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 can 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.

Introduction

Climate change mitigation is one of the greatest challenges faced by humanity in the 21st century, which has triggered the European Union's (EU) response to promote an energy transition, by committing to achieve net-zero greenhouse gas (GHG) emissions by 2050. Accordingly, the EU targeted to, 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).

The strategy to accomplish the energy transition is complex and has many lines of action, which compelled the EU to develop, in 2019, the "Clean Energy for all Europeans Package" (CEP), with concrete measures and targets, and, in 2021, the "Fit for 55" package, with even more ambitious goals. For the purpose of this work, special emphasis should be placed on the idea of maximising the deployment of renewables, the use of electricity to fully decarbonise Europe's energy supply and the engagement of citizens in energy matters.

The increase of renewables, besides reducing GHG emissions, increases the EU's energy security, by enabling more energy generation without the need of fuel imports (The European Parliament and the Council of the European Union, 2019). 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).

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, due to renewable energy growth and promotion of energy generation decentralisation, which in turn will create more efficiency, whilst also increasing quality of service and, consequently, social well-being. (Caramizaru & Uihlein, 2019)

ECs, in particular, 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 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.

In this context, the main goal of this work is to perform an analysis of the impact of a widespread dissemination of P2P market-based ECs in the Portuguese energy system, at municipal and national level, for the decarbonization targets in 2050, assessing economic and environmental indicators.

Literature Review

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, both ECs and P2P markets are still relatively growing concepts and many of their studies have only been published in recent years.

Baroche et. al (Baroche et al., 2019) proposed a formulation to describe a decentralised P2P market without a limit to the number of community agents. The goal is to minimize the community's total cost, which is equal to the sum of each agent's individual cost. 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. This formulation was used as a base to design the P2P market in this work.

Long et. al (Long 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%.

Perger et al. (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, 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.

Finally, Nguyen et. al (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 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.

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 (which 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.

Methodology

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.

In this work, 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 potential of photovoltaic (PV) electricity generation was assessed, since it is the renewable technology with highest deployment potential at local level. The agents involved in the energy trading market were determined by demanding economic sectors, as residential, industry and services, considering each one as a member. 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).

The annual consumption data was retrieved from (DGEG, 2019) for the residential, industry and services sector. Since SFH and MAB display different electricity usage intensities, these were used, together with their floor area to compute their annual consumption. Then, each members' hourly energy consumption was calculated by multiplying annual consumptions by normalised load profiles.

The installed nominal power was computed based on the share of decentralized PV power in the electricity production sector, the annual consumption and the annual average capacity factor, which depends on the municipality's location. Since PV generation is mainly dependent on the rooftop area available for installation, for SFH and MAB it was calculated 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. Then, each members' hourly PV generation was calculated by multiplying the installed nominal power by the hourly power output representative of a 1 kW standard capacity, for the geographic location of each municipality.

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* (1) for each EC and each hour of the year, with energy exchanges as its components:

$$P[kWh] = \begin{bmatrix} 0 & p_{SFH/MAB} & p_{SFH/IND} & p_{SFH/TERC} & p_{SFH/GRID} \\ p_{MAB/SFH} & 0 & p_{MAB/IND} & p_{MAB/TERC} & p_{MAB/GRID} \\ p_{IND/SFH} & p_{IND/MAB} & 0 & p_{IND/TERC} & p_{IND/GRID} \\ p_{TERC/SFH} & p_{TERC/MAB} & p_{TERC/IND} & 0 & p_{TERC/GRID} \end{bmatrix} \quad (1)$$

Clustering was performed to aggregate municipalities with similar characteristics *a priori*, due to the high number of municipalities (278) and computing time for each. This way, *k*-means clustering was run in *Matlab*, using 9 variables. The first 4 (Annual PV Production for each member) differentiate municipalities when setting them apart by their solar electricity production potential, whereas the following 4 discern them by dividing each residential member's annual consumption (SFH or MAB) by industry and services' annual consumptions. These are meaningful, since the availabilities and needs of these sectors are the main drivers of energy exchanges. Finally, the last variable, the number of accommodations per MAB, aims at further distinguishing rural 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 capacity factor 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.

Case Study Definition

In order to operate the previously described model, datasets concerning electricity demand, solar PV electricity production, buildings' dimensions and electricity prices are needed. To estimate electricity demand, normalised load profiles and annual demand were retrieved from E-Redes (E-Redes, 2020) and DGEG (DGEG, 2019), respectively. Considering solar PV electricity, hourly power outputs and PV installed capacities were retrieved, from the Renewables Ninja (*Renewables.Ninja*, 2019). 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, 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. Both were obtained from ERSE (Entidade Reguladora dos Serviços Energéticos, 2020), and vary according to the voltage level, daily consumption periods and the year's trimesters.

The "selling-to-grid" price was indirectly retrieved from OMIE (OMIE, 2021), since that, according to the current legislation, it is independent of the selling agent and equal to 90% of the monthly OMIE average price. However, p^{OMIE} has had large fluctuations over the course of recent years and therefore, a sensitivity analysis is made to see how this variation affects the results, based on its values during 2020 and 2021.

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

To assess the energy community's performance three scenarios where designed. 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 into (2. 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 matrix in (3 represents the origin of consumed energy: the first column aggregates self-consumption of member *i*, whose energy can be generated, in this case, in member *i* or the remaining community members. The second column corresponds to the energy coming from the grid.

$$P_{PS}[kWh] = \begin{bmatrix} p_{SFH/grid} \\ p_{MAB/grid} \\ p_{industry/grid} \\ p_{services/grid} \end{bmatrix} \tag{2}$$

$$P_{CSC}[kWh] = \begin{bmatrix} p_{SFH/EC} & p_{SFH/grid} \\ p_{MAB/EC} & p_{MAB/grid} \\ p_{industry/EC} & p_{industry/grid} \\ p_{services/EC} & p_{services/grid} \end{bmatrix} \tag{3}$$

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.

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 trade 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 the methodology.

Results

In order to identify the number of clusters, a plot between the sums of the municipalities' distances to their centroids and the number of centroids was made (Figure 1). The elbow point of this plot occurs for 6 clusters and thus this became the number of clusters used for *k-means*.

The more industrialised municipalities compose **Cluster 1**, as seen in Figure 2, where its points, in black, have the highest values of annual PV production in industry. Also, in Figure 4, all points from Cluster 1 have a very low annual consumption ratio (SFH / Industry), 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 3 clarifies this statement, as its points, in red, have the largest annual PV production in MAB and services. 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 2 and Figure 3. It is composed by 22 municipalities.

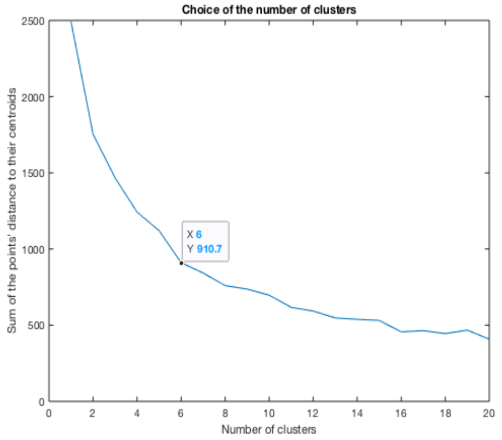


Figure 1 - Choice of the number of clusters

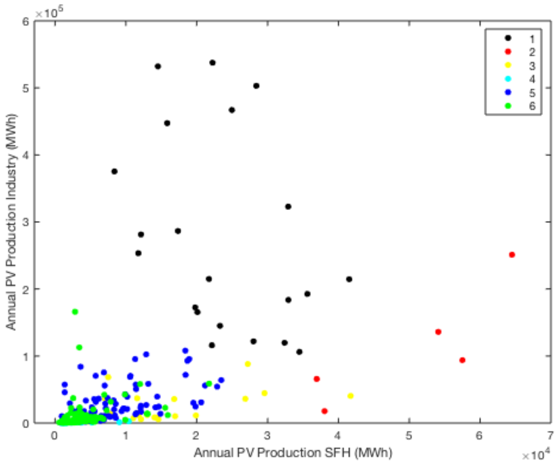


Figure 2 – Annual PV Production: SFH vs Industry

Cluster 4 groups the most rural municipalities (19), with their residential sectors mainly composed by SFH and almost no industry, as perceived in Figure 4, where its points, in light blue, have the largest annual consumption ratio (SFH / Industry), whereas in Figure 2 and Figure 3, 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 annual consumption ratio (SFH / Industry) in Figure 4). It is the largest cluster, with 118 municipalities.

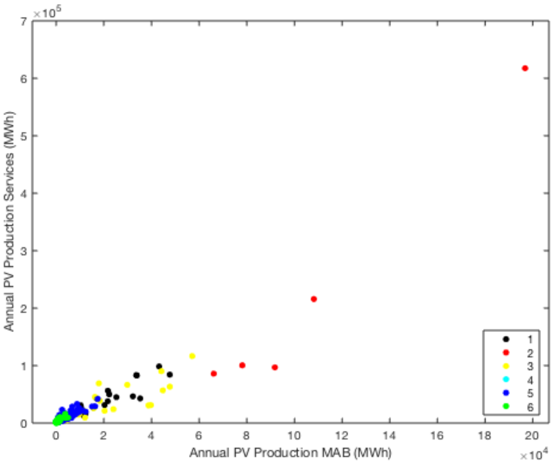


Figure 3 - Annual PV Production: MAB vs Services

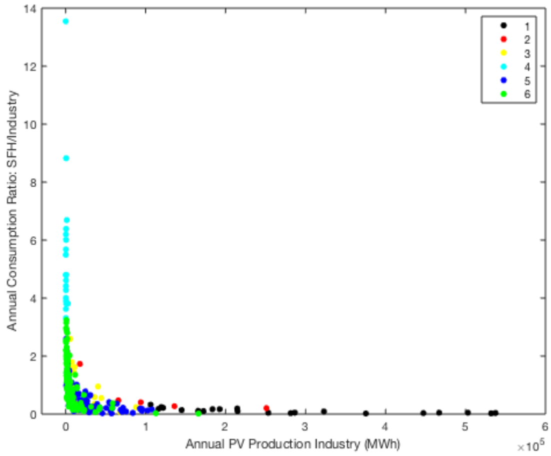


Figure 4 – Annual PV Production (Industry) vs Annual Consumption Ratio (SFH/Industry)

In the following figures detailed displays of results are made for Lisbon, followed by more succinct displays for other representative municipalities, which include graphic representations of energy consumption. 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”.

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.

Figure 5 and Figure 6 show Lisbon’s energy trades for PS and CSC, respectively. Appropriately, in PS, the grid only sells, whereas the members only buy. The size of the blue bridges indicates that the main buyers from the grid are the services (65.27%), followed by MAB (20.80%), which is a fitting result for this municipality, as a member of Cluster 2. The total grid consumption is equal to 3.423 TWh. In CSC, the main buyers from the grid are still the services (65.42%), followed by MAB (20.90%), but the total grid consumption has dropped to 2.487 TWh, due to self-consumption, represented in Figure 7.

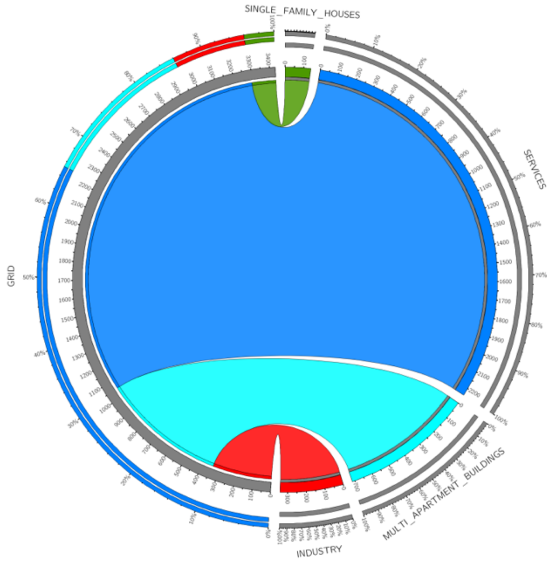


Figure 5 - Energy Consumption for Lisbon (GWh) - Present Scenario

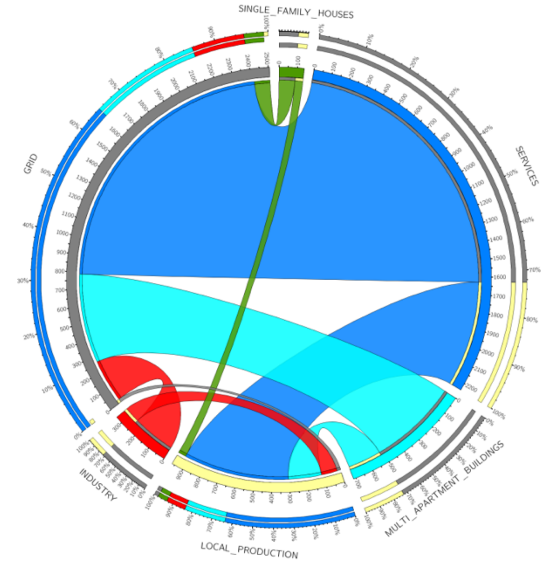


Figure 6 - Energy Consumption (GWh) for Lisbon - Collective Consumption Scenario

In P2P, Figure 8 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 consumption sums for a total of 2.487 TWh. In this plot, self-sufficiency has slightly decreased in comparison with CSC, as expected, since the energy received from peers is accounted in self-consumption in the CSC.

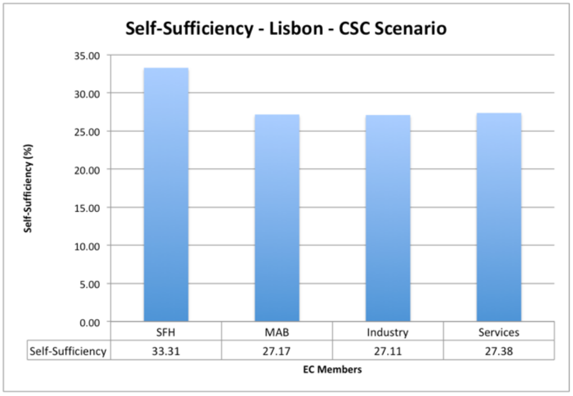


Figure 7 - Self-sufficiency in Lisbon – CSC Scenario

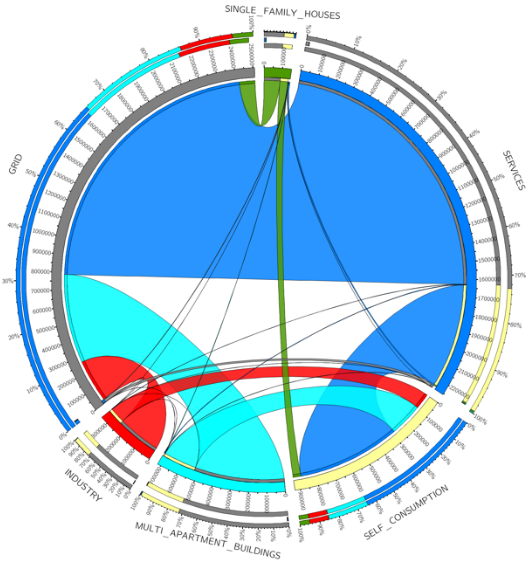


Figure 8 - Energy Consumption (GWh) for Lisbon – P2P Scenario

To better understand P2P trading tendencies, Figure 9 displays the same results, 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. 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.

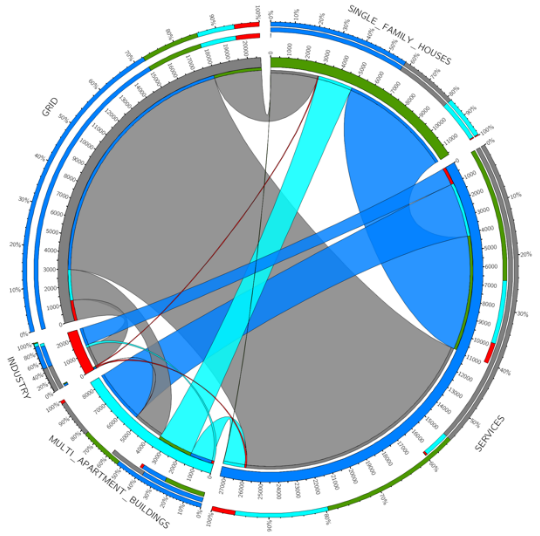


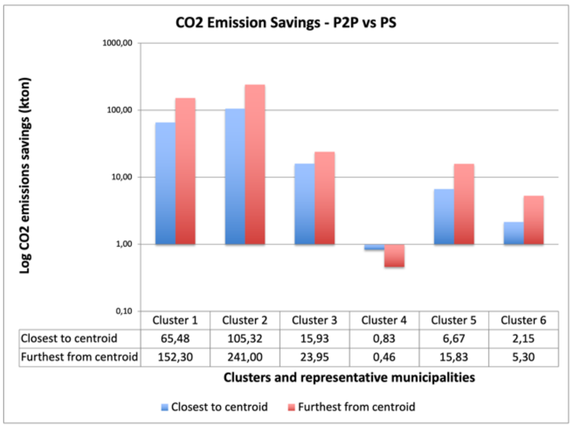
Figure 9 - Energy Consumption (MWh) for Lisbon (no grid purchases) - P2P Scenario

Table 1 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 is paid, which is lower than the average of what would have been paid to the grid. Highlighted in grey 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), 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. No trading occurs between SFH and MAB, while the services get the best P2P price from SFH.

Table 1 - Purchase Prices – Lisbon P2P

	Avg	Grid	Avg	Grid	Avg	Grid	Avg	Grid
€/MWh	SFH		MAB		Industry		Services	
SFH	-	-	-	-	61.9	61.9	61.9	61.9
MAB	56.5	61.9	-	-	35.8	61.9	35.9	61.9
Industry	42.5	46.5	35.8	47.0	-	-	35.8	47.2
Services	69.1	70.3	69.7	71.2	71.1	74.6	-	-

A comparison between scenarios for each representative municipality is shown from Figure 10 to Figure 13.



	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 10 - CO2 emission savings P2P – PS

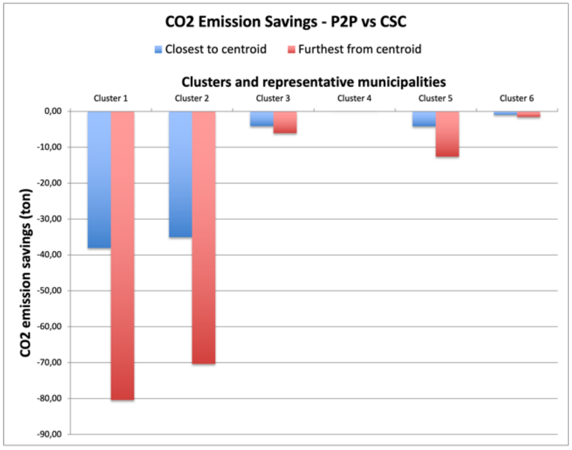
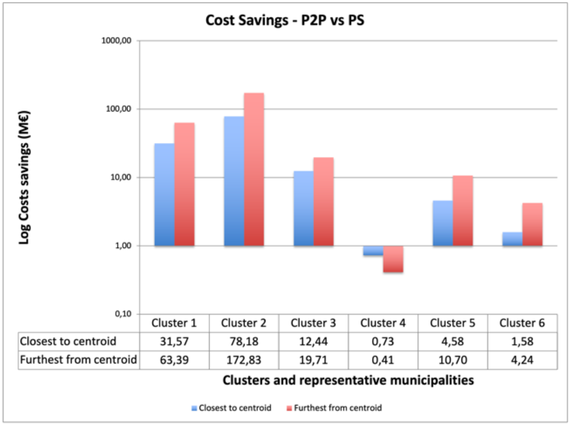
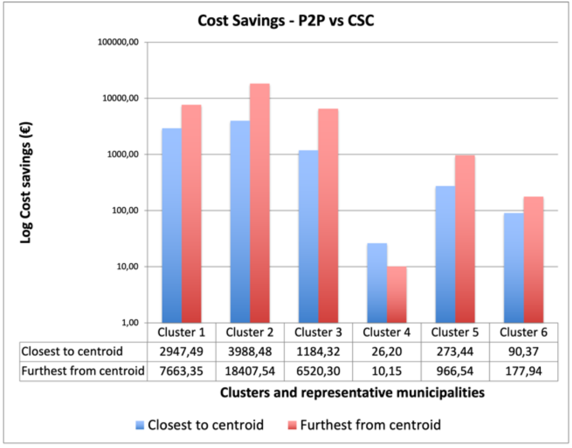


Figure 11 - CO2 emission savings P2P – CSC



	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 12 - Cost savings P2P – PS



	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 13 – Cost savings P2P – CSC

Starting with CO_2 emissions, the P2P scenario, in contrast with the PS scenario, reaches reductions ranging from hundreds of kton to hundreds of ton. Figure 10 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 11). 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.

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 12. 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.

Contrarily to emissions, Figure 13 shows P2P costs savings, compared to CSC. Even though CSC maximizes the production's utilization, this scenario does not minimize costs for all its members. 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.

The results in Table 2 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 2- 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 2, 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 largest municipalities.

The OMIE price sensitivity analysis, performed with the 2020 average monthly prices for p^{OMIE}, shows some differences. In Figure 14, 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.

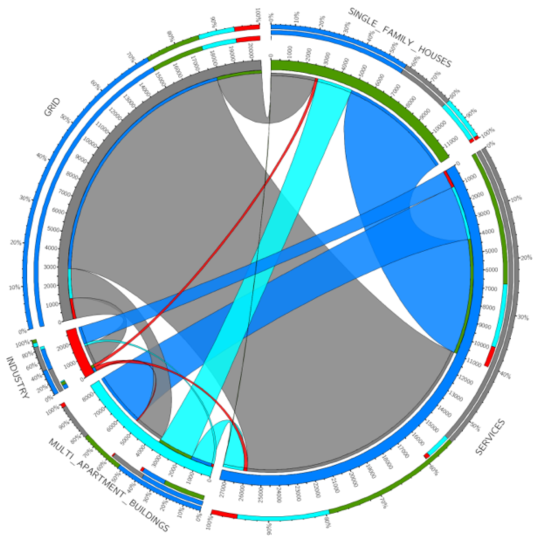


Figure 14 - Energy Consumption (MWh) for Lisbon (no grid purchases) - P2P with 2020 values for p^{OMIE}

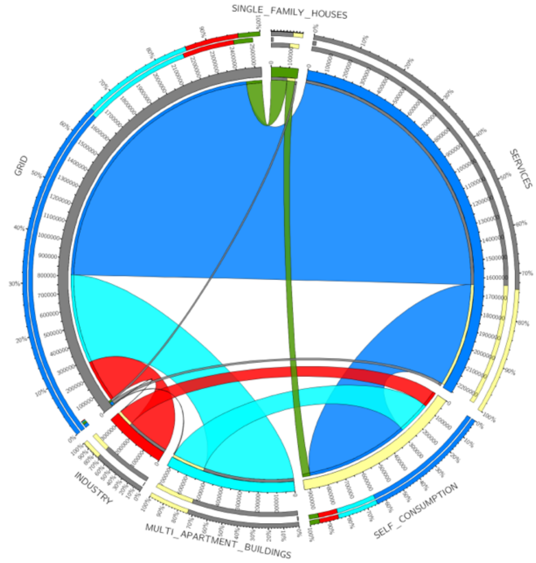


Figure 15 - Energy Consumption (MWh) for Lisbon) - P2P with 2021 values for p^{OMIE}

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.
Using data based on record prices, from September 2021, the results show that it is always more convenient for members to sell to grid, to a point where no P2P trades occur – Figure 15. 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.

Conclusions

In this work, 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. 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.

At national level, it was estimated that, nationally, 3141.35 kton of CO_2 would be avoided and 1954.07M€ would be saved, 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 and 0.14 M€ in savings, comparing 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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