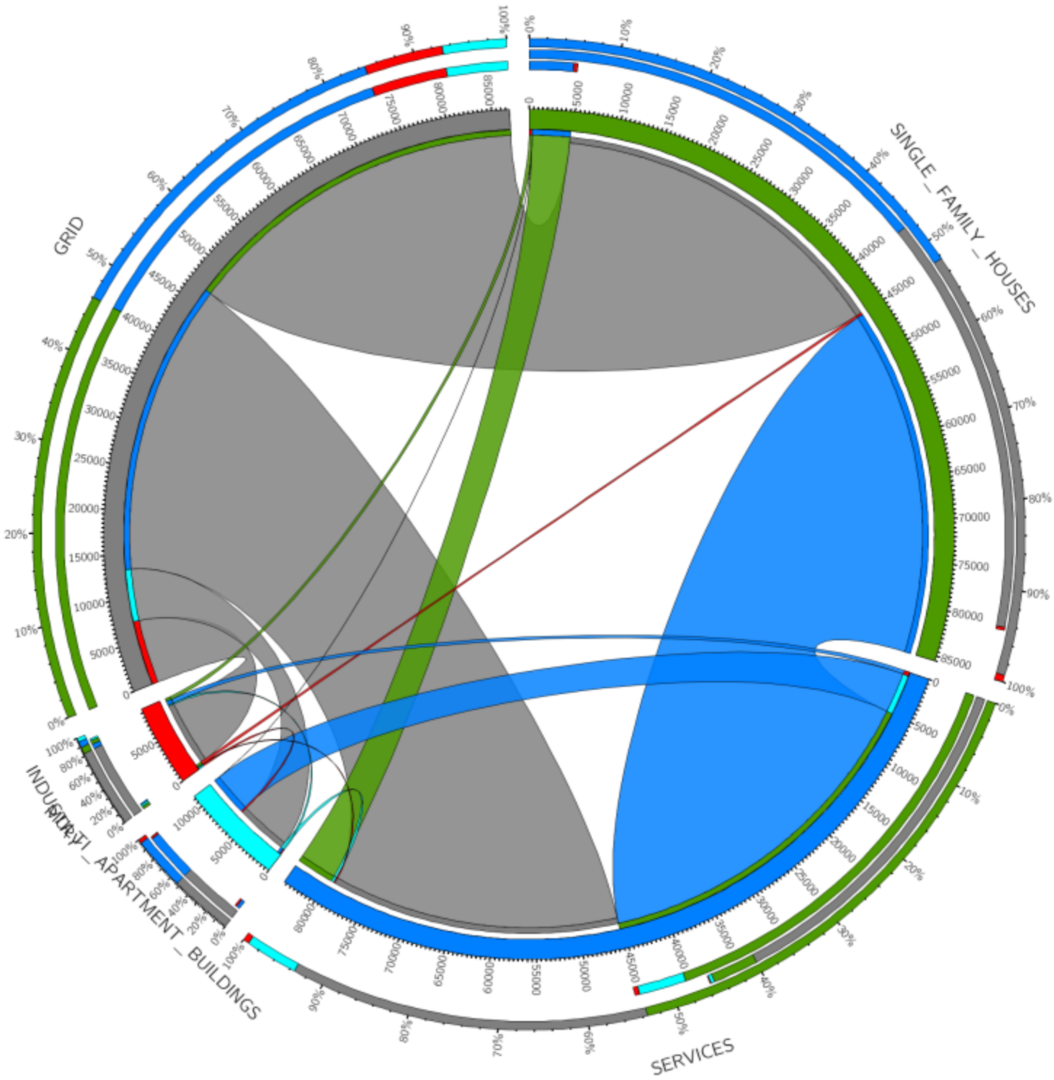


Figure 28 - Energy Consumption (kWh) for Alfândega da Fé (no grid purchases) - P2P Scenario

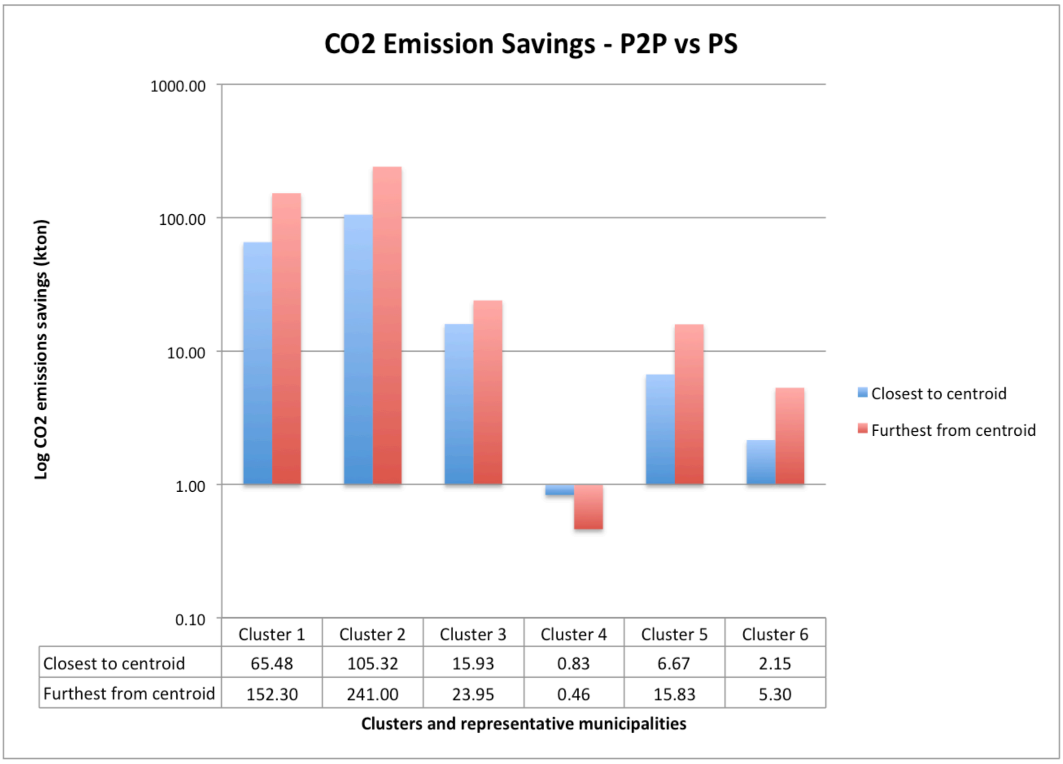
Table 9 presents the average trading and grid prices for the hours when energy transactions occur, for Alfândega da Fé. Industry once more buys at the lowest prices. However, in comparison with Lisbon, SFH's prices have dropped and MAB's have increased, which is due to that fact that SFH have replaced MAB as the main residential type for this municipality.

Table 9 - Purchase Prices – Alfândega da Fé P2P

	Avg	Grid	Avg	Grid	Avg	Grid	Avg	Grid
€/MWh	SFH		MAB		Industry		Services	
SFH	-	-	48.78	61.88	45.57	61.88	50.36	61.88
MAB	-	-	-	-	47.12	61.88	50.35	61.88
Industry	35.80	55.72	35.84	55.50	-	-	46.57	54.59
Services	50.69	71.61	50.64	71.73	35.80	77.15	-	-

A comparison between scenarios for each representative municipality is shown in the following figures. Starting with CO_2 emissions, the P2P scenario, in contrast with the PS scenario, reaches reductions ranging from hundreds of kton (for example, 105.32 kton in Porto and 241.00 kton in Lisbon) to hundreds of ton (834 ton in Alfândega da Fé and 462 ton in Penedono). Figure 29 contains all values. Using the closest to the centroid municipalities, emissions savings of 25.48% in Cluster 1, 27.12% in Cluster 2, 27.48% in Cluster 3, 26.6% in Cluster 4, 26.70% in Cluster 5 and 27.11% in Cluster 6 are reached.

However, comparing with CSC, there is a slight increase, which can be as big as dozens of tons for Clusters 1 and 2, as well as practically negligible for Cluster 4 (hence the negative values in Figure 30). Noticing that in CSC electricity production is expended internally to satisfy all members before, hypothetically, being sold, then this scenario is the one that consumes less energy from the grid, because it maximizes the utilization of locally produced electricity. P2P, on the other hand, allows a member to sell its excess to the grid even if a peer has deficit, which will require extra grid supply.



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	65.48	105.32	15.93	0.83	6.67	2.15
Furthest from centroid	152.30	241.00	23.95	0.46	15.83	5.30

Figure 29 – CO_2 emission savings P2P – PS (See Table 6 for correspondence with municipality)

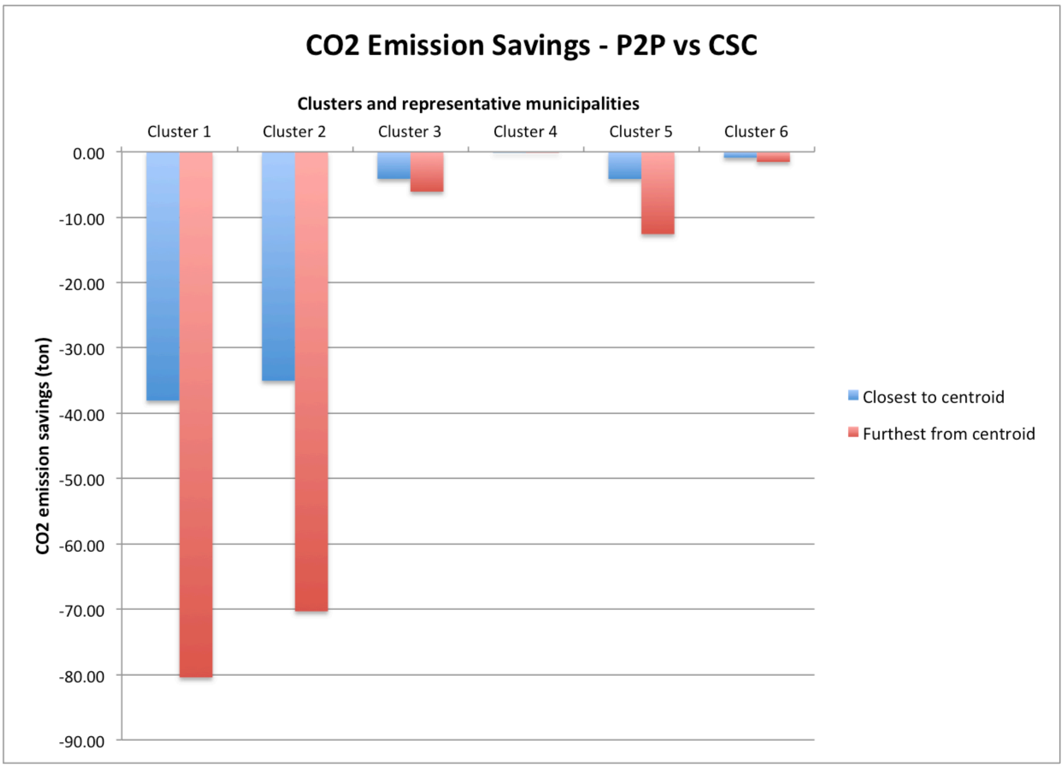
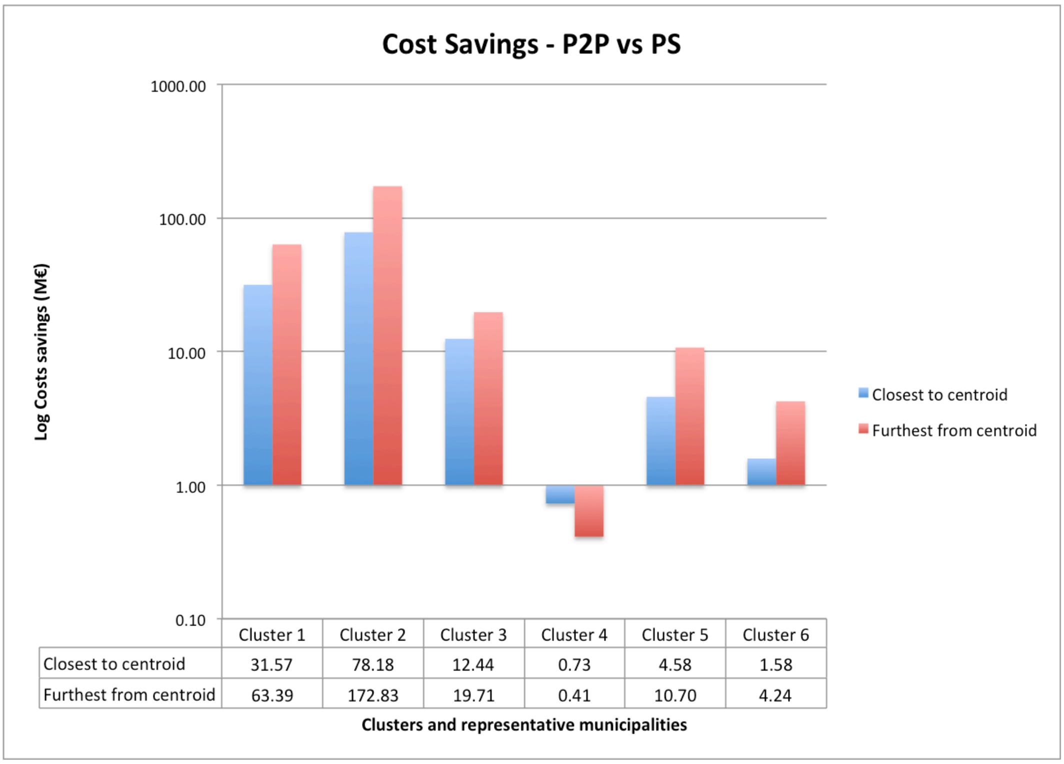


Figure 30 – CO_2 emission savings P2P – CSC (See Table 6 for correspondence with municipality)

Concerning costs, the range of savings P2P achieve relative to PS starts at the hundreds of thousands of €, for Cluster 4, and end at values close to a hundred million €, for Cluster 2. This information is detailed in Figure 31. Exploring the financial savings across all modelled municipalities, the highest value for SFH (46%) occurs for Cluster 3's Odivelas that exhibits both surplus and self-sufficiency even higher than in Lisbon (11.35% and 34.73%, respectively), while the lowest (33%) occurs for Alfândega da Fé, Lamego, Penedono and Viana do Castelo, that have very similar values of self-sufficiency (between 26.07% and 26.70%) and surplus (between 1.26% and 1.98%). For the remaining EC members, the savings do not show such large differences between minimum and maximum. For MAB all savings are within the range of 32% and 34%, for industry they lay between 28% and 32% and for services between 30% and 32%. The values are stable because self-sufficiency is also more stable between municipalities for these than for SFH.

Furthermore, using the closest to the centroid municipalities, cost savings of 30.03% are reached in Cluster 1, 32.33% in Cluster 2, 32.94% in Cluster 3, 32.05% in Cluster 4, 31.81% in Cluster 5 and 32.41% in Cluster 6.

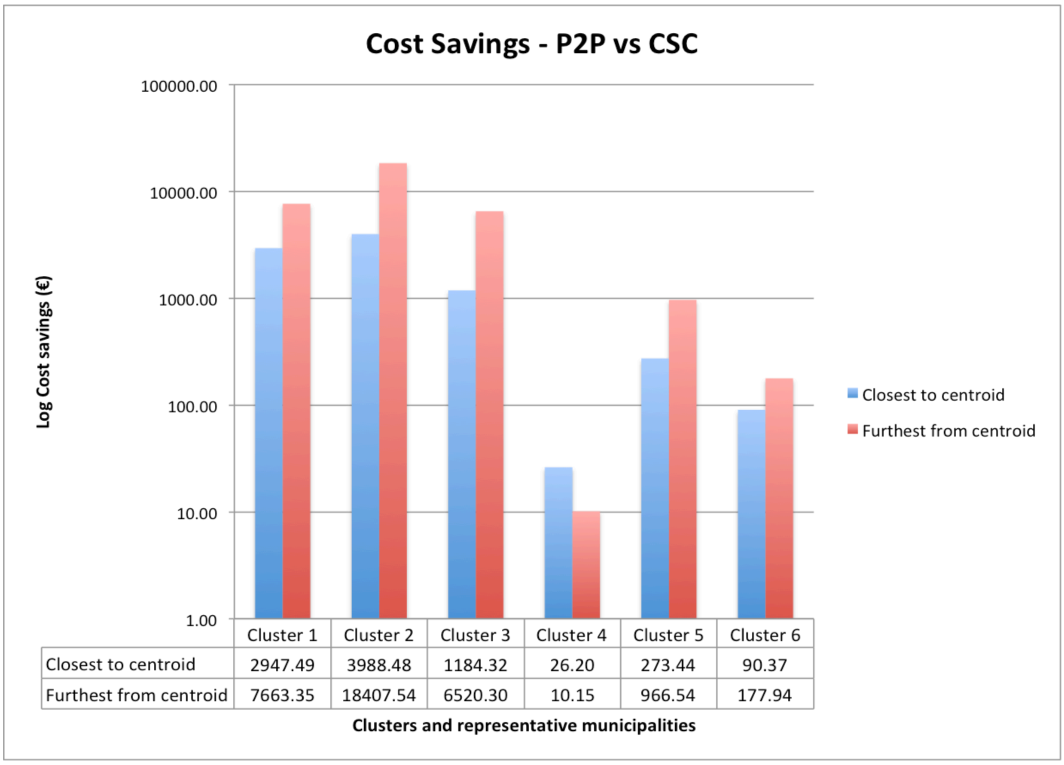


	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	31.57	78.18	12.44	0.73	4.58	1.58
Furthest from centroid	63.39	172.83	19.71	0.41	10.70	4.24

Figure 31 – P2P cost savings in comparison with PS (See Table 6 for correspondence with municipality)

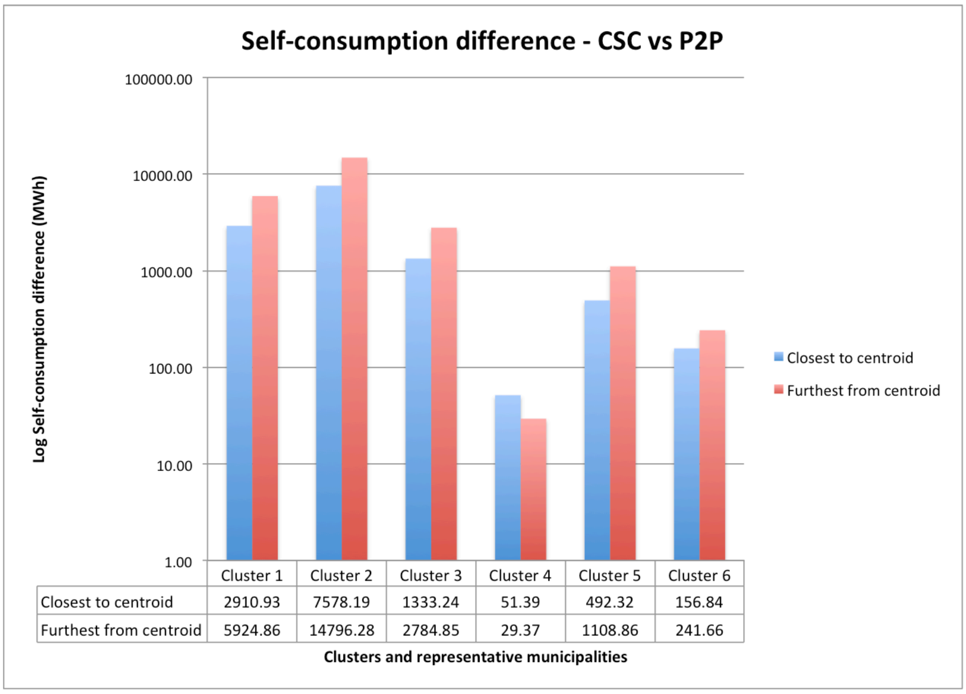
Contrarily to emissions, Figure 32 shows P2P costs savings, compared to CSC. Even though CSC maximizes the production's utilization, this scenario does not minimize costs for its member. Even so, just like emissions, cost savings are slim, in the order of thousands of € for Cluster 2 and negligible for Cluster 4, thus proving that main savings come from self-consumption and very little from P2P trading.

Finally, the differences in self-consumption are plotted in Figure 33. As mentioned in 5.2.2, in CSC self-consumption includes energy originated from other members, and consequently it is larger than in P2P. Still, these differences only represent between 1% and 3% of total self-consumption in CSC. This means that CSC communities are more community oriented in environmental terms, while P2P communities, in aiming to maximize individual profit, provide the EC with better economic outcomes.



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	2947.49	3988.48	1184.32	26.20	273.44	90.37
Furthest from centroid	7663.35	18407.54	6520.30	10.15	966.54	177.94

Figure 32 – P2P cost savings in comparison with CSC (See Table 6 for correspondence with municipality)



	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Closest to centroid	2910.93	7578.19	1333.24	51.39	492.32	156.84
Furthest from centroid	5924.86	14796.28	2784.85	29.37	1108.86	241.66

Figure 33 – Self-consumption difference between CSC and P2P (See Table 6 for correspondence with municipality)

5.3. Upscaling for National level

The following results were obtained by multiplying the representative municipalities' results by the number of municipalities in their clusters. For better representation, a dispersion range was computed by calculating the maximum and minimum value of the interval by respectively adding and subtracting the absolute value of the difference between closest and furthest from the centroid's results to the municipality closest to the centroid results. However, in most cases, this difference is larger than the actual representative municipality result, which creates unfeasible outcomes. This issue is explained by the fact that clusters have some dispersion among its municipalities and a positive dispersion does not necessarily presents an equal amplitude in the opposite direction. In the cases where the minimum value would be negative, a logical minimum value of zero is defined.

Table 10 - P2P comparison with reference scenarios - Upscaling

	P2P scenario compared to	Min	Closest to centroid	Max
CO_2 Emissions Savings (kton)	PS	0	3141.35	7050.92
	CSC	-3.53	-1.56	0
Cost Savings (M€)	PS	0	1954.07	4144.26
	CSC	0	0.14	0.51

According to Table 10, it can be concluded that even after upscaling, the differences between P2P and CSC are narrow in comparison with those relating P2P and PS. Using the average values, by implementing P2P over PS, 3141.35 kton of CO_2 (26.33% of the total emissions in PS) are not emitted and 1954.07 M€ (31.49% of PS total costs) are saved. However, implementing P2P over CSC results in extra 1.56 kton of CO_2 emitted, but this represents 0.018% of the total emissions in CSC and 0.050% of the value saved by changing from PS to P2P. Despite emitting more CO_2, P2P costs less 0.140 M€ (0.003% of CSC costs and 0.007% of PS savings). This means that, by implementing CSC over P2P, 89.74€ are being paid for each ton of CO_2 avoided. On the other hand, by choosing P2P over PS, 622.05 € are being saved for each ton of CO_2 avoided.

Furthermore, it should also be mentioned that each cluster's dispersion does not contribute equally to the differences between the average and maximum values. Concretely, for emission savings, the influence of Cluster 2's furthest from the centroid municipality is such that, despite only having 5 municipalities, this cluster accounts for 17% of the differences in results, while Cluster 5, with 93 municipalities, accounts for 24% and Cluster 4, with 19, has a negligible influence in this matter. Concluding, the upscaling's uncertainty is mainly related to dispersion among clusters with the biggest municipalities.

5.4. OMIE Price Sensitivity Analysis

The OMIE price sensitivity analysis is performed for a single municipality, Lisbon. Using the 2020 average monthly prices for p^{OMIE}, the results show some differences. In Figure 34, red bridges are now visible, indicating an increase in P2P purchases for industry. The main consumer, services, acquires 10.935 GWh of P2P energy, 61.53% of which from SFH, 29.02% from MAB and 9.45% from industry, while the second, MAB, buys 3.450 GWh - 60.90% from SFH, 3.86% from industry and 35.24% from services. Industry now buys 425.40 MWh (48.48% from SFH, 14.36% from MAB and 37.16% from services). Overall, the total grid consumption reduces 303.69 MWh.

The biggest seller is also the services, with practically the same amount (16.361 GWh), although only the industry increases its purchases (from 0.54% to 1.26% of total services sales). The second biggest seller is SFH (11.604 GWh), with a growth in sales to MAB (from 17.78% to 18.11% of total SFH sales) and industry (1.36% instead of 0.40%). Despite increasing purchases, industry behaves similarly in terms of sales.

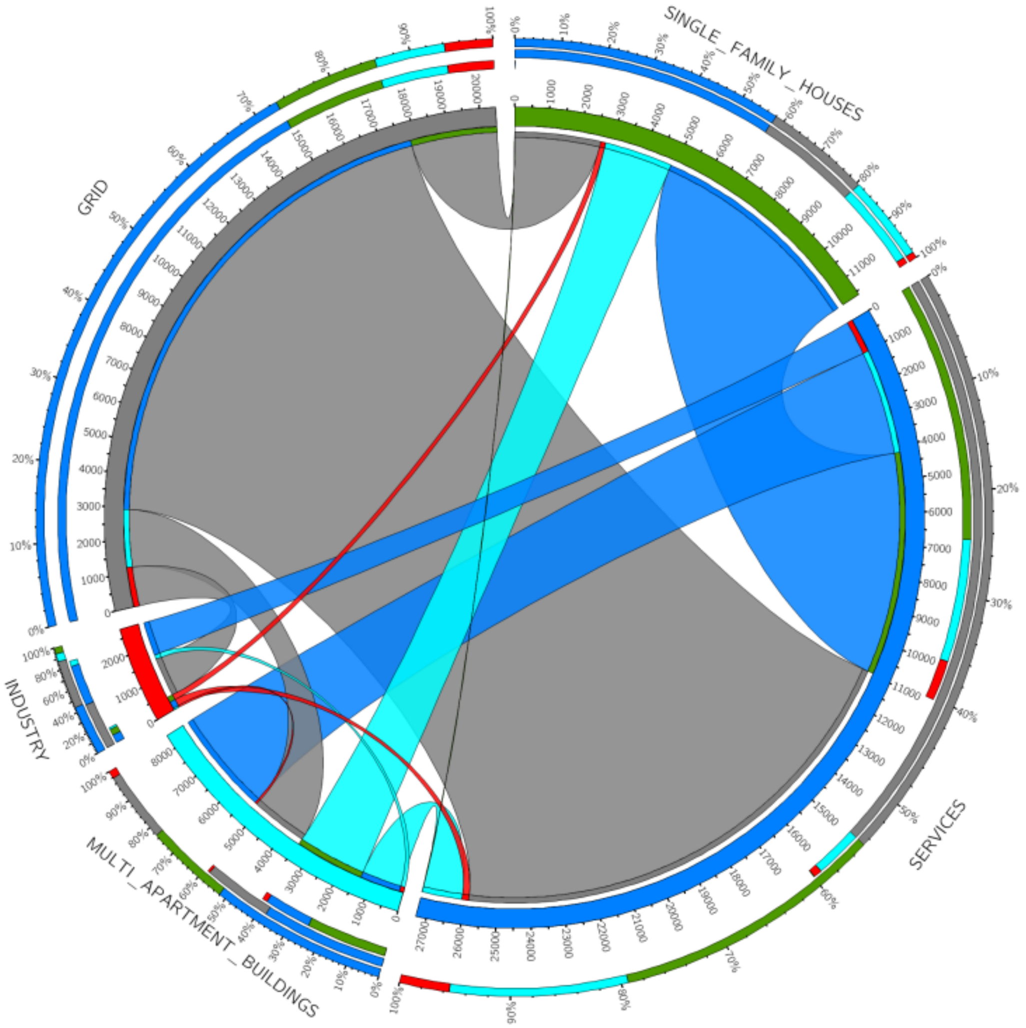


Figure 34 – Energy Consumption (MWh) for Lisbon (no grid purchases) - P2P Scenario with 2020 values for p^{OMIE}

Figure 35 presents the money fluxes for the same situation. Overall, the EC total costs slightly increase from 356.340 M€ to 356.653 M€. The main difference in P2P trading is the increase of sales from peers to industry, so, even though industry is benefited from this situation, the other members are actually increasing their costs, since these trading prices are lower than p^{OMIE} in the main study.

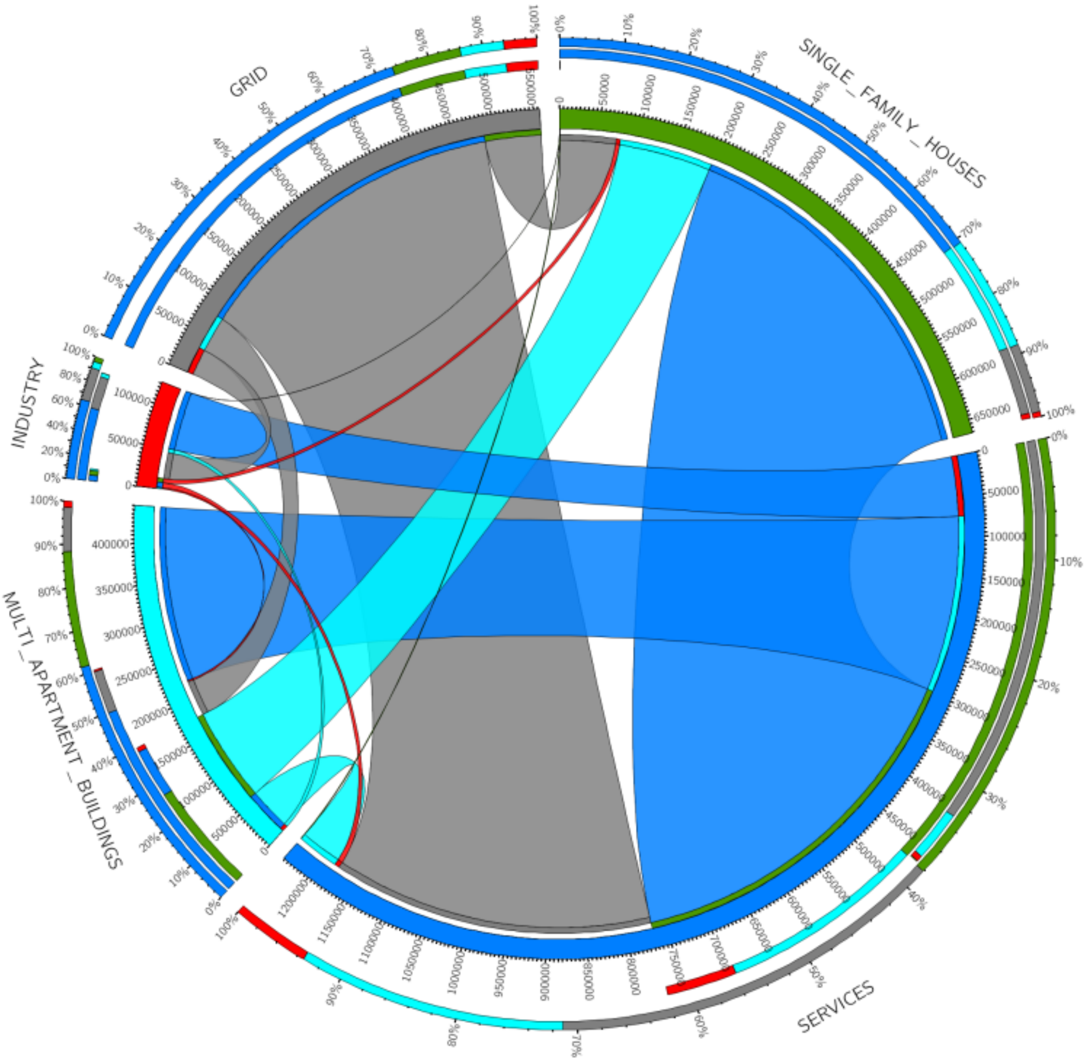


Figure 35 – Money Fluxes (€) for Lisbon (no grid purchases) - P2P Scenario with 2020 values for p^{OMIE}

Proceeding with the analysis, p^{OMIE} will now use data based on record prices, from September 2021. In this situation, the results show that it is always more convenient for members to sell to grid, to a point where no P2P trades occur – Figure 36. The total grid consumption sums up to 2.502 TWh, whereas the grid sells a total of 35.259 GWh to the EC. The total EC costs get reduced to 353.398 M€, due to increased income.

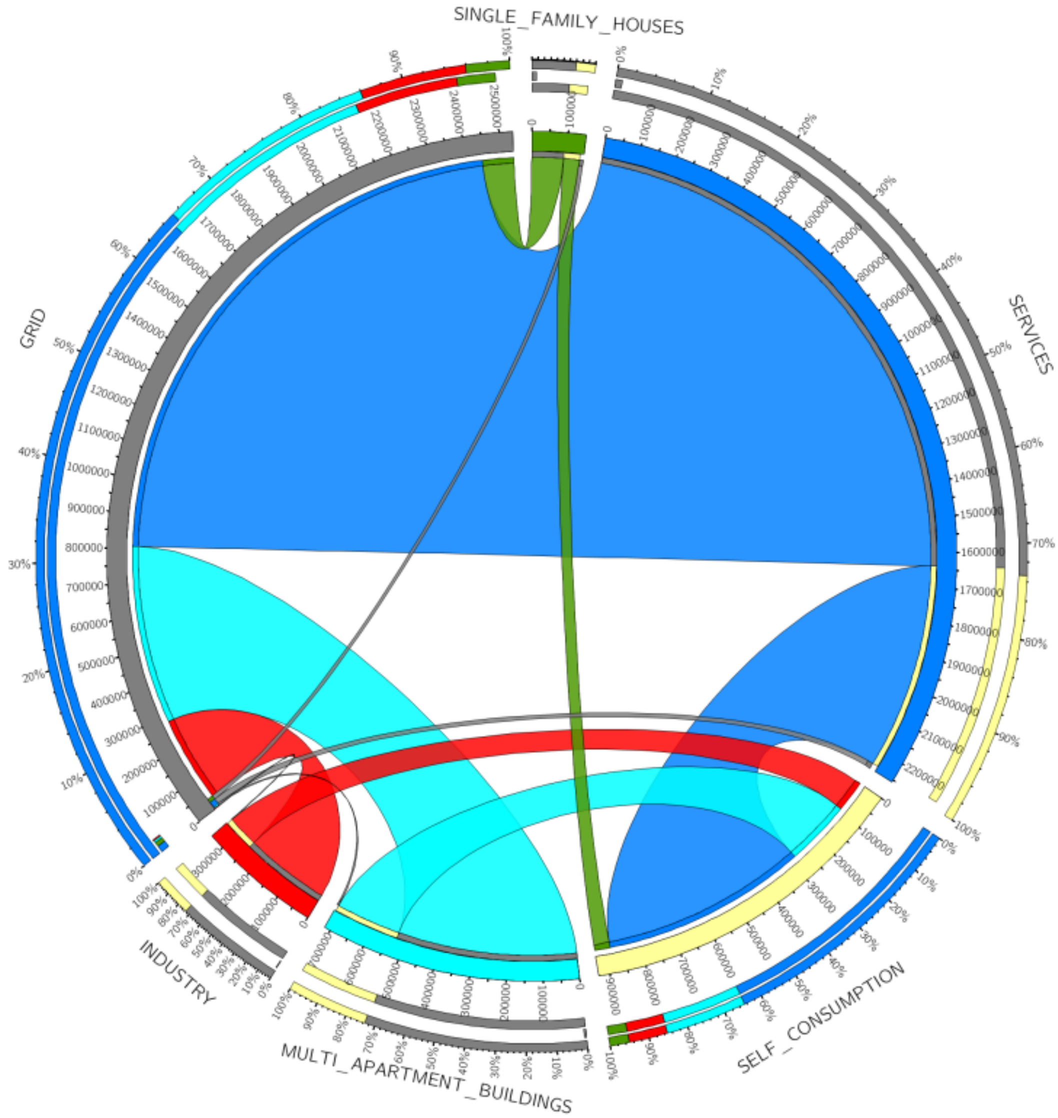


Figure 36 – Energy Consumption (MWh) for Lisbon - P2P Scenario with 2021 values for p^{OMIE}

From this analysis, it can be concluded that a significant decrease of p^{OMIE}, below the average grid purchase price of all participants, stimulates member participation, as demonstrated by the increased consumption of P2P electricity by the industry, which results in lower grid consumption and, consequently, less emissions. Generally, this reduction results in added total costs for the EC because even though selling to the grid becomes a less profitable operation for the EC's members in comparison with selling to their peers, the P2P trades that now occur also generate less profit than the grid sales that occurred in the event of no p^{OMIE} reduction.

In contrast, a significant increase of p^{OMIE}, above the average grid purchase price of all participants, discourages P2P trading, potentially to a point, as revealed in the second case, where P2P trades simply do not occur. When this happens, the revenues increase, leading to reduced total costs for the EC, but at the expense of increase emissions, due to the fact that members cannot buy from their peers and must purchase their electricity from the grid.

Consequently, it is evident that P2P results, namely the magnitude of collective and individual engagement in trading and reluctance to rely on the grid (which directly affects emissions), as well as community savings, are deeply dependent on market prices, both on absolute values and tariff structure. Moreover, as seen from the analysis on different municipalities in the previous subchapters, they also change significantly whenever the EC's members' demands and surplus differ, which is directly related to the municipality's structure.

5.5. Literature comparison

The existent literature regarding P2P energy markets diverges from the work here developed in its approach, namely in the size of the EC considered. Literature frequently presents EC based with dozens or even less participants, representing fewer demand, while in this work, although only with 4 members, the ECs presented high demand (the municipality aggregated demand of all electricity demanding sectors. Another topic often disregarded is the EC composition, frequently only considering the residential sector, very appropriate for decentralized PV electricity generation, while the services and industry are left out. Nonetheless, using the studies by Perger et. al (Perger et al., 2021) and Nguyen et. al (Nguyen et al., 2018) (mentioned in the literature review), a comparison is made with this thesis.

In the study by Perger et. al, the results include a scenario where only households are considered (10). Contemplating it and excluding batteries, annual financial savings of up to 38% were achieved individually by prosumers, whereas these vary between 33% and 46% for SFH and between 32% and 34% for MAB, in this work. This maximum saving was equivalent to nearly 800 €/year, whereas in this work the average savings, obtained by dividing total savings by the number of buildings, is at most 639.14 €/year for SFH and 1652.04 €/year for MAB.

In the study by Nguyen et. al an optimization model to maximize the economic benefits for rooftop PV-battery distributed generation in a P2P energy trading environment is proposed. The case study composes an EC with 500 households, based on real-world data. Once more, besides being smaller, this community only has residential buildings. For the case with no batteries (only PV systems), maximal financial savings of up to 23.74% can be achieved by households equipped with larger PV systems.

When compared with the literature review, the results in this study are similar in the first case and show some difference in the second. The maximum individual financial savings in the study by Perger et. al (38%) are smaller than the maximum savings in this study (46%) but, nonetheless, do not incorporate a big number of members neither those belonging to other economic sectors, that could foment P2P, like in our case. The maximum financial savings in the second study (23.74%) are well below our values for the same reason, with the extra factor of, unlike the first study, not including the willingness to pay, which ends up compensating its users. Still, it should be overstated that these studies show larges differences in their framework, compared to this work.

6. Conclusions

In this thesis, an analysis of the impact of a widespread dissemination of P2P market-based energy communities in the Portuguese energy system was performed. Three scenarios were compared: present scenario, collective self-consumption and P2P. PS serves merely as a base scenario, as it does not comply with the EU's vision for 2050 because it does not incorporate decentralized energy generation.

The main conclusion is that, even though CSC and P2P, when compared to PS, show large reductions in CO_2 emissions and costs, they present very similar results and these reductions are essentially due to self-consumption, i.e., the influence of P2P trades is residual and also due to overall low surplus, which is a consequence of data retrieved from RNC2050. Furthermore, CSC shows a better environmental performance than P2P but achieves worse economic results.

In the processes considered for this study, the agents involved in the energy trading market were economic sectors, namely residential (subdivided in SFH and MAB), industry and services, considering each one as a member. The services showed the biggest predisposition for P2P trading, actively buying and selling independently of the municipality in question. SFH mainly acted as a seller, due to relatively high surplus rates, although it also acted as buyer in rural municipalities. On the other hand, MAB, whilst mainly acting as a seller too, behaved as a buyer as well in the most urbanised municipalities. Industry showed little participation in P2P trading, by almost never purchasing energy from its peers and essentially selling to the grid, given their low retail tariffs.

Concerning the municipal level, since savings arise predominantly from self-consumption, the municipalities that exhibit the best results environmentally and economically are those that display the higher self-sufficiency and surplus, specially concerning SFH and MAB, as they generally buy from the grid at the highest prices. These are grouped in Cluster 3 and have high values for these indicators due to their solar potential and/or the ratio between production and demand in residential members.

Regarding the research questions and addressing the first ("What would be the reduction of emissions of CO_2 in the scenario of the dissemination of P2P energy communities in Portugal in 2050?"), it was estimated that, nationally, 3141.35 kton of CO_2 would be avoided, when comparing to PS. Nevertheless, it should be mentioned that this scenario would result in an increase of 1.56 kton in CO_2 emissions, comparing to CSC. Concerning the second question ("What would be the costs or earnings of this implementation?"), the estimation is 1954.07 M€ worth of savings at national level, if compared to PS and 0.14 M€ if compared to CSC.

Furthermore, it was also concluded that P2P markets are highly volatile and can change significantly depending on types of participants, energy constraints such as electricity demand and surplus, market prices and tariff structures. In particular, market regulation is necessary in the future to incentivize market participation, as certain values may discourage P2P trading and leave peers more grid dependent.

Discussing the main limitations in this work, it should be stated that the option to rely on clustering, evidently adds a degree of uncertainty to the results. The results are highly dependent on the predictions of final electricity prices and network charges for 2050 that are, on a certain level, difficult to forecast. Moreover, this work, despite considering entire economic sectors as members in ECs, does not take into account the technical feasibility of trading the large quantities of electricity associated with such large agents.

For future research, it would be interesting to have a larger granularity for the country's model, as ECs are not predicted to have such large scales in the future. Reducing the scale to parish level, for example, would produce more refined results. Furthermore, a model including battery storage systems, which should complement renewable electricity production, would provide more information on the functioning of P2P markets at night, inexistent in this study. Additionally, other renewable sources, such as wind, could be considered in ECs, for industry, where its implementation may be possible in some cases. Finally, investment costs for the PV systems should be taken into consideration.

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Annex

Table 11 - Clustering Results

Cluster 1 •	Cluster 2 •	Cluster 3 •	Cluster 4 •	Cluster 5 •	Cluster 6 •
37-Aveiro	62-Cascais	6-Albufeira	11-Alcoutim	1-Abrantes	3-Aguiar da Beira
41-Barcelos	115- Lisboa	17-Almada	13-Alfândega da Fé	2-Águeda	4-Alandroal
51-Braga	195-Porto	25-Amadora	15-Aljezur	5-Albergaria-a-Velha	14-Alijó
75-Coimbra	230-Sintra	43-Barreiro	18-Almeida	7-Alcácer do Sal	16-Aljustrel
86-Estarreja	265-Vila Nova de Gaia	56-Caminha	22-Alter do Chão	8-Alcanena	20-Almodôvar
94-Figueira da Foz		83-Entroncamento	35-Arronches	9-Alcobaça	21-Alpiarça
108-Guimarães		90-Faro	59-Carrazeda de Ansiães	10-Alcochete	23-Alvaiázere
114-Leiria		104-Gondomar	99-Fronteira	12-Alenquer	24-Alvito
124-Maia		111-Lagoa	102-Góis	19-Almeirim	26-Amarante
128-Marinha Grande		112-Lagos	109-Idanha-a-Nova	31-Arganil	27-Amares
130-Matosinhos		116-Loulé	134-Mértola	36-Arruda dos Vinhos	28-Anadia
166-Oliveira de Azeméis		117-Loures	135-Mesão Frio	39-Azambuja	29-Ansião
174-Palmela		142-Moita	149-Montemor-o-Velho	44-Batalha	30-Arcos de Valdevez
209-Santa Maria da Feira		162-Odivelas	161-Odemira	45-Beja	32-Armamar
213-Santo Tirso		163-Oeiras	183-Penedono	46-Belmonte	33-Arouca
221-Seixal		165-Olhão	252-Viana do Alentejo	47-Benavente	34-Arraiolos
226-Setúbal		194-Portimão	257-Vila do Bispo	48-Bombarral	38-Avis
229-Sines		198-Póvoa de Varzim	266-Vila Nova de Paiva	52-Bragança	40-Baião
253-Viana do Castelo		225-Sesimbra	274-Vimioso	55-Caldas da Rainha	42-Barrancos
260-Vila Franca de Xira		237-Tavira		61-Cartaxo	49-Borba
263-Vila Nova de Famalicão		249-Valongo		64-Castelo Branco	50-Boticas
		270-Vila Real de Santo António		66-Castelo de Vide	53-Cabeceiras de Basto
				73-Chaves	54-Cadaval
				76-Condeixa-a-Nova	57-Campo Maior
				77-Constância	58-Cantanhede
				79-Covilhã	60-Carregal do Sal
				82-Elvas	63-Castanheira de Pêra
				84-Espinho	65-Castelo de Paiva
				85-Esposende	67-Castro Daire
				87-Estremoz	68-Castro Marim
				88-Évora	69-Castro Verde
				89-Fafe	70-Celorico da Beira
				91-Felgueiras	71-Celorico de Basto
				100-Fundão	72-Chamusca
				105-Gouveia	74-Cinfães
				106-Grândola	78-Coruche
				107-Guarda	80-Crato
				110-Ílhavo	81-Cuba
				113-Lamego	92-Ferreira do Alentejo
				118-Lourinhã	93-Ferreira do Zêzere
				119-Lousã	95-Figueira de Castelo Rodrigo
				120-Lousada	96-Figueiró dos Vinhos
				122-Macedo de	97-Fornos de

				Cavaleiros	Algodres
				123-Mafra	98-Freixo de Espada à Cinta
				125-Mangualde	101-Gavião
				126-Manteigas	103-Golegã
				131-Mealhada	121-Mação
				139-Mirandela	127-Marco de Canaveses
				141-Moimenta da Beira	129-Marvão
				148-Montemor-o-Novo	132-Meda
				150-Montijo	133-Melgaço
				152-Mortágua	136-Mira
				156-Murtosa	137-Miranda do Corvo
				157-Nazaré	138-Miranda do Douro
				158-Nelas	140-Mogadouro
				164-Oleiros	143-Monção
				168-Oliveira do Bairro	144-Monchique
				169-Oliveira do Hospital	145-Mondim de Basto
				170-Ourém	146-Monforte
				172-Ovar	147-Montalegre
				173-Paços de Ferreira	151-Mora
				175-Pampilhosa da Serra	153-Moura
				176-Paredes	154-Mourão
				180-Penafiel	155-Murça
				185-Peniche	159-Nisa
				186-Peso da Régua	160-Óbidos
				192-Portalegre	167-Oliveira de Frades
				196-Porto de Mós	171-Ourique
				204-Rio Maior	177-Paredes de Coura
				208-Santa Comba Dão	178-Pedrógão Grande
				211-Santarém	179-Penacova
				212-Santiago do Cacém	181-Penalva do Castelo
				214-São Brás de Alportel	182-Penamacor
				215-São João da Madeira	184-Penela
				219-Sátão	187-Pinhel
				220-Seia	188-Pombal
				228-Silves	189-Ponte da Barca
				231-Sobral de Monte Agraço	190-Ponte de Lima
				236-Tarouca	191-Ponte de Sôr
				239-Tomar	193-Portel
				242-Torres Novas	197-Póvoa de Lanhoso
				243-Torres Vedras	199-Proença a Nova
				245-Trofa	200-Redondo
				246-Vagos	201-Reguengos de Monsaraz
				247-Vale de Cambra	202-Resende
				248-Valença	203-Ribeira de Pena
				251-Vendas Novas	205-Sabrosa
				258-Vila do Conde	206-Sabugal
				268-Vila Pouca de Aguiar	207-Salvaterra de Magos
				269-Vila Real	210-Santa Marta de

					Penaguião
				271-Vila Velha de Ródão	216-São João da Pesqueira
				276-Viseu	217-São Pedro do Sul
				277-Vizela	218-Sardoal
					222-Sernancelhe
					223-Serpa
					224-Sertã
					227-Sever do Vouga
					232-Soure
					233-Sousel
					234-Tábua
					235-Tabuaço
					238-Terras de Bouro
					240-Tondela
					241-Torre de Moncorvo
					244-Trancoso
					250-Valpaços
					254-Vidigueira
					255-Vieira do Minho
					256-Vila de Rei
					259-Vila Flor
					261-Vila Nova da Barquinha
					262-Vila Nova de Cerveira
					264-Vila Nova de Foz Côa
					267-Vila Nova de Poiares
					272-Vila Verde
					273-Vila Viçosa
					275-Vinhais
					278-Vouzela

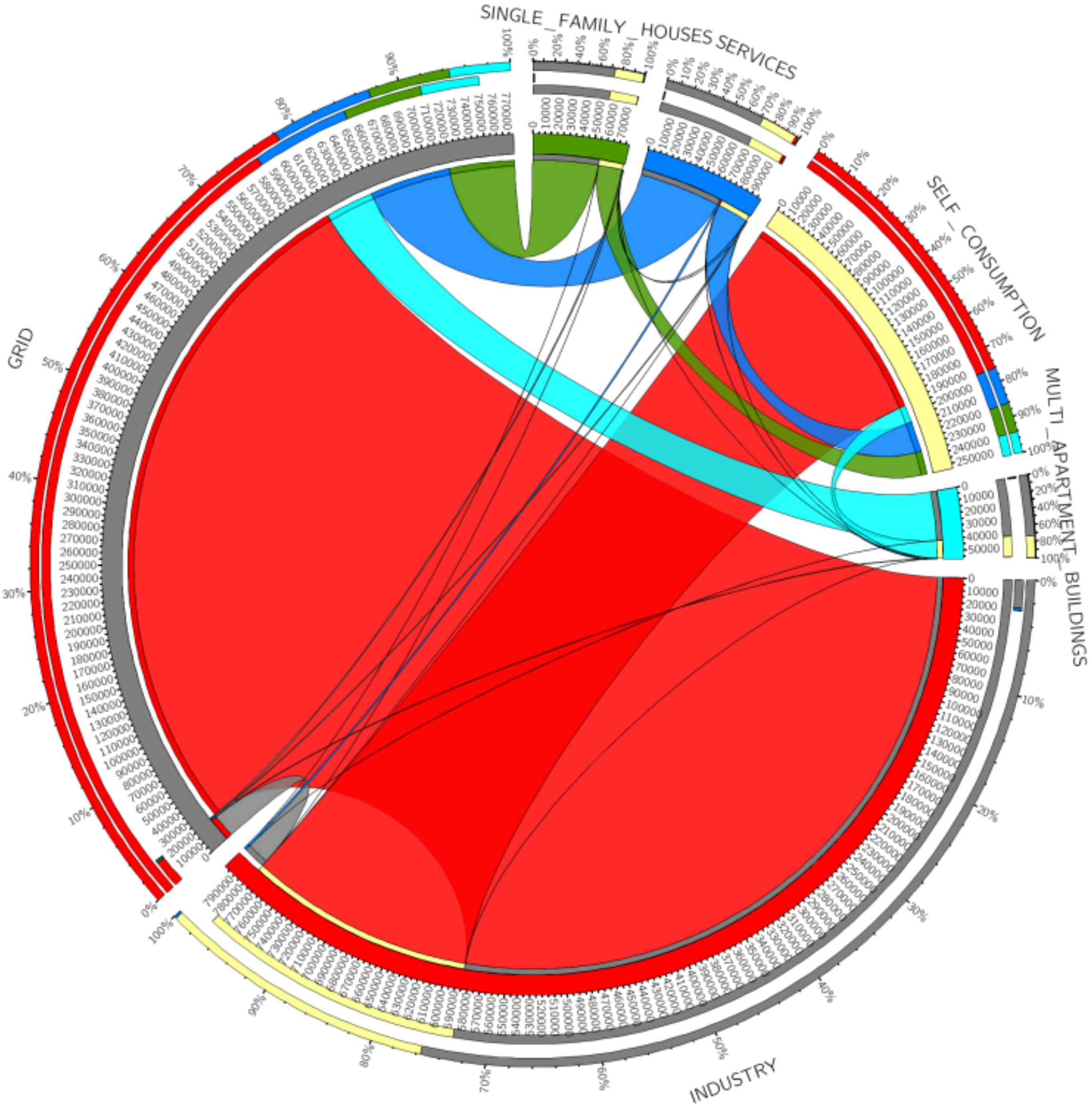

Figure 37 - Energy Consumption (MWh) for Viana do Castelo - P2P Scenario

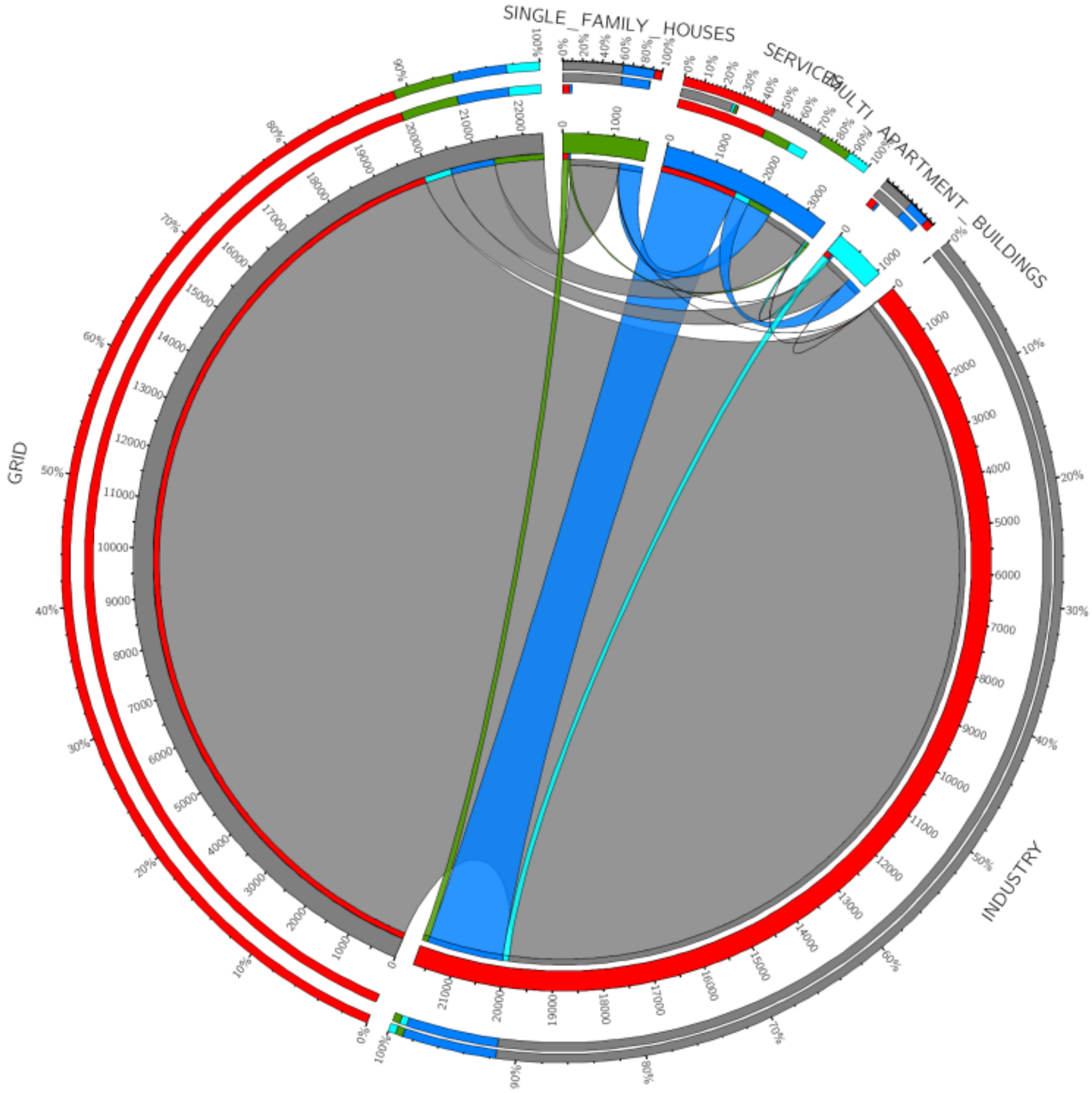

Figure 38 - Energy Consumption (MWh) for Viana do Castelo (no grid purchases) - P2P Scenario

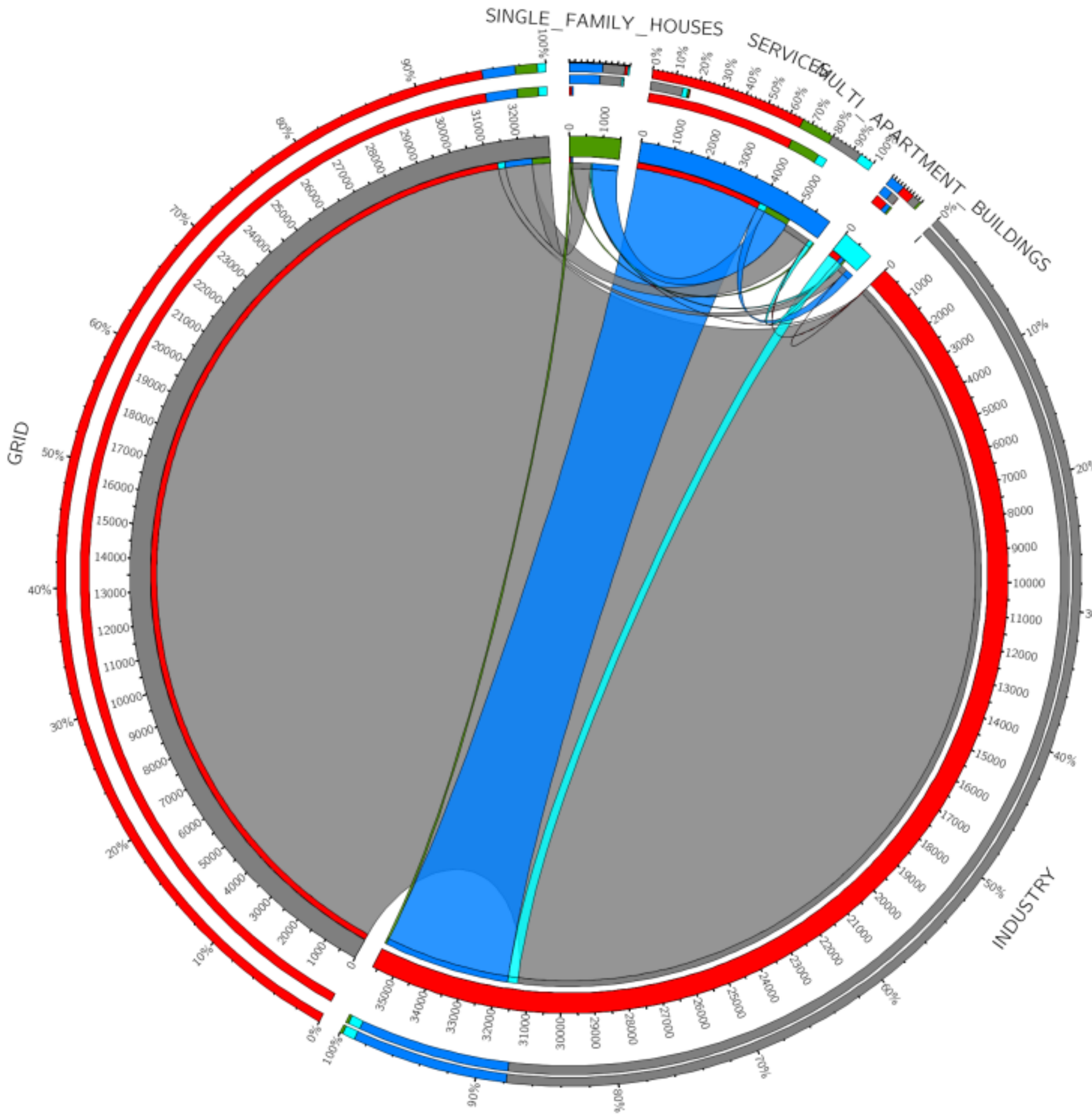

Figure 39 - Energy Consumption (MWh) for Setúbal (no grid purchases) - P2P Scenario

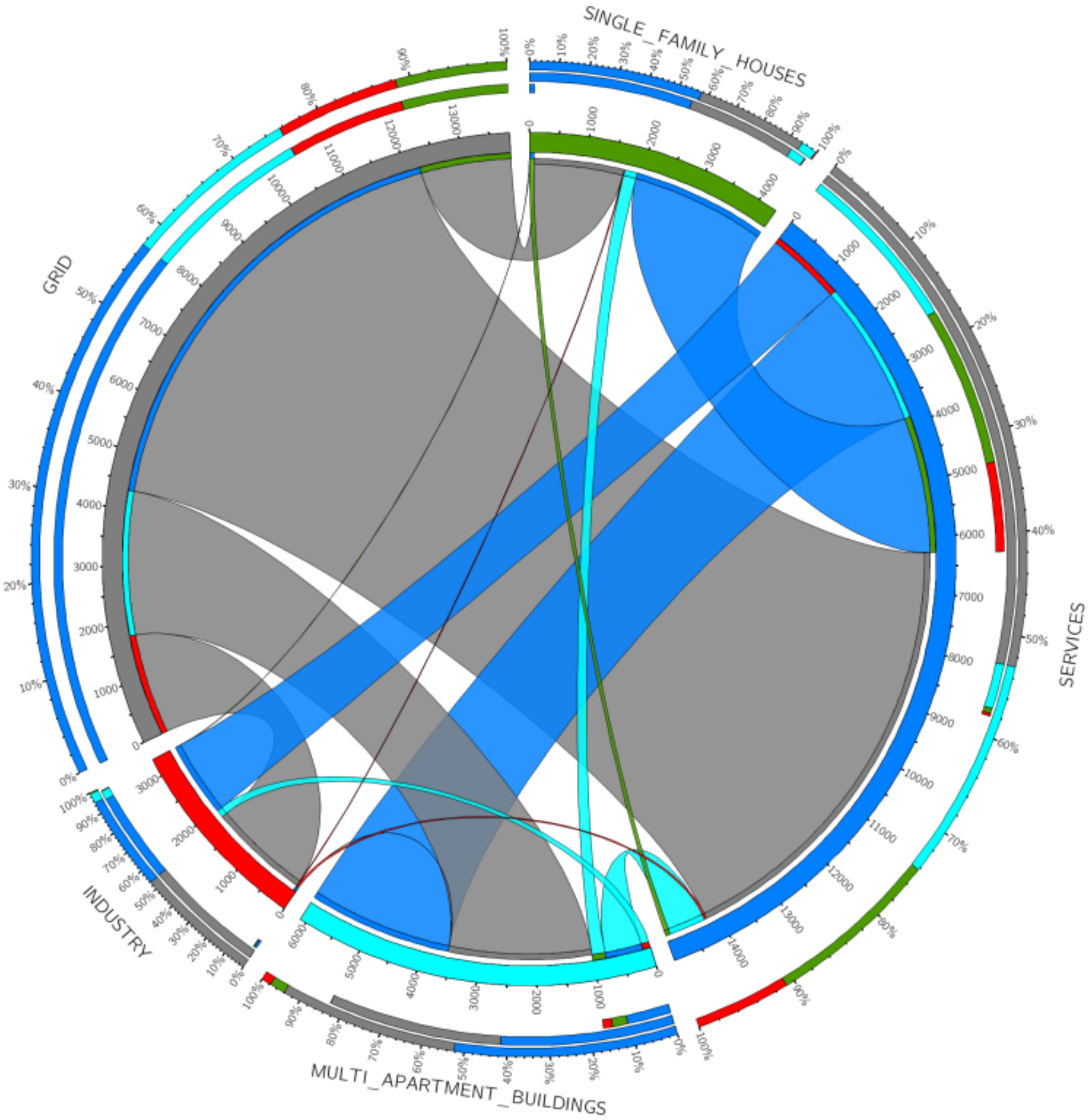

Figure 40 - Energy Consumption (MWh) for Porto (no grid purchases) - P2P Scenario

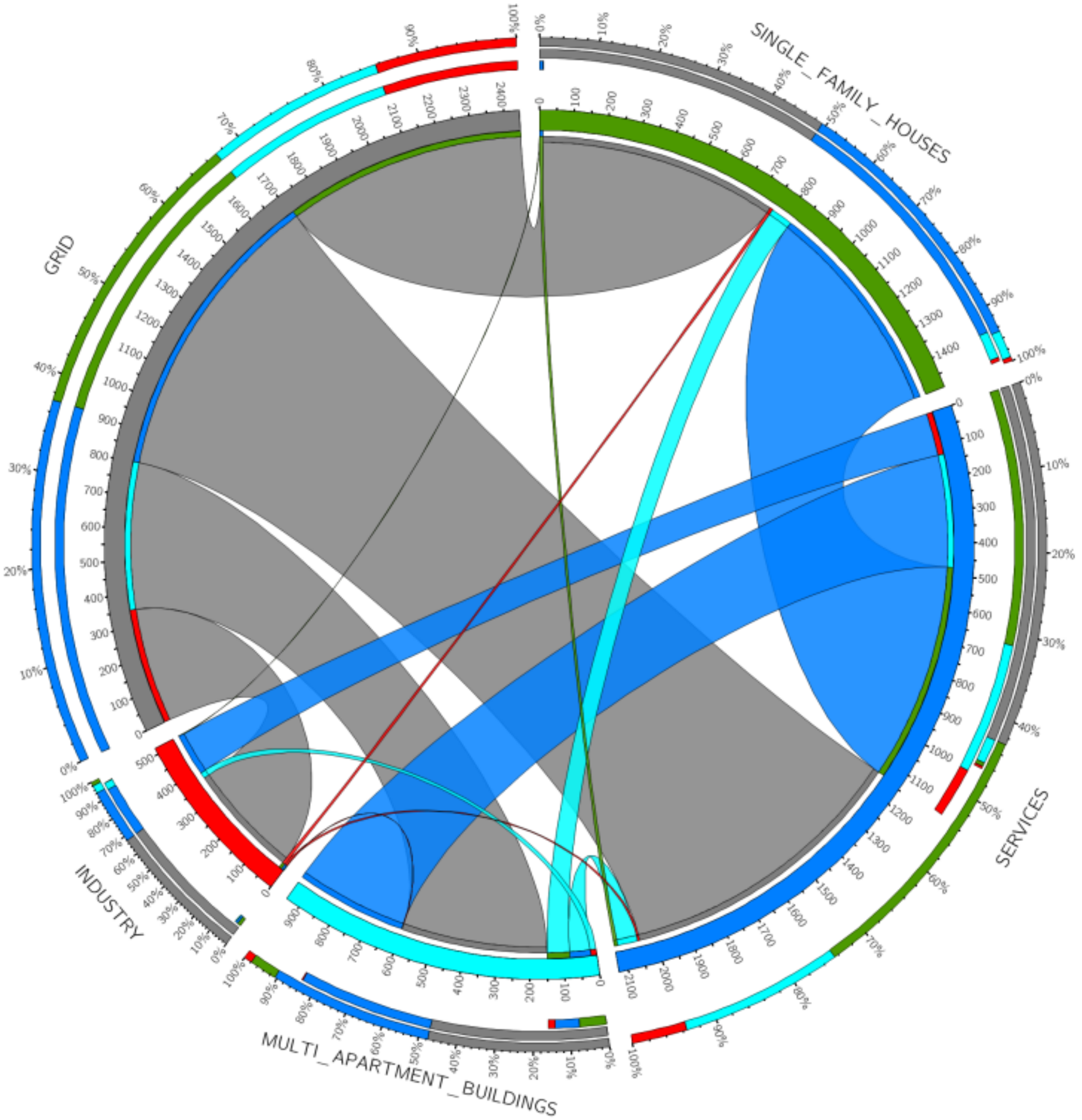

Figure 41 - Energy Consumption (MWh) for Póvoa de Varzim (no grid purchases) - P2P Scenario

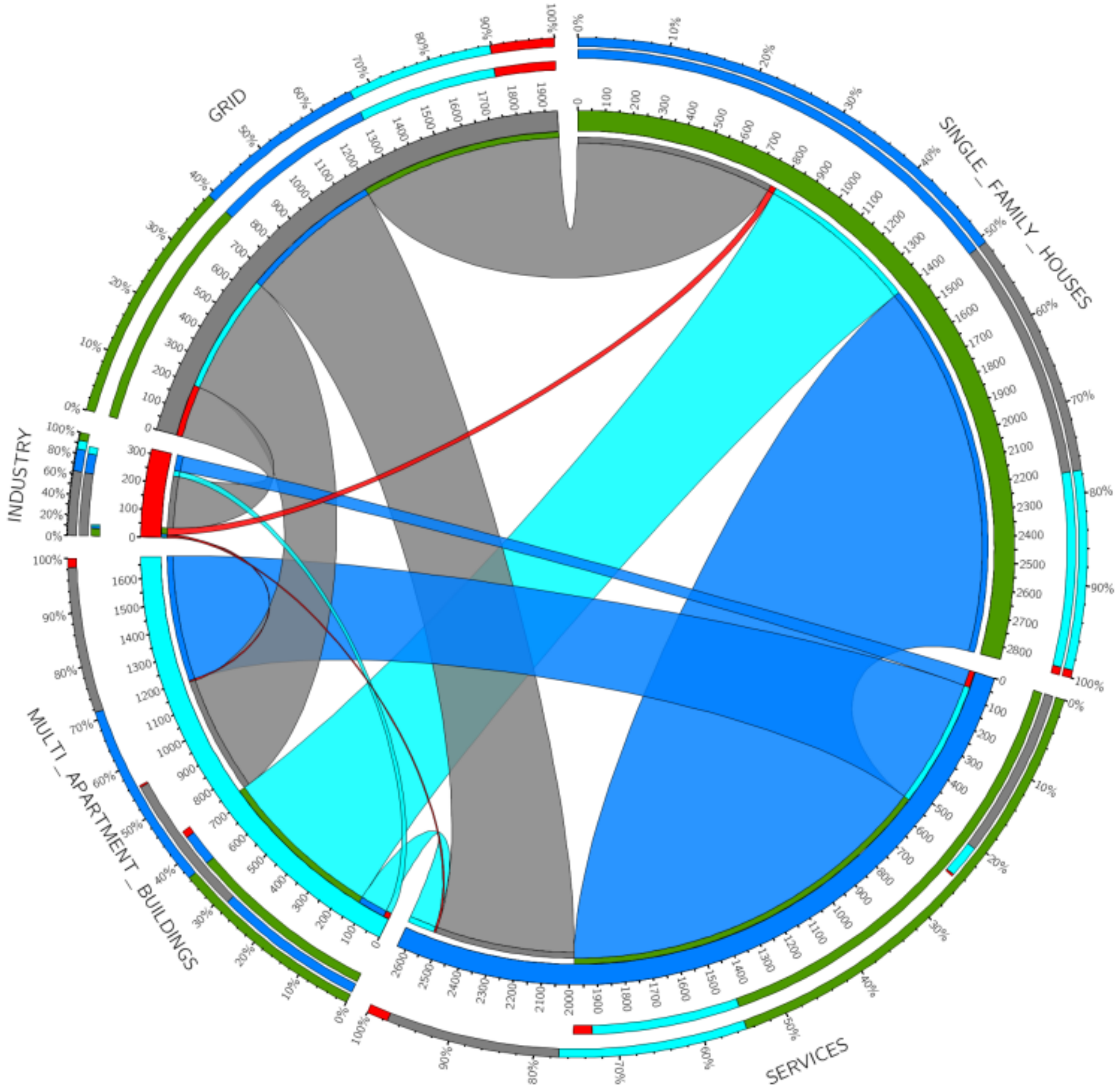

Figure 42 - Energy Consumption (MWh) for Odivelas (no grid purchases) - P2P Scenario

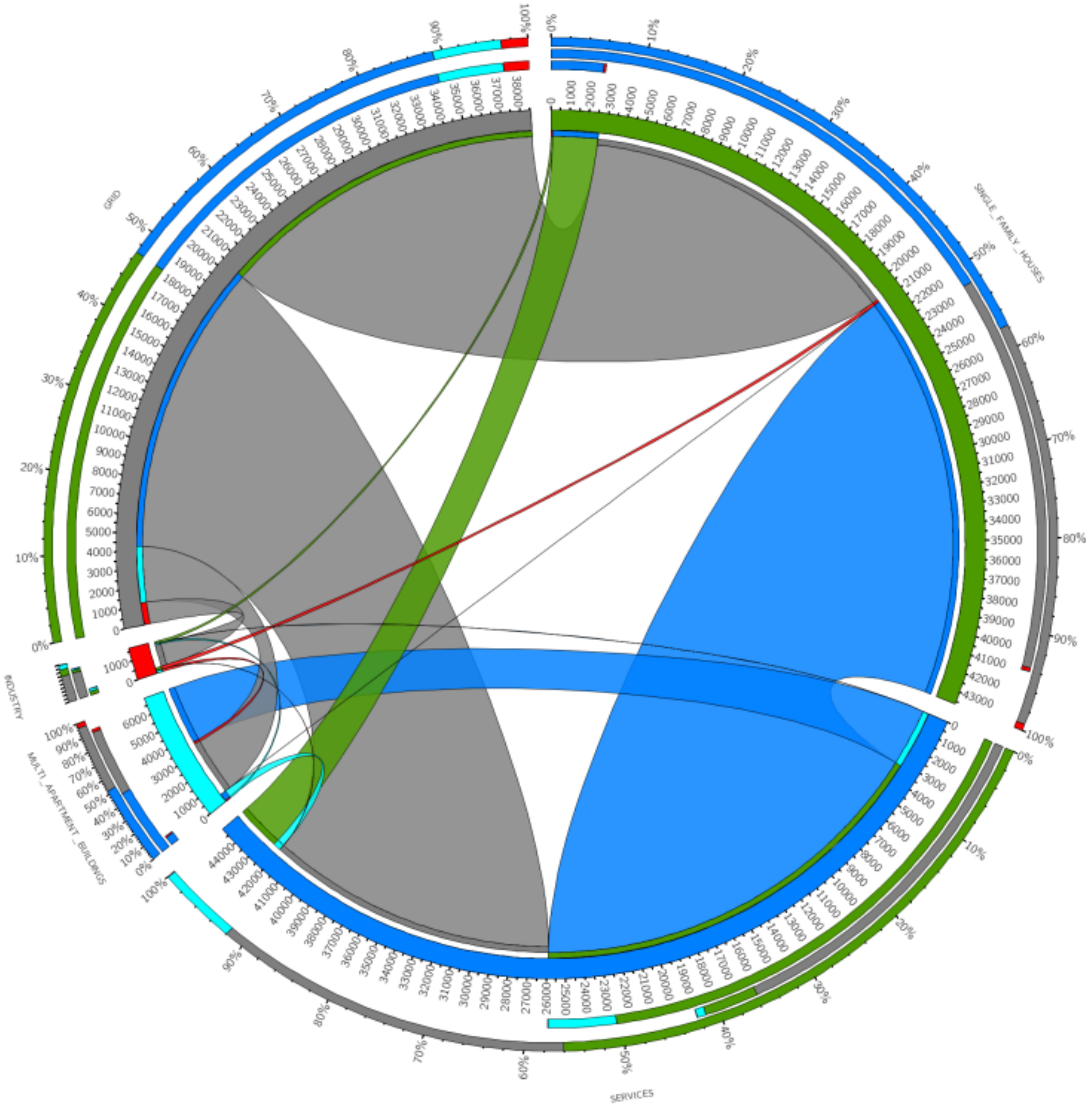

Figure 43 - Energy Consumption (kWh) for Penedono (no grid purchases) - P2P Scenario

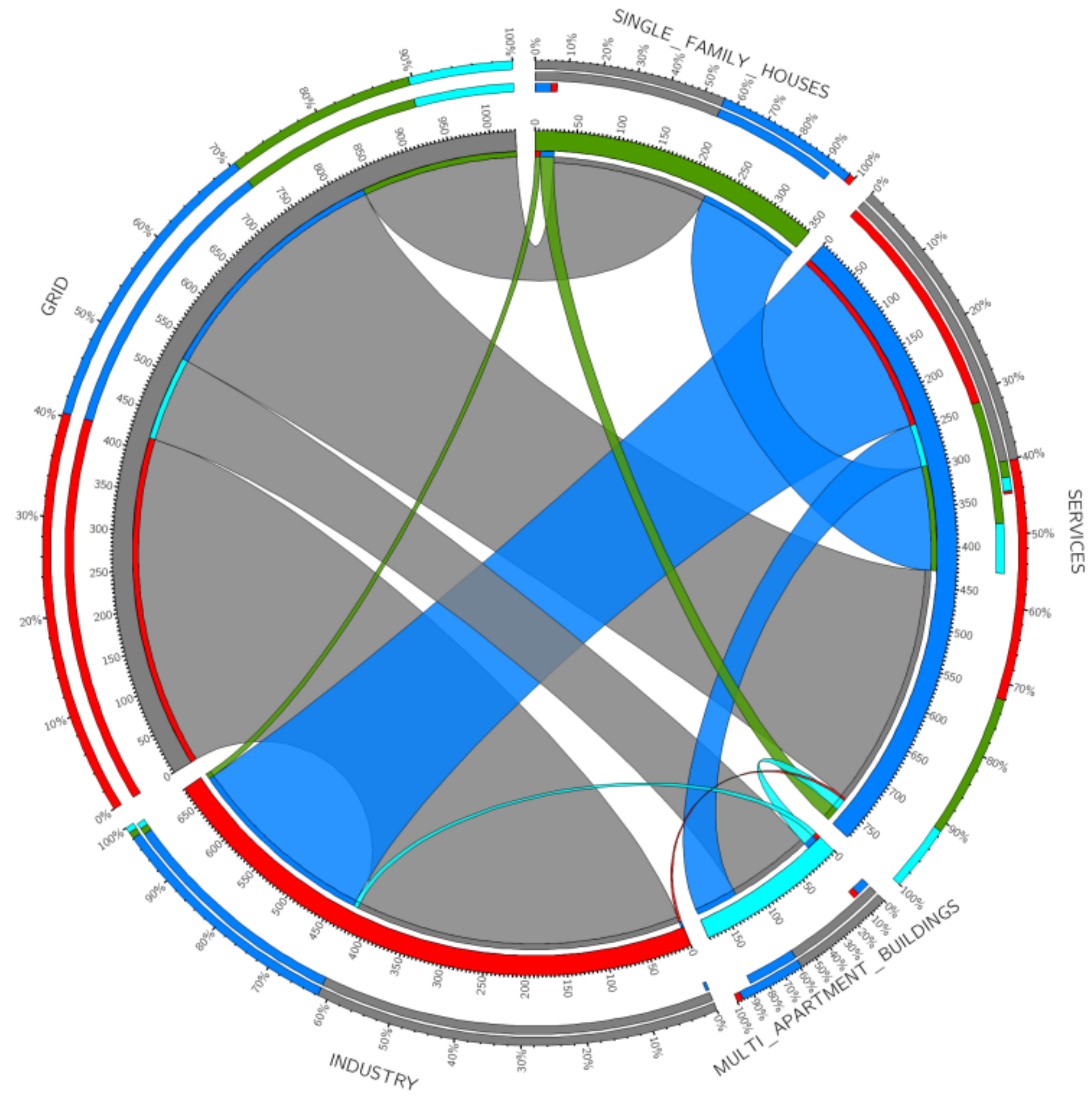

Figure 44 - Energy Consumption (MWh) for Lamego (no grid purchases) - P2P Scenario

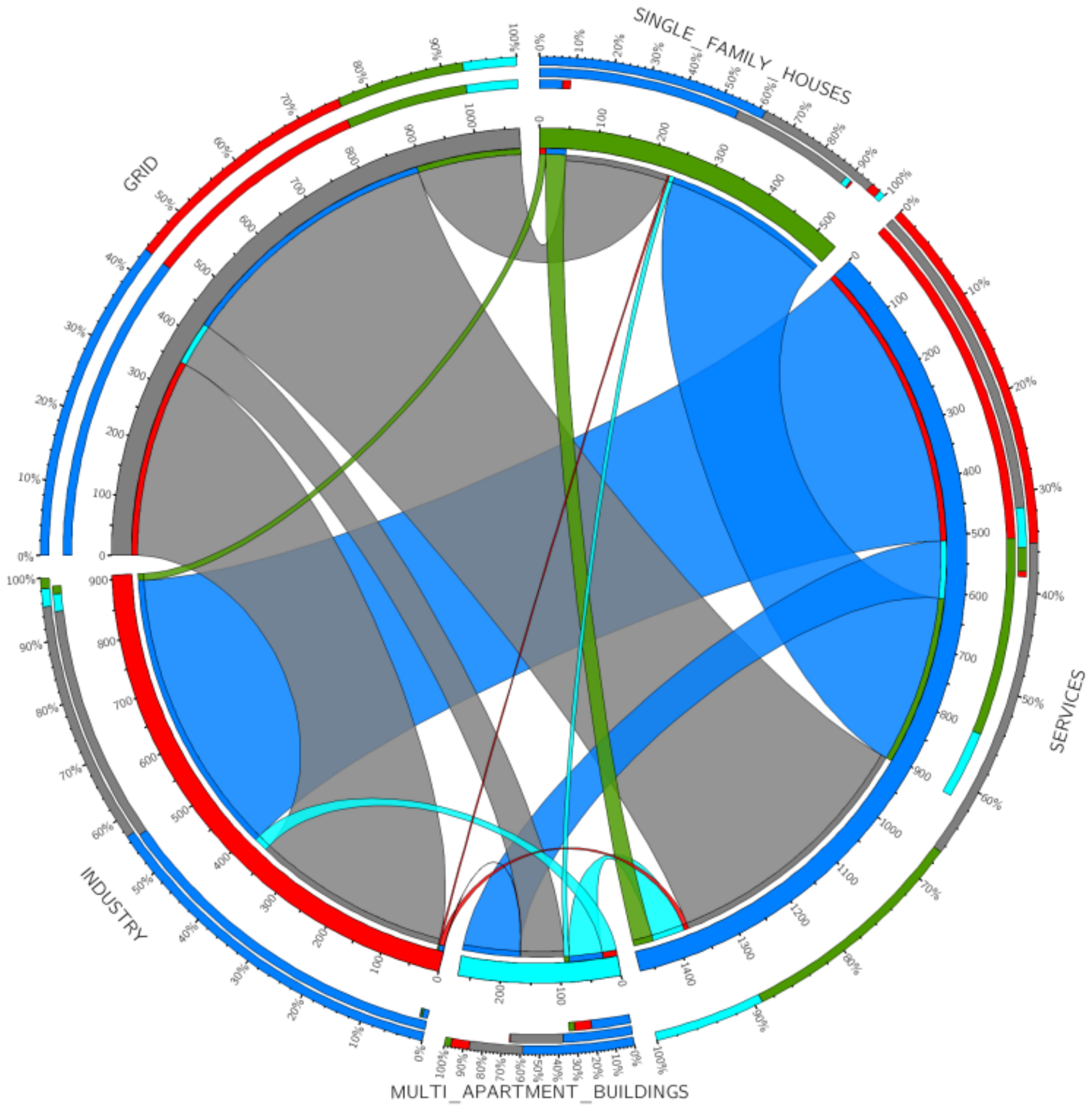

Figure 45 - Energy Consumption (MWh) for Montijo (no grid purchases) - P2P Scenario

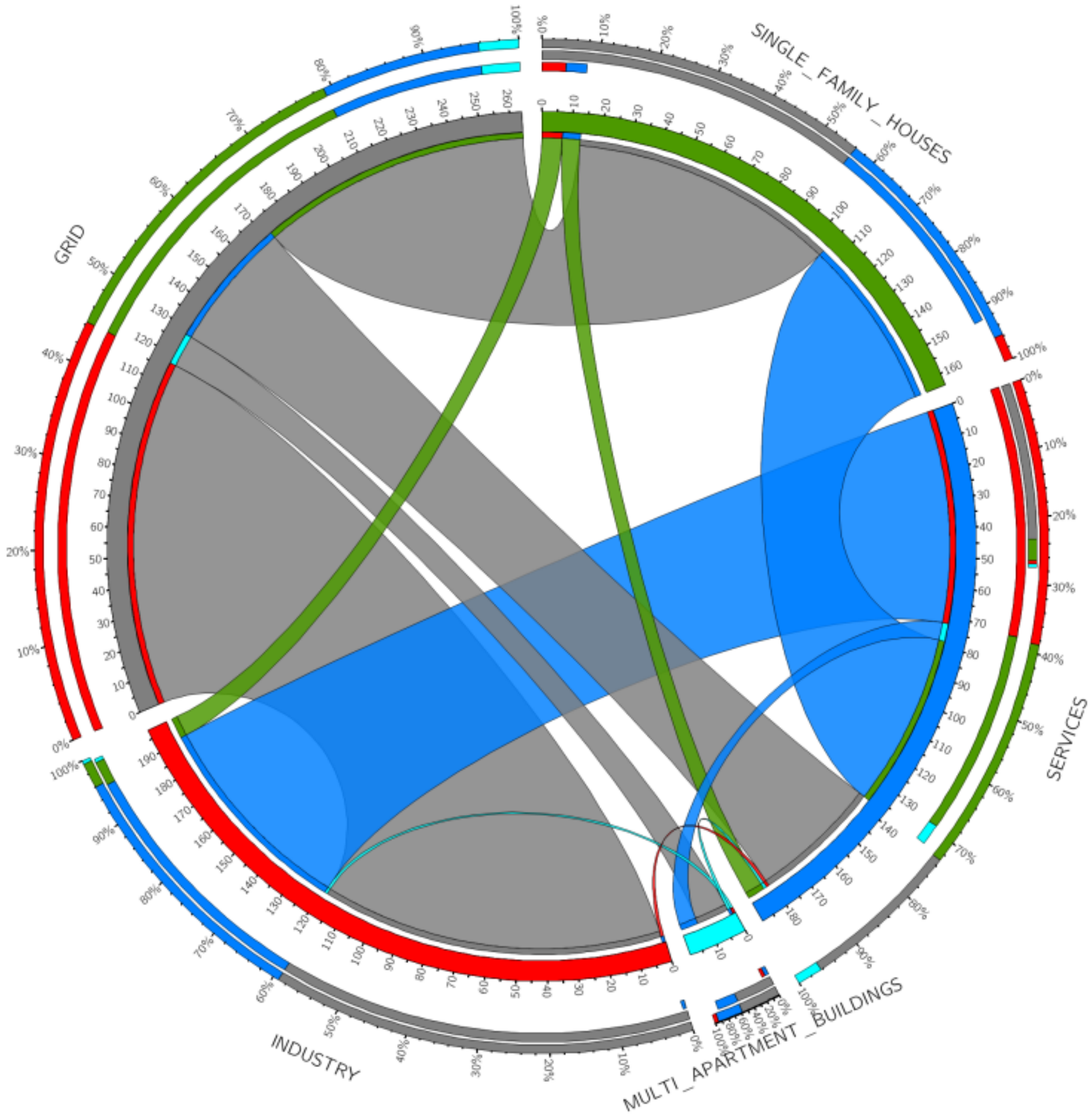

Figure 46 - Energy Consumption (MWh) for Vouzela (no grid purchases) - P2P Scenario

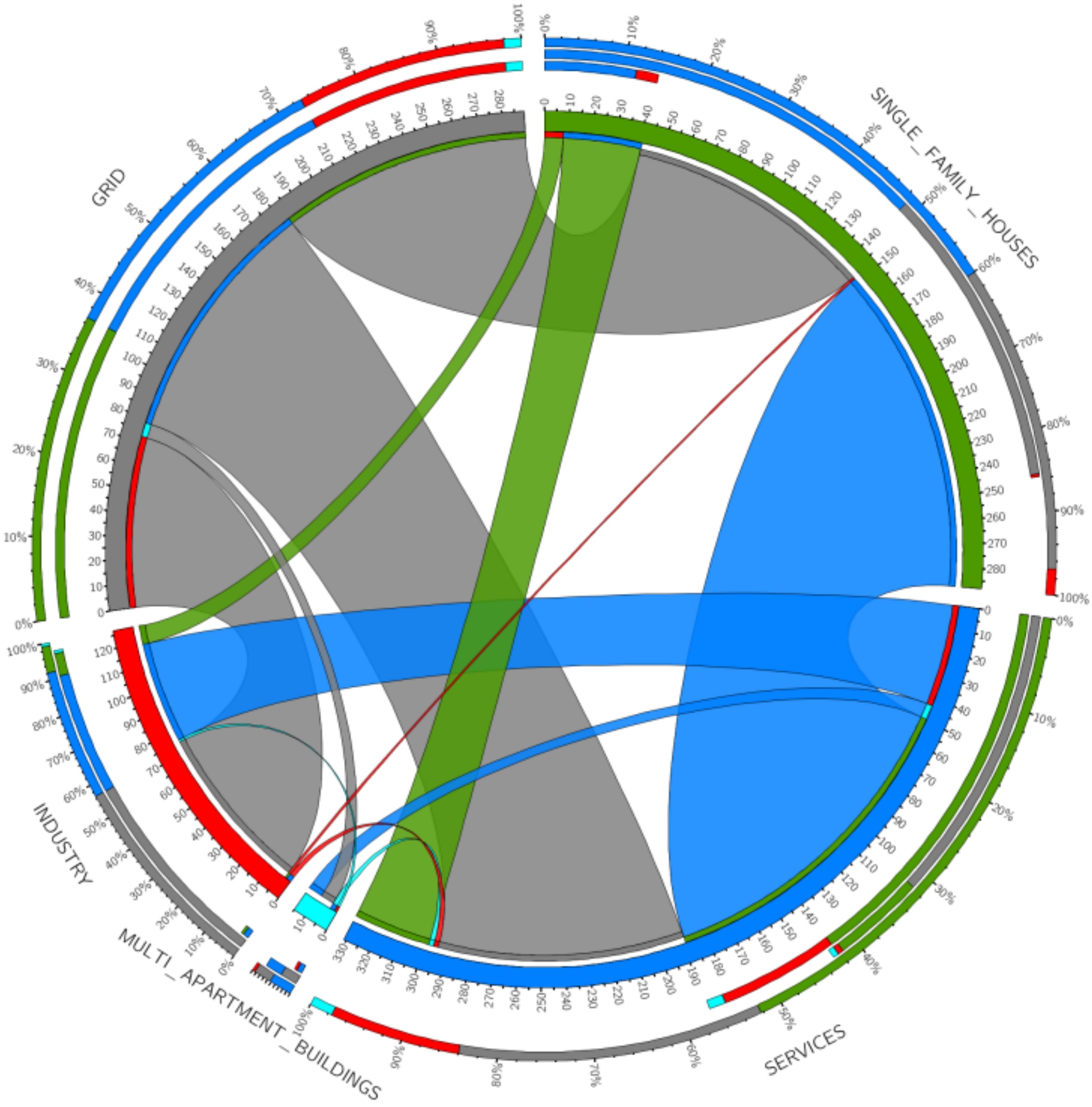

Figure 47 - Energy Consumption (MWh) for Salvaterra de Magos (no grid purchases) - P2P Scenario