# Alleviation of precarious access to electricity through decentralised electricity market design

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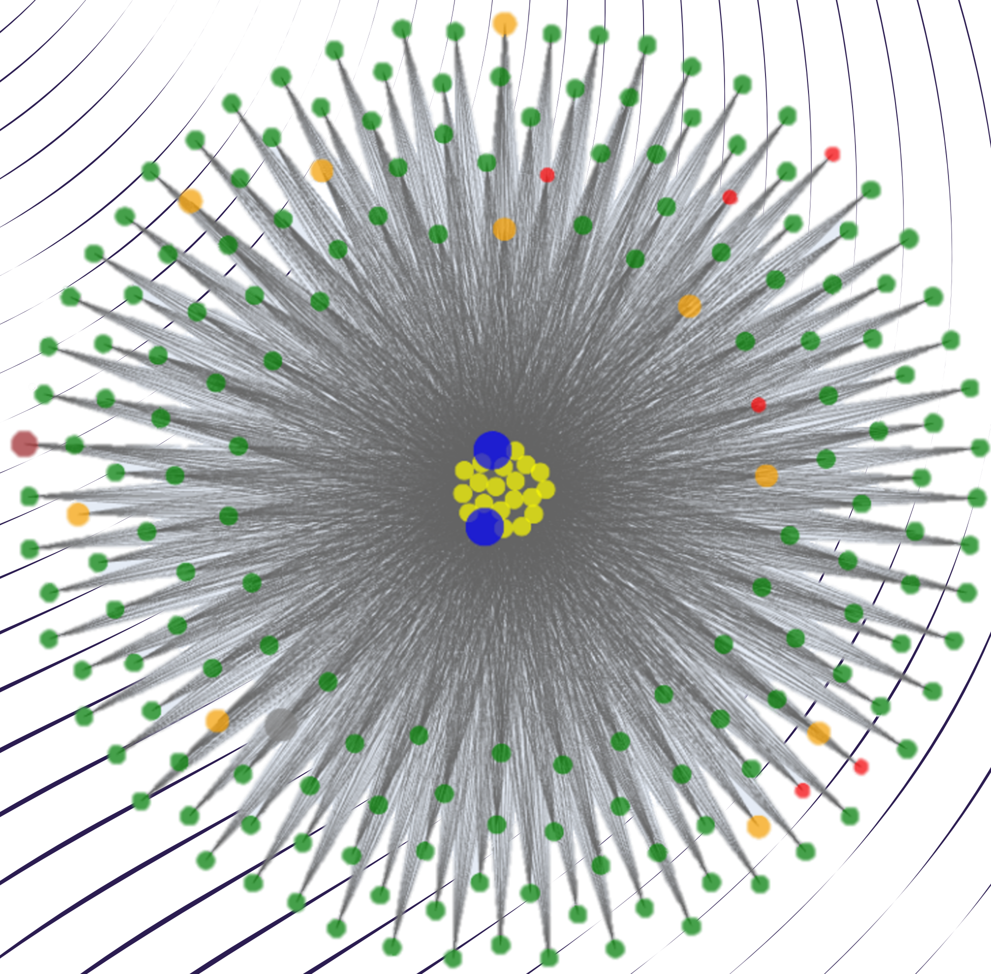
Sustainable Energy Planning and Management, June 2021

Master's Thesis



STUDENT REPORT

AALBORG UNIVERSITY

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**Title:**
Alleviation of precarious access to electricity through decentralised electricity market design

**Project:**
Masters' Thesis

**Project Period:**
February 2021 - June 2021

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**Page count:** 101

**Appendices:** 1

**Finished:** 03/06/2021

**Abstract:**

Precarious access to electricity is one of the possible manifestations of Energy Poverty and is still a live issue in regions such as the EU. In parallel, emerging decentralised markets are set to have a crucial role in the future of the electricity sector. This opens a window of opportunity to investigate how can these markets be designed to internalise the costs of alleviating precarious access to electricity.

A methodology is proposed to calculate a minimum decent consumption and affordable electricity prices for low-income households, depending on the household's characteristics. Moreover, two methods are presented to internalise the cost of guaranteeing affordable electricity to those more vulnerable. First, an Energy Poverty tariff, set to be paid for those agents in a better position in the market. Second, a Price Intervention scheme, where the price of trades between large producers and low-income households is fixed.

Results from the Case Study analysis show that, although it is noticeably dependent on the characteristics of the market agent sample and architecture, the cost of the needed support can be internalised without an excessive impact on the rest of the agents' welfare. How the distribution of costs of the needed support is done should be tailored to each specific case.

# Preface

This Master's Thesis has been done as a culmination of the Master's Programme in Urban, Energy and Environmental Planning with specialisation in Sustainable Energy Planning and Management at Aalborg University, Denmark.

The two authors would like to acknowledge Steffen Nielsen for his help and feedback as a project supervisor, especially under the conditions that the Covid-19 pandemic imposed.

The acknowledgement wants to be extended to the rest of the professors of the Master Programme, fellow students, friends and family that provided support during this sometimes challenging but exciting journey.

# Summary

This Thesis proposes a methodology to calculate a minimum decent consumption and affordable electricity prices for vulnerable households, as well as two methods to internalise the cost of alleviating precarious access to electricity in decentralized markets. This is done as precarious access to electricity is identified as a live and relevant issue that affects regions such as the EU, and that emerging decentralized electricity markets are set to play an important role in the future of the electricity sector.

The proposed solutions to tackle precarious access to electricity are built using the principles of Social and Solidarity Economy, where social objectives are prioritized over profit gain, while accounting for the possibilities that Sharing Economy brings to the table in terms of how goods and services such as electricity can be exchanged. Using Innovative Democracy theory, it is identified that direct market design can be used to reach societal goals such as ensuring affordable and sufficient electricity for everyone.

In order to design the above-mentioned support schemes, and with Electricity Market Design theory as background knowledge, a decentralized electricity market base model developed by Moret [2020] is presented. How agents are modelled using supply and demand curves is described, as well as how different market architectures can be represented making use of partner matrices and virtual agents. Moreover, it is explained how the negotiation algorithm is modelled through an objective function that aims to maximize consumers satisfaction and producers profits while minimising production and trade costs.

Once the model is described, modifications to reach this Thesis' objectives are included. First, a new way of modelling low-income households is designed so as to then ensure that they receive affordable prices for a decent threshold of electricity consumption. The minimum consumption is calculated by setting a Minimum Standard Consumption and then accounting for the specific characteristics of the household: its efficiency, members, whether electric heating is used and whether mechanical support through vital medical devices is required. Moreover, their expenditure on electricity is limited to a certain share of their income, which ensures an affordable price.

With the appropriate modelling of low-income households, the support mechanisms are designed. The first one is an Energy Poverty (EP) tariff, which redistributes social welfare within the electricity market. Net consumers are to pay a tariff according to the amount of money that they could give up while staying within their budget, whereas net producers pay proportionally to their net earnings. As a result, vulnerable households receive a customized subsidy. The second designed mechanism is Price Intervention, which fixes the prices at which low-income households buy electricity from large producers in a way that they can afford to pay for their electricity bill while having a decent consumption. In this case, the producers pay for the whole needed support and do it proportionally to their net earnings.

To obtain relevant results on how the proposed methodologies perform, a Case Study is built. First, a base market agents sample is analysed under three different market architectures without the implementation of energy poverty alleviation mechanisms, so as to have a reference on how does the system behave. Then, the proposed schemes are tested, observing what are their main differences and identifying how they operate under the different market architectures. Finally, variations to the base market agents sample are done by changing the number of low-income households and Renewable Energy (RE) share of the system, which is useful to assess the sensitivity of the support schemes.

Results from the Case Study show that in most cases both schemes can be used to internalize the costs of alleviating precarious access to electricity without this having an excessive impact on market agents' welfare. However, when increasing the number of low-income households or when increasing the applicable tariffs on trades there can be cases where the total needed support cannot be paid by market agents and thus has to be externalized. When increasing the share of RE, prices tend to be lower, alleviating the issue but also reducing the net earnings from producers, which are important support contributors. This shows that the contribution that each market agent type has on financing the support scheme should be adjusted to each scenario. When comparing both schemes, the EP tariff seems to be a more viable option due to its flexibility potential, although Price Intervention is also attractive in cases where producers have higher net earnings.

This Thesis also discusses the accuracy of the model used and how it affects the obtained results, the design choices of the methodologies proposed and the relevance of the results obtained given the assumptions made. In addition, a reflection is made on whether internalising costs is a good idea, on how could the methodologies be implemented and what barriers could be encountered in the process. Finally, a perspective on the issue of precarious access to electricity in the future is given.

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# Problem Analysis 1

## 1.1 The concept of energy poverty

According to United Nation's former Secretary-General Ban Ki-moon: *"Energy is the golden thread that connects economic growth, social equity and sustainable development"* [UN, 2012]. Numerous literature has also widely shown the importance of energy as an enabler of human development [Koomanoff, 1992] and, in fact, ensuring access to affordable and clean energy for all has been set as UN Sustainable Development Goal number 7 [UN, 2015].

The lack of access to energy is a relevant issue especially in developing countries, with about 1.2 billion people still in 2017 lacking access to electricity and 40% of the world population not having access to clean cooking fuels [UNDP, 2017]. The inability to have enough energy to satisfy basic needs is known as "energy poverty" or "fuel poverty".

Energy poverty embeds a multi-layered and complex issue. It can be defined as the situation in which a household is unable to access essential energy services, such as adequate warmth, cooling, lighting, and/or energy to power basic appliances to guarantee a decent standard of living and health [EPOV, 2020a]. In developed countries, despite having more resources, energy poverty is also present due to the existing and growing economic inequality.

In this context, energy poverty can be explained as a combination of different factors such as specific conditions due to geographic location, high energy prices, low income, and the quality and efficiency of dwellings, as can be seen in Figure 1.1 [Castaño-Rosa et al., 2020].

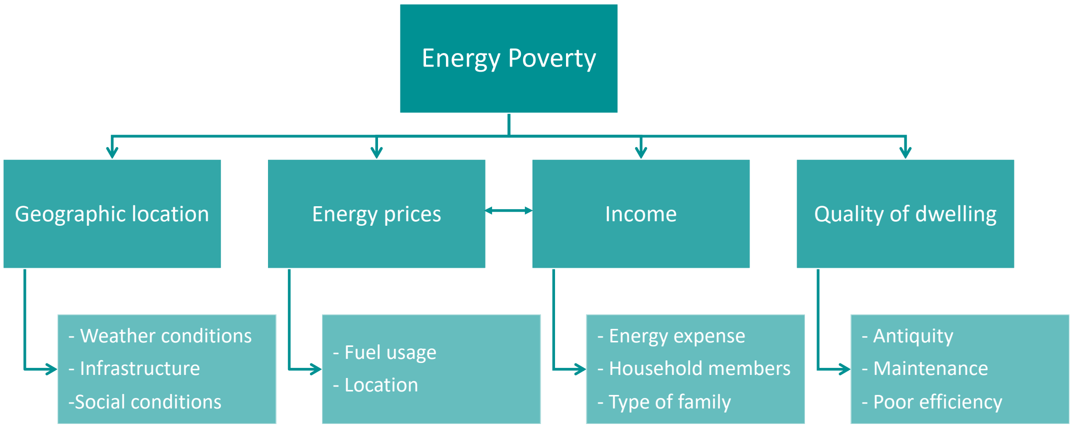



Figure 1.1: Energy poverty definition. Based on [Castaño-Rosa et al., 2020], own elaboration.

The geographic location of a household has a relevant influence on the energy needs and the ability to satisfy them due to weather conditions, available infrastructure, and social conditions of the neighbourhood. Having an understanding of the characteristics of a specific location is crucial in order to identify households with energy poverty, as in different areas different amounts of energy might be required to satisfy a basic need.

Another aspect influencing energy poverty are energy prices, which depend on the type of supply technology, its usage, and are also linked to geographic location. Parallel to them, it is also crucial to consider the affordability of energy. Knowing what is the household's income and comparing it to the energy prices to be paid gives a good picture of the situation of energy poverty. However, the share of income that a household spends on energy can not be the sole indicator of energy poverty, since there could be households that prioritise other needs over their energetic ones. A dimension of this issue is what is known as the "heat or eat" dilemma, where households undergo inadequate temperatures so that they can afford food [Lambie-Mumford and Snell, 2015]. This particular issue shows the difficulty of measuring energy poverty since there are many complex dimensions at play simultaneously. Moreover, the characteristics of each household need to be taken into account, such as the number of members in it and whether there are elders and/or children.

Finally, it is important to consider the quality of the dwelling. If the dwelling is old and poorly maintained a higher amount of energy is most likely required to satisfy basic needs, especially heating. Therefore, improving the efficiency and quality of the dwellings can represent a decrease in the need for energy, alleviating energy poverty.

Due to the multi-dimensional reality of energy poverty the consequences that it has on the health and well-being of citizens are also diverse. Studies show how illness related to low temperatures appear in those countries with a higher share of energy poverty, resulting in a higher mortality rate [Recalde et al., 2019]. Moreover, other issues might affect citizens such as stress associated with paying the energy bills or experiencing impromptus blackouts, resulting in lower living standards [EPOV, 2020a].

## 1.2 Current situation in the European Union

As energy poverty is a complex issue, it is difficult to assess the extent in which it affects a diverse region such as the European Union. However, to help visualize and identify where and how energy poverty is present, there exist several indicators which have been reviewed, analysed and expanded in metrology literature such as [Castaño-Rosa et al., 2019], [Trinomics, 2016] or [Sareen et al., 2020].

In 2020, the EU commission established some recommendations to the Member States as to how to approach energy poverty [European Commission, 2020] and specified its own list of indicators. The list included: the share of the population at risk of poverty (those individuals with a disposable income below 60% of the median); the share of the population claiming not being able to keep their home adequately warm; the share of population with arrears on utility bills; or the share of households whose absolute energy expenditure is below half the national median. Moreover, other complementary indicators were suggested such as electricity prices for consumers, population with leak or rot in their dwelling, or energy consumption per squared meter, among others. Due to the multi-dimensional aspect of energy poverty, it is recommended to use multiple indicators at the same time.

The Energy Poverty Observatory [EPOV, 2020a] collects data on some of the aforementioned indicators, making use of surveys such as EUR-SILC and HBS as well as other European data sets. As they are representative indicators, Figures 1.2 and 1.3 represent arrears on utility bills and low absolute energy expenditure in combination with the inability to keep the house warm for the different EU countries.

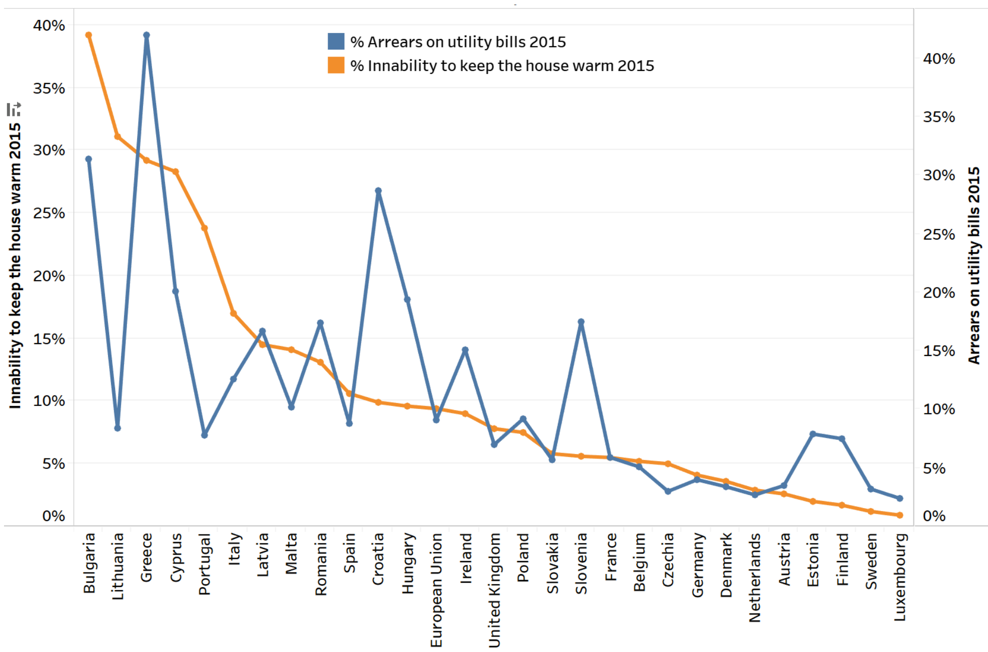



Figure 1.2: Inability to keep the house warm vs arrears on paying utility bills (including heat, electricity and water). Data from EU Energy Poverty Observatory [EPOV, 2020a], own elaboration.

Figure 1.2 allows identifying those countries with a higher impact of energy poverty, hence when both represented indicators are high. As it can be seen, Bulgaria has the highest percentage of citizens unable to keep their house warm at 39.2%, followed by Lithuania, Greece and Cyprus while Greece (42%), Bulgaria and Croatia have the highest share of arrears on utility bills. It is worth mentioning that the weight of the expenditure on electricity with respect to the total energy bills of an average EU household in 2015 was of 40%, while it was of 45% for fuels for heat and cooking, and 15% for water supply [EUROSTAT, 2020a].

Both indicators' curves follow a similar trend, showing that in most of the cases those citizens unable to keep their houses warm have also arrears on utility bills. There are though exceptions as Lithuania and Portugal, with a significantly lower percentage on arrears than lack of warmth, or Croatia and Greece, that are in the opposite situation. These differences in prioritising keeping the house warm or not having arrears on utility bills between countries could be related to stricter/laxer regulation on payments and/or behavioural habits [EPOV, 2020b].

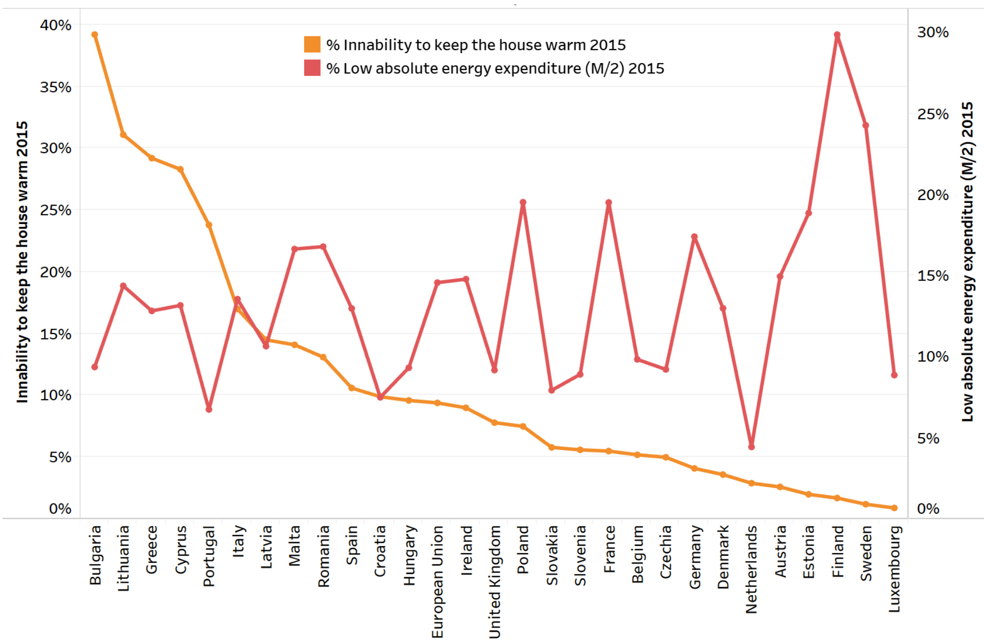



Figure 1.3: Inability to keep the house warm vs low absolute energy expenditure (M/2). Data from EU Energy Poverty Observatory [EPOV, 2020a], own elaboration.

In Figure 1.3, the inability to keep the house warm indicator can be seen in comparison with the percentage of low absolute energy expenditure (M/2). This is defined as the share of households whose energy expenditure is below half the national median and therefore can capture to a certain degree the inequalities within a country. Comparing the two indicators is useful to illustrate if energy poverty affects a country in a homogeneous way or not, and to which extent.

For instance, Luxembourg and Bulgaria have similar M/2 values at around 10%, despite being at extreme opposites on the percentage of houses without climatic comfort. Therefore, despite both countries having a similar distribution of energy expenditure, in Luxembourg those in the low end have no problem keeping their houses warm whether in Bulgaria even those with an average expenditure have not enough warmth. On the other hand, if we compare Bulgaria with Lithuania we can observe how, while both countries have a similar percentage of households without enough heat, in Bulgaria there is a lower inequality, hence energy poverty affects in a more homogeneous way.

From observing these figures it can be seen how the usage of indicators must be done in combination to get a full picture of a countries situation. Moreover, they show how energy poverty is a relevant issue within the EU, and that affects different countries in different degrees.

## 1.3 EU's approach

The issue of energy poverty within the European Union has been gaining relevancy in recent years. In 2018, the Commission launched the Energy Poverty Observatory [EPOV, 2020a], whose aim was to provide information regarding this issue to decision-makers at all levels of governance, promote public engagement on tackling energy poverty, and diffusion of good practices among stakeholders. Its first phase finished in 2020 and provided extensive reports on the current situation of energy poverty in the different member states, as well as information on how the different countries are attempting to alleviate the issue.

The concept of energy poverty also appeared in the Clean Energy for all European package [European Commission, 2019], whose goal is to facilitate the transition away from fossil fuels towards cleaner energy, fulfilling the goals agreed upon in the Paris Agreement. While doing so, it places emphasis on leaving no member state or individual behind, hence avoiding that existing inequalities are accentuated. In the package, the commission classified energy poverty as a "*major challenge*" and stated that "*lifting vulnerable citizens out of it is an urgent task for the EU and its members*", making the task a "*policy priority*" [European Commission, 2019]. Energy poverty is treated in more detail in the Energy Efficiency Directive [Council of the European Union, 2018a], the Energy Performance on Buildings Directive, Electricity Directive [Council of the European Union, 2019] and the Renewable Energy Directive [Council of the European Union, 2018b] [STEP, 2019].

After publishing the Directives, the commission launched a recommendation on energy poverty in October 2020 [European Commission, 2020]. The document first defined energy poverty as a major challenge for the EU, as nearly 34 million Europeans were unable to keep their home warm in 2018. Secondly, it left to Member States *"develop their own criteria according to their national context"* as no standard definition of energy poverty exists, even though some indicators to measure energy poverty were recommended, as presented in Section 1.2. Moreover, it urged the Member States to develop policies to tackle energy poverty on the basis of public participation and cooperation between administrations. Finally, it recommended developing a systematic approach to the liberalisation of energy markets, ensuring that the shared benefits with all members of society, especially those more vulnerable.

### 1.3.1 Measures to alleviate energy poverty

Currently, all the EU Member States have specific policies to alleviate energy poverty, to a greater or lesser extent following the guidelines laid down by the European Commission. The Energy Poverty Observatory has gathered all existing policies and measures related to energy policy and classified them by country, type of measure or organisational level responsible among others. Moreover, in their most recent report [EPOV, 2020b] key indicators of energy poverty in each member state are presented, as well as the most relevant policies implemented. In Table 1.1 a summary on what are the focus of these main measures per country is shown.

| | Building insulation | Disc. protect. | Energy audits | Bill support | Heating system | Household appliances | Info. | Renewable Energy | Social support | Social tariff | TOTAL measures |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **AT** | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 13 |
| **BE** | ✓✓✓ | ✓ | ✓ | | ✓ | | | | ✓ | ✓ | 36 |
| **BG** | ✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | 11 |
| **HR** | ✓✓✓ | | ✓ | ✓✓ | ✓ | | ✓ | | ✓✓✓ | | 13 |
| **CY** | ✓ | ✓ | ✓ | | ✓ | ✓ | | ✓ | | ✓ | 10 |
| **CZ** | ✓ | | ✓ | | ✓✓ | | ✓ | ✓✓ | ✓✓ | | 12 |
| **DK** | ✓✓ | | ✓ | ✓ | ✓ | | ✓ | | ✓ | | 9 |
| **EE** | ✓ | ✓ | ✓ | | ✓ | | | ✓✓ | ✓ | | 6 |
| **FI** | ✓ | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | 7 |
| **FR** | ✓✓✓ | ✓ | ✓✓ | ✓ | ✓✓✓ | ✓✓✓ | ✓✓ | | | | 32 |
| **DE** | ✓ | ✓✓✓ | ✓ | ✓ | ✓ | ✓ | ✓✓ | | ✓ | ✓ | 21 |
| **EL** | ✓✓ | | | ✓ | ✓✓✓ | | ✓ | ✓ | | ✓✓ | 12 |
| **HU** | ✓ | ✓ | | | ✓ | | | ✓ | | | 6 |
| **IE** | ✓✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | | | 18 |
| **IT** | ✓✓✓ | ✓ | | ✓✓ | ✓✓✓ | ✓ | ✓ | ✓ | | | 17 |
| **LV** | ✓ | | | ✓ | ✓ | | ✓ | | ✓ | | 7 |
| **LT** | ✓ | | | ✓ | ✓ | | ✓ | | | | 6 |
| **LU** | ✓ | | | | ✓ | | ✓✓✓ | ✓ | ✓ | | 9 |
| **MT** | ✓ | | ✓ | ✓ | ✓ | ✓ | ✓✓ | ✓ | | | 6 |
| **NL** | ✓ | ✓ | ✓✓ | ✓✓ | ✓ | ✓✓ | ✓ | ✓ | | | 13 |
| **PL** | ✓ | | | ✓ | ✓ | | ✓ | ✓ | ✓ | | 9 |
| **PT** | ✓ | | | | ✓ | ✓ | ✓ | ✓ | | ✓ | 4 |
| **RO** | ✓✓ | ✓ | ✓ | ✓ | ✓✓✓ | | ✓ | | ✓ | ✓ | 9 |
| **SK** | ✓✓✓ | | | | ✓✓✓ | | ✓ | ✓✓✓ | ✓ | | 8 |
| **SI** | ✓ | ✓ | | ✓ | ✓✓✓ | ✓ | ✓ | | ✓✓✓ | | 12 |
| **ES** | ✓✓✓ | ✓ | | ✓ | ✓✓ | | ✓ | ✓ | | | 17 |
| **SE** | ✓ | ✓ | | | ✓ | | ✓✓ | ✓ | ✓✓✓ | | 12 |
| **UK** | ✓✓✓ | | ✓ | ✓✓✓ | ✓✓✓ | ✓ | ✓✓ | | ✓ | | 35 |
| **TOTAL measures** | **98** | **31** | **51** | **38** | **99** | **28** | **61** | **46** | **30** | **11** | **301** |

Table 1.1: Table showing existing measures and policies regarding energy poverty by country and type. One check-mark (✓) indicates measures that involve one level of governance, two check-marks two or three levels, and three check-marks four or more levels. National, regional and local are the main levels of governance at which measures are implemented. Based on [EPOV, 2020b].

As seen in Table 1.1, actions adopted by the governments encompass a wide range of measure types. It includes measures focusing on the heating dimension of energy poverty, such as policies to facilitate insulation in buildings or to improve the existing heating systems. There are other measures focusing more on the electricity supply, such as protection against disconnection or renovation of household appliances to increase efficiency.

An example of measure focusing on electricity is proving households with smart meters that only allow the power supply to be reduced down to 1000W in case of non-payment, instead of disconnection, as it happens in Cologne, Germany. Moreover, there are other measures that can be designed to tackle both the electricity and heat dimension of the issue, such as bill support, social tariffs or the promotion of renewable energy, which are often financed by taxes. Examples of these are limiting electricity bills for low-income households to a certain percentage of their income, setting price caps, providing financial assistance in terms of vouchers or tax exemptions, or guaranteeing a minimum consumption free of charge for those in need. In addition, some measures such as social support focus on a more general aspect of poverty, such as the guaranteed minimum income, established in countries as Luxembourg. Finally, there are measures focused on spreading awareness and knowledge such as performing energy audits or information campaigns.

Observing the trend per countries, it can be seen how the total number of measures adopted varies largely among the Member States, with the most proactive countries being Belgium, France and the United Kingdom. However, if wanting to identify where current measures are not sufficient and should be reinforced, it is not only important to consider the number of measures adopted, but also the nature of each measure and the magnitude of the issue of energy poverty in each country.

Analysing Table 1.1 per type of measure, it can be seen how all Member States have policies to facilitate insulation in buildings and to improve the existing heating systems. These types of measures are followed by those regarding information and awareness since usually they have a low cost and are easy to apply. There is also a relevant focus of Member States on facilitating the integration of renewable energy as a mean to alleviate energy poverty, with around half of the countries having some measures of this type. Measures regarding disconnection protection, bill support, household appliances or social support have a lesser focus. Finally, there exist very few measures regarding the implementation of social tariffs. The numbers show how the trend within the EU is to focus more on the heating dimension of energy poverty rather than on the electricity supply, while also promoting social awareness of the issue.

On top of the main policies of each country, there are also multiple pilot projects, especially on the local and regional level. Gangale and Mengolini [2019] review existing pilot projects where innovative energy policies are adopted. Innovative projects are classified into four groups, being: digital technologies, behavioural change, financing and sharing of best practices. Many of them are focused on giving vulnerable consumers tools to fight against energy poverty, mostly through information. Other than direct support to vulnerable consumers, these innovative projects also include new ways on how energy can be exchanged, such as the Mieterstrom-Modell in Germany, which facilitates the inclusion of energy communities as a mechanism to reduce the energy bill for those more vulnerable. Moreover, in ENGAGER [2018] it is concluded that grassroots innovation and participatory approaches have shown success in alleviating energy poverty.

## 1.4 A particular issue: precarious access to electricity

One of the ways in which energy poverty can be manifested is as precarious access to electricity, which prevents households from using modern commodities above a certain threshold and with certain quality and safety standards. When being in this situation, households face difficulties in powering basic appliances and having enough lighting to guarantee a decent standard of living [EPOV, 2020a].

It is worth mentioning that while around 10.43% of the world's population still remains without access to electricity, in the EU statistics show that almost all inhabitants do have access to this form of energy [OurWorldInData, 2018]. Therefore, in this particular region the problem of electricity access is mostly due to the quality of it rather than not having access at all. Nevertheless, it constitutes an issue that the EU Member States are tackling with different measures, as observed in section 1.3.1 above.

Effects of precarious access to electricity can be made visible to the public eye in extreme situations. An example would be disconnections to the grid in periods of vulnerability which can force people to rely on cheaper and more hazardous sources of energy – for instance, substituting light bulbs with candles (as seen in Figure 1.4) or electric heaters by gas or wood ones – and as a consequence suffer fatal accidents, see [BBC, 2016].

Moreover, precarious access to electricity can bring as a consequence illegal connections to the grid, which might be a safety hazard, impact the stability of the grid and the bulk of the consumers' electricity price. In fact, illegal connections account for the majority of non-technical grid losses in the EU [CIRED, 2017]. Energy poverty and precarious access to electricity is a live problem in the EU, and especially affects low-income households in the most vulnerable moments when the demand is higher. Particular examples of how energy poverty has in recent years been a problem can be found in Spain [The Guardian, 2021] , Portugal [Politico, 2021], Greece [Reuters, 2017], Romania [Politico, 2019] or Bulgaria [Euractiv, 2013].

Figure 1.4: Example of situation where precarious access to electricity is manifested [Xarxanet, 2021]

It has been found difficult to quantify precarious access to electricity. In fact, at the moment specially dedicated indicators to observe issue have not yet been implemented in the EU. Nevertheless, its effect is accounted in indicators such as the share of the population having arrears on utility bills, which also include those bills for heating, gas or water. In 2007 7.3% of the EU population had arrears on utility bills, a percentage that increased during and after the financial crisis of 2009 up to 10.2 %. Finally, arrears decreased to 6.6% in 2018 [EPOV, 2020a]. Following the same trend as in the past, a similar increase in arrears due to the Covid-19 crisis can be expected [European Commission, 2021].

### 1.4.1 Affordability of electricity

One of the ways in which precarious access to electricity is accentuated is with the increase of the price of electricity and when, in comparison, household purchasing power is reduced, hence reducing the affordability of electricity. In the EU, electricity prices including taxes and adjusted to inflation from 2008 to 2019 increased 23% [EUROSTAT, 2020a], mainly due to the increased weight of taxes in the total price [EUROSTAT, 2020b]. However, during the same period, the average first quintile purchasing power (threshold of income under which 20% of the population is situated) has only increased by 18% [EUROSTAT, 2020a], hence being noticeably lower than the increment of electricity prices. This shows the live nature of this issue, which has been aggravated in 2020 by the Covid-19 pandemic and its associated economic crisis [European Commission, 2021]. In addition, and although appliances are now more efficient than ever before, during the last decade electricity needs to ensure decent standards of living have increased with new technological developments, especially for communication and information access, which further stresses the need for action to alleviate this issue.

To observe how the issue of affordability of electricity is present among the Member States, a box and whisker plot has been created representing the range of expenditures on electricity as a percentage of income. The result is Figure 1.5.

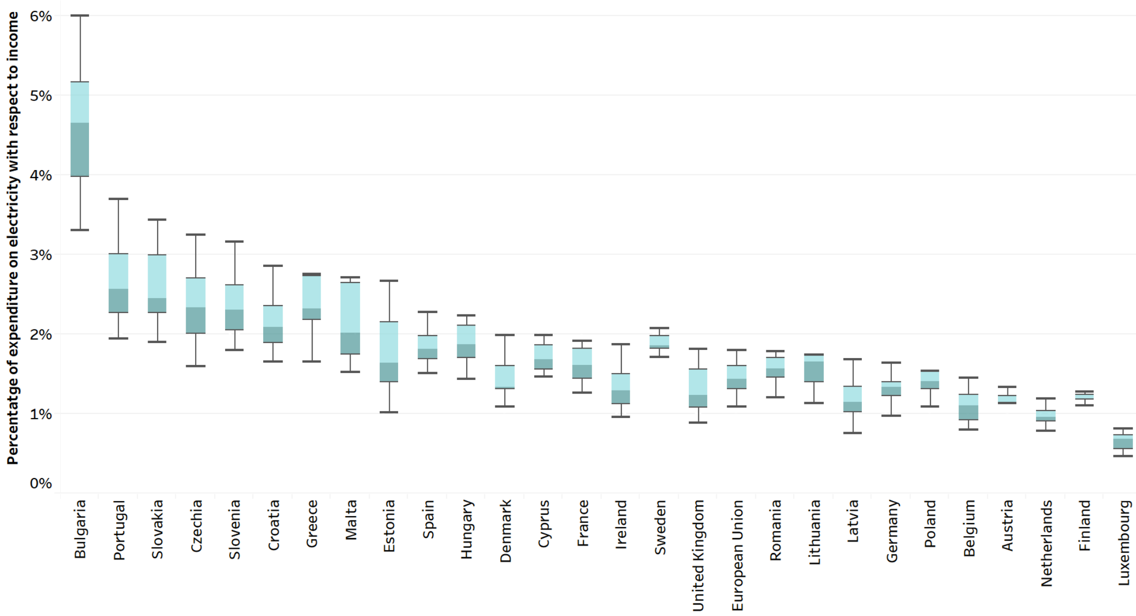



Figure 1.5: Expenditure on electricity as percentage of quintiled income, ordered by expenditure of electricity by consumers in the first income percentile in 2018. Data from EUROSTAT [2020a], own elaboration.

In Figure 1.5, countries are ordered regarding the upper value of each box plot, which depicts the expenditure on electricity of those consumers that have an income in the first quintile of the total country's distribution, therefore those that can be considered the most vulnerable ones. The higher this value is, the higher the burden of electricity expenditures is for low-income households. As it can be seen, this especially happens in Bulgaria, Portugal, Slovakia and Czechia.

The rest of the marks in each box plot represent, by order, the percentage of expenditures on electricity of those consumers in the range of second, third, fourth and fifth quintile of income. With those, inequalities within a country can be identified. The longer the length of each country's box plot is, the more difference there is between what low and high-income households spent on electricity, which mostly happens for countries with higher percentages of expenditure, like Bulgaria, Portugal, Czechia or Estonia. Large inequalities can be the result of big differences in income, high electricity prices for those consumers in the low range of consumption or, for instance, high consumption of low-income households due to the lack of energy-efficient appliances.

To illustrate one of the possible causes for inequalities, the extent to which electricity prices are high in relation to the income perceived by low-income households is represented in Figure 1.6.

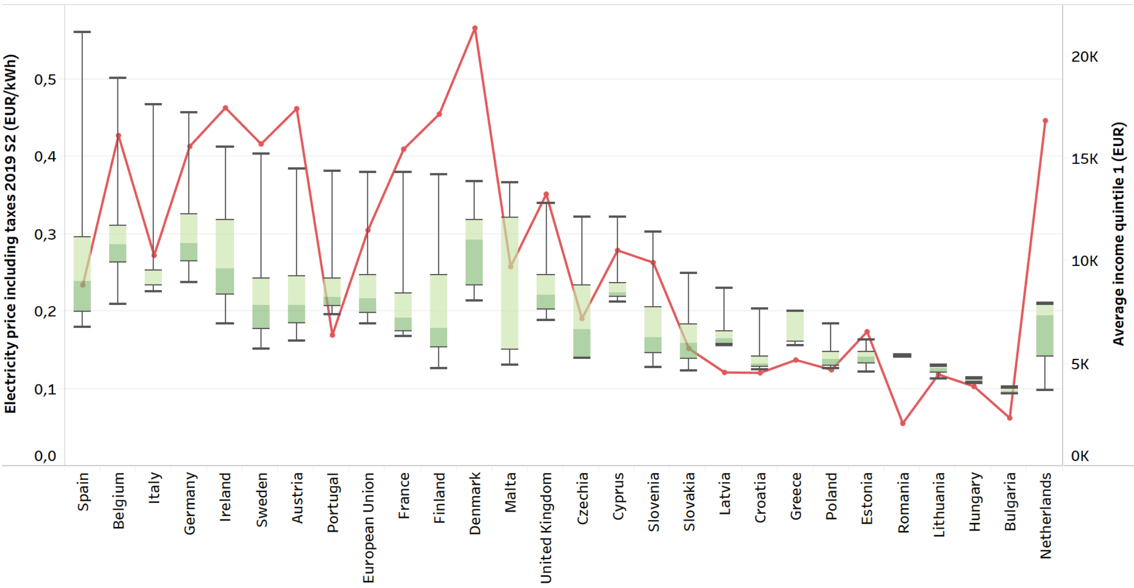



Figure 1.6: Electricity prices per country and demand band (in green), ordered by price perceived by the smaller consumer, and first quintile income per country (in red). Data from EUROSTAT [2020a], own elaboration.

Similarly to the previous graph, each country has its box plot for electricity prices, with each mark representing the average electricity price for households in different ranges of consumption (demand bands DA, DB, DC, DE and DD as defined in the Directive 2008/92 of the European Comission [2008]). In the vast majority of cases, electricity prices are higher when having a lower yearly consumption mainly due to a large fixed part of the electricity bill, which is charged in the form of various tariffs. Therefore, when consumption is low, this fixed part has a higher impact, whether in large consumption this gets diluted when calculating the total price paid per kWh. Since taxes are usually paid as a percentage of the total expenditure, it equally affects all consumption bands. However, one special case differs from the rest, the Netherlands, where households with low consumption perceive a lower price per kWh of electricity than large consumers due to specially targeted refunds/tax allowances introduced in 2020.

In Figure 1.6 countries are ordered by price perceived by those households consuming the least amount of electricity: those in the demand band DA of fewer than 1000 kWh per year. This consumer band can include very efficient consumers, consumption aware ones, but also those with low income who cannot afford average electricity consumption. Countries as Spain, Belgium, Italy and Germany have especially high prices per kWh for DA demand band consumers. However, if looking at prices for the highest share of household electricity consumers (those with demand band DC consumption between 2500 and 5000 kWh per year) it is Germany, Denmark and Belgium that have the highest prices.

Differences between small and big consumer prices can also be extracted if looking at each box plot length. Countries as Spain and Portugal have a large spread of prices, which might be induced by a large part in the electricity bill being independent of the electricity consumed. However, countries as Denmark or Cyprus have fewer differences in prices per kWh due to the electricity bill being dominated by the variable part.

In parallel to electricity prices, the first quintile income has also been depicted in red in Figure 1.6. Countries with low first quintile income and high electricity prices, especially for low demand bands, suffer the risk of leaving low-income households with precarious access to electricity. Some examples of this would be Spain, Italy or Portugal. Moreover, precarious access to electricity can also be manifested with low electricity prices but also very low income, for instance, in Romania, Lithuania, Hungary or Bulgaria. On the opposite side, countries as Denmark, Finland, Austria and Germany are in the higher tiers of first quintile income while not having, in comparison, as high electricity prices for lower demand bands.

## 1.5 Electricity market design as a possible measure to alleviate energy poverty

In the last 20 years, the EU has taken the path towards full liberalization of electricity markets [Pepermans, 2018]. Although it was argued that the liberalisation would encourage competition and therefore low prices, it has been seen how affording electricity is still a problem for many households and overall how precarious access to electricity is still an issue that affects the EU (see section 1.4). Moreover, it has seen been seen how under extreme conditions liberalised markets accentuate these issues, such as with the recent storms in Texas [Halkias, 2021] or Spain [Ibar, 2021].

The solution proposed from the European Commission to this "market failure" in the Electricity Directive [Council of the European Union, 2019] has been to adopt correction measures emerging from *"social policy or by other means than public interventions in the price"*, arguing that the former affects competition, discourages investments and the emergence of new market players. Nevertheless, the directive also argues that exceptions can be done if focused on *"energy poor consumer"* and *"vulnerable households"* and limited in time, leaving it to each member state how to define these terms.

Although they are the measures that the European Commission proposes, it is unclear whether implementation of social policies and limited public intervention in prices are sufficient to protect those more vulnerable and alleviate energy poverty. Through this chapter, it has been seen how energy poverty has remained a relevant issue – also in its particular dimension of precarious access to electricity – and is far from being eradicated in most of the EU countries. It could therefore be argued that more profound reforms on how electricity markets operate might be needed to alleviate energy poverty from the root. Before doing that, it is however necessary to have an understanding of the specific situation of each Member State, identifying whether the issue with the affordability of electricity comes from unfair price distribution, lack of resources in the country, chronic poverty, high costs of production, or other causes.

In parallel to the liberalization of markets, in recent years new agents have appeared in the electricity sector due to technological and social development. These include distributed energy resources, prosumers, aggregators or flexible loads such as EVs or heat pumps. These new agents challenge existing markets and claim for reforms so that they can actively participate in energy exchanges. Current markets were designed to have an active part (producers) and a passive one (consumers), with physical energy exchanges through transmission and distribution grids and economic exchanges with intermediaries through pool market structures. However, with new agents the difference between producers and consumers is diluted as many agents – prosumers – participate in both sides of the market. This has forced the emergence of new and innovative decentralised market designs.

First existing decentralised market structures include peer-to-peer trading, where agents directly trade with multiple selected agents at the same time; energy communities, where its members trade internally following agreed rules and priorities; and hybrid models, that include combinations of these structures, even having interactions with the pool market [Sousa et al., 2019]. On one hand, these type of decentralised markets could threaten grid reliability if poorly designed, reduce privacy for its users, or not be able to perform adequately because of limitations in ICT, among other issues. On the other hand, if more widely spread they could help maximize energy efficiency, democratize energy markets (for instance, accounting for supply preferences and allowing a consumer to have multiple suppliers) and facilitate the integration of renewable energy sources [Parag and Sovacool, 2016]. With all these potential benefits, it is crucial that these types of markets get further researched both in literature and through pilot schemes. Only then they will be able to overcome the existing challenges and become a viable and attractive alternative.

There are already many existing pilot cases of such nature with considerable success. In the case of energy communities, there are already around 3500 operational communities in the EU [Caramizaru and Uihlein, 2020], present in almost all Member States and going from neighbours owning a wind turbine, to an apartment building with PV or cooperative-shaped energy suppliers, among others [REScoop, 2021]. In the case of P2P networks, they are less extended due to regulatory and technical limitations. However, as reviewed in IRENA [2020b], there are many consolidated pilot projects such as the Brooklyn Microgrid connecting local PV owners with consumers; the SonnenCommunity in Germany, which allows sharing of self-produced renewable power by prosumers who are using Sonnen's batteries, or the Vandebron platform in The Netherlands, which allows consumers to buy power directly from prosumers, at the price set by prosumers, to name a few.

Most of these peer-to-peer networks or energy communities are built under sustainability values, prioritizing the use of RES and thus accounting for the externalities that using fossil-fuel energy sources cause. In fact, going back to energy poverty, an argument can be made to treat it also as an externality since reducing energy poverty causes a reduction in expenditure on health, reduces air pollution, guarantees comfort and well-being, improves household budgets, and increases economic activity [EPOV, 2020a].

## 1.6 Problem Formulation

Given that energy poverty and its particular dimension of precarious access to electricity is a live and relevant issue; that the proposed solutions from regions such as the EU have mainly been in the form of social policy and not through profound market reforms; and that there are new emerging decentralised markets set to play an important role in the future of the electricity sector; there is a window of opportunity to investigate whether these decentralised markets can help alleviate precarious access to electricity by integrating the solution to this issue in its core design.

This leads to the following Research Question and Sub-Questions:

**How can the cost of alleviation of precarious access to electricity be internalized in decentralized electricity markets and what is the impact of the internalization on market agents?**

1. How can decentralised electricity markets be modelled?
2. How can the issue of precarious access to electricity be included in decentralized electricity market modelling?
3. Which market mechanisms can internalize the cost of alleviating precarious access to electricity in decentralized electricity markets?
4. What impact does the internalization of costs have on the different market agents?

### 1.6.1 Scope and limitations

This Thesis focuses on developing a methodology to internalize the costs of alleviating precarious access to electricity in decentralized markets, as well as on evaluating the impact that this can have on different types of market agents. It has the following limitations whose impact will be discussed in Chapter 6:

- Only the decentralised market model developed by Moret [2020] will be used, leaving other ways of modelling markets out of the scope. Due to this model, demand and supply curves for market agents are assumed to be linear, not all types of agents are modelled, and grid constraints and losses are not considered.
- A monthly time-frame is used.
- Non-strategic behaviour is assumed by all members of the market, hence their bids show their true range of needed consumption and the prices that they are willing to pay.
- The analysis of hybrid market architectures is left out of the scope of this Thesis.
- The implementation of the proposed methodologies is out of the scope of this Thesis.

# Theories 2

This Chapter first presents the theoretical framework used through this Thesis, which is built based on Social and Solidarity Economy principles, Sharing Economy and Innovative Democracy. Then, theory regarding how markets are designed is presented, showing the differences between current market designs and innovative decentralised ones, which will be the focus of this work.

## 2.1 Theoretical framework

To answer the research question presented in section 1.6, first, the theoretical framework needs to be defined. Since the goal is to further investigate how decentralised market design can help alleviate energy poverty, it is necessary to define the principles under which this new design will be proposed. To do that, it has been chosen to use Social and Solidarity Economy, Sharing Economy and Innovative Democracy as the core theories under which build an adequate theoretical framework.

### 2.1.1 Social and Solidarity Economy

Throughout the 20$^{\text{th}}$ century, several ideological movements have questioned the adequacy of capitalism. With the economic crisis of 2007, the raising awareness on climate change or the Covid-19 pandemic, this questioning has been accentuated. The main concerns about the current tendency of capitalism are the legitimacy of using monetary profit as a goal rather than a mean, and its responsibility in perpetuating systemic inequalities, from which energy poverty is just an expression [Gomez-Alvarez, 2016].

One of the alternatives to the current dominant economical model is the Social and Solidarity Economy (SSE). SSE questions the current profit-based capitalist economy and acts as an umbrella for new forms of economic activity that prioritise social and often environmental objectives; involving producers, consumers and citizens to act collectively and in solidarity [Utting, 2015]. According to Chaves-Avila and Monzon [2012], the common SSE principles are: priority of the people over the capital, voluntary adhesion, democratic control by its members, alignment of interests between the members and the general interest, defence of the solidarity and responsibility principles, management autonomy and independence from public power, and use of any surplus towards sustainable development and the general interest.

Alternative approaches such as SSE are far from becoming the norm in modern societies. However, there is a growing tendency for initiatives based on SSE, mostly in the form of cooperatives. According to CIRIEC [2017], there are over 13.6 million paid employees in

SSE organisations, which amounts to 6.3% of the EU's working force. Moreover, there are 82.8 million volunteers, equivalent to 5.5 million full-time workers. In total, there are more than 232 million members of cooperatives, mutuals, associations, foundations or similar organisations, which account for over 2.8 million entities. It needs to be noted that the disparity between organisations that fall under the umbrella of SSE is quite large, going from conglomerates such as Mondragón Corporación Cooperativa with over 80.000 workers to local neighbourhood associations; from renewable energy communities to voluntary-based organisations such as Médicins sans Frontièrs.

According to OECD Secreteriat [2020], the SSE has played a crucial role in mitigating the negative effects of the Covid-19 pandemic in the short term, providing innovative solutions to complement public services. Historically, SSE has been proven to be a pioneer, with many of its innovations becoming mainstream and adopted by the rest of the economy such as fair trade, organic food movements or environmental initiatives. Therefore, in the doorsteps of a new economic crisis, SSE can partake a much larger role in the post-COVID era, going from simply repairing social problems of the modern economy to transform the root of the issues, helping rebuild a more inclusive and sustainable society, and alleviating existing inequalities such as energy poverty.

### 2.1.2 Sharing Economy

In hand with the reconsideration of the basis of the economy and due to both technological and social development, new approaches on how to exchange goods and services have emerged, such as Sharing Economy.

Traditional market models are based on ownership, while this new paradigm is built on sharing products and services among peers. It can be defined as a *"collaborative consumption made by the activities of sharing, exchanging, and rental of resources without owning the goods"* [Lessig, 2008]. In a recent Eurobarometer [European Comission, 2018], 23% of Europeans admitted having used collaborative platforms, growing from 17% in 2016, showing the growing tendency of these initiatives.

Three main drivers for the uprising of Sharing Economy can be identified according to Puschmann and Alt [2016]. First, a change of consumer behaviour, with temporary usage becoming more attractive due to convenience, lower prices and environmental sustainability. Secondly, the rapid expansion of social networks, allowing citizens to connect with peers that are willing to share their goods combined with electronic market platforms that facilitate this connection while ensuring a safe environment. Finally, the development of the "App economy", hence the simplicity and convenience that mobile apps facilitate compared with traditional physical methods.

Most of the large companies that are built under the Sharing Economy approach such as Airbnb or Uber are still based on profit-making. Despite that, Sharing Economy approaches have a huge potential of allowing the implementation of SSE principles, since with this approach goods are decentralized and thus can be shared under the priorities that each user establishes. These priorities can be aligned with those of the Social and Solidarity Economy.

Going back to the energy markets, there are already existing cases of this combination, with peer-to-peer networks based on renewable prosumers or energy communities built along with some sharing principles. However, these types of energy exchanges are still a small exception in the EU, with around 3500 operational energy communities [Caramizaru and Uihlein, 2020]. In particular, sharing economy initiatives based on SSE principles might be a good option to alleviate energy poverty, setting it as a priority on the market design process.

### 2.1.3 Innovative Democracy

In order for innovative market designs to become more widespread, it is first needed to understand how current energy markets are built and what can enable a change of paradigm. According to Hvelplund [2014], the traditional political and economical paradigm used to regulate energy market policy is the Neoclassical approach. Under Neoclassicism, it is believed that the market regulates itself and naturally tends towards an optimum, satisfying the goals of society. Energy policy should merely consist on correcting a few "market failures" such as environmental consequences or energy poverty, ensuring that these externalities are internalized in the market. The role of the parliament and governments should be to maintain order in the free market without direct intervention and avoiding external interference.

However, [Hvelplund, 2014] presents an alternative paradigm called Innovative Democracy. With this approach, it is explained that the market rules are designed through political processes and the economy is not per definition at an optimum, since the market is a human-made construction. How these political processes take place needs to be analysed, redesigning them if wanting to avoid dependency on the current *status quo*.

As illustrated in Figure 2.1, the Innovative Democracy approach claims that a reform of the political processes that induce institutional market design is needed, so that not only the old "energy market dependent" lobbyist influence the decisions from the parliaments and governments, but also the new "energy market dependent" lobbyist as well as market independent agents such as NGOs or the public debate. Once this is done, measures can be adopted either indirectly, through institutional market design such as defining taxation schemes, or directly, when changing the existing market design. Through these policies, it should be ensured that the goals of society are satisfied.

Although Hvelplund [2014] 's theory is designed to facilitate the integration of renewable energy sources in the energy markets, a parallelism can be done to the issue of energy poverty as shown in Figure 2.1. In this case the "old energy market dependent" lobbyists are the traditional producing companies or large consumers that are benefited the most from the current electricity markets; the "new energy market dependent" lobbyists are associations of prosumers in peer-to-peer prosumer networks or energy communities; and the "energy market independent" lobbyists are NGOs advocating for the reduction of energy poverty and redistribution of wealth as well as the existing public debate on this issue.

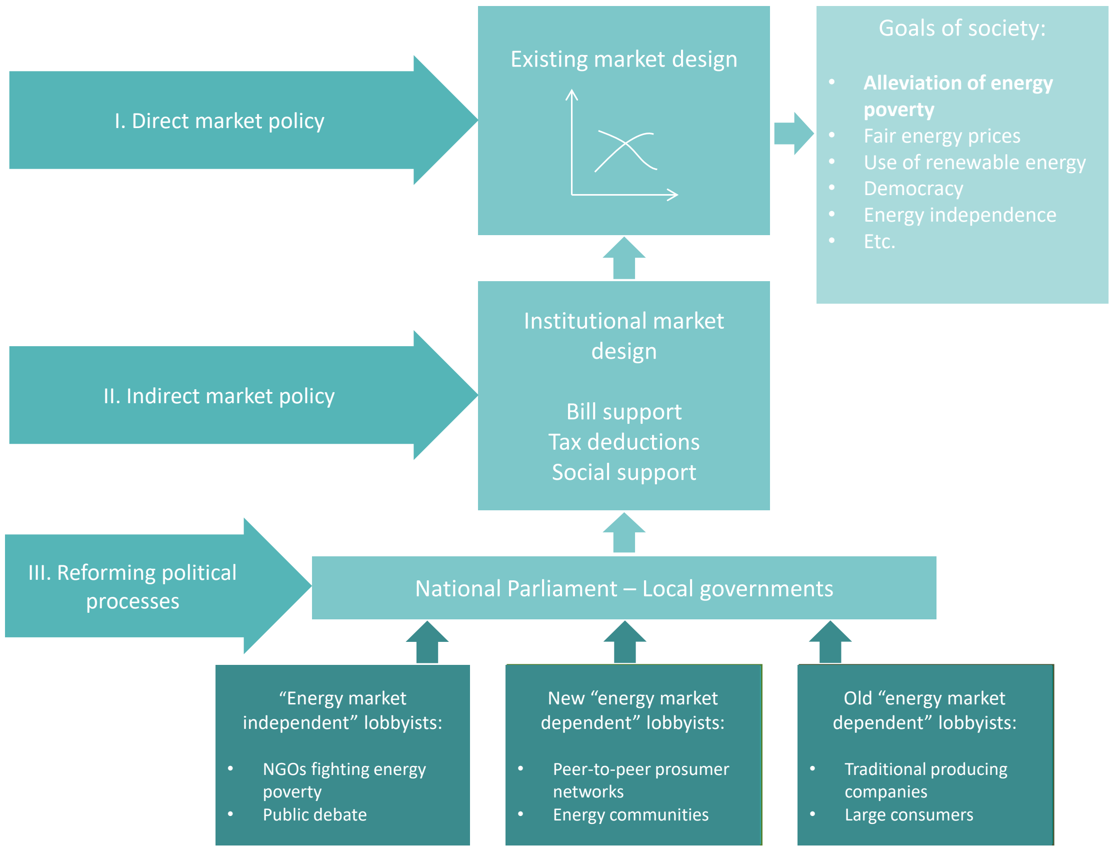



Figure 2.1: Adaptation of the *Innovative Democracy* political and economical paradigm based on [Hvelplund, 2014]

Once the political processes are reformed, the market can be modified directly or indirectly so that the goals of society are achieved, including the alleviation of precarious access to electricity. Currently, the EU is tackling this issue through indirect market policies, hence through tax deductions, bill support or social support, as seen in Section 1.3.1. These measures are set to compensate for the market failure that is energy poverty, but there is a different approach: direct measures. These consist of modifying the market itself to prevent the market failure, instead of trying to fix the issue *a posteriori*.

In this Thesis direct market policies to alleviate precarious access to electricity will be analysed, making use of the possibilities that Sharing Economy brings to the table while following the principles of a Social and Solidarity Economy.

## 2.2 Electricity market design

Complementary to Section 2.1.3 where who is it that can change electricity markets and how can it be done has been described, in this section, through market theory, the elements of the market that can be modified will be outlined.

One of the possible approaches to market theory within the Economics discipline as per reviewed by Harrison and Kjellberg [2014] is Market design, which is the main theoretical background of this Thesis.

Similar to Innovative Democracy, this approach defines markets as institutions with their own set of rules and mechanisms, but which, as they were once created, they can also be changed by deliberate action. This puts the focus on how it is actually possible to solve market failures. Market designers can change the structure, negotiation mechanisms and constraints in markets so as to address specific issues such as supply-demand imbalances or in order to modify market outcomes that are considered non-optimal. In addition, with this approach markets are considered to be solved by matching algorithms, which could be shaped to account for market actor preferences or specific market objectives [Harrison and Kjellberg, 2014].

Electricity markets are a good example of markets whose rules and mechanisms have gradually been shaped by progressive regulatory processes. This visibly happened during their liberalization in regions like the EU, which has completely modified the way in which electricity is now exchanged in many of the Member States, and is still an ongoing process. New regulatory measures are still changing the design of markets to address new challenges as the expansion of renewables or the incorporation of new actors (such as prosumers, energy communities or aggregators) and services (such as storage service or demand-side management). Changing market features can have a significant impact on all market actors, so it has to be done consciously. However, the possibility to do so can also be seen as an opportunity to modify market outcomes so that they are aligned with new societal goals [Cramton, 2017].

Electricity markets can be characterized by its **architecture, negotiation mechanism and actors** [Moret, 2020] and thus it is possible to shape a market by acting upon these elements. It is possible to decide how is the market built (for instance, which connections and intermediaries are there between producers and consumers), which actors can participate, and how are they enabled to negotiate between them. With these choices, completely different markets can be built, from the current pool electricity market to future decentralized ones.

### Market actors

There are three main traditional electricity market actors that are related to each other by power supply and economic exchanges: producers, suppliers and consumers. Producers sell electricity through the wholesale market to suppliers, who buy electricity in bulk and sell it to consumers at retail price. Additional to those there are traders and brokers, who operate as intermediaries [Plejdrup Houmøller, A., 2020].

Moreover, there is a market regulator that fixes the rules under which electricity price is set. Other actors involved are the transmission grid operator or TSO (who as a natural monopoly owns and operates the high-voltage grid and receives compensation through a tariff from producers and consumers) and the distribution grid operators or DSOs, that also receive payment through electricity tariffs. Finally, the government is also an involved actor as it determines complementary taxes and tariffs that will be charged to consumers in their electricity bills [European Parliament, 2016].

Apart from traditional market actors, new ones are appearing in hand with the decentralised energy markets. Some examples are aggregators (collectives of consumers that gather to buy electricity in bulk and thus leave retailers behind), prosumers (consumers with production units that might sell electricity to the grid), energy communities, or actors with demand-side management and storage services.

### Market architecture

Market architecture is defined by the negotiation links between those actors who buy and sell electricity. In Figure 2.2, an overview of the different existing market architectures is shown.

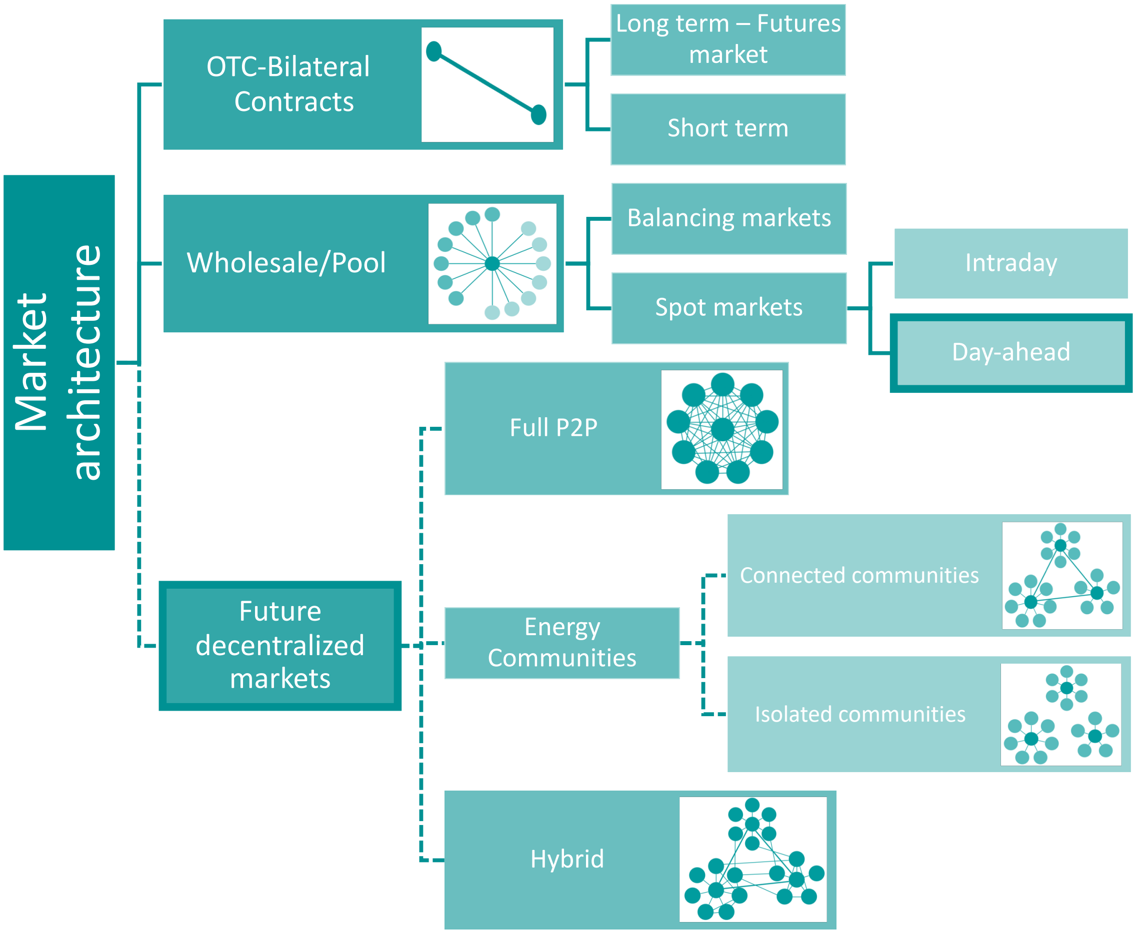



Figure 2.2: Electricity market architectures. Inspired on [Moret, 2020] and [Parag and Sovacool, 2016], own elaboration.

As portrayed in Figure 2.2, the simplest market architecture is reached with bilateral/over-the-counter contracts, where there is only a negotiation link between sellers and buyers because the amount and price of electricity exchange are directly agreed between producer and consumer (although intermediary brokers can facilitate the transaction). These type of contracts normally involve large consumers, can be made much before the moment of delivery (Futures market) or just before, and can be materialized through Power Purchase Agreements [CRE, 2020].

Wholesale/Pool markets involve a more complex market architecture. These are centralized platforms where buyers (mainly retailers but also traders, brokers and large consumers) and sellers (owners of large production units) can exchange electricity according to the prices they are willing to pay and receive respectively, under a supervisory node – the market operator. This node is in charge of all communication between agents, fixes the prices of electricity and allocates the amounts exchanged accounting for the capacity of the transmission and distribution grids [Bundesnetzagentur, 2020]. The vast majority of the electricity is often exchanged through the spot day-ahead market [European Comission, 2016]. However, in order to make sure that electricity demand and supply perfectly match (which is a challenge due to the intermittence of renewable electricity production, the unpredictability of demand and the lack of storage), exchanges are also arranged on the same day of the delivery of electricity with intraday markets and up to the instant with balancing/capacity markets [Plejdrup Houmøller, A., 2020]. It is worth pointing out that the wholesale/pool electricity market refers to the market where electricity is bought in bulk, and thus most consumers do not directly participate in it. Instead, electricity consumers typically buy electricity through the retail market, where they can choose from a variety of suppliers, who themselves have bought electricity in the pool [European Parliament, 2016].

Apart from the above more traditional market architecture, new ones are also emerging with the decentralization of electricity markets, more precisely due to the appearance of new actors and the development of the technology that enables them to do transactions, which comes in hand with Sharing Economy as explained in Section 2.1.2. New market structures are even more complex than traditional wholesale ones, with more negotiation links between market actors, fewer supervisory nodes and fewer intermediaries [Sousa et al., 2019]. This makes them less vertical and thus with more consumer control, which is only possible with the increase in flexibility of demand and the improvement of communication technology [Sorin et al., 2019].

Not only bilateral contracts take place in decentralized markets, but multilateral ones too. Prosumers using technologies such as blockchain are able to exchange electricity with not only the grid but directly to multiple peers at the same time, which gives birth to Peer-to-peer (P2P) structures as displayed in Figure 2.2. As it can be seen, these type of structures is characterized by the absence of a supervisory node that connects all actors. Instead, direct connections between them are created resulting in complex networks. Its complexity lies in having to negotiate the price and amounts of energy exchanged between all peers simultaneously and having to match supply and demand for all of them, which is exponentially more difficult to technically manage the more agents there are [Parag and Sovacool, 2016]. Despite the technical challenge that these market architectures might represent, they offer a transparent clearing mechanism and the possibility to exchange electricity at cheaper prices than with the retail market [Moret, 2020]. Moreover, if peers live in proximity, electricity can be exchanged locally and thus grid losses are reduced.

Parallel to prosumers, energy communities are also appearing, them being groups of prosumers or groups of consumers with shared production units. In both cases, its members can share electricity according to their own rules and objectives in isolated community mode, and/or interact as a single agent (through a virtual agent or community manager) with external ones such as the pool, other communities, individuals, suppliers or directly with electricity producers [Parag and Sovacool, 2016].

New decentralized market structures are being implemented already and will have to coexist with the current dominant pool market structure. This market architecture will be referred to as hybrid [Moret, 2020], a combination of P2P structures with energy communities and the existing pool.

### Negotiation mechanism

How market agents negotiate their electricity procurement is largely dependent on the communication links between them, thus the market architecture, and essentially entails a resource allocation problem.

In pool markets and precisely the spot market, energy is exchanged through a common node (the marketplace) and an auction mechanism. Through it, producers place offers of amounts of energy they can produce as well as the price they are willing to accept. Ordering these offers from lowest to highest price builds up the supply curve, also known as the merit order curve. As seen in Figure 2.3, it often accommodates renewable energy sources with the lowest price as their marginal cost for electricity is very close to zero. In the same way, buyers place offers of amounts of electricity which they are willing to buy and the price they are willing to pay for it. These are ordered from highest to lowest and build up the demand curve [Plejdrup Houmøller, A., 2020], as seen in Figure 2.3.

The intersection of the demand and supply curves determines the spot market price for a given hour, which in the most probable case that uniform pricing is in place, is the same that all producers receive and all buyers pay. Finally, all producers having offered a price below or equal to the resulting market price will sell their electricity, while all buyers that were willing to pay a price higher or equal to the market price will buy that electricity at market price [Plejdrup Houmøller, A., 2020].

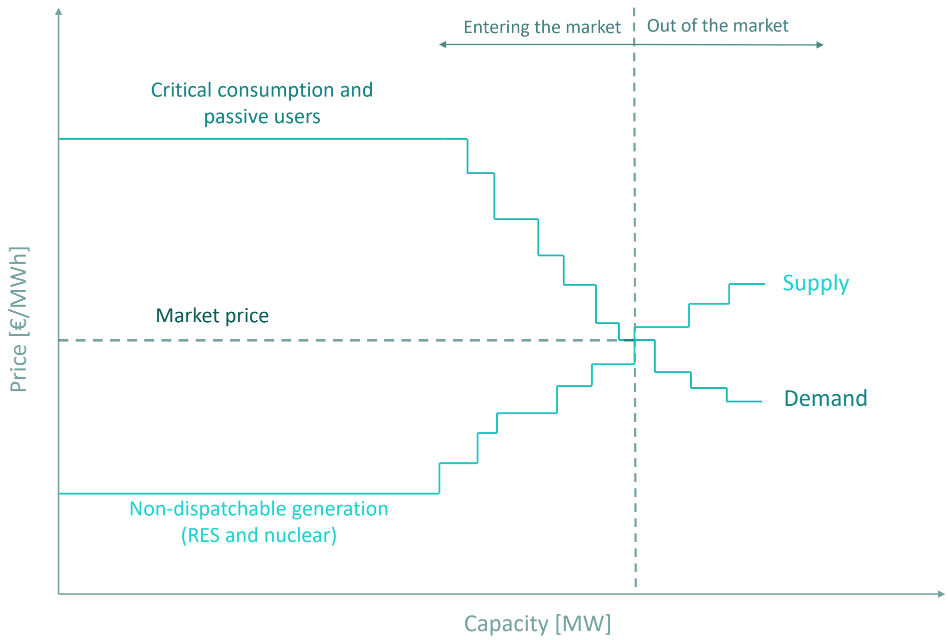



Figure 2.3: Merit order curve. Own ellaboration

As described, there is no direct negotiation mechanism among agents with a wholesale market structure and the rules of the transaction are determined by the market regulator, whose only objective is overall cost minimization while respecting physical grid constraints. Moreover, it is worth pointing out that the resulting transactions are in most of the cases between a producer and a retailer, and not directly to a consumer. To get the electricity, the consumer has to participate in the retail market and contract a retailer that will sell her all the needed electricity. In this case, the consumer will have various retailers and contracts to choose from but the negotiation mechanism is simple because only one retailer can be chosen to supply electricity imported from the grid.

The negotiation mechanisms in decentralized markets can be much more complex than the ones happening in the pool and retail markets. In fact, the main difference among decentralized and centralized markets, apart from the quantity and variety of agents that can participate in them, is the negotiation mechanism itself [Moret, 2020].

Opposite to pool markets, where the market is cleared by a trusted market operator that receives and shares all needed information from a limited amount of agents, on decentralized markets actors face the challenge of solving the resource allocation problem without a trusted central node and with a higher diversity of agents. In addition, decentralized markets can be designed to offer the possibility to consumers to obtain electricity from multiple sources, incorporating agent preferences such as the local or renewable origin of the electricity, a specific trading partner, low-cost electricity, etc., which adds an extra dimension to the challenge. Moreover, each electricity trade can have its own different price as opposed to uniform pricing, which is described as the concept of product differentiation [Sorin et al., 2019]. Finally, decentralization can open the door for markets to be optimized with other objectives than cost minimization such as integration of RES or alleviation of energy poverty [Moret, 2020].

On one hand, for P2P market architectures, two peers can agree on a bilateral transaction for a certain amount of energy and a price without centralized supervision [Parag and Sovacool, 2016], and multi-bilateral contracts can be set with different peers, each one with its price and exchanged energy. On the other hand, such decentralized markets can be also designed with a consensus-based approach. The negotiation process can be automatized, making the different prosumers iteratively seek consensus on the exchanged energy and price for all trades until all demands are matched, while also accounting for preferences in supply option. This can be done by translating them into economic value, for instance in costs of trading with a peer that is not desired and then trying to minimize all costs. Moreover, optimization can also be sought with commonly agreed objectives. This complicated decentralized market clearing problem can be solved by distributed optimization techniques, game-theoretical algorithms and online matching algorithms [Moret, 2020].

For community architectures, the negotiation processes can be similar to what happens with a pool market, but on a smaller scale and with the possibility to consider preferences and specific community objectives when doing the resource allocation. Allocation of resources is done between community members but also between the community itself and external agents. An example of a common set objective is community autonomy, which means minimizing imports from the external grid [Moret, 2020].

Finally, with hybrid architectures – which include all combinations of the pool, P2P and community structures– the negotiation mechanisms can be similar to those described with a P2P architecture, but integrating communities, as well as allowing all agents to interact with the pool market either directly or via a retailer.

### Summary of electricity market designs

Table 2.1 summarizes the main points explained in this section and is used to illustrate the main differences between current and new market designs.

| | **Main actors** | **Architecture** | **Negotiation mechanism** |
|---|---|---|---|
| **Wholesale /pool** | Consumers, producers, suppliers and market operator. | Buyers and sellers are only linked to the central node (market operator) which sets the rules of the transactions. | Intersection of supply and demand curves determines market price, which is uniform for all participants and set by the market operator. |
| **P2P** | Consumers, producers and prosumers . | All actors are linked, so multi-bilateral trades are possible without a central node. | Multi-bilateral trades at different prices. Can also be consensus-based, hence market is solved accounting for individual preferences while matching supply and demand. |
| **Energy communities** | Consumers, producers, prosumers and community manager. | Community members are only linked to the community manager, who can be linked to external market agents. Rules for internal and external transactions are commonly set. | Small-scale pool system while considering preferences for internal and external trading. |
| **Hybrid** | Market operator, producers, suppliers, consumers, prosumers and communities. | Actors can be linked among themselves, within communities, with suppliers and with the market operator. | Combines P2P and energy communities negotiation mechanisms, as well as the pool market. |

Table 2.1: Main agents, architecture and negotiation process of current and new decentralised electricity market designs. Own elaboration.

The information shown in this section and summarized in Table 2.1 will be used as the core theoretical background from which the rest of the knowledge in this thesis will be built.

In specific, the focus will be set on the design of decentralized markets that can complement or substitute wholesale and retail markets. New markets will have to incorporate new actors and new trading possibilities between them, which will shape its architecture and negotiation mechanisms.

New innovative markets might include other objectives than cost minimization in their clearing process, or even mechanisms that help alleviate precarious access to electricity.

# Research Design 3

This Thesis' Research Design is depicted in Figure 3.1.

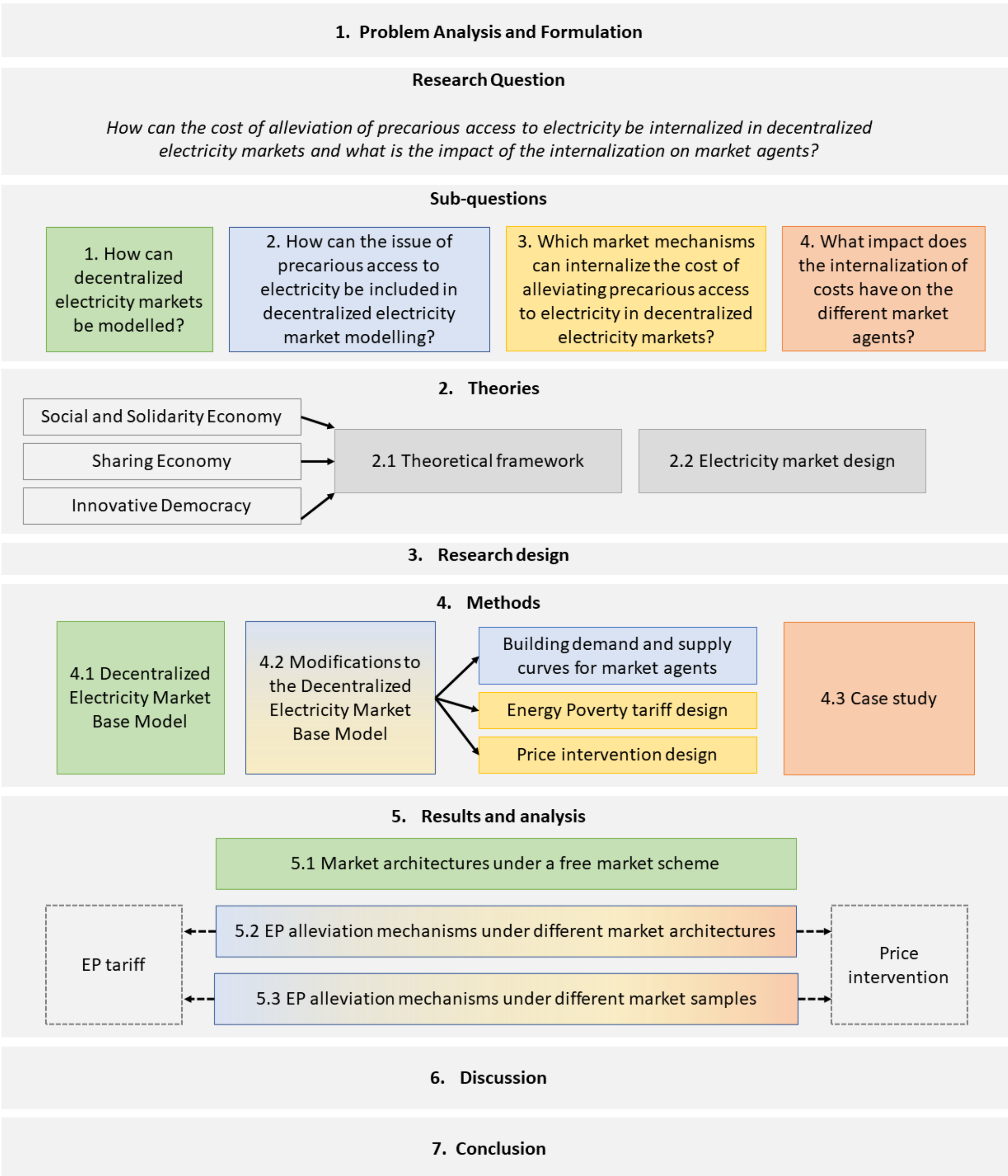



Figure 3.1: Illustration of the used Research Design. Own elaboration

As it can be seen, the Thesis starts with the problem analysis and its formulation through a Research Question and four Sub-Questions. Next, the theoretical framework is set by presenting three different theories: Social and Solidarity Economy, Sharing Economy and Innovative Democracy. These are complemented by a general theoretical background on Electricity Market Design, which sets the fundamentals to understand the Decentralized Electricity Market Base Model. The model is then modified to include the issue of precarious access to electricity as well as two support schemes that allow the internalization of its costs in decentralized electricity markets: EP tariffs and Price Intervention. After that, a Case Study is built and Results are obtained and analysed with the objective of understanding the operation of the proposed schemes and the impact that they can have on market agents. Finally, the discussion and conclusion of this Thesis are presented.

The first Research Question is *How can decentralised electricity markets be modelled?*. This is answered in Section 4.1, using the Electric Market Design theory presented in Section 2.2, based on the model developed by Moret [2020] and analysing its outputs in Section 5.1.

The second Research Question is *How can the issue of precarious access to electricity be included in decentralized electricity market modelling?*. This is mainly answered in Section 4.2.2, where the methodology to model low-income households affected with precarious access to electricity is developed, as well as the way to calculate their needed support.

To answer the third Research Question, which is: *Which market mechanisms can internalize the cost of alleviating precarious access to electricity in decentralized electricity markets?*, two schemes are proposed in Sections 4.2.3 and 4.2.4. The operation of these two schemes is further analysed in Sections 5.2 and 5.3 and discussed in Chapter 6.

The fourth RQ is *What impact does the internalization of costs have on the different market agents?* and is answered through the Case Study presented in Section 4.3 and through the obtained Results in Chapter 5.

Answering these four questions is then possible to answer the main RQ of the Thesis, *How can the cost of alleviation of precarious access to electricity be internalized in decentralized electricity markets and what is the impact of the internalization on market agents?* and extract relevant Conclusions in Chapter 7.

# Methods 4

This Chapter presents the methods used in this Thesis.

First, the decentralized electricity market base model developed by Moret [2020] is explained, describing how agents, market architecture and negotiation mechanism are modelled.

Then, the proposed modifications to the base model are presented, starting with a new way of modelling vulnerable households and followed by two support schemes that allow internalizing the costs of alleviation of precarious access to electricity: Energy Poverty tariffs and Price Intervention. The base model including these modifications can be accessed by the reader and is included as an Appendix.

Finally, a Case Study is chosen as a method to evaluate the operation of the proposed support schemes, and its design is presented in this Chapter's last section.

## 4.1 Decentralized Electricity Market Base Model

This Thesis aims to present direct decentralized electricity market design measures that help alleviate precarious access to electricity. In order to do so and to answer this Thesis' first sub-question, a decentralized market model developed by Moret [2020] is presented in this section. This baseline model will then receive some modifications in Section 4.2 in order to satisfy the Thesis' objective.

In the used market model, market agents are characterized by their demand or supply curves depending if they are net producers or consumers, and market architecture is set by partner matrices. Moreover, the negotiation mechanism is an automatized process with a consensus-based approach and with different commissions applied to the market price for each different trade. The final objective of the negotiation mechanism is to maximize the total social welfare (SW) of the system: minimize consumer costs, and maximize producer earnings and consumer satisfaction.

As a disclaimer, since the modelled market is set for an hourly time-step, in this section the terms power and energy are used interchangeably.

### 4.1.1 Agents modelling

The first step in order to model decentralized electricity markets is to characterize the different agents participating in them. As it will be explained, consumers are defined by their demand curves and thus utility function, and producers by their supply curves and thus cost function. Moreover, virtual agents can be defined as agents without supply and demand curves and are used to account for certain market architectures.

### Demand and supply curves

Consumer demand is modelled by demand curves: a direct relation between the power willing to be consumed and the price willing to be paid for it. The lower the price is, the more power is to be consumed. In this case, consumption is considered as negative power, therefore a consumer linear demand curve can be represented as in Figure 4.1:

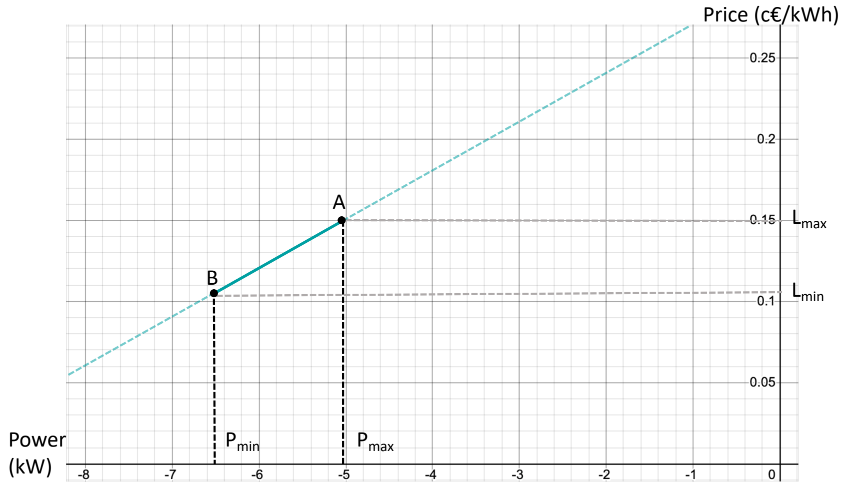



Figure 4.1: Example of a linear demand curve for a given consumer. Own elaboration.

This line can easily be obtained with points A and B. Point A represents the maximum price ($L_{max}$) that a certain consumer is willing to pay for a minimum threshold of consumption (named as $P_{max}$ as consumption is considered negative power). On the opposite side, point B represents the price ($L_{min}$) that the consumer can afford for a maximum consumption ($P_{min}$).

It is worth pointing out that the amount of money to be paid for electricity throughout all points of the curve does not necessarily have to be the same. Typically, for lower consumption and thus when the price is high, consumers assign a lower budget to spend on electricity. However, if the price is low, consumers can take advantage of the situation and consume more – activating all the appliances that were not used before – and thus tend to spend more. That is why normally, and as can be checked with the example in Figure 4.1, $P_{max} \cdot L_{max} < P_{min} \cdot L_{min}$.

The further from (0,0) the demand curve is, the higher the consumption and the higher the prices the consumer is willing to pay, which is the case of large consumers and those with the ability to pay high prices. On the other side, close-to-zero supply curves better represent low-income households, those with lower consumption and lower ability to pay. Moreover, the steeper the linear demand curve is (the bigger its slope is) the more inelastic the demand is, as a high increase of price does not translate into a significant decrease in demand. This models more accurately high-income households than low-income ones, whose demand curve is flatter, demand is more elastic, and therefore a small increase in prices translates into a high decrease in demand [MIT, 2018].

Mathematically, the demand curve can be expressed as a linear function between price ($L$) and power ($P$) as seen in Equation 4.1 [Moret, 2020]:

$$L = a \cdot P + b \tag{4.1}$$

Where $a$ is the slope of the line and thus $\frac{L_{max}-L_{min}}{P_{max}-P_{min}}$, while $b$ is the threshold of price below which a consumer is willing to start consuming, thus $L_{max} - a \cdot P_{max}$ (as $P_{max}$ is negative for consumption).

Different types of consumers have different demand curves according to their $L_{min}$, $L_{max}$, $P_{min}$ and $P_{max}$, which are to be given to the market in the form of bids. To exemplify, Table 4.1 depicts the agent information needed as an input for the described model for a simple case with four consumers and a producer that satisfies all demand. This example will be used throughout this section to illustrate the given explanations. How $L_{min}$, $L_{max}$, $P_{min}$ and $P_{max}$ can be estimated for different market agents when doing simulations is explained in Section 4.2.2. From these $P$ and $L$ values, the characteristics of the demand and supply curves are calculated.

| **Agent** | **Type** | **Pmin (kW)** | **Pmax (kW)** | **Lmin (c€/kWh)** | **Lmax (c€/kWh)** |
|---|---|---|---|---|---|
| **1** | **Consumer** | -6.51 | -5.15 | 0.12 | 0.15 |
| **2** | **Consumer** | -8.26 | -6.54 | 0.12 | 0.16 |
| **3** | **Consumer** | -17.05 | -13.5 | 0.11 | 0.16 |
| **4** | **Consumer** | -18.55 | -14.68 | 0.12 | 0.15 |
| **5** | **Producer** | 0 | 50.37 | 0.08 | 0.14 |

Table 4.1: Example of agent input information needed for the decentralized market model.

In parallel, production is modelled by supply curves, which set the price that producers are willing to accept for certain production. As production is considered as positive power, an example of a linear supply curve could be the one displayed in Figure 4.2:

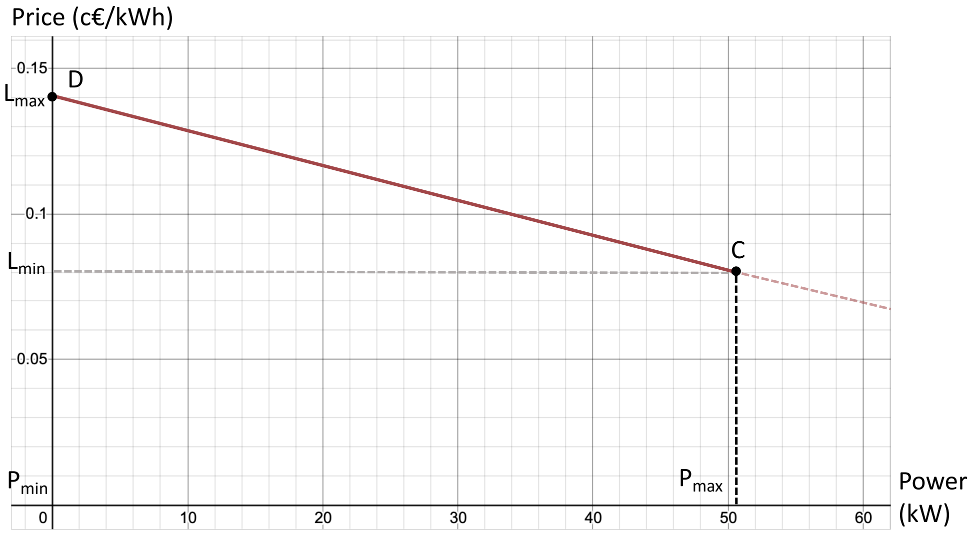



Figure 4.2: Example of linear supply curve for a given consumer. Own elaboration.

As it can be seen, the more power is demanded, the lower the price a producer can offer. In this case, the production unit is modelled to be able to produce from 0 up to $P_{max}$, where electricity can be sold at $L_{min}$. The formulation of the supply curve is the same as the demand curve, considering production as positive power.

Supply curves closer to (0,0) tend to represent more competitive production units as the offered prices are lower, which could be the case of gas when compared to coal or oil. Production curves for renewable energy production units such as wind turbines or solar PV can be represented as flat curves (as their operation marginal costs can be assumed to be very close to 0) and offering to sell at 0 c€/kWh as they are always willing to enter the market. This is also the case of prosumers with surplus production, which otherwise act as consumers for the part of the consumption not satisfied by their own production.

Apart from consumers, producers and prosumers, two other types of agents are also present in decentralized electricity markets: community managers and market operators. These are agents with no assets (that is without any consumption or production) which only act as a communication node between other agents. For this reason, no demand or supply curves apply to them and they can be referred to as "virtual agents", as will be further explained in Section 4.1.2.

### Cost and utility functions

Utility and costs functions can be obtained from the demand and supply curves explained above. While cost functions depict cost as a function of quantity ($P$), utility functions are negative cost functions that are used to quantify consumer satisfaction, also as a function of power. The closer the consumer is to consuming $P_{min}$ (its maximum level of consumption), the more satisfaction the consumer will obtain. Although it is not always the case, due to the formulation used for the present Thesis utility and cost units are set the same.

Mathematically, utility functions are obtained when integrating demand curves, while cost functions are the integral of the supply ones [MIT, 2018]. With linear demand and supply curves, quadratic cost and utility functions are obtained:

$$Cost = \frac{a}{2} \cdot P_x^2 + b \cdot P_x \tag{4.2}$$

$$Utility = -Cost \tag{4.3}$$

Graphically, the utility that a consumer obtains from a certain level of consumption $P_x$ corresponds to the area below the demand curve between 0 and $P_x$, as represented in Figure 4.3. As it can be seen, the more P is consumed, the more utility is obtained. However, there is a diminishing marginal utility as every next unit of P brings less and less utility [MIT, 2018].

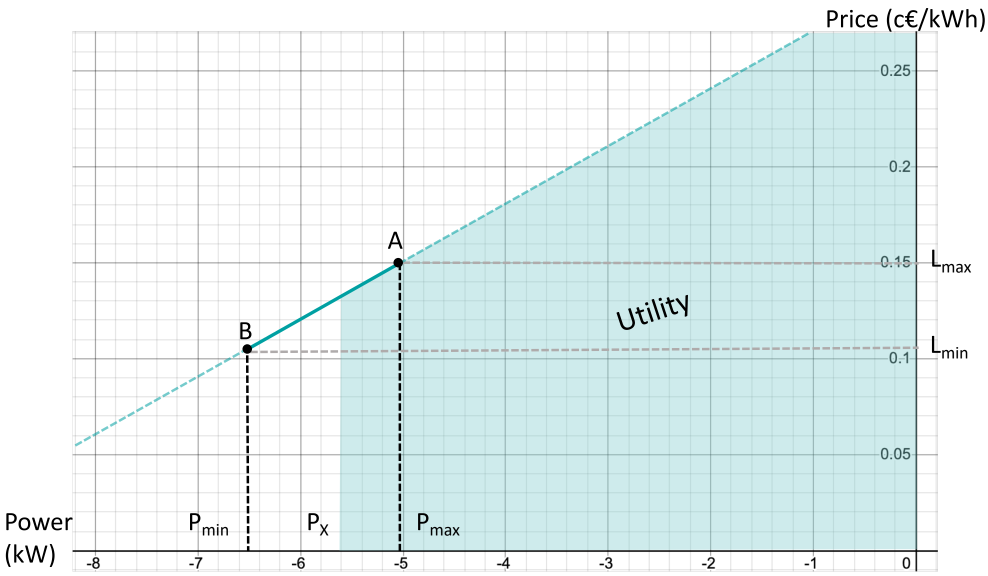



Figure 4.3: Utility at $P_x$ for a given consumer. Own elaboration.

Analogously, as seen in Figure 4.4, production costs are graphically the area below the supply curve and thus increase with the increase of $P$. In the same way as utility, there are typically diminishing marginal costs as the next unit of production is often less expensive to produce than the previous one [MIT, 2018].

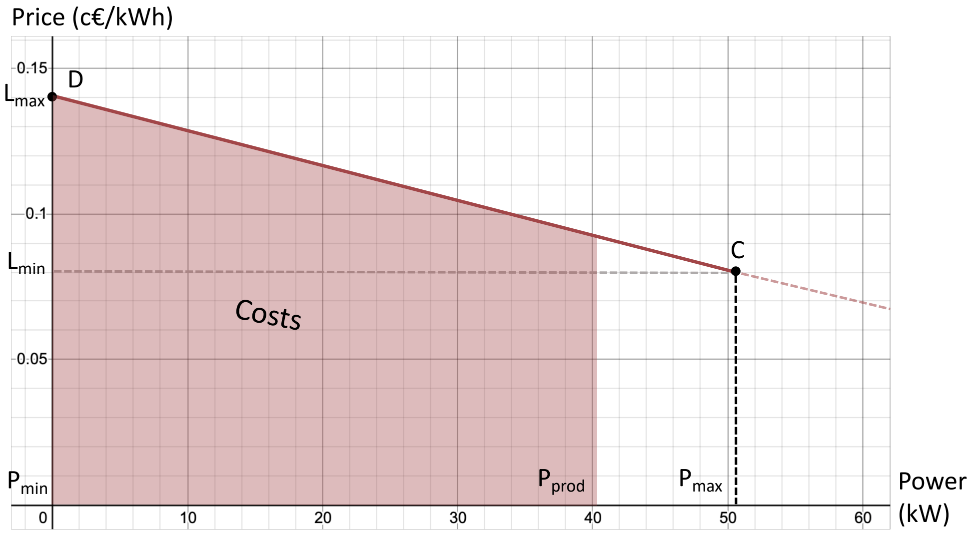


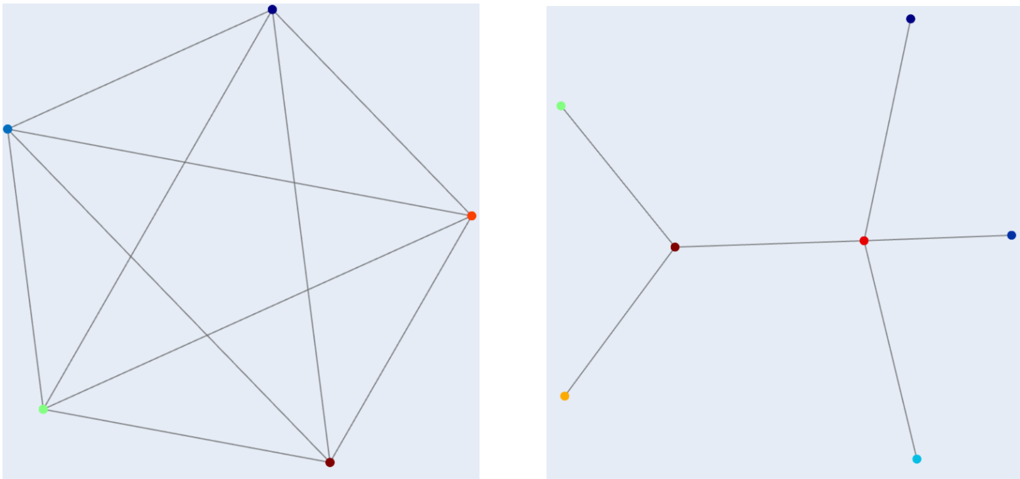

Figure 4.4: Production costs at $P_{prod}$ for a given producer. Own elaboration.

The diminishing marginal costs for producers can be explained if the production costs are divided between fixed and variable costs. If production is low, these fixed costs divided by the total production results in a higher cost per unit of energy. When total production is higher, these fixed costs get diluted resulting in a lower cost per kWh. However, it is important to remark that these are assumptions and simplifications of producers behaviour, which might not reflect the behaviour of all types of production plants.

### 4.1.2 Market architecture modelling

Once the agents of the market have been modelled by their demand and supply curves (as depicted in Table 4.1), the next step is to define how they are connected, hence the market architecture. To do so, the unified formulation presented in Moret [2020] is used, allowing to represent all types of market architecture under the same parameters and equations.

Given that the market is formed by $n$ agents, the market architecture can be represented as an $n$ x $n$ matrix, with boolean parameters $p_{i,j}$ indicating whether the two agents are connected (1 meaning they are and 0 they are not). These parameters therefore determine how trades can occur under that market architecture. Two examples of market architecture are represented in Figure 4.5:



(a) P2P (b) 2 connected communities

Figure 4.5: Example of two market architectures. Based on [Moret, 2020].

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP |
|---|---|---|---|---|---|
| **Cons 1** | 0 | 1 | 1 | 1 | 1 |
| **Cons 2** | 1 | 0 | 1 | 1 | 1 |
| **Cons 3** | 1 | 1 | 0 | 1 | 1 |
| **Cons 4** | 1 | 1 | 1 | 0 | 1 |
| **PP** | 1 | 1 | 1 | 1 | 0 |

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP | CM 1 | CM 2 |
|---|---|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **Cons 2** | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **Cons 3** | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| **Cons 4** | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **PP** | 0 | 0 | 0 | 0 | 0 | 0 | 1 |
| **CM 1** | 1 | 1 | 1 | 0 | 0 | 0 | 1 |
| **CM 2** | 0 | 0 | 0 | 1 | 1 | 1 | 0 |

Table 4.2: Partner matrices (**P**) for Figure 4.5 market architectures.

In the case of a full P2P architecture, all agents are connected among themselves (although they might not be able to trade between each other), hence the *connectivity* or *partner* matrix (**P**) has ones on all their cells -except the diagonal since an agent cannot trade with himself- as can be seen in the left side of Table 4.2.

To model other architectures such as pool or communities, the Market Operator (MO) or the Community Manager (CM) are added as an agent with no assets, but with the ability to trade. For this reason, in the case of a pool architecture, all the agents are only able to trade with the MO agent, hence the partner matrix being all zeros except the row and column of the MO.

For communities, the same principle as the pool market is applied, since it can be understood as a small scale pool system. However, there could be multiple CMs so that each agent is only connected to their own, as seen in the example on the right side of Table 4.2. In this case, consumers 1, 2 and 3 are connected to the first community, and consumer 4 and the power plant (PP) to the second one. As it can be seen, both community managers are also connected, which allows trades between communities through them. Finally, by modifying these matrices it is possible to obtain hybrid architectures, combining CM, MO and P2P systems, as well as specific choices made by the users to exclude certain agents from being their trading candidates.

Other than the presence of links that define the market architecture, in this market design costs associated with each specific trade apart from the price of energy can be added. In

Moret [2020], these costs are understood as perceptive costs of each agent used to prioritize some agents over others. To do so, costs associated with trades with agents with which one does not want to trade are added, leaving the agents with which one has the priority to trade without extra costs. In this Thesis, although built on the same principles, these extra trade costs are interpreted as the actual costs of using the system when trading a certain amount of electricity between agents $i$ and $j$. These commissions can therefore be equivalent to feed-in tariffs or DSO and TSO ones, but with the possibility of being more fairly distributed.

Commissions or extra trade costs are added with a *commission* matrix (**C** matrix). This matrix has the same shape than the partner matrix, but in this case the non-zero cells include the cost of each trade other than the cost of the energy traded. There are only costs for those trades that can occur in the before-mentioned market architecture and are to be paid both for consumers and producers. In Table 4.3, the commission matrices for the two examples presented earlier in Figure 4.5 are shown:

| | **Cons 1** | **Cons 2** | **Cons 3** | **Cons 4** | **PP** |
|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 1 |
| **Cons 2** | 0 | 0 | 0 | 0 | 1 |
| **Cons 3** | 0 | 0 | 0 | 0 | 1 |
| **Cons 4** | 0 | 0 | 0 | 0 | 1 |
| **PP** | 2 | 2 | 2 | 2 | 0 |

| | **Cons 1** | **Cons 2** | **Cons 3** | **Cons 4** | **PP** | **CM 1** | **CM 2** |
|---|---|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Cons 2** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Cons 3** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Cons 4** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **PP** | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **CM 1** | 0.5 | 0.5 | 0.5 | 0 | 0 | 0 | 1 |
| **CM 2** | 0 | 0 | 0 | 0.5 | 0.5 | 1 | 0 |

Table 4.3: Commission matrices (**C**) for Figure 4.5 market architectures, in c€/kWh.

In the P2P case, a commission for buying electricity of 2 c€/kWh is added, which could account for DSO and TSO tariffs. Moreover, a feed-in tariff of 1 c€/kWh for producers is implemented, which would also be paid in the case of prosumers selling surplus electricity. Note that trades between consumers, in this case, are assumed to have a 0 c€/kWh commission since they do not have production units and thus do not have surplus to exchange between them. In the case that prosumers were present, they would have to pay a feed-in tariff for selling their surplus electricity, and buyers of this electricity the applicable grid tariffs.

In the right-hand side matrix for the 2 connected communities example, we can see how there is a fixed tariff for using the internal community grid of 0.5 c€/kWh, and a tariff for exchanges between communities of 1 c€/kWh. In this case, internal trading is therefore incentivised since the total cost of electricity turns to be lower.

Modifying the above commissions by making them more accurate to reality and tailoring them to each specific type of trade can allow to include all electricity system costs. This means not only the TSO and DSO tariffs but also externalities such as energy poverty, which might allow having a fairer cost allocation. This will be explored in Section 4.2.3.

### 4.1.3 Negotiation mechanism modelling

Once the agents have been modelled and the market architecture defined, including the cost of trades, it is now possible to define the negotiation mechanism. The negotiation mechanism of the model is an automatic, distributed, consensus-based optimization process that solves a resource allocation problem by iterative price discovery.

The objective of the optimization is to maximize the social welfare of the system, hence minimizing costs and maximizing earnings and consumer satisfaction. Therefore, a function must be built for each agent to represent their respective costs and benefits. Based on [Moret, 2020] unified formulation, the objective function in Equation 4.4 is built, which can be used for all agents of the system.

$$Obj = min[\sum_i C_i] = max[\sum_i SW_i] = min[\sum_i -SW_i] \tag{4.4a}$$

$$= min\left[\sum_{i,k}\left(b_{i,k}\cdot P_{i,k} + \frac{a_{i,k}}{2}\cdot P_{i,k}^2\right) + \sum_{i,j}(p_{i,j}\cdot c_{i,j}\cdot |t_{i,j}|) + \sum_{i,j}(p_{i,j}\cdot \tau_{i,j}\cdot t_{i,j})\right] \tag{4.4b}$$

$$\text{s.t.} \qquad P_{max,i,k} \geq P_{i,k} \geq P_{min,i,k} \tag{4.4c}$$

$$\sum_{i,k} P_{i,k} = \sum_{i,j} t_{i,j} \tag{4.4d}$$

$$t_{i,j} = -t_{j,i} \tag{4.4e}$$

$$\tau_{i,j} = \tau_{j,i} \tag{4.4f}$$

In Equation 4.4a , $i$ stands for the agent, which could be either a consumer, prosumer, producer or virtual agent. Each agent's goal is to minimize their total costs, which could also be understood as maximising its social welfare.

The first sum of the Equation 4.4b, refers to the production cost or consumer utility- depending on whether power is produced or consumed- from the agent's $i$ asset $k$ (which is understood as either a consumption or production unit). Normal consumers and producers only have one asset, while prosumers have both a consumption and a production asset. Virtual agents do not have any assets and therefore they do not have any cost nor utility in this part. The $a$ and $b$ parameters for this part of the equation are obtained as explained in Section 4.1.1. Since $P$ is negative for consumption and positive for production, this sum pushes agents towards $P_{min}$. This means that consumers are encouraged to consume more to maximize their utility, and producers to produce less to minimize their costs.

The second sum of Equation 4.4b accounts for the commissions to be paid for each trade provided that there is a communication link between agents, which is determined by the boolean value of the partner matrix $p_{i,j}$, as explained in Section 4.1.2. The $t_{i,j}$ variable accounts for each trade between agent $i$ and agent $j$ (being positive when agent $i$ is consuming), while the variable $c_{i,j}$ are the commissions to be paid for each exchange, represented in the commission matrix **C**. Note that the absolute value of $t_{i,j}$ is used for this part of the equation, as regardless if the trade is an import or an export of electricity, the commission needs to be paid and is added as a cost. The goal for each agent is to minimize these costs since they are integrated into their objective function, tending to minimize trades, especially those with higher commissions.

The final sum of Equation 4.4b corresponds to the agreed price to be paid for each trade (before commissions), $\tau_{i,j}$, times the amount of electricity traded. As in the previous sum, only those trades between agents with a communication link can occur, hence when the $p_{i,j}$ value is 1. Since a decentralised market is modelled, the agreed price $\tau_{i,j}$ is not necessarily the same for all trades. The price is always positive, so the sign of $t_{i,j}$ determines whether it is a cost or a benefit. The trend for producers is to maximize the energy traded and its price, whereas consumers tend to lower their imports and have lower prices to reduce their costs.

While trying to minimize their costs, agents are also subject to some constraints. In Equation 4.4c, it is depicted how the power of each agent's asset must be within their $P_{min}$ and $P_{max}$ limits. In Equation 4.4d, it is stated that the sum of all power consumed or produced by all the assets of an agent is equal to the sum of all trades of said agent. Therefore, this ensures that a consumer has its consumption satisfied through exchanges with other agents and that all the electricity produced is dispatched. Moreover, for virtual agents such as CM, since they do not consume nor produce power, it ensures that there is a power balance in the community. Equation 4.4e ensures that the trades between agent $i$ and agent $j$ are the same but with the opposed sign, ensuring reciprocity in all trades. Finally, in Equation 4.4f it is assured that there is also reciprocity in the prices before commissions, hence that agent $i$ pays the same as what agent $j$ receives.

It is possible to find the minimum cost of the system treating the problem as a resource allocation consensus-based one. This means that in each exchange both agents must agree on the energy to be traded ($t_{i,j}$) and the price ($\tau_{i,j}$). To solve this consensus problem, an Alternating Direction Method of Multipliers (ADMM) algorithm is used as defined on [Moret, 2020].

The algorithm calculates the $P$ of each asset within their limits to minimize costs, which is to be distributed through their trades $t_{i,j}$, as well as an optimal price $\tau_{i,j}$ for each of the trades. Then, the trades and prices from each agent are communicated to the rest of the agents, who re-calculate their optimal trades and prices with this new information. This process is repeated iteratively until the problem converges, hence having reciprocity in all trades and prices while having the maximum social welfare of the system. Therefore, the outputs of the algorithm are the $P$ of each asset, as well as the trades ($\mathbf{T}$) and prices ($\boldsymbol{\tau}$)matrices. More detail on the optimization algorithm used can be found in [Moret, 2020]

To better understand how the algorithm operates, a graphical representation of the results obtained from the P2P example presented in Table 4.1 and Figure 4.5 is displayed in Figure 4.6:

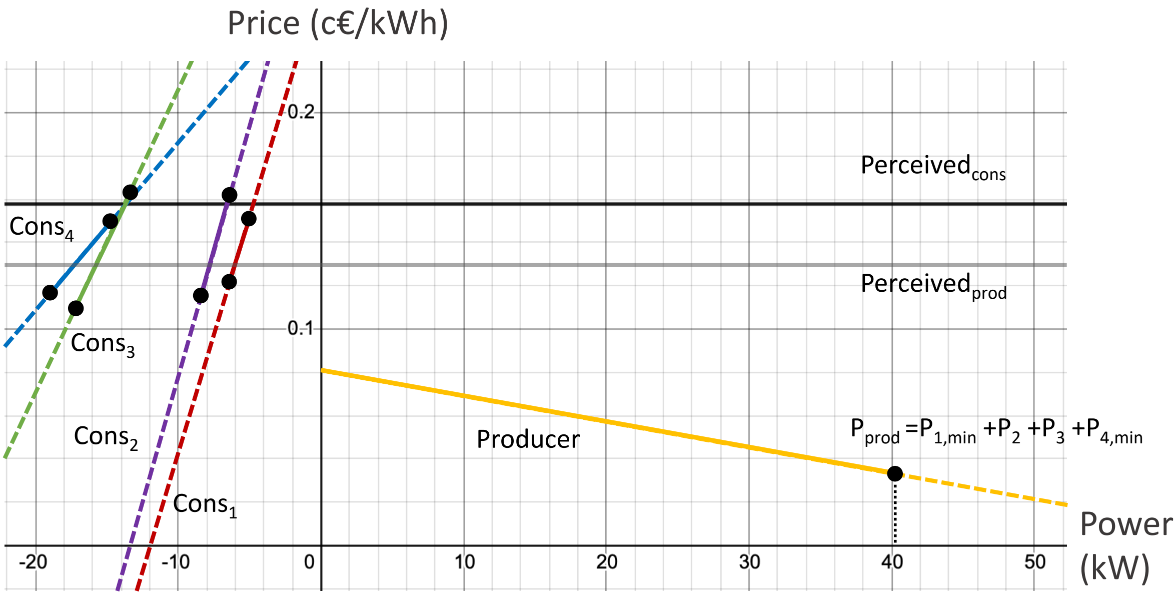



Figure 4.6: Schematics of the optimization solution for the P2P example from Figure 4.5. Own elaboration.

Due to its simplicity, in this example all agreed prices are the same, although this does not necessarily always happen. To this agreed price it is necessary to apply the commissions from Table 4.3, in order to obtain the *perceived price*. The perceived price is the actual price that agents are going to pay or receive, once the commissions are applied. Therefore, consumers perceive a higher price, since commission costs are to be paid on top of the agreed price. For producers, they perceive a lower price, since the commissions are subtracted to the price they would receive. In this case, since commissions are uniform, all consumers have the same $Perceived_{cons}$ price, and the producer the same $Perceived_{prod}$ for all trades, as seen in Figure 4.6.

The demand and supply curves are built respectively as explained in Section 4.1.1 using the parameters presented in Table 4.1, with the black dots depicting the $P_{min}$ and $P_{max}$ limits.

As it can be seen, the $Perceived_{cons}$ price crosses the demand curves of consumers 1 and 4 below its minimum threshold of consumption, with a higher price than their maximum. However, since there is a constraint that $P$ should be within their limits as in Equation 4.4c, they end up consuming $P_{max}$ (their minimum consumption) despite the higher price. For the 2 and 3 consumers, the $Perceived_{cons}$ crosses their demand curves within their range, hence their $P$ consumed is in their demand curve. The utility, as seen in Section 4.1.1, is calculated as the area under the demand curve between zero and $P$. Hence, in consumers 1 and 4 this is done with $P_{max}$ and in consumers 2 and 3 with the obtained $P$, which is between $P_{min}$ and $P_{max}$. To calculate the trade costs, the $P$ of each consumer is multiplied for their $Perceived_{cons}$ price.

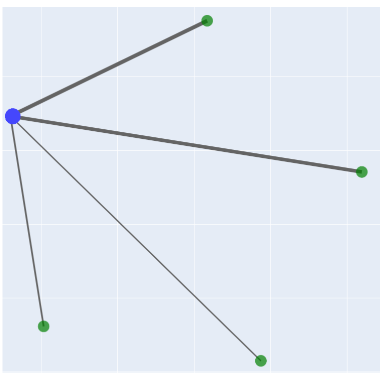
In the case of the producer, $P_{prod}$ is calculated as the total consumption (respecting that it should be a value below $P_{max}$) since there should be a power balance. The production costs are calculated as the area under the supply curve between 0 and $P_{prod}$, whether the trades cost -in this case, earnings- are calculated by multiplying the $Perceived_{prod}$ by the power produced. As it can already be seen, the total earnings are higher than the total costs since the $Perceived_{prod}$ is above the average marginal cost of production, hence the producer will have profits. Since the marginal costs of the producer are lower the more power is produced, this means that there will be a trend to maximizing the capacity of the larger producers rather than equally distributing the share among all producers. When comparing trade costs between consumers and the producer, they are two rectangles with $P_{prod}$ as their base, and the respective perceived price as height. Therefore, when adding trades cost and earnings, only the cost of the commissions remains, since what is paid by the consumers for electricity is what is received by the producers.

Overall, if the agreed price was lower, the consumers would be able to increase their consumption while being in their demand curves, increasing the total consumers' utility. However, the higher demand would imply a higher production, hence increasing production and commission costs. The same can be said on increasing the prices, where demand would be lower, lowering utility, but also lowering production and commission costs. Therefore, what the algorithm does is find the optimum price at which increasing or decreasing the agreed price would cause a decrease in total social welfare.

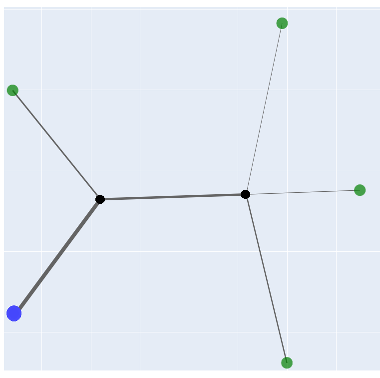
The same logic for this simple case can be applied to cases with more consumers, multiple producers, less trivial architecture and different agreed prices, resulting in more complex problems solved by the ADMM algorithm.

### Optimization results

The results from the optimization process are graphically depicted in Figure 4.7, where the trades between agents are represented as lines between nodes whose width is proportional to the amount of electricity traded. Consumers are represented in green, producers in blue and virtual agents (CMs in this case) in black:



(a) P2P



(b) 2 connected communities

Figure 4.7: Graphical results of the market architecture examples presented in Figure 4.5. Based on [Moret, 2020].

The actual values of trades ($t_{i,j}$) are stored in trades matrices $\mathbf{T}$, as the following ones:

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP |
|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 5.15 |
| **Cons 2** | 0 | 0 | 0 | 0 | 6.64 |
| **Cons 3** | 0 | 0 | 0 | 0 | 13.66 |
| **Cons 4** | 0 | 0 | 0 | 0 | 14.68 |
| **PP** | -5.15 | -6.64 | -13.66 | -14.68 | 0.00 |

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP | CM 1 | CM 2 |
|---|---|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 0 | 5.15 | 0 |
| **Cons 2** | 0 | 0 | 0 | 0 | 0 | 6.58 | 0 |
| **Cons 3** | 0 | 0 | 0 | 0 | 0 | 13.56 | 0 |
| **Cons 4** | 0 | 0 | 0 | 0 | 0 | 0 | 16.07 |
| **PP** | 0 | 0 | 0 | 0 | 0 | 0 | -41.36 |
| **CM 1** | -5.15 | -6.57 | -13.56 | 0 | 0 | 0 | 25.29 |
| **CM 2** | 0 | 0 | 0 | -16.07 | 41.37 | -25.29 | 0 |

Table 4.4: Trades($\mathbf{T}$) matrices for the examples of Figure 4.5.

Moreover, the prices perceived for each trade are also calculated with the resulting price of each node ($\tau_{i,j}$) and the specific commission applied ($c_{i,j}$), as previously explained. For the same two examples than above, the two resulting perceived price matrices are the following:

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP |
|---|---|---|---|---|---|
| **Cons 1** | 0 | n/a | n/a | n/a | 0.128 |
| **Cons 2** | n/a | 0 | n/a | n/a | 0.128 |
| **Cons 3** | n/a | n/a | 0 | n/a | 0.128 |
| **Cons 4** | n/a | n/a | n/a | 0 | 0.128 |
| **PP** | 0.158 | 0.158 | 0.158 | 0.158 | 0 |

| | Cons 1 | Cons 2 | Cons 3 | Cons 4 | PP | CM 1 | CM 2 |
|---|---|---|---|---|---|---|---|
| **Cons 1** | 0 | 0 | 0 | 0 | 0 | 0.154 | 0 |
| **Cons 2** | 0 | 0 | 0 | 0 | 0 | 0.154 | 0 |
| **Cons 3** | 0 | 0 | 0 | 0 | 0 | 0.154 | 0 |
| **Cons 4** | 0 | 0 | 0 | 0 | 0 | 0 | 0.134 |
| **PP** | 0 | 0 | 0 | 0 | 0 | 0 | 0.134 |
| **CM 1** | 0.159 | 0.159 | 0.159 | 0 | 0 | 0 | 0.134 |
| **CM 2** | 0 | 0 | 0 | 0.139 | 0.129 | 0.154 | 0 |

Table 4.5: Perceived price matrices for the examples of Figure 4.5.

In Table 4.5, it can be clearly seen how in the case of 2 connected communities the price of buying electricity from within the community (which is the case of consumer 4 at 0.139 c€/kWh) is lower than buying electricity in the other community (which is the case of consumer 1, 2 and 3 at 0.159 c€/kWh). This is the result of applying the different designed commissions to the applicable prices of electricity. Moreover, with both examples, it can be seen how the net price received by the producer is always lower than the price that the consumer pays for it, as there are costs associated with using the system.

With each actor trades and perceived prices, their utility, trade costs and total costs can be calculated. As explained before, the negative utility of consumers or the production costs of the producers, can be expressed as $Neg_{utility} = \sum_{i,k}\left(b_{i,k} \cdot P_{i,k} + \frac{a_{i,k}}{2} \cdot P_{i,k}^2\right)$. At the same time, trade costs (which can be negative in case of producers as trades represent an earning) is the result of multiplying trades times the agreed prices plus or minus the applicable commission, depending if the energy is bought or sold: $Trades_{cost} = \sum_{i,j}(\tau_{i,j} \cdot t_{i,j}) + \sum_{i,j}(c_{i,j} \cdot |t_{i,j}|)$. The total costs for each market agent is the sum of their negative utility/production costs plus the trade costs: $Total_{cost} = Neg_{utility} + Trades_{cost}$. For the P2P example treated above, Table 4.6 displays all these costs for each market agent, as well as relative costs with respect to the net power either consumed or produced:

| **Agent** | **Net prod (kW)** | **Neg utility (c€)** | **Trades cost (c€)** | **Total cost (c€)** | **Relative neg utility (c€/kW)** | **Relative Trades cost (c€/kW)** | **Relative total cost (c€/kW)** |
|---|---|---|---|---|---|---|---|
| **Cons 1** | -5.15 | -106 | 81 | -25 | -20.7 | 15.8 | -4.9 |
| **Cons 2** | -6.64 | -156 | 105 | -51 | -23.5 | 15.8 | -7.7 |
| **Cons 3** | -13.66 | -347 | 216 | -131 | -25.4 | 15.8 | -9.6 |
| **Cons 4** | -14.68 | -304 | 232 | -72 | -20.7 | 15.8 | -4.9 |
| **PP** | 40.13 | 417 | -513 | -96 | 10.4 | -12.8 | -2.4 |
| **TOTAL** | 0 | -496 | 120 | -376 | | | |

Table 4.6: Costs and social welfare results for the P2P example from Figure 4.5

As it can be seen, all consumers obtain a positive utility component due to their consumption being within their desired consumption interval, between $P_{min}$ and $P_{max}$. Moreover, the bigger their net consumption is, the more absolute utility they will obtain. This also happens the bigger their demand curve parameters $a$ and $b$ are (which happens with high $L_{min}$ and $L_{max}$ and a high difference between both), as it can be observed by the results of relative negative utility. For instance, consumer 3 has the highest relative negative utility, and the highest and more different prices, see Table 4.1. These results already show that those larger consumers with more ability to pay have more weight in the optimization process given the objective function (Eq 4.4b). For this reason, the resulting prices will be generated to satisfy them more than smaller consumers.

Other than utility, consumers have positive costs of trades, also proportional to the amount of power exchanged and depending on the applicable commissions. As it can be observed, if agreed prices and commissions are the same, relative trade costs (average perceived prices) are also the same.

In parallel, Table 4.6 shows how the producer of the example obtains a positive production cost for the total amount of electricity generated. However, its costs are recovered by the earnings resulting from trading with consumers, leaving the producer with a net profit of 96c€. This can be seen graphically in Figure 4.6 as the rectangular area from $P_{prod}$ and the perceived production price is greater than the area below the supply curve between 0 and the total production.

On one hand, analysing the first column of Table 4.6 it can be observed how the total utility of the system remains positive, as by the way it is quantified the satisfaction of consumers out-weights the production costs borne by the producer. This can be graphically seen in Figure 4.6 as the sum of the areas below the demand curves from 0 to the consumption of each consumer is greater than the area below the supply curve of the producer between 0 and the total production.

On the other hand, the second column of Table 4.6 shows that total trade costs are positive, which is the consequence of commission related costs, paid both by both producers and consumers. Since there is reciprocity of prices and trades, the cost of energy doesn't have an influence on the total trades costs. This means that the agreed price does not directly affect the total social welfare of the system, it only marks the consumption that each consumer can have and thus the total utility. Due to the trade cost part, it is the commissions that directly determine the behaviour of the agents.

Overall, the total costs of this example's system are negative, which means that the total social welfare is positive. In this case, the system has been optimized at a maximum social welfare of 376 c€, while respecting all constraints. The SW value *per se* does not mean anything, since it has mixed real costs with the "price" given to the user's satisfaction. Hence, it is merely used as a tool to compare markets with similar characteristics, since the higher the SW the more satisfied are their users.

To sum up, through this section it has been explained how decentralised markets can be modelled using a unified formulation, which allows representing the different market architectures presented in Section 4.1.2 and answers this Thesis' first sub-question. It has been seen how the key aspects of this model are the modelling of agents, the implementation of tailored commissions and the design of the objective function itself. Moreover, it has been observed how the results of the model can be interpreted. With all that, it is now possible to make modifications to this model to answer the second and third sub-questions.

## 4.2 Modifications to the Decentralized Electricity Market Base Model

Once the decentralized model from Section 4.1 has been explained, the next step is to propose modifications so that the RQ can be answered. In Figure 4.8, a representation of the inputs and outputs of the model can be seen, including this Thesis' proposed modifications.

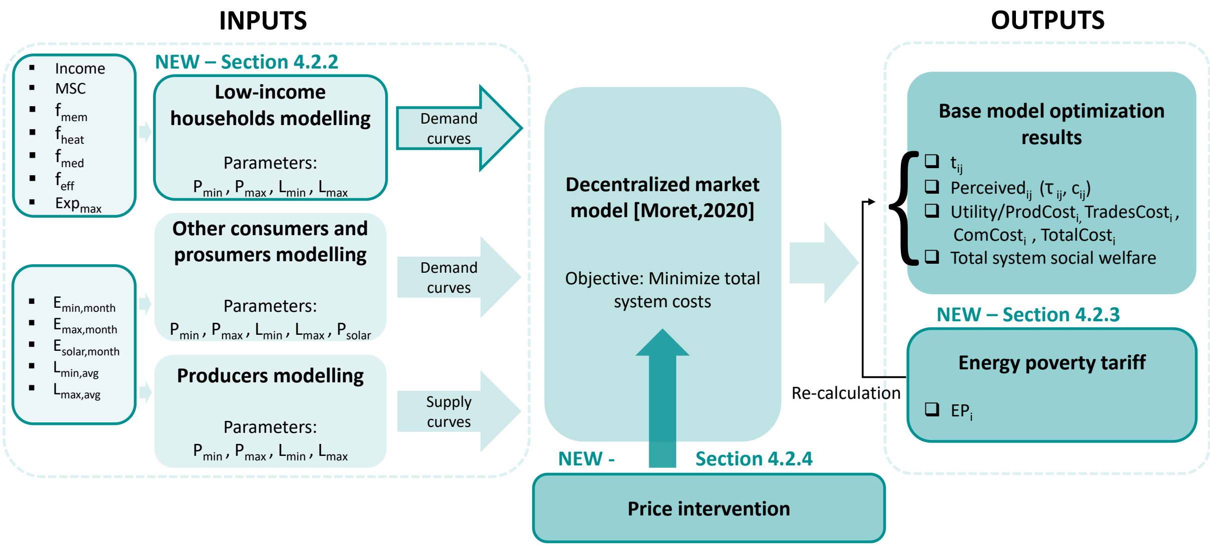



Figure 4.8: Model scheme, including the proposed modifications from this section. Own elaboration.

Proposed modifications include a new methodology for modelling low-income households, the design of an Energy Poverty tariff and the design a Price Intervention scheme. In order to understand how these modifications can be included, this section starts by defining the time frame used in the model.

### 4.2.1 Time frame

On one hand, for an ideal operation of the used market model non-strategical hourly bids for each market agent would have to be provided, that is each agent's $P_{min}$, $P_{max}$, $L_{min}$ and $L_{max}$, as introduced in Section 4.1.1. However, how market agents -especially consumers-could submit their hourly bids in a real-life application is still not clear, being one of the areas where more research is needed in the study of decentralised electricity markets [Mengelkamp et al., 2017]. This makes simulating hourly bids a task out of the scope of this Thesis. Moreover, since it is not possible to identify situations of energy poverty in an electricity market from the behaviour of agents on one specific hour, a bigger sample time is needed. In this case, using a time frame of a month appears to be a reasonable solution so that consumption and expenditure on electricity can be observed in a more representative way. For this reason, instead of simulating directly hourly bids, monthly values need to be used, with prices being equivalent to monthly averages and consumption and production being monthly totals in kWh.

On the other hand, despite bids can only be simulated as monthly values, the market is designed to find an optimum for hourly operation, as its calculations depend on the values of $P$ in kW. If monthly values would be used instead of hourly ones, utility and production cost, which are quadratic functions with respect to production and consumption values, would have a disproportionate weight in the optimization process compared to trades and commission costs, as they are linear to production and consumption values. This shows the need to use hourly values in the used model.

The found solution has been to translate monthly bids to an equivalent hour-type, so that the magnitude of the values resemble what could be found in real market operation, see Equation 4.5:

$$P[kW] = \frac{Energy_{month}[kWh/month]}{24[h/day] \cdot \frac{365}{12}[day/month]} \tag{4.5}$$

The proposed methodology will be based on using monthly values, converting them into an equivalent hour-type to solve the market, and converting the results back to the monthly time frame. With that, the goal is to modify the existing model so that these modifications are time-independent, and thus can be introduced in the base model.

Although the results in a real-world implementation are expected to differ since not all the consumers have the same pattern of consumption -among other simplifications- it is believed that the results to be obtained are relevant and can be used to draw conclusions on the overall market operation. The impact that this simplification has on the results will be further discussed in Chapter 6.

### 4.2.2 Building demand and supply curves for market agents

As seen in Section 4.1.1, the modelling of agents is one of the key aspects of the market model used in this Thesis. It has been seen how agents are characterized by their demand or supply curves, which are built with their $P_{min}$, $P_{max}$, $L_{min}$ and $L_{max}$.

To obtain these capacities and prices, the methodology explained in this section is adopted. Three main agents are identified: low-income households, other households and commercial consumers, and producers. Specific methodology for each type of agent is then developed, as represented in Figure 4.9:

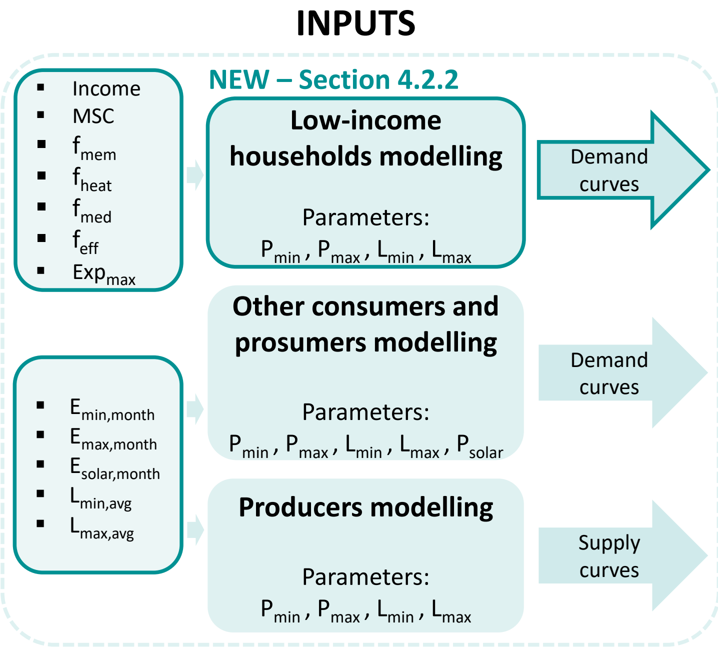



Figure 4.9: Model inputs scheme. Own elaboration.

### Low-income households

In order to ensure that low-income consumers can have a guaranteed minimum consumption at affordable prices, it has been chosen to model their demand curves in a different way than other consumers. This includes the issue of precarious access to electricity in the market modelling and thus answers sub-question 2.

Instead of receiving bids from them with the consumption they can afford at retail prices, it has been decided that their bids should reflect the price they can afford for a minimum standardized consumption, using the monthly time frame explained previously. In this way, their utility function better shows their true satisfaction with the obtained market price. Moreover, modifications to the model can be done afterwards to ensure that with a minimum standardized consumption, low-income households have a final welfare similar to other consumers.

In reality, vulnerable households would have to let know some key parameters such as income and the main characteristics of the household to the optimization algorithm so that they could be taken into account. The amount of low-income households would therefore be known beforehand. This gathering of information could be done through social services or other governmental institutions in a similar way to with already existing energy poverty alleviation mechanisms. Hence, an application process could be implemented with specific requirements so as to be able to obtain the status of vulnerable household and therefore be treated differently in the market.

In this case, the low-income households bidding is done automatically by the algorithm. First, a Minimum Standard Consumption (MSC) is defined to account for the minimum expected monthly consumption that guarantees a basic standard of living, which can be different in each specific location and time of the year. This MSC is then multiplied by different correction factors. Based on Figure 1.1, these multiplying factors account for the members of the household ($f_{mem}$), whether they use electric heating ($f_{heat}$), whether they have a member that requires mechanical support through vital medical devices ($f_{med}$) and the efficiency of the household ($f_{eff}$). Hence, the minimum monthly energy consumption ($E_{min-cons}$) is calculated in Equation 4.6b for all the low income households (those agents $i$ in the set $LowInc$), and also its equivalent consumption in an hour-type ($P_{max}$) in Equation 4.6b:

$$E_{min-cons,i}\left[\frac{kWh}{month}\right] = MSC_i\left[\frac{kWh}{month}\right]\cdot f_{mem,i}\cdot f_{heat,i}\cdot f_{med,i}\cdot f_{eff,i}, \quad \forall i \in LowInc \tag{4.6a}$$

$$P_{max,i}[kW] = \frac{E_{min-cons,i}[kWh]}{24\frac{h}{day}\cdot\frac{365}{12}\left[\frac{day}{month}\right]}, \quad \forall i \in LowInc \tag{4.6b}$$

$E_{min-cons,i}$ is fixed to avoid those cases where vulnerable households go below acceptable standards of living to lower their electricity bill. The minimum standard consumption, as well as the value and distribution of the different factors, should be set according to the specific context of where the system is implemented.

For the pricing part of the bidding, information on income is to be used. First, an established maximum percentage of expenditure ($Exp_{max}$) on electricity is introduced, to limit the impact that the electricity bill has on vulnerable consumers. The budget that vulnerable households have to spend on electricity is thus limited to $Exp_{max}$ times their income. Dividing monthly consumption by the available budget the $L_{max}$ is obtained:

$$L_{max,i} = \frac{E_{min-cons,i}}{Exp_{max,i}\cdot Income_{household-month,i}}, \quad \forall i \in LowInc \tag{4.7}$$

Summing up, the main inputs for the modelling of low-income households are their income, the different multiplying factors according to the household characteristics ($f_{mem}$, $f_{heat}$, $f_{med}$, $f_{eff}$ and $f_{Pmin-Pmax}$), the minimum standard monthly consumption ($MSC$) and their maximum percentage of expenditure on electricity ($Exp_{max}$). With these, the monthly hour-type equivalent $P_{max}$ and $L_{max}$ are calculated. Moreover, in this case, this type of agents are assumed to have a maximum consumption $P_{min}$ slightly higher than $P_{min}$ and a $L_{min}$ slightly lower than $L_{min}$ (both by randomized factors), only to be able to obtain demand curves and thus be able to calculate utility values, which is done in the objective function, as seen in Equation 4.4.

### Other households and commercial consumers

For the case of other households and commercial consumers, in real case application minimum and maximum monthly consumption as well as minimum and maximum prices could be obtained from the information known for the previous month. Then, the hour-type equivalent values $P_{min}$, $P_{max}$ as well as the prices $L_{min}$ and $L_{max}$ could be calculated.

To simulate these consumers bid prices can be set as similar to current retail prices, as consumers under this category are expected to be able to afford them. Large consumers such as factories can however have slightly lower bid prices because they typically acquire better deals with the supplier. Moreover, some variability between consumers should be included, to account for the different supply prices as well as for the different behaviour of each consumer. With respect to consumption, all maximum and minimum monthly values can be directly assumed for the different consumer types using available consumption data.

**Producers**

Producers are divided into two groups: the non-dispatchable RES such as wind turbines and solar PV, and traditional power plants (PP).

Non-dispatchable RES are modelled to have no marginal cost and a bid price of zero, and therefore their cost function is also zero. This means that all their electricity is automatically sold in the market. This simplification well models the process of selling non-dispatchable renewable energy when there are also other dispatchable electricity production units with non-zero cost functions, but it has its limitations when the system is 100% renewable. However, this case is largely improvable when a monthly time frame is used. For non-dispatchable RES, only their maximum possible monthly production is needed for the simulation, which will be converted to $P_{max}$.

Solar PV plants are considered to be installed behind-the-meter for self-consumption. They are also non-dispatchable and therefore are always used by the prosumer, having a zero-cost function. If the prosumer consumption is higher than its Solar PV production, the surplus electricity does not enter the market. However, if there is a surplus, it is to be sold to other market agents. To simulate a prosumer the only parameter that is therefore needed is the monthly Solar PV production which can be converted to an equivalent $P_{solar}$.

For power plants, since their cost functions are not zero, in addition to their hour-type monthly equivalent $P_{max}$, their $L_{min}$ and $L_{max}$ are also needed.

### 4.2.3 Energy poverty tariff design

As the second addition to the decentralized market model developed by Moret [2020], a social or energy poverty tariff has been introduced to reduce precarious access to electricity among low-income households, which have been previously modelled as explained in Section 4.2.2. The tariff calculation method is represented schematically in Figure 4.10:

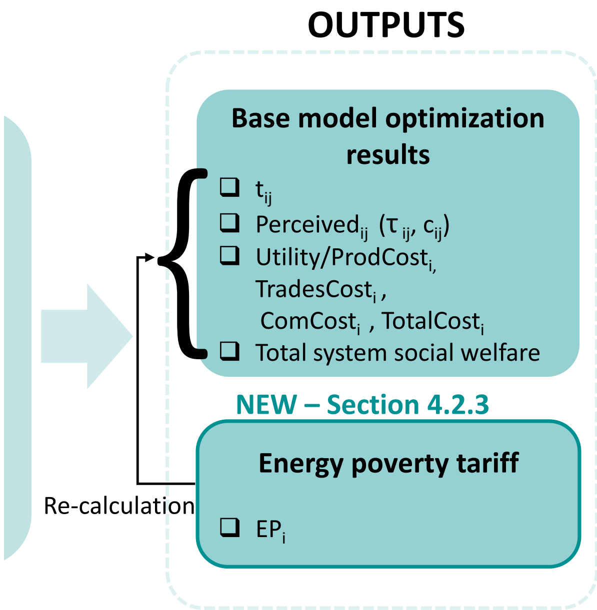



Figure 4.10: Energy Poverty (EP) tariff calculation method. Own elaboration

The designed tariff redistributes social welfare within the modelled system, as it transfers part of the social welfare from those without electricity affordability issues and those who directly benefit from the system, to those in need. For this reason, this tariff is to be paid by satisfied producers and consumers (and/or partially financed by state taxes) while it acts as a subsidy for vulnerable households so that they can afford a minimum standard level of consumption. This is aligned with the SSE as described in Section 2.1.1, specifically with the following SSE principle: "use of any surplus towards sustainable development and the general interest".

The intention of this section is to design a tariff in (c€/kWh) which is tailored to each market agent, varies every month, can work for all the previously stated market architectures and is calculated after the initial base model optimization solution. This is different from current approaches for similar energy poverty alleviation mechanisms, as tariffs to be paid are the same for all market agents and because vulnerable households typically receive the subsidy in the form of fixed checks [EPOV, 2020b]. Since it is calculated by the market algorithm itself, tailored to each market agent and it directly modifies the perceived electricity price of low-income households, the designed tariff can be considered a direct market measure (see Innovative Democracy theory in Section 2.1.3).

A benefit of the explained approach is that the constant update of tariffs ensures that those that can afford it on a monthly basis are those who pay more for electricity, at the same time that it prevents agents from abusing the system since targeted households can be required to prove their vulnerable status each decided period of time and have the subsidy removed if necessary.

#### Low-income households received Energy Poverty tariff

Low-income households receive the Energy Poverty tariff according to the deficit of budget they have in order to be able to afford the minimum standard level of consumption that ensures decent standards of living, which is $E_{min-cons}$ as developed in Section 4.2.2. As displayed in Equation 4.8, the deficit of budget of low-income households is calculated as the difference between what they would spend on electricity with the initial market solution and what they can really afford for $E_{min-cons}$, which is $L_{max}$:

$$Deficit_i = TradesCost_{initial,i} - L_{max,i} \cdot |P_{max,i}|, \quad \forall i \in LowInc \tag{4.8}$$

To calculate the energy poverty tariff in c€/kWh, it is enough to divide the deficit of budget by the level of consumption which households are modeled to have when perceiving $L_{max}$: $E_{min-cons}$ or $P_{max}$ in an hourly basis:

$$EP_i = \frac{Deficit_i}{P_{max,i}}, \quad \forall i \in LowInc \tag{4.9}$$

It is important however to introduce a cap on the support that can be received so as to avoid the abuse of the system. This is done by limiting at $E_{min-cons}$ the amount of electricity for which a social tariff can be received. If a low-income household is to consume more than $E_{min-cons}$, a possible option would be that the full market price is to be paid for the extra consumption.

Typically low-income households (without considering the energy poverty tariff) will perceive an average price for electricity higher than $L_{max}$. The EP tariff for each vulnerable household is such that the final average perceived price is equal to their $L_{max}$:

$$Perceived_{avg,final,i} = L_{max,i} = \frac{\sum_j (\tau_{i,j} + c_{i,j}) \cdot t_{i,j}}{\sum_j t_{i,j}} - EP_i, \quad \forall i \in LowInc \tag{4.10}$$

The new perceived prices allow these type of consumers to be placed on their demand curve and consume a minimum standard consumption, tailored for each case depending on the household characteristics. Therefore, their overall utility will drastically increase.

**Energy Poverty tariff financing**

In order to be able to guarantee that low-income households receive an affordable price of electricity as a result of applying the EP tariff, this mechanism has to be financed somehow. Three alternatives are proposed:

The first option is to **finance the tariff publicly**. This would mean that the financing comes from already existing general taxation schemes and results in a money allocation problem for the public authority. This has a clear advantage, simplicity, since there is no need to further analyse the market. However, this also means that the issue of e precarious access to electricity is externalised and not solved internally in the market.

The second financing option would be to **charge the totality of the tariff to the large producers** since they are the ones with an economic profit, understood as the difference between the cost of production and earnings. The total cost of the tariff could be split between the different producers proportionally, according to their benefits. The downside of this option would be to disincentivize producers to join the market if their profit margin is reduced substantially.

The last proposed option is to **proportionally distribute the cost of this tariff among satisfied market agents** so that the total social welfare of the system remains the same. With this solution not only producers would partially finance the tariff with their earnings, but other non-vulnerable consumers would also contribute. A way of doing that could be to divide the total needed contribution of consumers by the sum of their total consumption so that all non-vulnerable consumers would have the same tax. However, it could be done more fairly using the tools that the decentralised market model provides, as explained in the following section.

**Proportional tariff financing**

First of all, not all consumers which do not have the vulnerable status are to finance the EP tariff. Some of them are also in a situation of discomfort with their average perceived price being higher than their $L_{max}$ and are therefore paying for $P_{max}$ more than they would want as defined in their demand curves. These type of consumers will be excluded from contributing to the social tariff.

Consumers that could finance the tariff are those that are paying a perceived price lower than their maximum price $L_{max}$, and therefore are consuming more than the minimum $P_{max}$. For those, increasing their perceived price through a tariff would mean that they would simply reduce their consumption since they are not at a minimum. To put it in other words, instead of being able to afford to turn on a certain amount of appliances, they would simply be stimulated to turn on a little less of them. The amount of money that consumers could provide without leaving their demand curve - their margin or maximum possible contribution - can be calculated as with Equation 4.11:

$$Margin_i = max\left(\left(L_{max,i} - \frac{TradesCost_i}{\sum_j t_{i,j}}\right) \cdot (|P_{max,i}| - P_{solar,i}), 0\right), \quad \forall i \in NetCons \notin LowInc \tag{4.11}$$

Note that in the case of prosumers that are net consumers, their minimum consumption is $P_{max}$ - $P_{solar}$, since their self-consumption share needs to be accounted for.

In parallel, the maximum possible contributions of net producers are equal to their net earnings, provided they have any. It is worth mentioning that while for non-renewable producers with non-zero supply curves $ProductionCosts_i$ have been calculated from their cost functions, for non-dispatchable renewable energy producers $ProductionCosts_i$ have been obtained from their Levelized Cost of Energy (LCoE). This is to account for the real costs of energy despite their bid prices are modelled to be zero.

$$Margin_i = max\left(Earnings_i - ProductionCosts_i, 0\right), \quad \forall i \in NetProd \tag{4.12}$$

However, the goal is not to force all these agents to contribute their maximum margin (and so force consumers at their minimum consumption), but to identify which consumers are more benefited from the market and make them proportionally contribute.

The proposed scheme is that consumers give a share of their margin so that they can finance a part of this tariff, the rest of which will be paid by producers. The numbers of these shares can be determined for each specific case. For instance, as Equation 4.13 generally displays, it could be decided that the consumers give up to 20% of their margin to finance the tariff, but never financing more than 40% of the total cost of the support scheme.

$$\begin{aligned} & & Contribution_i = Margin_i \cdot \%_{IndividualContr}, \\ where \quad & \sum_i Contribution_i \leq & \sum_{k \in LowInc} (Deficit_k) \cdot \%_{MaxTotalContr}, \\ & & \forall i \in NetCons \notin LowInc \end{aligned} \tag{4.13}$$

Producers would proportionally give their margins to finance the rest of the tariff mechanism, as it is represented by Equation 4.14. However, prosumers with net production are excluded from having to pay this tariff so as to incentivise their proliferation. Moreover, as their production is very low with respect to other producers, this does not have a high impact on the rest of the needed contributions.

$$\begin{aligned} Contribution_{NetProd} &= \sum_{k \in LowInc} Deficit_k - \sum_{l \in NetCons \notin LowInc} Contribution_l, \\ Contribution_i &= \frac{Margin_i}{\sum_i Margin_i} \cdot Contribution_{NetProd}, \\ & \forall i \in NetProd \end{aligned} \tag{4.14}$$

Once the contribution of each agent has been determined, the next step is to determine their applicable EP tariffs. It is important that these tariffs are calculated using each agent's final net consumption and not the calculated one with the initial average perceived price. The final net consumption of these agents corresponds to the one they can afford at a final average perceived price, including the EP tariff itself. That is to take into account the effect that an increase in prices due to the EP tariff would have on consumers' behaviour since they would tend to consume less. For this reason, a slightly more complex formulation than with net producers is to be used, as displayed in Equation 4.15:

$$\begin{aligned} Contr_i &= P_{final,i} \cdot EP_i = P_{final,i} \cdot (Perceived_{final,i} - Perceived_{initial,i}) \\ Contr_i &= \frac{Perceived_{final,i} - b_i}{a_i} \cdot (Perceived_{final,i} - Perceived_{initial,i}) \\ & \forall i \in NetCons \notin LowInc \end{aligned} \tag{4.15}$$

The contribution of each satisfied net consumer can be understood as its $P_{final}$ times the applicable EP tariff. $P_{final}$ is known to be on the demand curve since consumers that pay the EP are not forced to their minimum consumption, but only to slightly reduce their consumption. Therefore, the $a$ and $b$ parameters of the demand curve can be used. The only unkown value is that of $Perceived_{final}$, which can be obtained solving the second degree Equation 4.15. Then, the EP of each agent is obtained as the difference between final and initial perceived prices, as seen in Equation 4.16:

$$EP_i = Perceived_{final,i} - Perceived_{initial,i}, \quad \forall i \in NetCons \notin LowInc \tag{4.16}$$

For producers, the same needs to be done since the commissions have to be paid according to their $P_{final}$. In this case, due to power balance, the $P_{final}$ of each production unit can be calculated after calculating the one for net consumers. For the non-dispatchable RES, the $P_{final}$ will be the same as the $P_{initial}$, since all their electricity is considered to be always sold in the market. For Power Plants, it has been chosen to reduce their production homogeneously – the same percentage of reduction for all power plants – so as to satisfy the new reduced consumer demand. This is a simplification since ideally those producers with higher marginal costs reduce their production more than those with a lower one. However, it is believed that the impact of this simplification can be neglected. With the new $P_{final}$ and the $Contribution$ calculated in Equation 4.14, the $EP$ tariff of net producers is calculated as:

$$EP_i = \frac{Contribution_i}{P_{final,i}}, \qquad \forall i \in NetProd \tag{4.17}$$

With this third method of Energy Poverty financing, a more proportional and fair Energy Poverty tariff can be obtained for each of the agents of the market. With it, those agents that are currently more satisfied can give up part of their welfare so that those households with precarious access to electricity can have a minimum and affordable consumption. The total social welfare of the system -which was already at a maximum as a result of the optimization process- is not reduced, but is merely redistributed among its agents as will be seen in Chapter 5.

With the calculated EP tariffs for each agent, the final average perceived price and net consumption/production are found, and with these utility/production costs, trades costs, commission costs and total costs can be recalculated, showing the redistributive effects of the proposed Energy Poverty tariff.

For further clarity and discussion, the EP tariff calculation method explained in this section will be applied to different case studies with diverse market architectures, see Section 4.3.

### 4.2.4 Price intervention design

Other than the *a posteriori* application of a monthly energy poverty tariff, an alternative way to alleviate precarious access to electricity is through direct price intervention. As explained in Section 1.5, although discouraged, this type of measure is accepted by the European Commission as an exception if focused on *"energy poor consumers"* and *"vulnerable households"*.

The proposed intervention of prices means fixing the price of trades for low-income households so that their perceived price is the previously calculated $L_{max}$, see Section 4.2.2. In this way, the market becomes a semi-free market, with price intervention for specific trades and price-setting through market optimization for the rest of them.

In order to set the price for low-income households' electricity, a constraint has been set to the base model optimization algorithm, Equation 4.18:

$$\begin{aligned} \tau_{i,j} =& L_{max,i} - c_{i,j} \\ \tau_{i,j} =& \tau_{j,i}, \qquad\qquad \forall i \in LowInc \end{aligned} \tag{4.18}$$

As it can be seen, the intervened price is fixed as the maximum price that low-income households can afford for a minimum level of consumption minus the tariffs applicable to the trade, $c_{i,j}$, considering that low-income households also need to pay for system tariffs.

The price $\tau_{i,j}$ is the dual variable of the trade $t_{i,j}$ in the optimization problem that the market solves. This means that for the problem to converge, it is also necessary to initially fix the quantity of each trade. It is known that low-income households will be consuming their $E_{min}$, but it is unknown how this consumption will be distributed among their available trading partners. To fix this issue, the final share of each low-income household's consumption that each producer will assume is calculated to be proportional to the total earnings it would have under a free market scheme as seen in Equation 4.19. Net producer earnings are obtained after solving the market and, for non-dispatchable renewable producers with 0 supply curves, considering the LCoE as the costs of producing electricity. This distribution among producers of the burden that low prices for low-income households represents could also be a factor of decision by the regulator.

$$\begin{aligned} t_{i,j} =& P_{max,i} \cdot \frac{NetEarnings_j}{\sum_{k \in NetProd} NetEarnings_k \cdot p_{i,k}} \\ t_{i,j} =& t_{j,i}, \qquad \forall i \in LowInc \end{aligned} \tag{4.19}$$

Fixing the price of trades for low-income households implies that whoever is selling the electricity to them might go below production costs due to the low $L_{max}$ these agents have, which is regularly lower than average market prices. This can be fixed by readjusting the distribution of costs among contributors or externalising part of the needed support.

The amount of trades that each low-income consumer has with each one of the producers is proportional to the former's net earnings, so as to ensure fair assimilation of the economic burden that this kind of trades might represent. Finally, to stimulate local energy production, prosumers selling surplus electricity are excluded from price intervention and therefore are also excluded from being partners with low-income households.

With this market intervention, it is the large producers who internally assume the extra cost of providing an affordable minimum consumption to vulnerable households. The effects that this mechanism has on the rest of the consumers will be further analysed in Section 5.

## 4.3 Case study

In order to observe how an energy poverty commission and price intervention affect decentralized electricity markets, a case study has been prepared.

The case study is only a mean to be able to show how the market responds to the two proposed energy poverty alleviation mechanisms, thus the only requirement to fulfil is that it is composed of realistic input values, to which some variations will be applied. As long as inputs are realistic, conclusions extracted from the case study are believed to be exportable to other cases with different market agent distributions, thus the specific market agents sample chosen is not deemed as a critical factor.

Due to the heterogeneity of electricity markets, even within the EU, it has been chosen to select one country as the base case: Spain. Therefore, the used market agents sample will be a representative distribution of different types of Spanish consumers and producers with its corresponding demand and supply curves.

Spain has been chosen as the country from which to simulate the base case, as precarious access to electricity is still a live issue that can be observed, despite it is not the country in the worst conditions. Data from 2018 shows that 9.1% of Spanish households were unable to keep the house warm and 7.2% of the population had arrears on utility bills (with 40% of bill payments being charged for electricity). In addition, in 2015 13% of the people had abnormally low expenditure on energy – below half the national median – while 14.2% of households had a share of energy expenditure with respect to income more than twice the national median [EPOV, 2020a]. Moreover, Spain is the country where electricity is less affordable for low levels of consumption, as shown in Figure 1.6.

Spain has also been chosen due to data availability, especially on the percentage of households that can be considered vulnerable and thus in need of support. As depicted in Table 4.7, in 2018 3.03% of consumers received support so that they could face electricity payments.

The case study will be composed of the base Spanish market agent sample to which some variations of key parameters will be applied, as further explained in Section 4.3.2. Moreover, different market architectures will be simulated to further assess the performance of the previously proposed support schemes and the impact that they might have on different agents, which will contribute to the answer to research question number four.

### 4.3.1 Base market agents sample

To obtain the base market agent sable is has been first necessary to define the levels of consumption and supply for each market agent type as well as their range of acceptable prices.

### Consumers sample

First, the average consumption and number of clients per demand band in Spain have been used to define the base case consumer sample. Table 4.7 displays the used information.

| | Num. clients | % Num. clients | Total cons. (MWh) | % cons. | Average cons. (kWh/month) | Average price (€/kWh) |
|---|---|---|---|---|---|---|
| **Low-income** | 889,120 | 3.03% | 2,776,189 | 1.16% | 260 | 0.22 |
| **Households** | 26,706,438 | 90.99% | 65,640,651 | 27.42% | 205 | 0.22 |
| **Stores** | 1,634,412 | 5.57% | 45,494,671 | 19.00% | 2,320 | 0.18 |
| **Malls** | 94,739 | 0.32% | 16,099,205 | 6.72% | 14,160 | 0.16 |
| **Factories** | 22,811 | 0.08% | 56,168,220 | 23.46% | 205,166 | 0.13 |
| **Large factories** | 4,016 | 0.01% | 53,246,447 | 22.24% | 1,104,916 | 0.10 |

Table 4.7: Commercialized electricity and average prices per type of consumer in Spain in 2018. Consumption data from Ministerio para la Transición Ecológica [2018]
and prices from EUROSTAT [2020b]

In Table 4.7 the demand bands under which the distribution of clients, average consumption and prices are simplified and categorized to fit the used market model.

For **low-income households** the only data from Table 4.7 that has been used is the percentage of clients that consumers receiving the *bono social* price scheme represent with respect to the market. These are vulnerable households who receive support in the form of reductions in the electricity bill from 20% up to a 50% [Ministerio para la Transición Ecológica, 2021]. The level of consumption and acceptable prices for this type of consumers have been calculated as presented in Section 4.2.2.

First, a Minimum Standard Consumption (MSC) of 1500 kWh/year and the distribution and values of the different multiplying factors have been assumed as shown in Table 4.8.

| | Distribution | Value |
|---|---|---|
| $f_{mem}$ | 15% of agents with 1 member | 1 |
| | 35% of agents with 2 members | 1.2 |
| | 20% of agents with 3 members | 1.5 |
| | 20% of agents with 4 members | 1.7 |
| | 10% of agents with 5 members | 2 |
| $f_{heat}$ | 1/3 of agents with electric heating | 1.4 |
| | 2/3 of agents without electric heating | 1 |
| $f_{med}$ | 5% of agents with medical equipment | 1.3 |
| | 95% of agents without medical equipment | 1 |
| $f_{eff}$ | Random value between 1 and 1.2 | |

Table 4.8: Multiplying factors distribution for low income households

Low-income households are assumed to have between 1 and 5 members and a multiplying factor ($f_{mem}$) going from 1 to 2. Moreover, according to Cuchí et al. [2017], 33% of the Spanish households in a situation of energy poverty use electricity as their heating source, which represents an increase of 40% of their electricity demand. This has defined $f_{heat}$. The amount of low-income households with a member that requires mechanical support through vital medical devices has been assumed to be 5%, increasing the demand by a 30%. Finally, the efficiency factor ($f_{eff}$) has been assumed as a random value between 1 and 1.2, accounting for the lower efficiency of these type of households. With these values and the considered MSC, the minimum and maximum consumption of each low-income household have been defined.

The range of affordable prices for low-income households has been calculated assuming a maximum percentage of expenditure on electricity of 2.5% to match the country's average as displayed in Figure 1.5. Moreover, household income has been derived from Spain's first decile personal income (523 €/month [EUROSTAT, 2020c]), accounting for the number of household members and adding some random variability. This ensures that the simulated low-income households are in a situation of vulnerability.

For **the rest of consumer types** $E_{min}$ and $E_{max}$ values of each agent have been assumed to be slightly higher and lower than the monthly average consumptions displayed in Table 4.7, adding a randomizing factor to account for the heterogeneity of each category. Their respective ranges of prices $L_{min}$ and $L_{max}$ have been assumed using the average prices under each category also displayed in Table 4.7.

It has been chosen to work with a sample of 200 agents since this amount has been deemed to have a good balance between producing relevant results and respecting the technical limitations of the used model. Moreover, it has been chosen to exclude the large factories from the consumer sample since they represent a very low number of clients. For this reason, following the same distribution of the percentage of the client under each consumer type as Table 4.7, the base case will consist of 6 low-income households, 182 other households, 11 stores, 1 mall and 1 factory. It is worth pointing out that for a factory to be able to be included despite the lower percentage of clients that this demand band represents, its consumption has been reduced.

**Producers sample**

In 2020, 21.6% of the total Spanish electricity production came from wind turbines and 5.7% from utility-scale solar PV installations, hence amounting a total of around 27% of RES in the electricity mix [Red Eléctrica de España, 2021]. This percentage of production will be used in the base study case to calculate the $E_max$ value, although the actual RE production share will be depending on the amount of power consumed in each case.

A traditional PP will also be modelled to provide the remaining energy. In addition, according to Unión Española Fotovoltaica [2021] in 2020 in Spain almost 10% of the households were prosumers, which in the study case translates into 18 household prosumers as well as 1 prosumer store.

Both the prosumers and the non-dispatchable RES are assumed to bid at constant 0 marginal price. However, for non-dispatchable RES their LCoE has been considered in order to reflect their true net earnings, which will mark the level of contribution that these type of producers will have to support vulnerable households. According to (IRENA [2020a]), the LCoE for Spanish wind projects in 2019 was 0.042€/kWh and for solar 0.046€/kWh. Based on these values and observing the descending trend on recent years, the LCoE for RES in Spain in 2021 has been assumed to be 0.03 €/kWh.

For the traditional PP, it has been chosen to use the market price as a reference to build the supply curve. According to the market operator [OMIE, 2021] , the average spot market price in 2019 was 0.0477 €/kWh (with low variation in recent years), so $L_{max}$ has been chosen to be slightly higher than this value – assuming that the modeled PP would not be able to sell electricity in the average pool market for low levels of production – and $L_{min}$ slightly lower, assuming the opposite. Although this is a simplification since the real operating costs of a plant are not used, the used assumption is considered appropriate for simulating an average fossil fuel power plant, whose bids tend to be close to the market clearing price.

### Base market agents sample summary

With all the information presented above, the base market agents sample is created. Table 4.9 shows the number of agents as well as the information regarding their monthly bids.

| | Num. agents | $E_{max}$ [kWh/month] | $E_{min}$ [kWh/month] | $L_{max}$ [€/kWh] | $L_{min}$ [€/kWh] |
|---|---|---|---|---|---|
| **Low-income** | 6 | - | - | - | - |
| **Households** | 182 | [-110, -330 ] | [-340, -400] | [0.20, 0.23] | [0.17, 0.19] |
| **Stores** | 11 | [-2050, -2190] | [-2450, -2630] | [0.18, 0.21] | [0.15, 0.17] |
| **Malls** | 1 | [-12500, -13400] | [-14900, -15850] | [0.17, 0.20] | [0.14, 0.16] |
| **Factories** | 1 | [-30000, -32500] | [-36000, -38300] | [0.15, 0.18] | [0.12, 0.14] |
| **RES** | 1 | $\sum E_{cons} \cdot 27.7\%$ | 0 | 0 | 0 |
| **Power Plants** | 1 | $\sum E_{cons} - E_{RES}$ | 0 | [0.05, 0.07] | [0.03, 0.04] |

Table 4.9: Market agents sample summary table, including number of agents and monthly bids.

Note that the displayed intervals are there to add some variability in the bids of agents under each agent category. Therefore, each market agent will randomly be assigned an $E_{min}$, $E_{max}$, $L_{min}$ and $L_{max}$ value within the corresponding interval.

In addition, prosumers in the base market agent sample have been defined as seen in Table 4.10.

| | Share | Num. prosumers | Solar capacity |
|---|---|---|---|
| **Low-income** | 0 % | 0 | - |
| **Households** | 10 % | 18 | [30,120]% of Emin |
| **Stores** | 10 % | 1 | [30,80]% of Emin |
| **Malls** | 0 % | 0 | - |
| **Factories** | 0 % | 0 | - |

Table 4.10: Prosumers in the market agent sample per type of consumer.

A 10% share of household and store prosumers is assumed based on [Unión Española Fotovoltaica, 2021]. For households, solar capacity is designed to be between 30 and 120% of the maximum consumption, ensuring that some prosumers will have surplus, others will be consumers and others can be self-sufficient.

### Commissions

Once the consumers and producers samples have been defined, the next step is to add the cost of trades other than the agreed price. The average tariffs and taxes to be paid have been obtained from EUROSTAT [2020b], where all tariffs and taxes are depicted as variable costs. These can be directly added to the commission matrix as presented in Section 4.1.2.

Different tariffs are to be paid depending on the nature of the trade, as can be seen in Table 4.11, built based on data from EUROSTAT [2020b].

| | Households | Prosumers | Stores | Malls | Factories | Producers |
|---|---|---|---|---|---|---|
| **Households** | - | 0.002 | - | - | - | 0.006 |
| **Prosumers** | 0.06 + $Neg_{tariff}$ | 0.002 / (0.06 + $Neg_{tariff}$) | 0.05 + $Neg_{tariff}$ | 0.05 + $Neg_{tariff}$ | 0.04 + $Neg_{tariff}$ | 0.006 |
| **Stores** | - | 0.002 | - | - | - | 0.006 |
| **Malls** | - | 0.002 | - | - | - | 0.006 |
| **Factories** | - | 0.002 | - | - | - | 0.006 |
| **Producers** | 0.12 + $Neg_{tariff}$ | -/ (0.12 + $Neg_{tariff}$) | 0.1 + $Neg_{tariff}$ | 0.1 + $Neg_{tariff}$ | 0.08 + $Neg_{tariff}$ | - |

Table 4.11: Commissions to be paid for each trade by the agent in the column when trading with the agent in the row, in €/kWh. Based on EUROSTAT [2020b].

In Table 4.11, the columns show the price that the agent has to pay for each trade depending on the direction of the trade and the trading partner. For instance, a household would have to pay a tariff of 0.12 €/kWh for trading with a power plant, accounting for the distribution and transmission costs as well as taxes, plus a tariff to the market agent in charge of the negotiation of trades, the $Neg_{tariff}$.

In the case that a system with suppliers buying from the pool market is modelled, the negotiation tariff ($Neg_{tariff}$) has been assumed to be 0.05€/kWh and corresponds to the supplier margin. In the case that a decentralised market such as P2P or community is modelled the $Neg_{tariff}$ becomes 0.03€/kWh, corresponding to the cost of using the negotiation algorithm and assuming that with fewer intermediaries this value is lower.

Another important assumption is that when a household is trading with a prosumer with surplus electricity, the tariff of 0.12 €/kWh gets reduced to half this value, since it is to be expected that the trade will not use the Transmission lines and therefore does not have to pay the TSO tariff. Moreover, lower tariffs are there to stimulate these kind of trades. The same is applied for stores, malls and factories, with lower tariffs when compared to households to reflect the prices obtained from EUROSTAT [2020b].

Prosumers can act both as consumers and producers and therefore have different tariffs to be paid depending on the nature of their trade. If a prosumer is selling electricity, it is assumed that a feed-in tariff of 0.002 €/kWh is to be paid. However, when buying from another prosumer or a large producer, the same tariff as the other households is applied.

Finally, it is assumed that Producers have to pay a feed-in tariff of 0.006 €/kWh, slightly higher than the one prosumers have, which encourages local energy production.

## 4.3.2 Building multiple scenarios

Once the base market agent sample has been created, it has been possible to build multiple scenarios. These will allow a much more complete assessment of the operation of the two proposed energy poverty alleviation schemes and will help answer this Thesis last sub-question. Scenarios have been created in the following way:

First, it has been decided to compare the EP tariff and Price Intervention mechanisms with a "free market" operation scheme where no subsidies are given to low-income households. Second, it has been deemed necessary to analyse both schemes under three different market architectures. Last, multiple variations to the base market sample have been created by changing two key parameters: share of renewable energy and amount of low-income households.

### Market architectures

P2P, isolated community and a representation of the current model where suppliers act as intermediaries have been chosen as the three market architectures to analyse. Figure 5.1 graphically represents the base market agent sample under each one of them:

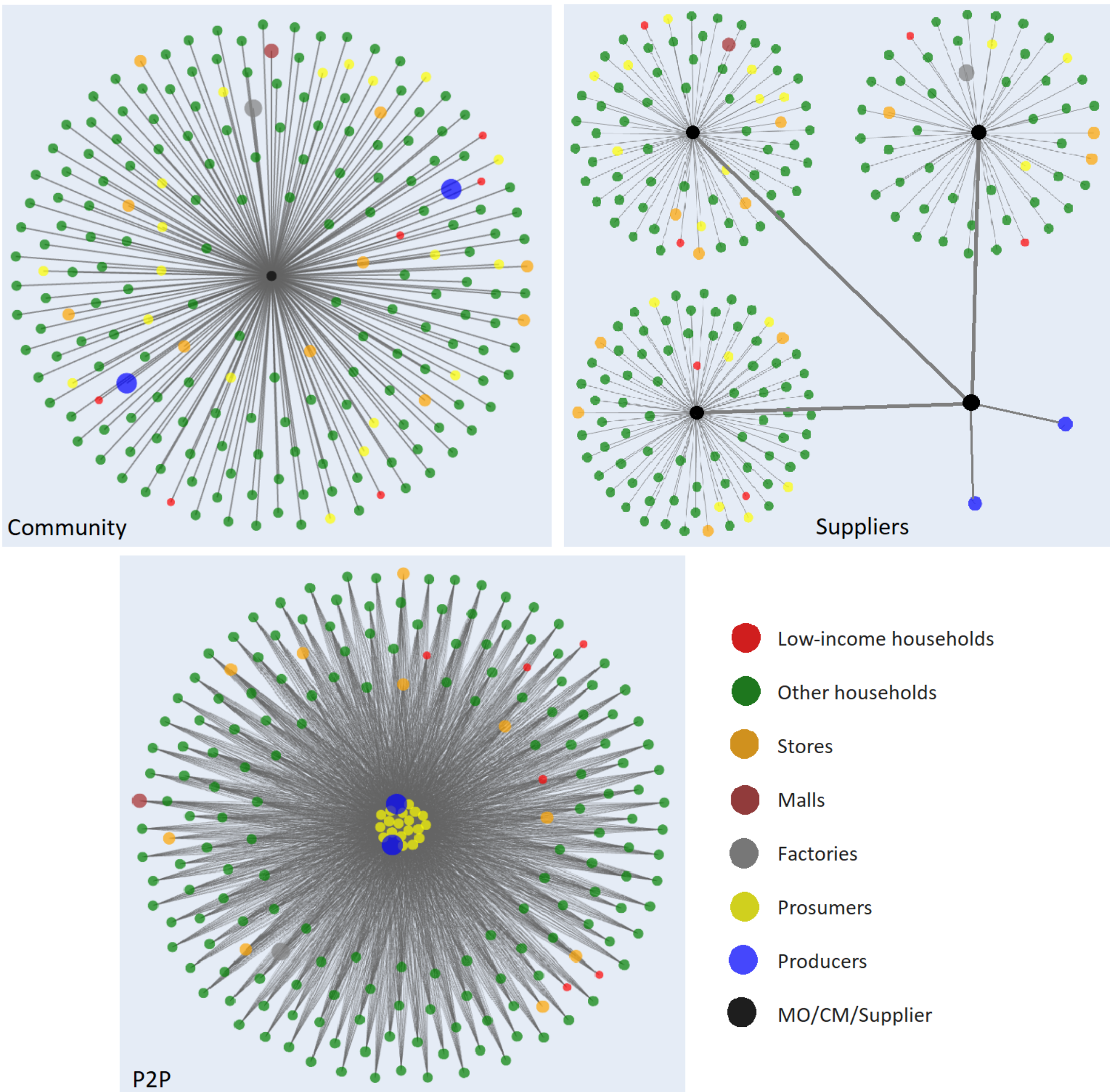



Figure 4.11: Market architectures for the Base Case. Own elaboration, based on the software developed by Moret [2020].

As it can be seen above, in the modelled P2P architecture consumers have only been connected to producers and prosumers and not between themselves. This has simplified the computation of the model and will not affect the obtained results since consumers will optimally not trade among themselves.

The isolated community architecture (also referred to as the "Comm" architecture) simulates a case as a pool market, where all agents interact directly with a common node, which could be a community manager or market operator. In this case, agents are not able to determine the origin of the energy they buy and it has been considered that the energy produced by large producers travels the transmission grid, so the reduction of the TSO tariff when buying from a local prosumer has been dismissed. It is worth pointing out that despite the representation given in Figure 5.1 and as per the rest of market architectures, with the Price Intervention scheme low-income households are modelled to be directly connected to large producers. This enables prices to be set directly between them without affecting the rest of agents, although low-income households continue paying the same taxes and tariffs as the rest of households.

Finally, a simplified version of the current electricity system (also referred to as the "Suppliers" architecture) has been modelled with three suppliers buying energy from two large producers through a pool market operator and selling it to different types of consumers, which are represented as the members of the three virtual communities seen in the above right image on Figure 5.1. In this case, as in the isolated community architecture, agents cannot get a reduced tariff for trading directly with prosumers and in the Price Intervention scheme the producers are directly connected to low-income households.

#### Modifications to base market agent sample

The amount of low-income households and the share of RE in the electricity mix have been chosen as the two parameters to vary in the base market agent sample. These are deemed key factors in order to further assess the robustness of the schemes presented as they have a high influence on the obtained results.

In the Base Case low-income households represent around 3% of the total number of consumers (there are 6 low-income and 182 households), so for more extreme cases it has been chosen to also simulate a market agents sample with 9% of low-income households (resulting in 17 low-income and 153 other households) as well as with an 18% of low-income households (resulting in 34 low-income and 136 other households).

As per the share of RE, while in the Base Case it has been considered a 27%, for more extreme scenarios simulations have also been done with 20% less of share (resulting in a 7% RE Share) and a 40% more (67% RE Share).

With these variations 5 different market agent samples will be created and from now on will be referred to as Base, 7% RE, 67% RE, 9% LowInc and 18% LowInc. It is important to point out that the sole difference between the base market agent sample and each one of the other samples will be one and only one of the two key parameters, either amount of low-income households or the RE share.

**Summary**

The 5 above-mentioned market agent samples (Base, 7% RE, 67% RE, 9% LowInc and 18% LowInc) will be analysed under 3 market architectures (P2P, Comm, and Suppliers) and 3 market schemes will be applied to them: EP tariff, price intervention and free market. This creates a case study of a total of 45 cases to analyse, from which results are depicted in Chapter 5.

# Results and Analysis 5

The present chapter gathers the results obtained from the Case Study which has been described in Section 4.3. All results raw data as well as the software used to obtain them is uploaded as an Appendix.

First, the base market agents sample is analysed under the three different market architectures without the implementation of energy poverty alleviation mechanisms. This is done to first observe the main characteristics and differences of the chosen market architectures as well as how the issue of energy poverty is manifested in them.

Then, the proposed energy poverty alleviation schemes - the EP tariff as well as the Price Intervention- are further tested with the base market agents sample, observing what are their main differences as well as identifying how they operate under the different market architectures.

Finally, variations to the base market agents sample are done as explained in section 4.3.2, observing the sensitivity of the schemes and the model itself to an increase of low-income households and a variation of the RE share in the electricity mix.

Obtained results are analysed in this section and further discussed in Chapter 6.

## 5.1 Analysis of market architectures under a free market scheme

Figure 5.1 displays the total Utility, Trades Costs and Social Welfare per market architecture without implementing any EP alleviation scheme. As explained in Section 4.1.3, Utility accounts for the user satisfaction as well as production costs, Trades Costs for the amount of money consumers pay and producers receive, and Social Welfare is the addition of the previous two and the objective function that the model maximizes (see Equation 4.4).

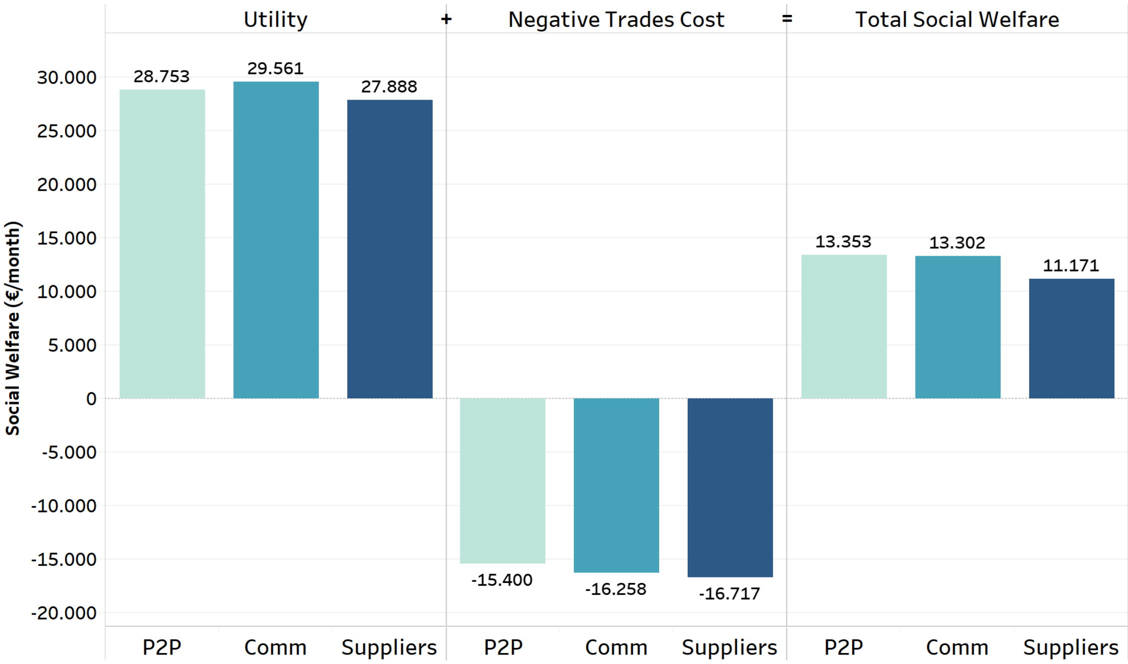



Figure 5.1: Utility, Trades Costs and Social Welfare per market Architecture without energy poverty alleviation schemes. Own elaboration

As it can be seen in Figure 5.1, under a Suppliers market architecture a significantly lower total Social Welfare is obtained when compared to the other two architectures, with P2P's SW being slightly higher than with Community. The lower SW with the Suppliers architecture can be explained due to the addition of the supplier's tariff, which noticeably increases the Trades Costs and also causes a lower energy consumption, which is reflected by the lower obtained Utility.

When comparing the P2P with the Community architecture, it can be observed that P2P's Utility is slightly lower than Community's. This is because there is a higher consumption in the Community architecture, since perceived prices are lower and consumers are prone to consume more than their minimum, which gives them satisfaction. The difference in prices between the two architectures can be explained because in the Community one producers are forced to sell all their electricity at the same price, and cannot offer a custom price for each consumer. In this case, all consumers act as a single big one and have more power influencing the market price. On the other hand, when observing Trade Costs, it can be seen how they are lower under P2P despite having higher prices, since there is less electricity being traded. In spite of that, in the end lower prices under the Community architecture end up causing a lower total SW, mainly because Producers are less satisfied and have their earnings reduced, which does not compensate for the increase of Utility by the consumers.

Other than the total Welfare of the system it is relevant to observe how it is distributed among the different agents. Figure 5.2 shows this distribution with a P2P market architecture.

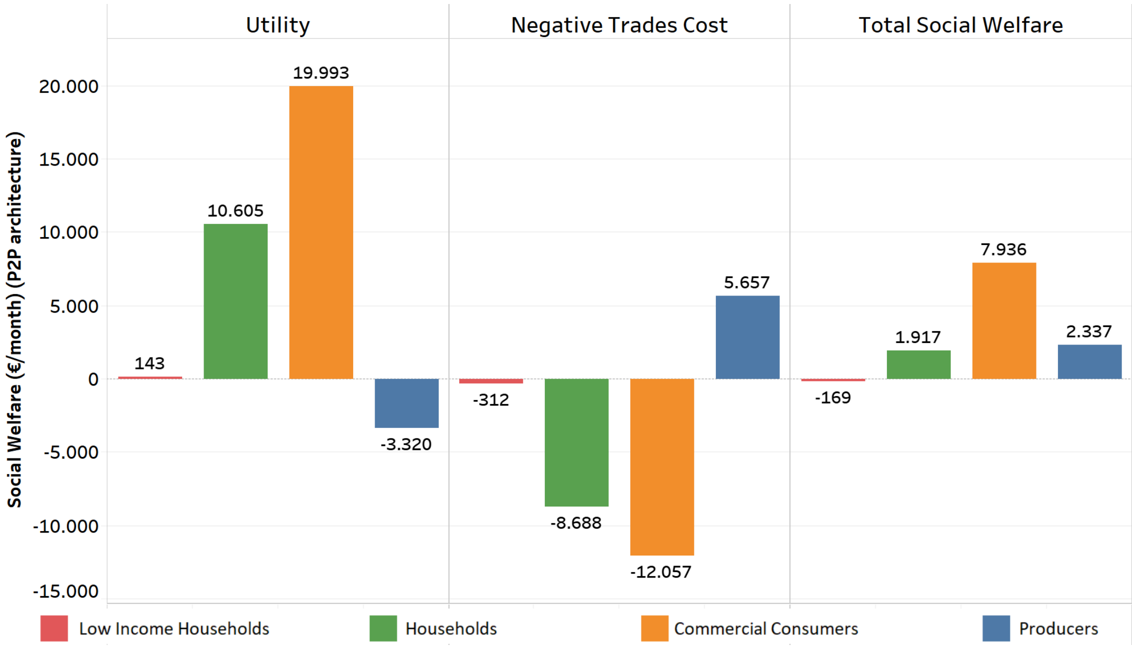



Figure 5.2: Utility, Trades Costs and Social Welfare per type of agent in the P2P market Architecture without energy poverty alleviation schemes. Own elaboration

As it can be seen, commercial consumers (which includes stores, malls and factories) have the highest share of final SW, followed by households (including prosumers) and producers, whose Utility and Trades Costs have opposed signs. The same distribution is present in the Community and Suppliers architectures.

It is worth pointing out that because of the buying and selling prices of trades, prosumers tend to consume what they produce instead of reducing their consumption to sell surplus electricity. This means that most prosumers end up being self-sufficient, or almost self-sufficient, and therefore having a negligible interaction with the market, also since only the monthly net electricity exchanges with the market are modelled. Prosumers only buy electricity when their production cannot cover their minimum desired demand and only sell when they have more production than their maximum desired consumption. Because their interaction with the market is very limited, prosumers are not displayed as a separated market agent type in the different analysis.

Price setting is done in order to maximize the total Social Welfare of the system, which is the sum of each market agent's Social Welfare and is proportional to their amount of consumption or production. This explains why the bigger the production or consumption the agent has, the more it will be taken into account for price setting, which will translate into a more satisfactory price for them and as a result a higher final Social Welfare. In the base market agent sample, low-income households only represent 2% of the total consumption, which makes that their Utility and Trades Costs are not as relevant to the system and therefore are almost overlooked when setting market prices. This and the fact that they require much lower prices than other agents explains why their Social Welfare without EP alleviation mechanisms is so low.

To better observe the differences between the agents, in Figure 5.3 the values of Figure

5.2 are divided per each agent type's energy consumed or produced, hence showing the average Utility, Trades Costs and Social Welfare per kWh. Moreover, results for the three chosen market architectures are shown.

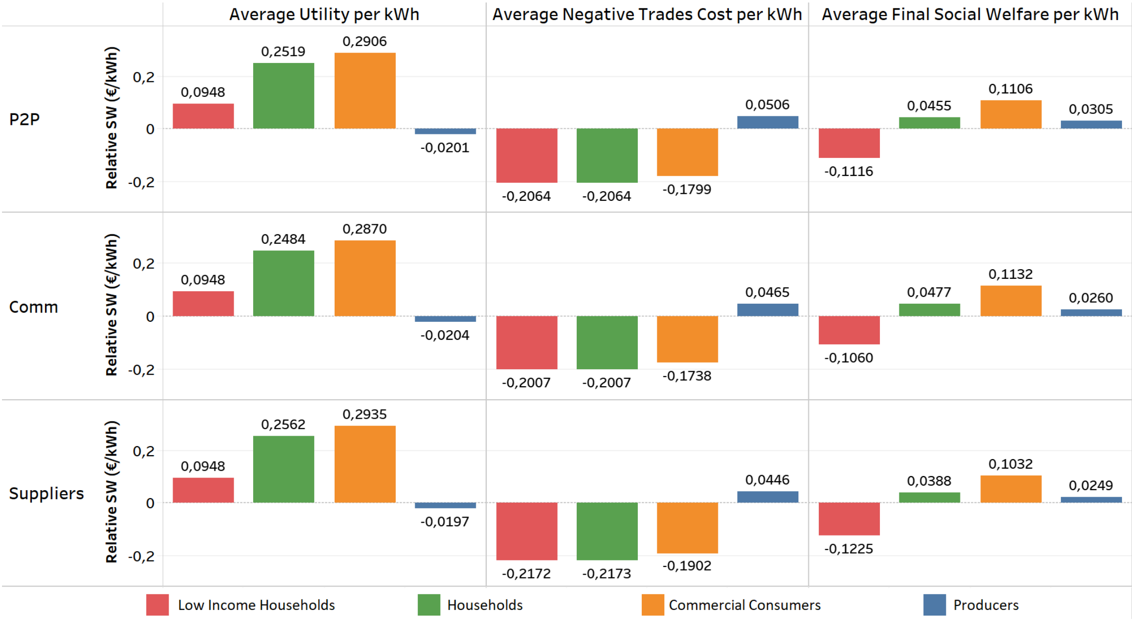



Figure 5.3: Relative Utility, Trades Costs and final Social Welfare per market architecture and type of agent without energy poverty alleviation schemes. Own elaboration

Through Figure 5.3 it can be observed how low-income households have a noticeably lower Utility even if relative to the energy they consume. However, when observing the relative Trades Costs -which corresponds to the perceived price they end up paying including taxes and tariffs- it is the same as the rest of households. This causes that their Social Welfare is negative and therefore they end up being unsatisfied or, in other words, in a situation of energy poverty and more specifically of precarious access to electricity.

Figure 5.3 also shows how commercial consumers have significantly lower prices, due to the lower tariffs and taxes they are modelled to pay. This allows them to have a higher consumption and therefore higher average Utility and SW. Finally, it can be observed how producers' perceived price is significantly lower than consumers' because it is the result of subtracting the consumer's commissions to their perceived price - thus obtain the agreed price of trades - as well as the commissions that producers also have to pay.

If comparing average relative values between architectures, it can be seen how the supplier tariff causes an increase of the perceived price for all consumers, as well as how in the Community system prices for all agents are lower. For the low-income households, this means that they are more satisfied in a Community architecture, followed by the P2P one, while they have the lowest welfare in the Suppliers market architecture. It is worth pointing out that in the Suppliers architecture the perceived price between the same agent types but under different suppliers can be different, due to the different price that each supplier will get when buying energy in the wholesale market.

## 5.2 Analysis of EP alleviation mechanisms under different market architectures

Once the main differences between the three architectures have been observed and the issue of precarious access to electricity has been identified, the next step is to evaluate the performance of the proposed energy poverty alleviation schemes.

Both the EP tariff - presented in section 4.2.3- and the Price Intervention - presented in section 4.2.4- are evaluated for the three proposed market architectures and compared with a Free Market scheme, where there is not a support mechanism in place. The goal is to show how low-income households can end up paying an affordable price for a reasonable minimum consumption and how that affects the rest of the market agents. The differences between both methods in terms of implementation will be further discussed in Chapter 6.

Figure 5.4 illustrates the total Social Welfare obtained with the three mentioned schemes, under each market architecture and divided by market agent type.

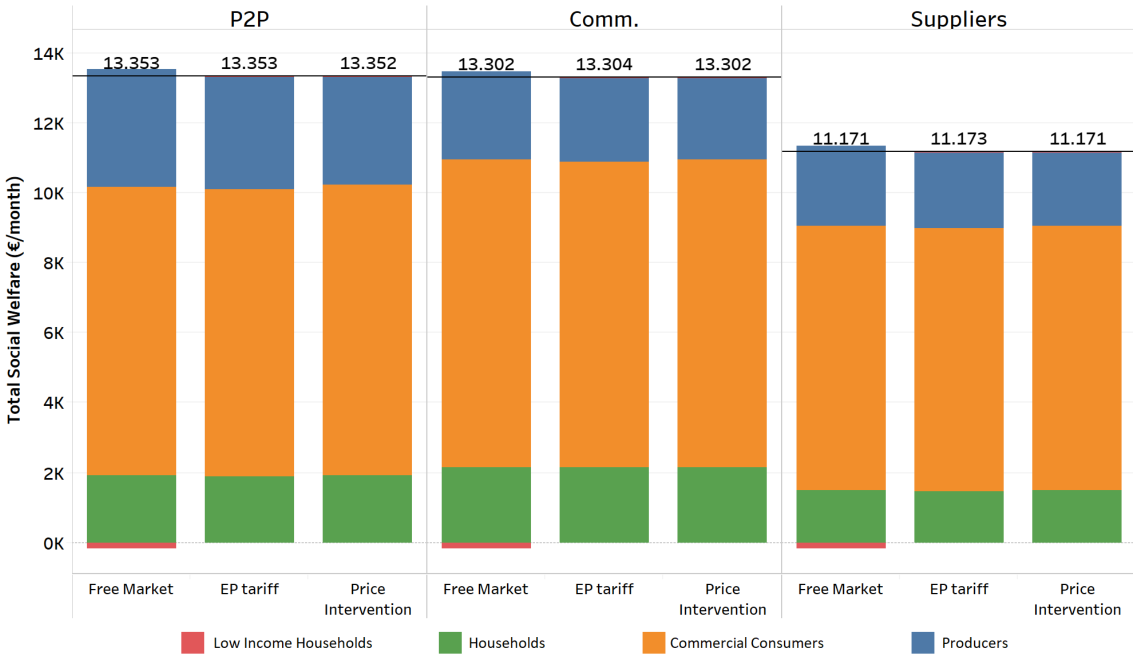



Figure 5.4: Total Social Welfare per market architecture and scheme. Own elaboration

As it can be noticed above, the Total Social Welfare of the system remains the same after applying both energy poverty alleviation schemes. The only difference is that low-income households -which have a negative Social Welfare in the Free Market- are supported and end up being satisfied. Hence, there is merely a re-distribution of welfare within the system, not moving away from the market-optimum obtained when solving the Free Market scheme. This redistribution comes at the cost of a reduction of other market agents' SW.

To further understand how the redistribution of welfare is performed in both schemes, Figure 5.5 depicts each agent type average monthly margin, calculated as per Equations 4.11 and 4.12, and understood as the net earnings for producers and the amount of money that consumers could give up - reducing their consumption- while staying within their budget.

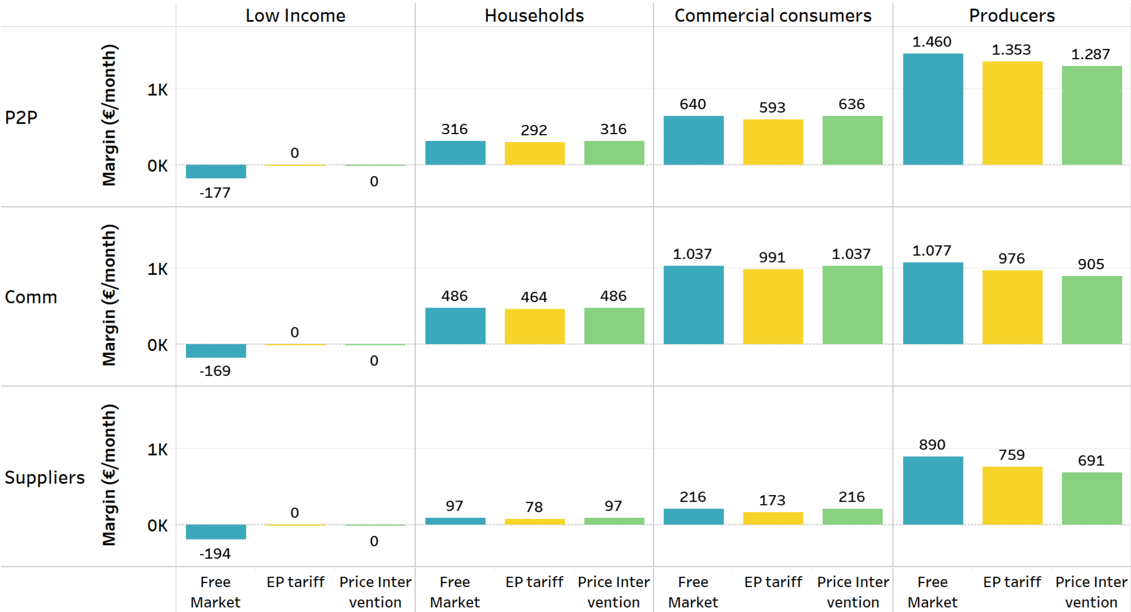



Figure 5.5: Average monthly margin per type of agent, depending on the market architecture and scheme. Own elaboration

The first observation that can be made is that with all market architectures without support schemes Low-Income households are unable to face electricity payments since the cost of electricity is higher than their budget. This is displayed in Figure 5.5 by a deficit of 177 €/month in the P2P architecture, of 169€/month in the Community one and of 194 €/month in the Suppliers architecture. Therefore, these are the quantities that other agents need to contribute by reducing their margins, so that the issue of energy poverty can be internalised in the electricity market. For the base market agent sample, this is made possible through both the EP tariff and price intervention, which can be seen by how low-income households deficit becomes zero, meaning that they end up paying for electricity exactly the budget they had assigned for it.

Observing the rest of households as well as the commercial consumers, it can be seen how their margin is reduced drastically in the Suppliers architecture -due to the higher tariffs- as well as it is considerably higher in the Community one. When comparing their margins obtained with the different schemes, it can be seen how in the price intervention case they are not affected, whereas in the EP tariff their margin gets slightly reduced. This is because in price intervention low-income households are only supported by producers. It is important to note that the EP tariff is applied to the consumers depending on their bids, and therefore it is not homogeneously distributed. Each consumer contribution to pay for the EP tariff is proportional to their margin, hence those with reduced margins are practically unaffected by this mechanism, as explained in Section 4.2.3. This happens with prosumers that are net consumers, who as mentioned previously tend to have little interaction with the market. For this reason, increasing the share of prosumers effectively reduces the number of households that help finance the support scheme, increasing the share of the total contribution needed from all other non-prosumer consumers.

In the case of producers, their net earnings get reduced with both support schemes, being noticeably lower with Price intervention since they are to compensate low-income households' deficit on their own without the contribution of consumers. This does not include prosumers who are net producers, since by design they are excluded from financing the support schemes. In any case, the net earnings of these prosumers are negligible when compared to large producers, so their contribution would not make a significant difference.

If analysing the effect of market architectures on producers support, it is worth mentioning how in the Community system they have to give up less margin since the amount of support that low-income households need is lower. However, in the Suppliers one, although they have a lower margin, the low-income deficit is higher, so they end up having an even larger reduction of their net earnings.

Another indicator that shows the impact that the support schemes have on the different agent types is the perceived price, hence the final price they end up paying/receiving for the energy traded. Perceived prices are shown in Figure 5.6 for the different market schemes and architectures. Moreover, as the perceived price is the result of the agreed price of trades plus or minus the total tariffs and taxes per kWh (depending on whether the agent is consuming or producing), these two values are also represented in the figure.

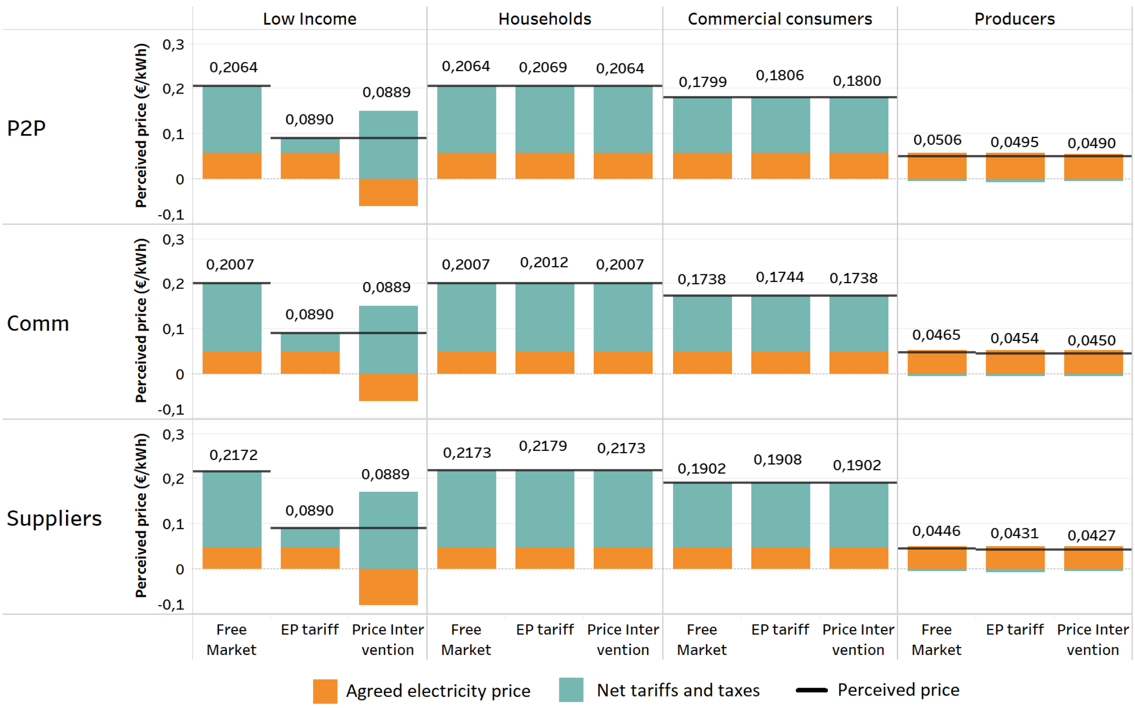



Figure 5.6: Average agreed price, net tariffs and taxes and perceived price per type of agent, depending on the market architecture and scheme. Own elaboration

The first observation that can be extracted is that with EP alleviation schemes in place the average perceived price for low-income households gets reduced drastically, particularly to each agent's maximum affordable price $L_{max}$. This shows how the designed mechanisms work as intended, ensuring affordable prices for those more vulnerable. For the rest of households, the presented EP tariff causes an increase of commissions of around 0.5 c€/kWh, and up to 0.7c€/kWh for the commercial consumers. For the producers, the increase of commissions is noticeably higher, with its applicable EP tariff being up to 2c€in the Suppliers-Price Intervention scenario. The exact values of this commission per type of agent and market architecture are shown in Figures 5.11, 5.12 and 5.13.

A second observation can be made relative to the components of the perceived price: net tariffs and taxes represent the vast majority of costs for consumers, while with lower tariffs and taxes producers sell their electricity at a price closer to the agreed price of trades.

Another remark can be made examining low-income households obtained prices under a free market: they are generally able to pay the agreed price, but the high taxes and tariffs make all of them unable to stay within their budget. This shows how a possible solution to alleviate energy poverty would be to reduce their tariffs, although these represent real system costs and they have to be paid from elsewhere. This is what is done through the EP tariff, where low-income households receive a subsidy that helps them pay the vast majority of net tariffs and taxes while maintaining the same agreed electricity price as the rest of households. Those more vulnerable households that cannot even afford the agreed price, will also receive funding so as to stay within their budget.

In the case of price intervention, the producers take care of all low-income households deficit and directly sell electricity to them at affordable prices, which end up being negative as low-income households have to pay all taxes and tariffs. Practically speaking, this means that the producers are responsible to cover the share of taxes and tariffs that the low-income cannot afford, at the same time that they sell them electricity for free. This ends up causing a lower perceived price in the producers when the average of all trades is computed.

Summing up, it has been observed how both schemes alleviate precarious access to electricity, internalizing its costs among all consumers and producers -in the case of the EP tariff-, or solely by the producers -in the case of the Price Intervention scheme-. To draw more relevant conclusions, the support schemes need to be tested with different market samples.

## 5.3 Analysis of the proposed support schemes with different market agent samples

In this section, the proposed energy poverty alleviation schemes are analysed for the different variations of the base market agents sample. Variations are obtained by modifying the amount of low-income households as well as on the share of RE, as explained in Section 4.3.2.

Before observing how the proposed schemes perform under the different scenarios, it is necessary to know how these changes affect the system without support schemes. Both under the Free Market scheme, Figure 5.7 shows the change in total SW with the different market agent sample variations while Figure 5.8 shows the changes in the perceived price.

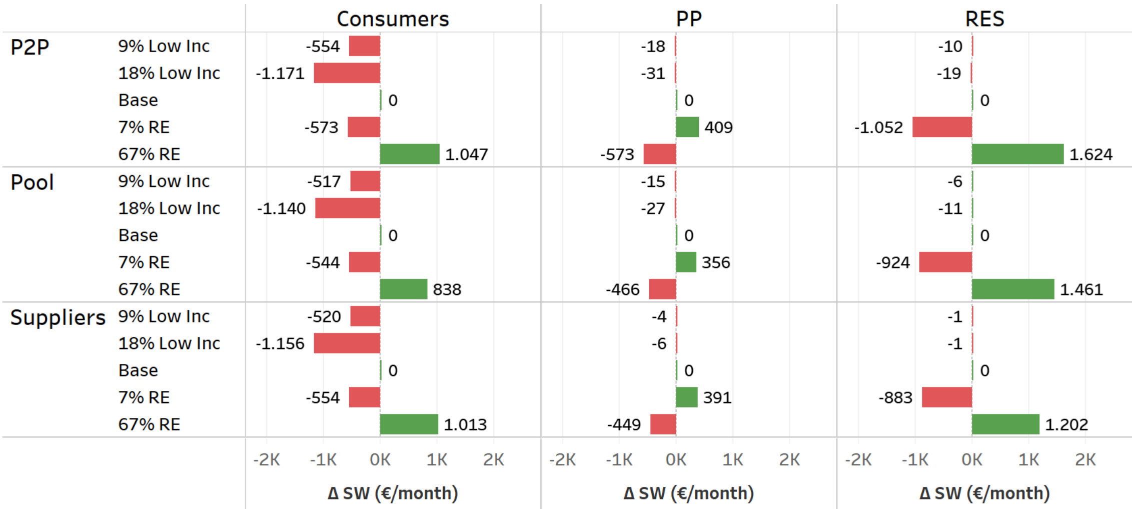



Figure 5.7: Change of Social Welfare per type of agent in the free market scheme, depending on the amount of low-income households, percentage of renewable energy on the electricity mix and market architecture. Own elaboration

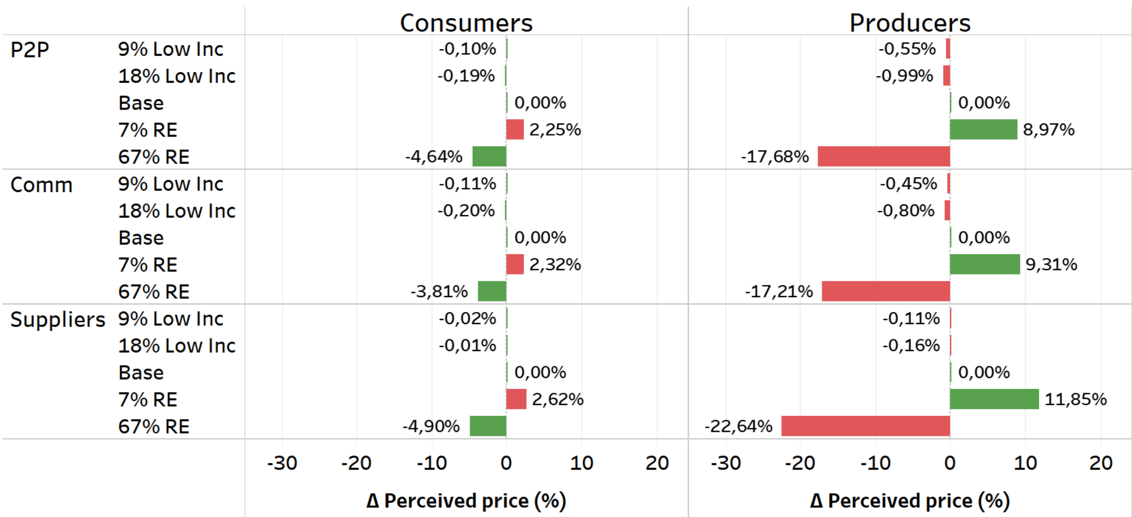



Figure 5.8: Change of perceived prices per agent in the free market scheme, depending on the amount of low-income households, percentage of renewable energy on the electricity mix and market architecture. Own elaboration

As it can be seen through Figure 5.7, increasing the number of low-income households decreases the overall SW of the system in all three architectures and in a very similar way, since there are more unsatisfied agents that bring much less Utility. However, the change has a limited impact on the perceived price that agents have to pay or receive. Although they tend to slightly lower market prices, since their percentage of consumption is quite low they do not cause a significant change, even when 18% low-income households are present. This can also be seen observing how both producers' SW is practically unaffected.

When non-dispatchable RE share is reduced to 7% from the 27% of the base market sample, the total SW diminishes significantly. Although the PP increases its SW since it has to cover up for the lack of RES and thus has more sales, the RES diminishes its SW noticeably, while consumers are also less satisfied. This is because when there is less RE production the PP has to provide the remaining energy with certain production costs to cover, which causes an increase of the agreed prices, making consumers reduce their consumption and hence have less Utility. The opposite happens when the RE share increases, where lower prices are obtained, increasing consumer satisfaction as well as RES total welfare. This happens at the cost of decreasing the SW of the PP, which sells less electricity and at a lower price.

To sum up, the biggest impact that increasing the amount of low-income households has is in the SW of the system as well as the total deficit that the rest of the agents need to pay to internalize the needed support, whereas increasing or decreasing the amount of RES is directly linked to the final perceived prices, which affect all agents SW.

### 5.3.1 The EP tariff mechanism

In this section, the EP tariff scheme is analysed and assessed for the different market agent samples and architectures. Figures 5.9 and 5.10 depict the percentage of margin that each type of agent losses to finance the EP tariff, when modifying the amount of low-income and RE share respectively.

As explained in Section 4.2.3, the share of EP tariff cost financed by each market agent is proportional to its margin. Moreover, it is worth pointing out that as a market design feature it was decided that the financing of the tariff would be fully internalised and that consumers would help finance up to 40% of the total needed support, without giving up more than 20% of their margin, while producers finance the rest with no limitations.

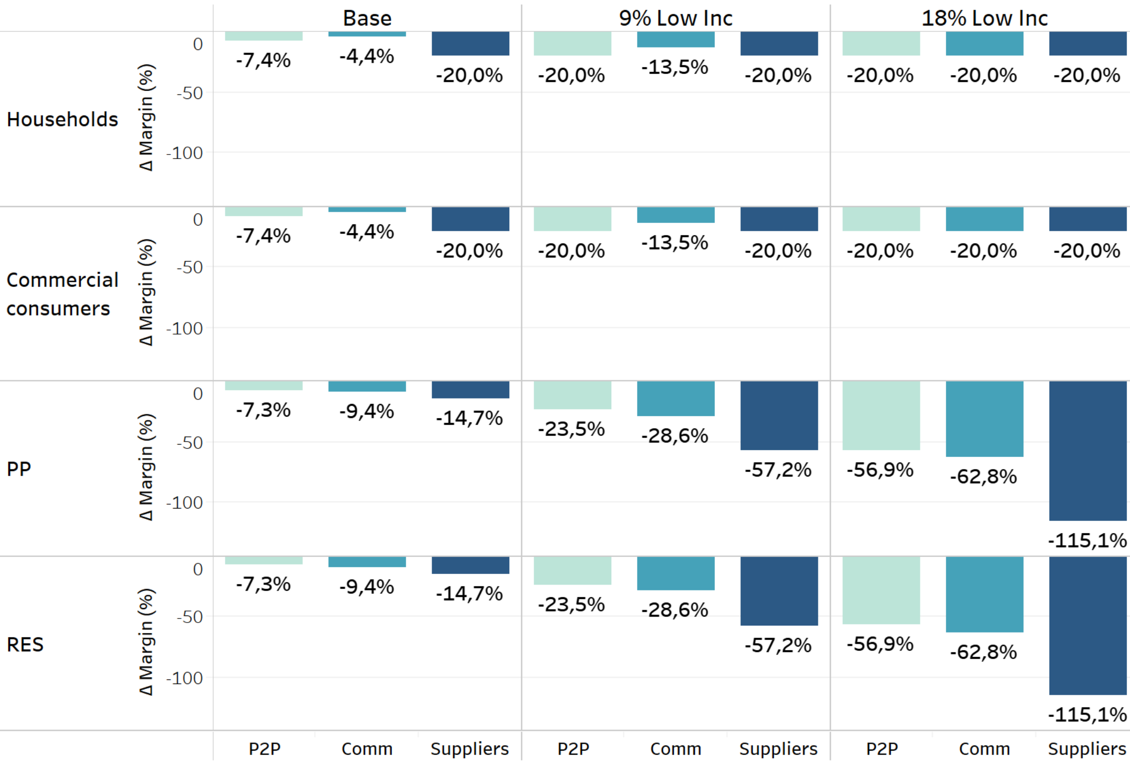



Figure 5.9: Loss of margin per agent with respect to free market scheme to finance the EP tariff, per market architecture and % of low income households. Own elaboration

Through Figure 5.9 it can be seen how under the Suppliers architecture and already with the base market agent sample, consumers' contributions are capped to lose 20% of the margin they had under a free market. This means that they are not reaching 40% of the financing of the EP tariff -in this case they cover a 32%-, hence Producers end up paying for the 68% remaining, since they do not have a cap on their contribution. In all scenarios, when consumers are capped at contributing with 20% of their margin, producers have to finance more than 60% of the support scheme.

Consumers contribution is locked to 20% of their initial margin in cases where there is a lot of needed support and/or when its margin is very low due to high market prices. This happens when having 9% of low-income households both under the P2P and Suppliers architectures, but not under the Community one due to its lower obtained prices. When 18% low-income households are introduced, all consumers contributions are capped to their maximum no matter the market architecture.

In the case of the producers, it can be seen how both the Power Plant and non-dispatchable RES have the same behaviour, giving up the same percentage of the net profit they would have under a free market. Their share of margin reduction is higher in the Community system than in the P2P due to the lower prices, which causes them to have lower earnings. In the case of Suppliers architecture, already with the base market agent sample, they have to contribute more than 60% of the total financing since consumers are locked at their 20% margin loss. The more low-income households are added, the higher the producers' net profit reduction is, accounting for both the increase of support needed as well as the reduced contribution by consumers.

In the case of 18% low-income with the Suppliers architecture, it can be seen how producers have a decrease of margin of 115%. This means that the amount of support that they need to provide is higher than their net earnings, meaning that they would incur losses to finance the EP tariff. This represents a market failure that could be solved either by increasing the share of margin that consumers can contribute or by obtaining additional financing support from elsewhere, as is further discussed in Chapter 6. However, even in this particular case, the costs of the EP tariffs could be internalised by the market since low-income households deficit amounts to 1075 €/month and the combined margin of all agents is 1185 €/month. Even in these conditions and despite all consumers would pay their maximum affordable prices and producers would practically only cover production costs, those more vulnerable would be able to have an affordable minimum consumption.

Changing the market agent sample by increasing and decreasing the RE share also has an impact on the contributions needed from each market agent type, as it can be observed from Figure 5.10:

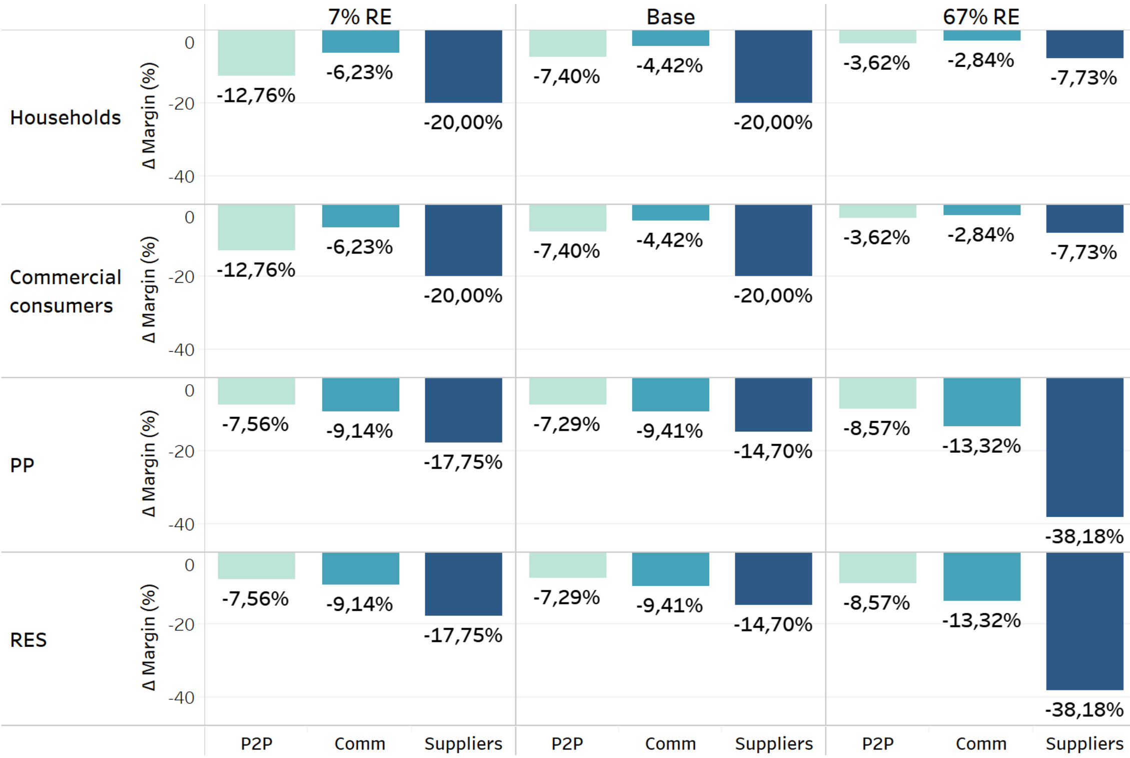



Figure 5.10: Loss of margin per agent with respect to free market scheme to finance the EP tariff, per market architecture and % of renewable energy in the electricity mix. Own elaboration

When the RE share decreases with respect to the base case, prices increase and become less affordable, leading to a higher deficit from low-income households. A higher deficit requires higher contributions and therefore the loss of margin by consumers increases with respect to the base case. An exception happens however under the Suppliers architecture where consumers keep locked to losing 20% of their margin. In the same way as consumers, with lower RE share both PP and RES also have to contribute with a higher percentage of their net earnings.

When the RE share increases, prices become lower and the amount to pay to low-income households gets reduced. When this happens, financing 40% of the tariff by consumers represents a significantly lower decrease of their margin and thus the 20% cap is not activated. For producers, however, with higher RE share and lower prices, they have a significantly lower margin, therefore causing them to give up a higher percentage of it: up to 38% in the Suppliers architecture. This high reduction of net earnings could be adjusted by modifying the share that consumers can finance from 40% to a higher value, since in this case they would have a substantially larger margin.

What margin represents is easier to understand when it comes to producers, since it is equivalent to their net earnings. With consumers it is however slightly harder to visualize. To help understand what the contribution to finance the EP tariff means for consumers, Figures 5.11 and 5.12 show the increase of the electricity bill that the EP tariff represents for each consumer type and for the different scenarios compared to the Free Market scheme. Moreover, the average value of the EP tariff that applies to each consumer type is shown, while Figure 5.13 shows the value of the EP tariff that producers must pay.

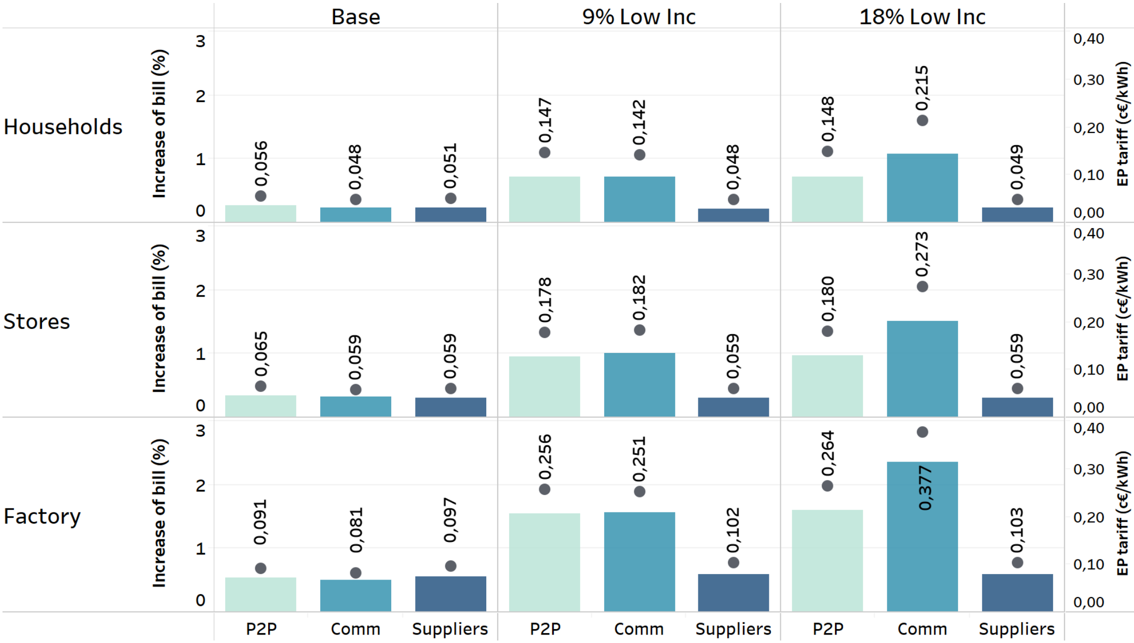



Figure 5.11: Increase of consumers' electricity bill to finance the EP tariff scheme (compared to the Free market) - represented in bars - and applicable EP tariffs - represented in dots -, per market architecture and % of low-income households. Own elaboration

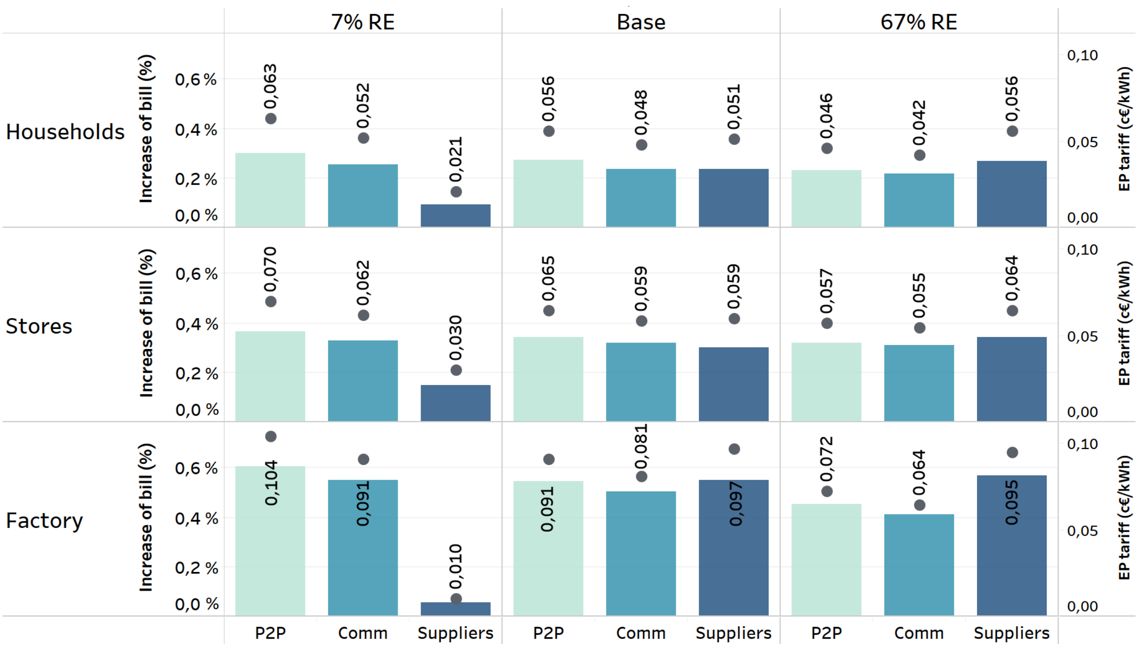



Figure 5.12: Increase of consumers' electricity bill to finance the EP tariff scheme (compared to the Free market) - represented in bars - and applicable EP tariffs - represented in dots -, per market architecture and % of renewable energy in the electricity mix. Own elaboration

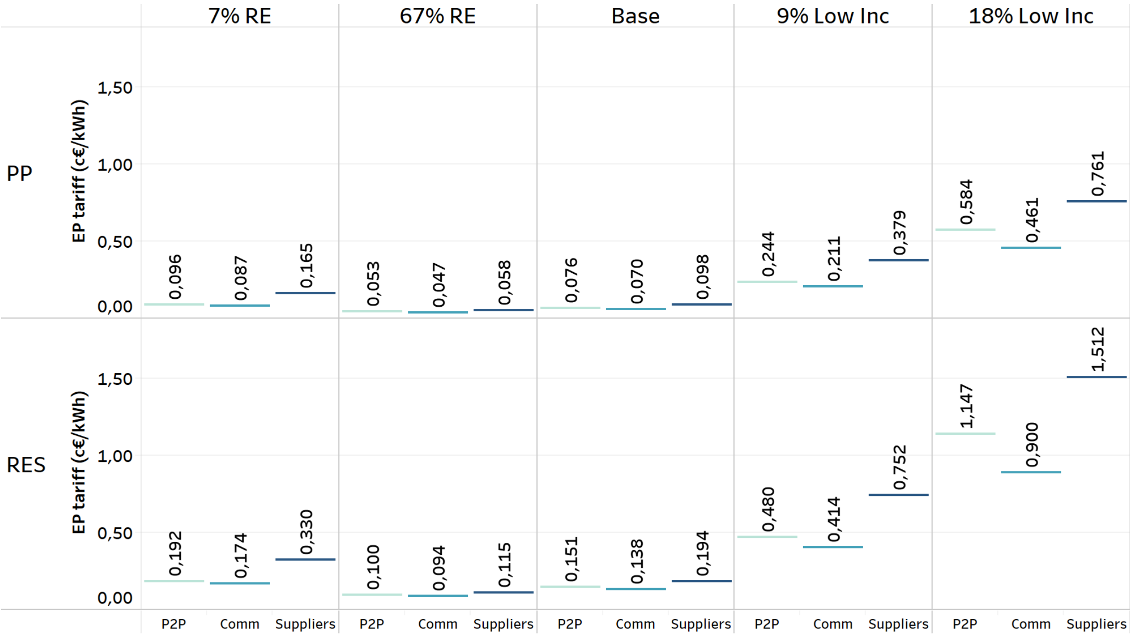



Figure 5.13: EP tariff charged on producers, per market architecture, amount of low-income households and % of renewable energy in the electricity mix. Own elaboration

Figure 5.11 shows how even in the most critical case with 18% low-income households, the rest of households' increase of the electricity bill represents less than a modest 1.1%, whereas for stores and factories the increase is up to 1.5% and 2.35% respectively. These percentages show how with the designed co-financing of the EP tariff by consumers and producers, consumers are not assigned an excessive burden even in the worst-case scenario. However, as previously shown in Figure 5.9 this is the case where producers lose from 56.9% up to 115.1% of their net earnings, thus even incurring in losses. A higher contribution by the consumers should therefore be set, better distributing the weight of internalizing the issue of precarious access to electricity. This highlights the importance of tailoring the contributions that each agent type has to do specifically to each scenario, as is further discussed in Chapter 6.

In parallel, when observing the increase of bill with different RE shares through Figure 5.12, it can be seen how values are much lower than when varying the amount of low-income households - since RE share mostly has an influence on prices, which does not change the needed support as much -. Only in the 7% RE with Suppliers scenario there is a substantial difference, with the increase of bill for consumers being much lower due to the increase of prices that makes them have a smaller margin. In this case, even in the worse scenario producers give up a 38% of their net earnings while consumers have increases on the electricity bill of less than 0.6%.

Looking into EP tariffs it can be seen that households are assigned lower ones than commercial consumers in all scenarios since they have lower consumption and higher system costs, thus lower margins from which to contribute. The order of magnitude of all consumer EP tariffs is in the tenths of c€/kWh, which is a low tariff when comparing them to other tariffs applicable to consumers as DSO or TSO ones.

For producers, Figure 5.13 shows how their EP tariffs go from the tenths of c€/kWh up to around 1.5 c€/kWh. Generally, these tariffs are in the same order of magnitude as the applied producers' feed-in tariffs and are not negligible with respect to the prices at which producers sell electricity.

### 5.3.2 The price intervention scheme

Price intervention is the second proposed support scheme, where only producers contribute to alleviating energy poverty by directly offering affordable prices to low-income households. The share of the total needed support that each producer offers is different in each case, as can be seen in Figure 5.14. As explained in Section 4.2.4, this share depends on the net profit they would obtain in the free market scheme.

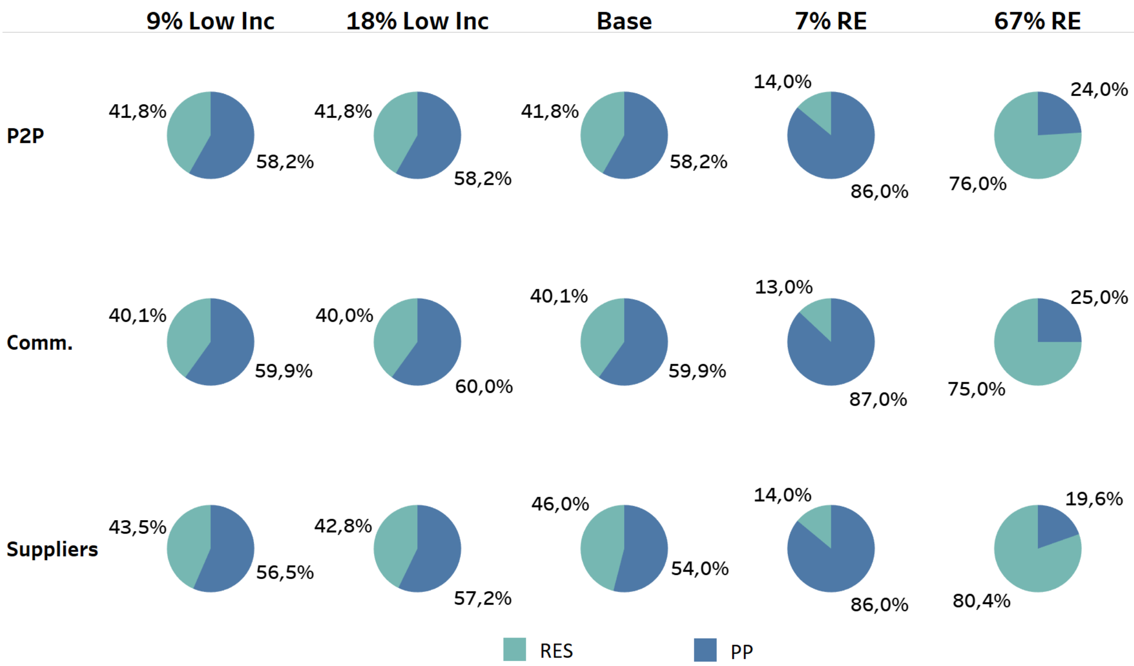



Figure 5.14: Share of total needed support payed by RES and Power Plants, per market architecture, % of low income households and RE share. Own elaboration

Varying the number of low-income households has almost no effect on how the producers split their share of contribution, since low-income households represent a small fraction of the market and therefore barely alter their net earnings under the free market scheme. When lowering the share of RE, the margin of the RES gets reduced and therefore also their contribution. The opposed happens when the RE share gets increased.

Contributions also vary depending on the market architecture. The share of contribution from the RES is the greatest with the Suppliers architecture, followed by the P2P and finally the Community one. This can be explained in the difference in prices, since with higher prices the total consumption gets reduced and, while RES continue selling the same amount because they have better bids in the market, the PP gets their sales reduced. This makes its net earnings decrease under the free market and thus also its contribution under the Price Intervention scheme.

Other than how the producers distribute the costs among themselves, it is also relevant to observe how do their net earnings diminish, since they have to cover the whole deficit from vulnerable households. Figures 5.15 and 5.16 show how net earnings decrease with each variation under price intervention with respect to the free market scheme.

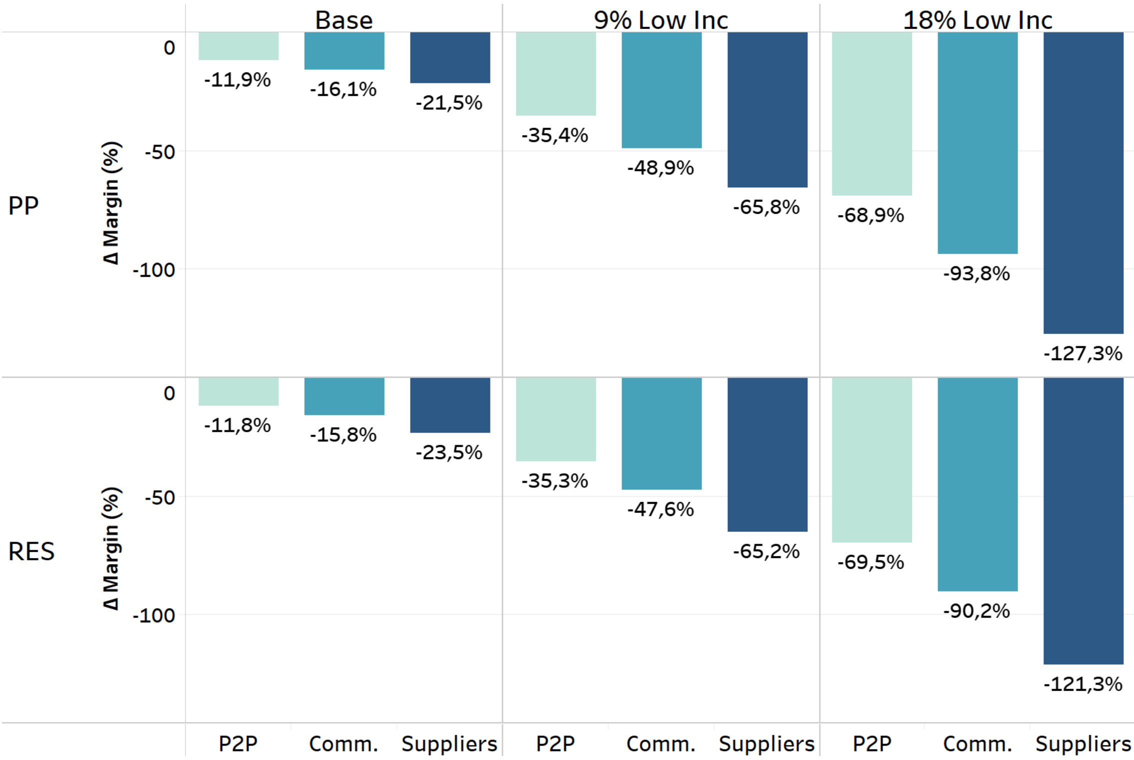



Figure 5.15: Loss of net earnings per producer with respect to free market due to the price intervention support scheme, per market architecture and % of low income households. Own elaboration

Through Figure 5.15 it can be seen how in the 18% Low Inc scenario with price intervention and under the Suppliers architecture both producers end up having losses, as happened with EP tariffs. This means that the costs of alleviating energy poverty cannot be internalized and paid solely by the producers. In the Community architecture, it can be seen how although both PP and RES can afford to finance the deficit of low-income households, it is at the cost of 90% of their net profits, suggesting that collaboration from consumers or external support might be needed.

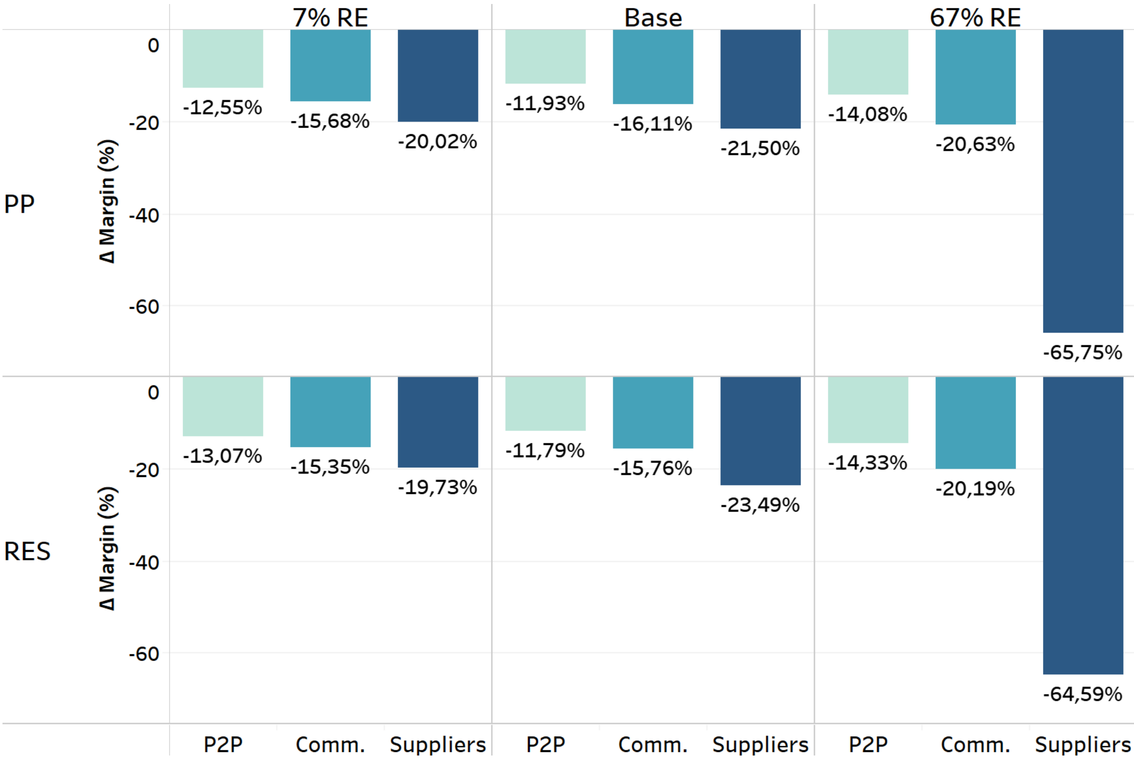



Figure 5.16: Loss of net earnings per producer with respect to free market due to the price intervention support scheme, per market architecture and % of renewable energy in the electricity mix. Own elaboration

When modifying the RE share, it is seen how in almost all cases their reduction is between 10-20% of their margin, except in the 67 % RE with a Suppliers architecture, since the lower prices they obtain drastically reduce their margin.

With the results above-displayed it can be also argued how it might not be fair that producers have their net earnings reduced differently. This is explained by how price intervention has been designed. Proposal of better ways to distribute the burden of support among producers will be presented in Chapter 6.

# Discussion 6

In this Chapter, some of the most relevant aspects of the Thesis are further examined.

First, the accuracy of the model used and the impact that its limitations have on the results are discussed. Then, the proposed methodology for calculating low-income households' support is evaluated, as well as the design of the EP tariff and the Price Intervention scheme. This is followed by a reflection on the obtained results and their relevance based on the inputs used.

In addition, it is briefly discussed whether it is necessary to internalize the costs of the support schemes in the market, the implementation of the proposed methodology and what major barriers could be encountered in the process. Finally, a brief reflection on the future of the issue of precarious access to electricity is done.

## 6.1 Accuracy of the model

The first thing that needs to be discussed is how accurately does the used model reflect the real operation of decentralized markets and which of its limitations can have an impact on the relevance of the results obtained.

An important limitation of the used model is its time frame since it is designed for a single-time operation and it does not allow simulations with various time-steps simultaneously, such as the simulation of an entire month with hourly values. Although this has been solved by using average monthly values for consumption and production -which are enough to calculate values of needed support and contributions- the lack of hourly resolution might have an impact on the results obtained. For instance, with hourly prices and low-income households consuming in peak hours, the total needed support might be higher than the one calculated with monthly average consumption and prices. At the same time, net profits from large producers could be reduced if calculated with hourly values and having large consumers consuming in off-peak hours with lower prices. In this case, there would be higher needed support and a lower available producer margin to pay for it, so results of contributions would differ from what would be calculated from monthly averages.

Prosumers would also be largely affected by the change of the model's time resolution, which could ultimately influence the needed support from low-income households. In the used model prosumers have been set to work under monthly net settlement, hence with only paying for their net monthly consumption or being remunerated for their net monthly production, which makes them have almost no interaction with the market. This could change if hourly profiles were used since their production profile is usually not synchronized with their consumption one, causing an increase in its participation in the market. They would sell more electricity at low prices due to the lack of marginal production costs, lowering market prices and potentially total needed support, as well as buy more electricity, potentially contributing to financing low-income households support.

Other than the time frame, another relevant assumption that influences results is modelling supply and demand curves of all agents as linear. In reality, the behaviour of market agents is not always so straightforward, with multiple factors affecting decision-making processes, especially on the consumers' side. For the producers, more accurate cost curves for the PP could have been used, integrating several production technologies with their cost functions, increasing the accuracy of the results. The modelling of RES is more complex since they are set to have 0 supply curves. This means that a case with a 100% RE share would not have a solution, since the operational costs of the PP are used to determine the rest of prices and otherwise the prices would be negative. Therefore, the existing formulation and negotiation mechanism would need to be modified to better allocate the RES so that a 100% RE scenario could be feasible.

Another limitation of the model is that the physical aspect of electricity is not accounted for. No grid constraints on exchange capacity or grid losses are considered, which might make the results of the model not feasible in real-life implementation.

Although there are some limitations to the way the used model represents the real operation of decentralized electricity markets, it is considered that these do not have an excessive impact on the goal of this thesis, which is designing support schemes to alleviate precarious access to electricity. Overall, it is considered that the advantages of the model – such as the capacity it has of representing different market architectures and types of agents under the same formulation– out-weight its limitations for what this thesis has intended to do.

## 6.2 Evaluation of the proposed methodology

### 6.2.1 Low-income households' support calculations

One of the key contributions of this Thesis has been a methodology to calculate the custom support that low-income households need to afford a certain threshold of consumption. For these calculations both the way low-income households demands have been modelled and the parameters chosen to be able to calculate these demands are crucial, and as such need to be further discussed.

As explained in Section 4.2.2, in this thesis vulnerable households are modelled differently than other market agents: with a minimum consumption $E_{min-cons}$ and an assigned affordable price for it $L_{max}$ so that at least a certain threshold of consumption can be guaranteed for them.

This minimum threshold of consumption is modelled to be different for each household as it is dependant on its efficiency, on its members, whether electric heating is used and whether mechanical support through vital medical devices is required. It can be questioned whether these parameters are enough, or more of them could be added – as for instance whether household members work from home or not – so as to better tailor the amount of consumption needed to each specific household. It is worth pointing out that this type of information could be harder to collect and prove as valid, and that requiring and managing more information from households comes at certain operational costs for the system.

Whether more parameters are to be added to calculate each households minimum consumption or not, what is clear is the obtained results depend a lot on the value assigned to each parameter as well as what is considered to be the Minimum Standard Consumption. The MSC is the minimum decent consumption for a household of 1 member, with an efficiency of 1 and without medical devices nor electric heating. There is not a commonly agreed value for the MSC, which can be dependant on the geographical location of the household and the time of the year, so it is a factor of decision of the regulator (understood as the decision-maker body in a certain market). Complementary to consumption in the modelling of low-income households demand, prices are set as affordable by limiting the amount of money that these type of consumers can spend on electricity with respect to their income. That is why the regulator has to carefully set this parameter, which will ultimately influence the amount of deficit obtained from consumers and the overall market solution when applying the two designed support schemes. Moreover, it could be argued whether other economic parameters rather than income should be also used when calculating electricity prices for low-income households.

As future work, more accurate studies for calculating the MSC, the value of the parameters reflecting the characteristics of the household and the % of expenditure on electricity for vulnerable households could be done if wanting to have custom support given to low-income households.

It is also worth discussing if it is necessary to calculate specific support for each agent as there are system costs associated with these calculations. For markets with a limited amount of agents, as for small local energy communities, calculations could be worth the effort. However, for complex markets with a lot of agents as the ones on a regional or country scale it could be that costs do not compensate for the benefits of tailoring retributions to each vulnerable household. As further work, a cost-benefit analysis could be done to find out the viability of custom support depending on the number of market agents. If custom support is not deemed viable simpler support schemes like the ones presented in Section 1.3.1 can be implemented, such as giving fixed vouchers each month, tax exemptions or reducing the total electricity bill by a certain percentage.

### 6.2.2 Design of the EP tariff and Price Intervention schemes

The other key contribution of this Thesis is the design of the EP tariff and the Price Intervention. Therefore, the main key design choices used need to be further discussed.

In both schemes, it was chosen to use the margin as the key indicator to calculate the distribution of costs. Especially for producers, it appears as a reasonable indicator since it represents the net earnings, and therefore it is to be expected that those producers with larger benefits contribute more. For consumers, the margin represents something different, the amount of money they can give up by reducing its consumption while staying within their desired budget, which might be harder to relate to reality. Using the margin ensures that consumers that are already satisfied -hence in their demand curve- will not be further penalized by forcing them to pay higher prices than their stated maximum. However, it can be argued that this way of calculating consumer's support is too dependent on the nature of their bids as well as the modelling of their demand curves, which might be inaccurate.

To make the distribution of costs fairer for consumers in the EP tariff scheme, an option could be to collect their information on income. With it, contributions could be calculated in a way that those with larger budgets pay more. However, that would not only increase the computational costs and the complexity of the system but could also raise privacy concerns. Another option to distribute the costs would be to use other calculated indicators such as total expenditure on electricity or power consumed. Although this would simplify the calculation process, it would also be less fair, since a higher consumption does not always mean a higher margin. The process could also be simplified by making all agents have the same contribution, perhaps depending on their agent type, again resulting in a less fair but also less complex system.

For producers, both with Price Intervention and EP tariffs, the distribution of costs to finance the support could be simplified so that it is not based on their net earnings. The share that each producer contributes could be a factor of decision of the regulator based on other concepts such as the yearly revenue, share of total consumers that the producer sells energy to, emissions or even the profits that the producing company has accumulated throughout the years.

Both schemes have been designed to assign tailored support for each low-income household. However, adaptations could be made in order to simplify both mechanisms if granting uniform support for all market agents. In the EP tariff case, the main information needed is the total support to pay, hence this value could be simply added as an input if, for instance, reducing the bill to low-income households a certain fixed percentage. In the case of Price Intervention, instead of setting a specific affordable price for each low-income household, an "average affordable price" could be set.

Another important topic of discussion is which market agents should finance the support given to vulnerable households. Other agents that participate in the market are the TSO and the DSOs, but their earnings tend to be under much stricter regulation as they are natural monopolies, which limits them. If they were to contribute to the support scheme, this would only increase their costs and could ultimately affect consumers via higher tariffs. For this reason, for P2P or community architectures it is difficult then to think of other agents than producers and consumers. However, if having an architecture with both wholesale and retail markets (as modelled with the Suppliers architecture), there is a clear type of market agents that could contribute: retailers. These are intermediaries that also have net earnings from the tariffs they charge and therefore have a margin from which contributions could be made. For instance, this is what happens in Spain, where the *bono social* scheme is financed by all retailers proportionally to the number of consumers they sell electricity to with respect to the total [BOE, 2016].

The support schemes presented have been designed with a special focus on decentralised markets without intermediaries. In cases where the market is more similar to current centralized ones, modifications could be made to the proposed schemes to include them in the financing.

## 6.3 Reflection on the obtained results

### 6.3.1 Validity of inputs used

Obtained results largely depend on the inputs used. If these are deemed valid and representative enough, there can be a generalization of the outputs of the model so as to extract relevant conclusions.

As there are multiple model inputs, this section will first discuss the validity of the base market agent sample and then that of the case study variations, which also allow obtaining more general conclusions.

#### Validity of the base market agent sample

To test the proposed methodology, realistic input values were needed. With that in mind the base market agent sample was based on Spanish values on prices, tariffs, consumption and production and distribution of agents, mostly due to data availability. The majority of the chosen values are similar to other countries of similar socio-economic level -for instance, many EU countries- so it is believed that using them for the base sample is a good starting point that should not have a considerable impact on the exportability of results.

If looking at European Commission statistics (EUROSTAT) it can be seen that chosen Spanish final electricity prices, distribution of market agents and consumption per agent type does not differ substantially from that of other EU countries. However, tariffs – which ultimately determine final perceived prices – are slightly different from the rest and thus influence the obtained results. This is because in Spain there is a large amount of fixed tariffs, consumption independent, which is not the case in other countries. For this reason, the base market agent sample could be also simulated for different tariff schemes. In any case, a sensitivity analysis on all of the base case input parameters could be done, even using several countries as a reference to further ensure the representativity of the results obtained. Moreover, a different distribution of consumption of market agent types could be chosen if wanting to simulate other cases different to the countries average, such as specific regions, cities or communities. An example would be to focus on a residential community with no large commercial consumers or areas where large factories or malls have a more important share. This shift on the power dynamics of the market agents would influence who has a higher weight at price-setting, and ultimately on the obtained results both with price intervention and EP tariffs.

#### Validity of the case study

It is through the case study that outputs of the model can be used to answer this Thesis' research questions. To do so, multiple scenarios are built by changing the market architecture, RE share and number of low-income households, which are deemed as the factors that mostly influence results.

Three very representative market structures were chosen for the case study, but additional ones could also have been tested. This would enable to see which are the most ideal architectures per type of agent when applying the proposed schemes. An example could be a case with several connected communities -results might show that some communities would be more affected than others- or the case of a hybrid market architecture. However, due to the complexity and non-default design that the hybrid architecture has it was chosen to exclude it from the case study.

The variations selected when changing the amount of RE or low-income households could also be discussed. Two variations to the base case from both parameters were deemed as enough to identify trends in the support schemes operation, although with more variations better conclusions might have been drawn. In addition, mixed scenarios with both parameters being different from the base case could have been simulated, such as one with 18% of low-income households and 67% of RE share. Going even further, it could have been interesting to relate the maximum amount of low-income households that can be supported by a system with its RE share or, put it differently, to which extend increasing the RE share allows financing more low-income households. This would have required doing many more simulations than the time constraints of this Thesis allowed, so this line of investigation was left as future work.

Overall, with the base market sample used and the selected caste study variations, it can be concluded that the obtained results are representative enough to answer this Thesis' research questions.

### 6.3.2 Operation of the EP tariff and Price intervention mechanisms

Observing the results obtained in Chapter 5 it can be seen that the operation of the EP tariff and Price Intervention mechanisms depends on the total needed support and the available margin to pay for it.

The amount of support needed decreases with the decrease of low-income households and when consumer electricity prices go down. Prices are lower with lower applicable tariffs –so in the Community or P2P architectures– as well as when the RE share increases. Conversely, the amount of consumers' available margin increases with lower prices while for producers it depends on their share of the market.

For this reason, with EP tariffs the ideal situation so that the system is able to finance comfortably low-income households is when having a low amount of them, high RE share and Community or P2P architectures. With Price intervention, producers can assume paying support more easily also with a low percentage of low-income households, under Community or P2P architectures but in this case with low RE share, since prices go up and thus they have higher net earnings.

Although in the vast majority of the simulated scenarios it has been possible to internalize the costs of alleviation of precarious access to electricity without them having an unbearable impact on market agents' final welfare, there are a few exceptions.

In some extreme scenarios –with 18% of low-income households or 67% of RE share – the Price Intervention scheme is unable to provide enough support or causes a substantial decrease of earnings for producers. However, under these scenarios with EP tariffs, a better distribution of costs is possible so that the burden of support is not that harmful to producers. In this case, due to its designed flexibility, the EP tariff scheme allows sharing costs between consumers and producers, setting the maximum percentage of their margin that consumers are able to lose as well as the share of total support borne by consumers and producers. These parameters need to be set accordingly to each scenario so that if the total needed support is higher, consumers might increase the share of margin given to have a more balanced distribution. Moreover, if consumers' margin is higher due to lower prices, it might be recommended that they pay for a higher share of the total support.

Summing up, the EP tariff scheme appears to be a more attractive option due to its customization potential. Moreover, it could be argued that the same results as using Price Intervention could be obtained by setting the EP tariff with 100% producers financing. However, Price Intervention can also be attractive in cases where producers have high net earnings as it allows setting up the support for low-income households by simply fixing their electricity price. In addition, it is a less computationally heavy option, since calculations do not need to be done after solving the market.

## 6.4 Should costs be internalized?

An important topic of discussion is whether the proposed support schemes – which internalize the cost of alleviating precarious access to electricity in the market – are worth being implemented or not, given the complexity that this might have and that the externalization of costs –which is what is done in most of the cases– serves the same purpose in a simpler way. With it, it is simply the taxpayers and not market agents that finance the needed support.

On one hand, the benefit of internalization through the proposed support schemes is that contributions can be tailored to each market agent or agent type. In fact, for how they have been designed, for both the EP tariff and price intervention the market regulator has a few adjustable parameters to decide how much does each type of agent have to contribute. It can be argued that this is a fairer allocation of costs than what happens with externalization, where what taxpayers pay for support might not be proportional to how much they can afford a certain consumption of electricity. An example of this could be to pay for the support that low-income households need for electricity through income or oil taxes, which could in some cases perpetuate or worsen the problem. Instead of tackling the issue directly, which is to ensure that all consumers gain and at the same time keep access to a certain good or service, externalization can make some consumers gain access through support at the same time that they lose it through badly-targeted charges, or even make others who could previously afford electricity not afford it anymore because of abusive charges. This reasoning could be embedded in the line of thought that poverty should be solved by a well-targeted re-distribution of wealth, one that independently and one at a time guarantees access to each one of the goods and services that are necessary for a decent standard of living.

On the other hand, while internalization can be considered a fairer cost allocation, it comes at a certain system cost and might be difficult to technically implement. For this reason in cases with a very large number of agents, the extra costs and limitations of internalization might not make it a worthwhile or even possible option, leaving externalization as the only viable alternative. A middle-ground option can also be met, which is to partially internalize the costs and leave the rest of the needed support to external financing.

## 6.5 Implementation

This section discusses under which real-life scenarios could the proposed support schemes be implemented, what would be the next steps towards its implementation, and which would be the possible barriers encountered.

### 6.5.1 Implementation of the proposed support schemes

The developed methodology for alleviation of energy poverty is set to be implemented in decentralised markets with automatic negotiation mechanisms such as the one described in Section 4.1.3. Therefore, what is deemed as the most suitable and viable implementation would be on newly-formed energy communities or P2P networks, which for social responsibility could want to include support mechanisms in their market platforms. In this way, apart from promoting values such as sustainability through renewable energy or independence from the grid through local production, these smaller-scale decentralized markets could also promote social and solidarity economy principles, which could also be at the core of their foundation. In the current wholesale and retail electricity markets much more opposition could be faced due to the big economic interests from different stakeholders that would go against the proposed solutions.

Overall, the proposal presented in this thesis would give some tools in order to be able to incorporate redistribution mechanisms in the automatic algorithms that are in charge of negotiation in decentralized electricity markets. A positive aspect of the proposal is its adaptability since with both schemes the amount of support that low-income households receive as well as the contributions that other agents do can be tailored to each specific case needs. First, support and contributions can be made custom or non-specific for each market agent. Second, if assigning custom values for support, regulators can easily change parameters such as the Minimum Standard Consumption or the percentage of income that vulnerable households can afford to spend on electricity. As previously mentioned, contributions can also be adjusted by the regulator, especially in the EP tariff case.

The actual implementation of the proposed methodology was deemed out of the scope of the project. However, some initial ideas on the areas that would need to be further developed would be the requirements to be considered a vulnerable household to avoid system abuse or the paying schedule for EP tariffs. Most likely the total amount of support needed would be different than the amount from the received contributions on a monthly basis since contributions are dependant on the real power consumed and produced, which can be different than what is estimated with the demand and supply curves. Therefore, the overall lack or surplus of contributions should be compensated on the following month, so a system to do that should be also designed.

Apart from the further research needed there are some implementation barriers that can already be identified.

### 6.5.2 Implementation barriers

As described by Moret [2020], there is still a long way to go in order to implement automatic decentralized market-solving algorithms. As the proposed support schemes are mechanisms to be included in these algorithms, there is too a long path to follow in order to implement them in real life. Moreover, there are also some specific barriers to their implementation that would need to be tackled.

#### Technical barriers

Internalization of the costs of alleviating precarious access to electricity through the designed support mechanisms might have some barriers to implementation with large market agent samples. As the iterative algorithms used for decentralized market-solving scale poorly [Moret, 2020], with a high number of market agents and thus a high number of links between them the computation of the market solution might require unreasonable times of convergence at the same time that it involves high transaction costs. The times of convergence increase even more when moving from a free market to one with EP tariffs or Price Intervention, as more information needs to be collected and more calculations need to be computed. In order to tackle this issue, a possible solution would be to promote the reduction of communication links between agents, thus simplifying the market architectures, by adding a cost or cap on the number of partnerships that agents have [Moret, 2020]. However, it should be studied how this simplification might make the results sub-optimal and therefore reduce the total system welfare. A trade-off between simplification for feasibility and maximization of welfare should be pursued.

In parallel, the simplification of the designed support mechanisms for cases with a large number of market agents might also be needed. As per the design, under both Price Intervention and the EP tariff mechanisms, low-income households receive individualized support based on what is defined as Deficit. This requires gathering and processing a significant amount of information, which ultimately also increases the time of convergence of the market negotiation algorithm and the costs of operating the system. In a similar way, contributions to pay for the needed support are also custom and are designed to be proportional to the Margin of the agents, so a simplification to distribute charges that implies fewer calculations might also be needed for larger agent samples. Non-custom support retributions and contributions might affect the fairness of the redistribution of welfare but at the same time might make the proposed support schemes easier to be implemented in real life.

#### Large agents engagement

Other than technical limitations, the other main barrier towards implementation is the possible lack of engagement from the different market agents. This could especially happen with large consumers and producers, who could be pushed back from participating in decentralized markets with EP tariffs or Price Intervention if encountering high electricity prices. This is a concern since these type of agents are the most needed to pay for the designed support schemes. With this in mind, a thorough stakeholder analysis would be needed to better analyse what are the different agents' main concerns in order to be able to join the market, and what could be modified in order to make the market more attractive.

It is worth mentioning though that decentralized markets can potentially generate lower electricity prices if a larger share of generation than traditional ones is renewable and local (which would decrease grid costs) and if having fewer intermediaries such as suppliers. These savings could be used to adopt redistribution mechanisms without them being an excessive burden.

Among all agents, producers might be especially reluctant to join markets with the designed support mechanisms if having business opportunities elsewhere and only looking at net profits. However, helping low-income households have more affordable prices could also be seen as an opportunity for them to increase their social acceptance and even as an "advertising" investment. It is also a possibility that the production facilities would be owned by the same community, built under Social and Solidarity Economy principles and therefore prioritizing the welfare of its community over the economical benefit, so in this case, their participation in the market would not be an issue.

## 6.6 A future perspective

Although out of the scope of this thesis, a future perspective on the issue of precarious access to electricity is presented in this section.

On one hand, following the energy transition, current trends point out towards more sustainable energy systems, which would on the paper lower prices and therefore could alleviate precarious access to electricity.

On the other hand, as recently highlighted by the Covid-19 pandemic, growing inequalities can be expected in the future if following current trends, which could accentuate the issue. Moreover, parallel to larger shares of RE, the future is thought to be much more distributed and decentralized, with consumers having a more active role. This could happen through the creation of parallel decentralized markets such as the ones described in this Thesis, and the active participation of consumers in them by selling surplus from their self-consumption units, by smart charging EVs or even by using heat pumps. Although these technologies are to empower citizens, there is still an investment barrier that makes only those in a more comfortable economic position afford them. This barrier can further contribute to inequalities in electricity markets and thus perpetuating the problem.

Taking advantage of the possible proliferation of decentralized markets, support schemes such as the ones proposed in this Thesis could be used to tackle some of the future challenges outlined in this section.

# Conclusion 7

Precarious access to electricity is identified as a live and relevant issue that affects many vulnerable consumers. Solutions to the problem could be incorporated in the decentralized markets core design, profiting the weight that these emerging markets could have in the future. Instead of externalizing the cost of alleviation of precarious access to electricity, i.e, making them be paid through general taxation schemes, new markets could internalize and distribute them among market agents.

This reflection has led to this Thesis' Research Question:

**How can the cost of alleviation of precarious access to electricity be internalized in decentralized electricity markets and what is the impact of the internalization on market agents?**

To help answer this Research Question, four sub-questions were formulated. They are answered as follows:

- **How can decentralised electricity markets be modelled?**

Decentralized electricity markets can be modelled through the unified formulation developed by Moret [2020].

First, market agents are defined by their demand or supply curves, depending on if they are net producers or consumers. If modelling net consumers, their range of consumption is needed as well as their maximum and minimum acceptable prices. For net producers, their maximum production is needed, as well as the price for which they are willing to start producing and the minimum price they can offer when producing at peak power.

Second, market architectures such as P2P, isolated community or connected community can be modelled through partner matrices and by adding virtual agents. These can be among others market operators, community managers or suppliers.

Last, the consensus-based market negotiation mechanism can be modelled by an automatised algorithm which goal is to maximize the total Social Welfare of the system. That is to minimize total consumer costs and maximizing total producer earnings and consumer satisfaction while taking into account the different commissions that apply to the different trades between market agents, and respecting the constraints given by demand and supply curves.

- **How can the issue of precarious access to electricity be included in decentralized electricity market modelling?**

To include the issue of precarious access to electricity in decentralised market modelling it is necessary to first model low-income households demand curves differently than other net consumers, reflecting a minimum decent consumption at a price they can afford. The minimum consumption is calculated by setting a Minimum Standard Consumption and then taking into account the specific characteristics of the household: its efficiency, members, whether electric heating is used and whether mechanical support through vital medical devices is needed. To ensure affordable prices, their expenditure on electricity is limited to a certain share of their income.

- **Which market mechanisms can internalize the cost of alleviating precarious access to electricity in decentralized electricity markets?**

Once low-income households are modelled, two different mechanisms are designed so as to internalize the cost of alleviating its precarious access to electricity, hence guaranteeing affordable prices for their calculated consumption.

The first mechanism is an Energy Poverty tariff paid by those agents who are in a better position in the market and received by vulnerable households as a subsidy. Net consumers are to pay a tariff according to their margin –that is the amount of money that could be given up while staying within their threshold of consumption and desired prices – whereas net producers will pay proportionally to their net earnings. The distribution of costs between the type of agents as well as the maximum margin that net consumers are able to lose is a factor of decision of the market regulator.

The second designed mechanism is Price Intervention, which is fixing the prices of trades between low-income households and large producers. In this case, vulnerable households are entirely subsidised by producers as each producer is forced to guarantee affordable prices and bears the burden of the needed support proportionally to its net earnings.

- **What impact does the internalization of costs have on the different market agents?**

The results of the Case Study show that with both designed support schemes it has been possible to internalize the costs of alleviation of precarious access to electricity in the vast majority of the simulated scenarios, without the needed contributions having an excessive impact on market agents' final welfare. For instance, in the base case used –which reflects the case of Spain with current input values–, with Price Intervention the loss of net earnings by producers to finance the support is between 10 and 25% depending on the market architecture. With EP tariffs, for consumers, their contribution to financing 40% of the scheme is translated into an increase of their electricity bill of less than 0.6 %, while produces give up 7 to 15 % of their net earnings to finance the rest of the needed support.

Obtained results are largely dependant on the characteristics of the system such as the supply mix, distribution of agents or applicable tariffs and there can be cases where full internalization of costs is not possible. Results show that when increasing the RE share, prices get lower and therefore the issue of precarious access to electricity diminishes, although the same happens to the net earnings from the producers. When increasing the amount of low-income households, the needed support increases and so does the contributions needed from other market agents. Finally, when having more applicable tariffs, such as what happens with a market architecture with suppliers, prices increase and thus also support and contributions. With other market architectures such as community or P2P, there is the potential to have fewer intermediaries, prices can potentially get lower, and so the total needed support.

Contributions that each market agent type has on financing the support for low-income households should be adjusted to the specifics of each case, and in some extreme cases, a partial or total externalization of costs can be needed.

Comparing both proposed schemes, the EP tariff scheme appears to be a more attractive option due to its customization potential, although Price Intervention can be a more viable option in cases where producers have high net earnings due to its lower computational costs.

Having answered all four sub-questions, the main research question can be answered. It can be concluded that the cost of alleviation of precarious access to electricity can be internalized in decentralized electricity markets by first applying the developed methodology to calculate individualized support for vulnerable households, and then with one of the proposed support schemes: either EP tariff or Price Intervention. The impact of the internalization on market agents depends largely on the nature of each case, that is mainly on the distribution of agents, market architecture, applicable tariffs, RE share of the system and distribution of the costs of the needed support among agent types. Although there can be extreme cases where internalization of costs is not possible, with non-extreme input values it tends to have a moderate impact on non-vulnerable market agents.

## 7.1 Future works

Taking this Thesis as a starting point, future works to improve and expand the research done could be the following:

First, some of the decentralised electricity market model limitations discussed in Section 6.1 could be tackled. The model could be adapted to operate using hourly profiles, which would give more realistic results. In addition, further investigation could be done regarding the modelling of supply and demand curves, obtaining more precise cost curves for producers and better reflecting consumers behaviour than just assuming linear demand curves. Moreover, the model could also be further optimized to facilitate the results-gathering processes.

Further investigation could also be done regarding where and under which terms could the proposed methodology be implemented, as discussed in Section 6.5. It would be very useful to know if different market agents would be willing to implement the proposed support schemes, and what would be their requirements in order to participate in markets with them in place. For that, a stakeholder analysis could be done. A collaboration with an Energy Community or a P2P network could also be an excellent way of expanding this Thesis, analysing which modifications would be needed for it to be implemented and how would its real-life operation look like.

The technical barriers encountered when using large agent samples could be also further analysed. For instance, some communication links could be dropped in these cases and contributions and retributions could be made more general rather than customised per agent. It could be interesting to see how much the results are affected by these simplifications: how sub-optimal and how fair would they be, for instance using the Quality of Service and Quality of Experience indicators developed by Moret [2020]. In addition, it would be interesting to explore how to technically include the designed support schemes in a real-life negotiation algorithm, how to gather market agent bids or how to apply and which requirements would be needed to be considered a vulnerable household.

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# Appendix A

An Appendix is uploaded as a .zip folder together with this Thesis and contains the following information:

- All raw data referring the results presented in Chapter 5 in Excel format.
- Software used to model decentralized electricity markets, developed by Moret [2020] and modified by the authors of this Thesis to include the issue of precarious access to electricity. Software is developed in Python and contains all necessary files for its operation, including an installation guide (Readme.txt).