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Business Models for Energy Communities with Vulnerable Consumers

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Abstract

As the global energy landscape evolves towards sustainability, the topic of energy communities keeps gaining prominence. Under this context, this document aims to explore the horizon of planning strategies and business models of energy communities, with a specific focus on incorporating and empowering vulnerable consumers to engage in this initiative. The study investigates the unique challenges faced by vulnerable populations in the energy sector and proposes comprehensive approaches to address their specific needs. By analyzing existing energy community models, both nationally and internationally, the dissertation aims to identify possible work routes and limitations regarding inclusive RECs. Furthermore, it delves into the socio- economic factors affecting vulnerable customers, providing a nuanced understanding of their energy consumption patterns, limitations, and aspirations. The proposed strategies aim to create inclusive and sustainable energy communities by fostering community engagement, promoting energy literacy, and ensuring affordability for all participants. By addressing the unique needs of vulnerable customers, two strategies are proposed: a local energy market discount application for vulnerable consumers, and a post-optimization economic benefit allocation, which aim to contribute to the development of a more equitable and resilient energy ecosystem, while still aligning with the interests of energy stakeholders and the broader community.

Sustainable Development Goals of the United Nations

In 2015, all member states of the United Nations (UN) adopted 'The 2030 Agenda for Sustainable Development' [1], whose core is composed by the 17 Sustainable Development Goals (SDGs) presented below:

1. No Poverty
2. Zero Hunger
3. Good Health And Well-Being
4. Quality Education
5. Gender Equality
6. Clean Water And Sanitation
7. Affordable And Clean Energy
8. Decent Work And Economic Growth
9. Industry, Innovation And Infrastructure
10. Reduced Inequalities
11. Sustainable Cities And Communities
12. Responsible Consumption And Production
13. Climate Action
14. Life Below Water
15. Life On Land
16. Peace, Justice And Strong Institutions
17. Partnerships For The Goals

In the light of these set targets, the research and development work conducted throughout this dissertation gives due consideration to the ambition of a sustainable future, as it actively explores subjects related to energy poverty, renewable energy sources, community building and inclusion.

Table 1 points out a few SDGs believed to be addressed in the course of this work, along with some of the defined targets by the UN. In addition, respective contributions of this dissertation and performance indicators related to each goal in question are also presented.

ODS	Targets	Contribution	Performance Indicators & Metrics
1	1.2: By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions	The work developed aims to formulate strategies and business models in the light of inclusive RECs which help to ease energy expenses of consumers in energy poverty	1.2.2: Proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions
	1.4: By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance	Inclusive RECs preach for a non-discriminatory and embracing approach, ensuring the accessibility and equality of opportunities in the energy consumption space	Reduction of the number of vulnerable households whose energy bill represents over 10% of the total household income
	1.5: By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters	By being part of energy communities, vulnerable consumers reduce their energy bill and are more easily able to adequately heat and cool their homes, being less susceptible to extreme climate events	Reduction of deaths related to extreme (high or low) outside temperatures
7	7.1: By 2030, ensure universal access to affordable, reliable and modern energy services	Energy communities allow the common citizen to easily access clean energy, at a more affordable price	7.1.2: Proportion of population with primary reliance on clean fuels and technology
	7.2: By 2030, increase substantially the share of renewable energy in the global energy mix	Energy communities increase the implementation of renewable energy sources and lower demand on large power plants reliant on fossil fuels	7.2.1: Renewable energy share in the total final energy consumption
10	10.1: By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average	Inclusive ECs allow vulnerable consumers to save money through the reduction of their energy bills	10.1.1: Growth rates of household expenditure or income per capita among the bottom 40 per cent of the population and the total population
	10.2: By 2030, empower and promote the social, economic and political inclusion of all, irrespective of age, sex, disability, race, ethnicity, origin, religion or economic or other status	Inclusive ECs actively preach and aim to build a sense of community and strongly focus their goals on environmental and social impacts	Increase percentage of vulnerable consumers included in Energy Communities
11	11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums	ECs bring alternatives to basic services, as are lightning and heating/cooling of homes, allowing the average citizen to access clean and affordable energy	Proportion of population living in households without basic lightning and the ability to adequately cool and heat the house
13	13.3: Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning	A lot of ECs put efforts into bringing awareness to necessary climate action and educating consumers on energy literacy	Improvement of the educational system in climate change and energy literacy matters

Table 1: Sustainable Develpoment Goals addressed

Agradecimentos

Só tenho tudo a agradecer aos meus pais.

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Abreviations and Symbols

EC	Energy Community
REC	Renewable Energy Community
EU	European Union
UN	United Nations
INESC TEC	*Instituto de Engenharia de Sistemas e Computadores, Tecnologia e Ciência*
CPES	*Centro de Sistemas e Energia*
SDG	Sustainable Development Goals
ELPPE	*Estratégia de Longo Prazo de Combate à Pobreza Energética*
PNEC	*Plano Nacional de Energia e Clima*
TSE	*Tarifa Social de Energia*
PVE	*Programa Vale Eficiência*
PRR	*Plano de Recuperação e Resiliência*
FA	*Fundo Ambiental*
PAEMS	*Plano de Apoio a Edifícios mais Sustentáveis*
PAACCER	*Plano de Apoio à Concretização de Comunidades de Energia e Autoconsumo Coletivo*
RES	Renewable Energy Source
P2P	Peer to peer
EV	Electric Vehicle
VC	Vulnerable Consumer
NVC	Non-Vulnerable Consumer
LEM	Local Energy Market
MILP	Mixed-Integer Linear Programming
DSO	Distribution System Operator
MMR	Mid-Market Rate
SDR	Supply and Demand Ratio
CSDR	Compensated Supply and Demand Ratio
VI	Vulnerability Index
NVI	Non-Vulnerability Index

Chapter 1

Introduction

1.1 Contextualization and Motivations

As we currently face a global climate crisis, change is a key word when it comes to solving it. Therefore, changing the way the world consumes and produces energy, while maintaining the same level of efficiency and reliability, is undoubtedly one of the main challenges of our time.

Longing for this change, several countries got together in 2015 for the Paris Agreement, compromising to make efforts in order to not surpass the pre-industrial global average temperature levels on more than 2 °C, while still striving to reduce this value to 1.5°C [2].

Following this initiative, the European Union (EU) has positioned itself as a leader in climate action by setting ambitious goals for the next few decades. In 2019, the EU introduced the European Green Deal which aims to achieve climate neutrality by 2050 [3], meaning that greenhouse gas 'production' must match its consumption by earth itself, leading to net zero emissions. Additionally, in 2021 the EU reinforced its ambition by coming out with the European Climate Law. This law sets a new target aiming to cut down net greenhouse gas emissions by at least 55% when compared to 1990 [3].

One important measure in the fight against climate change is the decentralization of energy production, making use of renewable sources. This allows energy generation to be cleaner and closer to the consumer, reducing the demand on large power plants relying on burning fossil fuels. Distributed energy resources also allow consumers to privately own their sources as to self-consume the locally produced energy, and, more recently, even share this energy with other nearby consumers. This concept is referred to as an Energy Community (EC).

As this is still a relatively new concept (only introduced by the EU legislation in 2019), a lot of research and pilot projects are still being carried out in order to explore the opportunities and challenges of this innovative approach, as well as the best strategies and business models to optimize the energy sharing process within the community. The present dissertation aims to pursue this same path while acknowledging and empowering the meaning of the word 'community'. As

intended by both the Portuguese and the EU legislation, an EC should have a stronger focus on social and environmental impacts as opposed to monetary returns. Keeping that line of thought, this document attempts to address these two concerns, valuing both at an equal significance level, by exploring different business models for a renewable energy community (REC) that would support the integration of members assumed to be in a situation of energy poverty and, hence, unable to make a fair contribution to the REC itself.

1.2 Proposed Goals

Under the related framework, this dissertation aims to validate business models that work in favor of the inclusion of vulnerable and neglected social groups, providing equal and nondiscriminatory access to opportunities in the energy sector. To achieve this, three main goals are set:

1. **Understand and Identify Vulnerabilities:** in order to work towards an inclusive EC business model, it's crucial to understand how vulnerabilities express themselves within an energy poverty setting, as well as how to identify them in a non-invasive and effective way, under a REC context.

2. **Design new business models:** the goal here should be to design a feasible solution around the identified vulnerabilities and implement it onto an existing INESC TEC optimization software for energy communities.

3. **Test and validate results:** last but not least, different testing scenarios must be designed in order to validate the developed hypothesis and showcase the achieved results.

1.3 Dissertation Structure

The present document is structured in the following manner:

- **Literature Review** - this segment starts by laying out relevant and complementary subjects collected throughout a literature revision, namely, a concise exposure of the legislation around Energy Communities, an assessment to the factors and implications revolving around energy poverty related vulnerabilities, and lastly a more detailed review on planning, financial and modeling aspects of some existent communities, under an inclusive approach.

- **Work Contextualization** - in this section of the document, an INESC TEC optimization module, that serves as a starting point for this work's implementations, is to be introduced.

- **Work Development** - here takes place the idealization and implementation of sharing strategies and business models in the light of inclusive RECs.

- **Tests and Results** - nearing the end, this section is accountable for presenting various test scenarios and analyze/discuss the resulting outputs.

- **Conclusions and Future Work** - lastly, the 'Conclusions and Future Work' chapter is introduced as way to summarized the main findings and conclusions related to this dissertation, as well as point out some limitations and potential future work routes sourced in this thesis' development.

Chapter 2

State of the Art

2.1 Introduction

In this chapter, it is presented a synthesized review of the available literature on energy communities, with a special regard to the inclusion of vulnerable consumers. In this sense, it has been prioritized the research of articles exploring the challenges and consequences of such inclusion, different energy sharing strategies and algorithms, as well as the resulting benefits for all community members.

2.2 What is a Renewable Energy Community?

A Renewable Energy Community is a collective entity composed by other singular or collective entities of private or public nature, whose adhesion is open and voluntary, that reside in close proximity to a renewable project and carry out activities related to that same project, including, necessarily, self-consumption of the generated energy [4]. The main focus of a REC should be to provide environmental, economic and social benefits to its members and/or local community as opposed to financial profits [4].

2.2.1 Legislation

The Decree of Law responsible for the legislation of RECs in Portugal is the nº 15/2022, january 14th. In this decree (and referring to the legislative guide published by ADENE and DGEG [4]) it is stated that a REC has the following rights:

- to produce, consume, store, buy and sell renewable energy with its members or third parties
- to share and commercialize with its members the renewable energy produced without compromising each member's rights and duties as a consumer
- to access all energy markets, including system services, either directly or through aggregation

Still referencing the same legislative guide [4], the portuguese legislation also recognizes three types of energy sharing models within an EC, which include:

- **Fixed Coefficients** that could be differentiated, for instance, by working days and weekends, and could also vary between seasons
- **Varying Coefficients** based on certain criteria, hierarchy or average consumption in a given timestep
- **Combination** of both models above mentioned

Dynamic management is also an option acknowledged by the legislation which would allow a real-time monitorization, control and dynamic management in order to optimize energy fluxes.

Another important topic mentioned in the decree of law 15/2022 is the definition of 'proximity' when it comes to forming a REC. Taken from the legislative guide [4], the Portuguese legislation states that if the renewable source is connected to a:

- **Low-voltage** distribution grid, the consumer must not be further than 2km away from the installation or, alternatively, connected to same low-voltage transformer substation
- **Medium-voltage** grid, the consumer must not be further than 4km away from the renewable source and both must be connected to the same substation
- **High-voltage** grid, the consumer must not be further than 10km away from the installation and both must be connected to the same substation
- **Extra-High-voltage** grid, the consumer must not be further than 20km away from the renewable source and both must be connected to the same substation

2.3 What is a Vulnerable Consumer?

A vulnerable consumer means a person or household in a situation of energy poverty. According to [5], the Directive 2023/1791 from the European Parliament and the Council, of September 13th, defines energy poverty as "a household's lack of access to essential energy services, when said services provide basic levels of lifestyle and health, namely adequate heating, hot water, cooling and lighting as well as the needed energy to power home appliances, taking into account the national context, social policy and other relevant national policies, caused by a combination of factors, including, at least, the lack of price accessibility, an insufficient available income, high energy expenses and a low energy efficient household infrastructure".

The main strategic indicators, defined in [5], to assess the energy poverty horizon in Portugal are:

1. population residing in houses without the ability to keep them adequately warm

2. population residing in houses without the ability to keep them comfortably cool during the summer
3. population residing in houses with infiltration, humidity or mold concerns
4. family households where energy expenses represent more than 10% of their total income
5. fraction of buildings with an energy efficiency class C or lower

2.3.1 Energy Poverty in Portugal

In Portugal, it is estimated that a total of 1.8 to 3 million people are in a situation of energy poverty, of which between 609 and 660 thousand are considered severe cases [5]. The ELPPE (*Estratégia de Longo Prazo de Comabate à Pobreza Energética*) established, as its main goal, to completely eradicate energy poverty in Portugal by 2050, through the integration of vulnerable consumers in the energy transition process [5]. Inclusive energy communities run towards the same goal and can be a big help in ensuring this transition is made as fair and as democratically as possible.

Below are presented, taken from [5], the 2030, 2040 and 2050 targets for the five strategic energy poverty indicators above mentioned. The reference levels are based on either the studies monitored under the PNEC 2030 program ('*Plano Nacional de Energia e Clima*') or on the last studies made available.

Indicator	Reference Value	Target 2030	Target 2040	Target 2050
1	17.5% ($\approx 1.8 million people$)	10%	5%	<1%
2	35.7% ($\approx 3.7 million people$)	20%	10%	5%
3	25.2% ($\approx 2.5 million people$)	20%	10%	<5%
4	1 202 567 ($\approx 3 million people$)	700 000	250 000	0
5	69.6%	50%	40%	30%

Table 2.1: Targets for Energy Poverty Indicators, [5]

2.3.2 Some Measures and Efforts

2.3.2.1 *Tarifa Social the Energia* (TSE)

Portugal has adopted, since 2010, a social energy tariff, applied to final consumers that present themselves in a state of economic vulnerability [5]. This tariff has an effect on energy and natural gas prices, as it applies a 33.8% discount over both networks' access tariffs [6]. In order to be an eligible consumer and benefit from this deduction, one needs an electricity supply contract, in its name, for domestic use only, with an associated contracted power of no more than 6.9kVA [6]. On top of that, the consumer must a beneficiary of one of the following social aids [6]:

- '*Complemento solidário para idosos*': a solidarity complement for the elderly
- '*Rendimento social de inserção*': a social integration income
- '*Prestação de desemprego*': a social unemployment benefit
- '*Abono de família*': a family allowance
- '*Pensão social de velhice*': an old-age social pension
- '*Pensão social de invalidez ou do complemento de prestação social para inclusão*': a pension for people unable to work or a social benefit complement for inclusion

If not benefited by any of these, one can still be eligible for the social energy tariff, if its annual income does not exceed 6 272,64€, with an additional 50% for every household member without any income (up to a total of 10 members) [6]. In Portugal, around 800.000 households benefit from this tariff which, in the energy sector, translates to about 13% of consumers [5].

The financial support for this measure relies on all electricity producers and retailers, as well as any market agents involved, according to consumption. In 2022, this value hovered around 115 million euros [5].

2.3.2.2 Fiscal Benefits

The Decree Law n.º 74/2020 was issued on September 24th in order to convey an intermediate VAT tax (13%) to all electricity supplies up to 100kWh, under contracted powers of no higher than 6.9kVA. This measure was extraordinarily reinforced two years later, in September 2022, as to lower this value to the reduced VAT tax (6%) [5].

The 2022 State Budget Law, approved by Law n.º 12/2022, of June 27th, instructed the application of the reduced VAT value regarding the delivery and installation of solar collectors and photovoltaic panels [5].

Additionally, the 2023 State Budget Law imposed that, for self-consumption production units up to 1MW of installed power and maximum value of 1000€, the revenue made from the sale of surplus produced energy is exempt from taxes directed towards singular incomes [5].

2.3.2.3 *Programa Vale Eficiência* (PVE)

The Program *Vale Eficiência* financially, and fully, sustains economically vulnerable family's investments regarding the thermal comfort of their homes [5]. Its goal is comprised of delivering 100.000 vouchers of 130.000€ each, all funded by the *Plano de Recuperação e Resiliência* (PRR) while the VAT value is supported by the *Fundo Ambiental* (FA) [5]. The first phase of this program took place between August 2021 and May 2023 in which 14 534 vouchers were assigned [5].

2.3.2.4 *Programa de Apoio a Edifícios mais Sustentáveis* (PAEMS)

This Program acts as a co-financing tool to help families invest in the thermal comfort improvement of their homes [5]. The second phase of this program, launched under the PRR in June 2021, ended in May 2023, with around 70 500 eligible applications, translating in a 122 million euro incentive [5].

2.3.2.5 *Programa de Apoio à Concretização de Comunidades de Energia e Autoconsumo Coletivo* (PAACCER)

This Program is intended to co-finance investments made under a collective self-consumption or a renewable energy community framework, whether on a residential, services or central public administrations building, individually or in combination [5]. The first phase of this program took place between June 2022 and February 2023, with a total spend of 30 million euros, 10 of which were destined to residential buildings [5]. The second phase would take place in the last trimester of 2023, aiming to support the integration of vulnerable consumers under this same framework [5].

2.3.2.6 Energy Literacy Promotion

One of the key factors in reinventing the energy sector is educating the population and bringing awareness to the needs and 'how's' of a more energy efficient and sustainable industry. As related in [5], Portuguese energy agencies provide various initiatives to educate and guide consumers, of which:

- *CINERGIA* - an Energy Information Centre looking to give citizens and energy retailers an integrated view of the energy sector
- *Observatório da Energia* - provides consumers with a more transparent and knowledgeable view of the sector, facilitating access to information and resources
- *Poupa Energia* - a platform that allows consumers to compare electricity prices and access all the necessary data to make an informed decision when choosing a retailer
- *Projeto "Consumidor Informado Consumidor Poupado"* - a project devoted to families and citizens with limited access to digital information
- *Projeto "LIGAR"* - a project dedicated to developing inclusive strategies to combat energy poverty

2.3.3 Building Energy Efficiency in Portugal

The level of energy efficiency of a certain household in Portugal is characterized with the help of 8 classes (A+ to F), where A symbolizes the best performance and F represents the lowest degree of energy efficiency.

This performance is evaluated according to a set of factors, such as [7]:

- Year of construction
- Location
- Household's floor and area
- Infrastructure materials (walls, ceilings, pavement)
- HVAC units (ventilation, heating and cooling)
- Materials associated to the production of hot sanitary water

Figure 2.1 below shows the class of all energy certificates issued between 2014 and 2022, where solely 17% of these buildings are classified as very efficient (classes A and A+), contrasting with a big majority (66.3%) of buildings with an energy efficiency class C or lower.

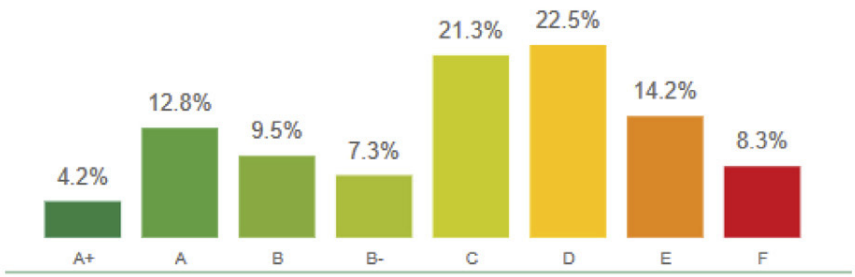


Figure 2.1: Classes of Energy Efficiency Certificates issued between 2014 and 2022 (source: ADENE, SCE)

According to [5], the residential sector represents about 18.6% of the total final energy consumption in the country, revealing an average of a 0.7% annual increase of this value in the last decade.

2.3.4 Energy prices in Portugal

As for the cost of electricity covering the domestic sector, in the first semester of 2021, the average final price (including all taxes) stood at 0.209€/kWh, 4.7% lower than the average EU27 energy price [5].

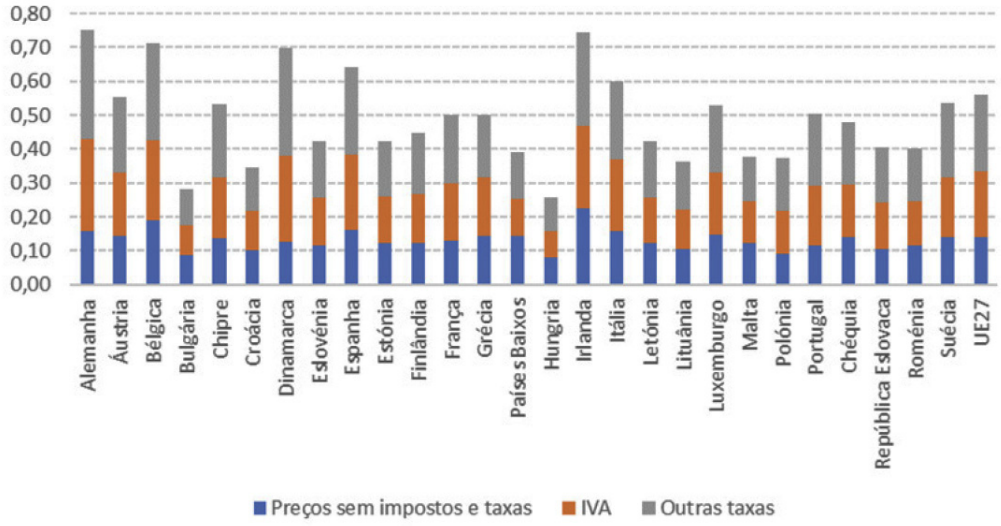


Figure 2.2: Electricity prices of the domestic sector in the EU27, 2021 (source: DGEG)

The average total annual expense per household in electricity, gas and other fuels stands at 1278€/year, corresponding to a monthly expense of 106.5€, which represents 6.3% of the average total annual expense per household and 5.4% of the average total household annual income [5].

In Table 2.2, it's possible to verify that at the lowest level of income, energy expenses represent around 14% of a household's total average annual income. In 2015/2016, 1.2 million households had an energy expense surpassing 10% of their total income, which translates to about 3 million people [5].

	Level of Income [€]					
	<6.790	6.790-13.580	13.580-20.370	20.370-27.160	27.160-40.740	>40.740
Total average annual income/household [€/year]	5.121	10.365	16.847	23.502	32.623	60.043
Total energy expense [€/year (€/month)]	726 (60.5)	995 (83)	1.182 (98.5)	1.282 (107)	1.519 (126.5)	1.959 (163)
Expense related to income	14.2%	9.6%	7.0%	5.5%	4.7%	3.3%
N.º households	263.033	939.534	944.228	743.549	742.819	471.546

Table 2.2: Electricity, gas and other fuels total average household annual expenses per level of income in 2015/2016 (source: INE, I.P.)

2.4 How to quantify vulnerability?

Accurately quantifying this multidimensional concept, positioned in such a wide spectrum, is surely a challenging task, especially when relying on rather subjective and unmeasurable parameters, like some of the previously mentioned in section 2.3. Nevertheless, it's a crucial step being able to estimate, as efficiently and fairly as possible, a certain degree of vulnerability among potential members of an energy community, in order to formulate a business model which performs in accordance to user's susceptibilities.

Diving into [8], one can reach a well thought out and robust evaluation method, built to cover a vast array of parameters, while providing some versatility in regard to the weight attributed to each set of factors. The author opted by focusing on two main categories under the vulnerability subject, each of them hosting 7 energy poverty indicators, like presented below:

Infrastructural Vulnerability	**Socioeconomic Vulnerability**
• Average outside air temperature	• Average IRS income
• Buildings with repairing needs or severely deteriorated	• Higher education rate
• Average building age	• Unemployment rate
• Heating needs	• Mortality rate
• Primary energy needs	• Percentage of deaths in winter months
• Useful floor area	• Average monthly income
• Climate winter zone	• Percentage of social housing

Table 2.3: Set of energy poverty indicators used in [8]

The vulnerability index would then be calculated with resort to the following expression:

$$\sum_{k} p_k \times n_{ik}, \quad with \sum p_k = 1 \tag{2.1}$$

where p_k represents a factor based on the chosen scenario (of the ones presented below), and n_{ik} are the normalized values of the i indicators belonging to criterion k.

A normalization scale was defined (classes between 1 and 5) for each one of the indicators above presented. Looking to understand the impact of each group of indicators, three scenarios were also defined:

- **Scenario I** - both groups of indicators (infrastructural and socioeconomic) have equal weights (p_k) of 0.5 each

- **Scenario II** - infrastructural indicators have a bigger weight (p_k=0.7) than socioeconomic indicators (p_k=0.3)
- **Scenario III** - socioeconomic indicators have a bigger weight (p_k=0.7) than infrastructural indicators (p_k=0.3)

The normalization of the various indicators is performed according to:

$$IE_i(\%) = \left(\frac{E_i - minE}{maxE - minE}\right) \times 100, \quad with \quad i = 1, ..., 14 \tag{2.2}$$

where IE_i is the normalized energy poverty exposure index for indicator i, E_i is the real value of the exposure index for the indicator i and lastly $min/maxE$ are the minimum and maximum values of the energy poverty exposure index.

Although the approach proposed in [8] attends to various relevant concerns and comprises a rather credible method to quantify a vulnerability index, it wouldn't work as a viable solution for this intended purpose, as it fails to operate with easily accessible and collectable data. Realistically, it would be quite a challenge to access all the required information to align with the respective 14 indicators above mentioned, for all members of an energy community.

A more feasible option is presented in [9], by working with a Low Income High Cost (LIHC) coefficient which combines the two most significant contributors to energy poverty: high energy expenses and a low income source. This index was quantified according to:

$$LIHC = I\left[[s_{e,i} > P50(s_{e,i})] \cup \left[\frac{y_i - s_{e,i}}{N_{ind_{income}}} < y^*\right]\right] \tag{2.3}$$

where $s_{e,i}$ is the sum of annual energy expenditure, $P50(s_{e,i})$ is the median value of the reference sample, y_i is the total annual income of the household, $N_{ind_{income}}$ is the number of individuals in the household that do or should benefit from a salary and y^* is the income threshold that identifies a household at a risk of poverty. I is a logical function that returns the value 1 when one or both conditions presented are true, otherwise the value 0 is returned.

As the previous index is only able to identify if a household is or isn't at risk of energy poverty and provides no quantification of this risk, the author of [9] proposed a continuous version of the boolean index shown above, which consists of the average value between two expressions:

$$Mean\left[\left[\frac{P50(s_{e,i})}{s_{e,i}}\right]; \left[\frac{y_i - s_{e,i}}{N_{ind_{income}} * y^*}\right]\right] \tag{2.4}$$

Where the first expression returns a higher value when associated to lower energy expenses (a higher value relates to a lower vulnerability) and the second expression returns a higher value when, per household member, there is a bigger discrepancy between income and energy expenses (in a way that a higher value also relates to a lower vulnerability).

An approach of the nature described in [9] is much more appealing given the context of a REC, as an EC member would have to provide far less data in comparison to the implementation seen in [8] (solely the annual income, annual energy expenses and number of residents in the household).

2.5 How welcomed is vulnerability?

As stated before, the main purpose behind an energy community should rely more on environmental and social benefits as opposed to financial ones. However, a fundamental aspect to take into consideration is the willingness and solidarity of non-vulnerable consumers when it comes to taking in members who are unable to make an equal contribution to the energy community itself.

A case study presented in [10] describes the trading methods observed in two off-grid villages in rural India, when a set of solar items (such as batteries, flashlights, etc) were provided to a selected citizen of each village. These two selected citizens were then in charge of commercializing the solar items with the remaining villagers. Under this setup, three types of exchanges were identified:

- **In cash returns** - the solar items were exchanged through payments in form of local currency
- **In kind returns** - the solar items were exchanged through payments performed through an item or service of economic value such as access to irrigation pump sets, agricultural vehicles, food or grain, medical consultations, etc.
- **Intangible returns** - the solar items were provided in exchange of payments in form of social gestures and actions measured neither quantitatively nor monetarily

The study concluded that the type of exchange performed by the citizen in charge and possession of the solar items was strongly influenced by the social proximity to the consumer in question. The following charts present this data, for every type of return, where the y axis measures the percentage of each kind of returns, according to the type of social relationship (x axis).

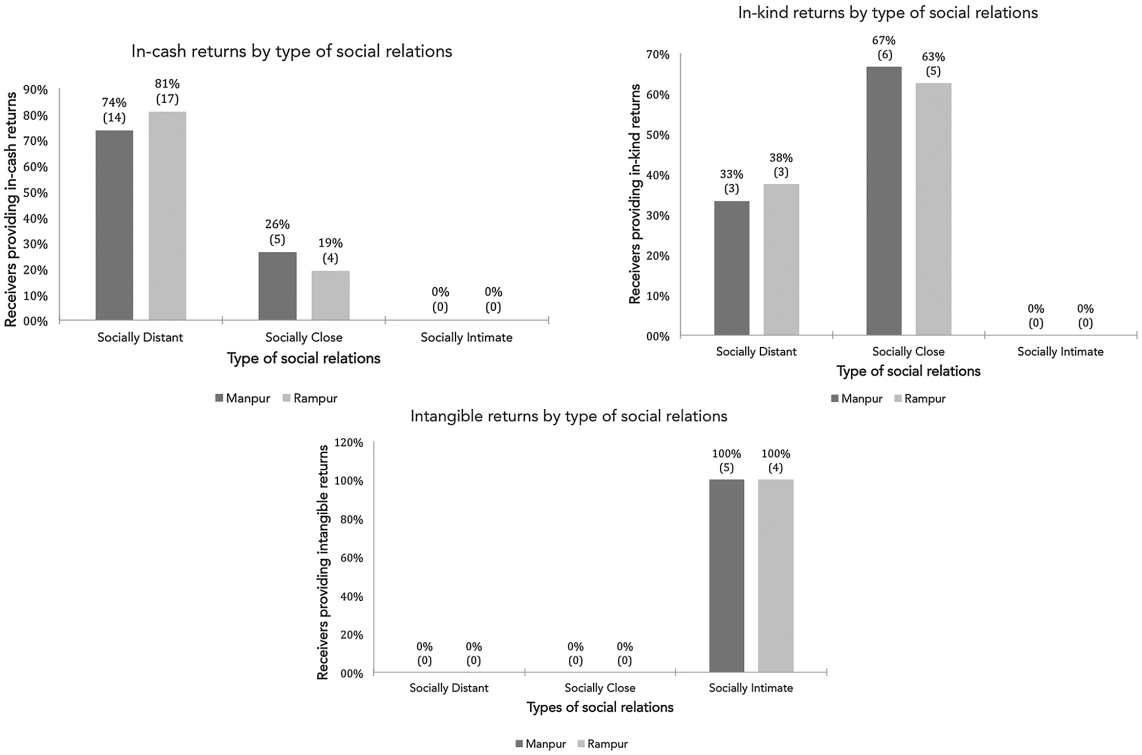


Figure 2.3: Returns by level of social proximity [10]

Referencing Figure 2.3, it is noted that the big majority of exchanges carried out without any required monetary payment were mainly performed between either socially close (neighbour, friend) or intimate (close friend, family) individuals. In fact, all trades performed under a no-return approach were exclusively carried out between socially intimate citizens.

The results shown above, as the study in [10] relates, reveal that a concept of 'profit' is very much present in exchanges between socially distant individuals, even though the seller has not made any investment in order to acquire the marketed solar items. On the other hand, the economical, geographic and social context of this study very much differs from any scenario intended for this research, as all participants involved are in a situation of severe vulnerability and isolation.

Another study taken from [11] presents an inquiry, in the Netherlands, to 74 individuals with various socio-demographic characteristics, looking to evaluate the receptiveness to the inclusion of vulnerable individuals at their expense.

Figure 2.4 reveals the participant's responses when inquired about the primary motives for joining an Energy Community, and the answer catalog seems to very much align with a sense of community and solidarity (however, it is to be noted that this specific inquiry only accounted for 34 respondents).

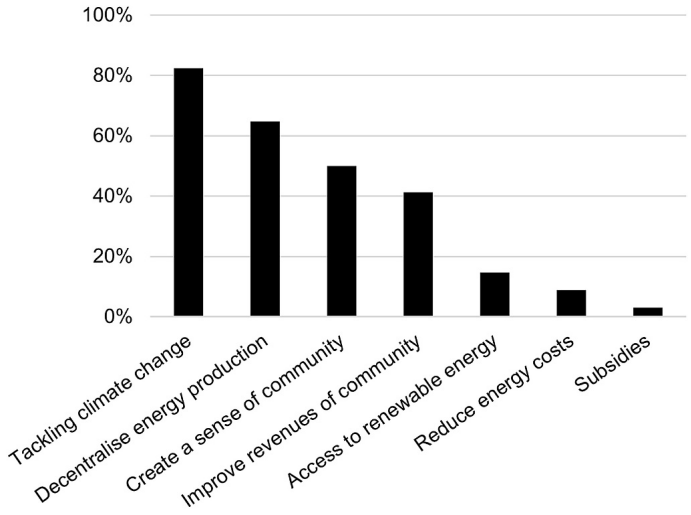


Figure 2.4: Reasons for becoming an EC member, [11]

Subsequently, all 74 participants were inquired on their willingness to share surplus electricity with no return or through an indirect return (not specified). The results are presented below:

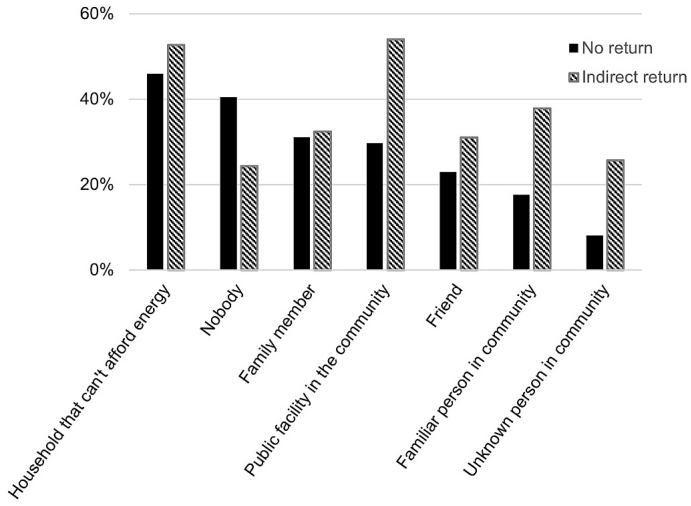


Figure 2.5: Willingness to share surplus energy with none or indirect return, [11]

Figure 2.5 shows rather satisfactory results, with a total of 60% of respondents willing to give away surplus electricity for free and 76% of respondents who would do it for an indirect return. Moreover, [11] states that 77% of the respondents who would do it for free and 70% of those who would do it for an indirect return state that they would share it with a household that cannot afford electricity.

Lastly, participants were asked about what they consider the most relevant aspect to keep in mind when trading energy between EC members (peer to peer transactions). Answers are shown below:

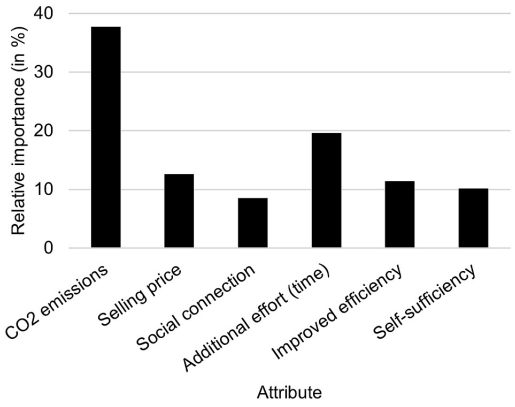


Figure 2.6: Most relevant concerns when trading energy within an EC, [11]

The prioritized concern, and rightfully so, are CO2 emissions, aligning with the main concern of 'tackling climate change' expressed by the majority of respondents relative to the inquiry in Figure 2.4. Nonetheless, standing at second place with significant support, comes 'additional effort\time'. This implies that EC members, although willing to share and help other consumers, don't want to be bothered with trading decisions and would prefer an automated trading method. On a last note, it is relevant to mention that the attribute 'selling price' (LEM tariffs) did not play such a significant role in the decision-making process of the inquired individuals.

On an European level, document [12] states that 86% of people questioned declare they would support new wind and solar projects near their residence area. Moreover, [12] also affirms that 79% of Europeans want their governments to provide more financial support for community groups to generate their own solar and wind energy, while an impressive 61% would be likely to join an energy cooperative in their respective region.

2.5.1 What can vulnerable consumers offer in return?

Given that a household in a situation of energy poverty would be, most likely, unable to make any initial investment usually required to join a REC, a reasonably asked question would be: what could they offer instead?

The author of [10] defends that the diversification of returns should be facilitated, allowing other goods or services to be traded for electricity. However, this alternative is defended in an off-grid and rural setup, where it could more easily fit into people's lifestyles and customs, as these types of returns are frequently already implemented in other areas of commerce.

In [13], the possibility of vulnerable households providing space in exchange of energy is brought up. Indubitably, free space is an imperative aspect when it comes to developing a REC, as (typically) solar panels need to be installed. Thus, vulnerable households could, for instance, provide their rooftops for that same purpose. On that note, one of the interviewees in [13] points out that most energy-poor households are usually tenants and therefore cannot let their rooftops

on the lease. To combat this adversity, the document also mentions the alternative of balcony PV plants when rooftops are not suitable for landlord-to-tenant-electricity models. Interviewees in [13] report that a small PV balcony would cost around 400€, thereby lowering the required investment.

Document [14] presents a social business plan to support vulnerable households in joining energy communities, which consists of a rent-a-roof scheme. As proposed by [14], these households could rent their roof to a Community Energy Fund, which pays for the equipment and installation, and also pays a rent to the respective house owner. In return the Fund could use the roof to install a PV system and surplus energy would be sold to the grid.

2.6 Energy Communities

In order to better understand the grand scheme of energy communities and be mindful of approaches and opportunities already explored under this framework, a literature review was conducted, on mainly inclusive RECs, as a way of gathering information relative to the modelling and energy sharing strategies of energy communities, as well as financial and funding aspects.

Table 2.4 gathers the main articles reviewed in this section as well as their main contributions to the ongoing work.

Article	Most relevant subjects addressed
[10]	• Diversification of returns in energy exchanges • Non-monetary returns' dependence on social relations
[15]	• Implementation and funding of inclusive energy communities
[16]	• Modelling of an inclusive REC • Algorithms for scheduling of P2P transactions
[17]	• Implementation and sizing of a REC • Economic results
[18]	• Energy sharing strategies and algorithms based on different 'sharing coefficients' scenarios
[9]	• Energy poverty index analysis • KPIs for energy sharing methods • Strategies and algorithms for energy sharing in a REC
[19]	• Implementation and funding of an EC in a low-cost social housing context
[20], [21]	• Implementation and funding characteristics of a REC
[22]	• Modelling and optimization of an EC
[23]	• Guide of an EC pilot project

Table 2.4: Main topics addressed in reviewed articles

2.6.1 Geographic Aspects

Firstly, it's useful to lay out the geographic context each EC is inserted in, as to easily identify which articles better relate to a given environment. Relevant to note that, in the case of article [10], the the rural area is not connected to any electrical grid, thus the off-grid classification. The behaviours studied do not rely on energy transactions, but instead over the sharing and commercialization of solar devices, such as solar batteries, in an off-grid isolated community.

Article	**Location**	**Rural/Urban Environment**	**off-grid community**
[10]	Gaya, India	rural	✓
[15]	Rome, Italy	urban	✗
[16]	Coimbra, Portugal (study case, not a real community)	urban	✗
[17]	Madrid, Spain	urban	✗
[18]	Madrid, Spain	urban	✗
[9]	Teglio, Italy	rural	✗
[19]	Amial, Portugal	urban	✗
[20]	Marco de Canaveses, Portugal	rural	✗
[21]	Odemira, Portugal	rural	✗
[22]	-	-	✗
[23]	Telheiras, Portugal	rural	✗

Table 2.5: Geographic aspects of reviewed articles

2.6.2 Energy Community Composition Aspects

Likewise, laying out the respective EC composition aspects also simplifies the research process as it facilitates the targeting of inclusive approaches.

Article	Includes vulnerable consumers?	Includes non-vulnerable consumers?	Includes public buildings?	Which RES is installed?	Includes batteries?	Includes EVs/charging stations?
[10]	✓	✗	✗	PVs	✗	✗
[15]	✓	✗	✓	PVs	✗	✗
[16]	✓	✓	✗	PVs	✓	✓
[17]	✓	✓	✓	PVs	✗	✗
[18]	✓	✗	✓	PVs	✓	✓
[9]	✓	✓	✓	PVs	✓	✗
[19]	✓	✗	✓	PVs	✓	✓
[20]	✗	✗	✓	PVs	✗	✗
[21]	✗	✗	✓	PVs	✗	no, but recognizes that possibility
[22]	✗	✓	✗	PVs	✓	✗
[23]	✓	✓	✓	PVs	✗	✗

Table 2.6: Composition aspects of reviewed articles

When analyzing Table 2.6, one can note a clear favoritism concerning the choice of a RES, as photovoltaic panels are unanimously preferred. It is also noticeable that public buildings play a role in the big majority of the referred articles. In fact, they often embody financial duties, by totally or partially funding RES installations and/or vulnerable consumers' integration, as well as pedagogical duties, since, due to their typical larger infrastructure, can more easily allow the hosting of lectures/workshops that look forward to a more aware and well-informed society on the energy literacy topic (articles [15] and [23] both follow this latter approach). Also thanks to their large infrastructure, public buildings often assume to be the installation site as they can generally provide a significant surface area for PV panels. As a final note, it is relevant to mention that many authors already opt for the inclusion of batteries and/or electric vehicles in their energy community models.

2.6.3 Financial Aspects

Another relevant subject to be evaluated under the energy community research, is how these projects are funded. For this purpose, table 2.7 is presented below:

Article	Public or private investments?	RES installation cost	Payback time	Vulnerable consumer (VC) entry fee	Financial returns
[10]	public	560€	-	through negotiation	-
[15]	public	previously installed by public building	-	no cost	-
[16]	-	previously installed by non-VCs	-	-	average weekly savings of 1.58€ (summer) and 2.27€ (winter) (2.12€ and 2.19€ for VCs)
[17]	private and public	66.768€ + 20.000€ (additional costs)	3 years and 2 months (no NPV)	weekly expense of 5.30€ for 15 years	monthly savings of 19-20€ (16€ for VCs)
[18]	public	-	-	no cost	dependent on strategy chosen
[9]	public	184.160€ (without EC extension)	24 years (no extension) or 8 years (with extension)	no cost	yearly savings of 13.858€ (no extension); with extension VCs' expenses get 80%-100% covered
[19]	public	-	8 years	no cost	10% savings in the first 8 years
[20]	private and public	32.000€	-	-	yearly savings of 5.500€
[21]	public	-	3-4 years	-	PVs could cover 45%-60% of public school's expenses
[22]	-	-	-	-	reduces EC's expenses in 32.4% and raises its profit by 39.6%
[23]	private and public	9.777€	4.5-5.6 years	1€ yearly expense	yearly savings of 284€ (public building), 135€ (non-VCs) and 96€ (VCs)

Table 2.7: Financial aspects of reviewed articles

Regarding the funding of the reviewed ECs, it is observable a clear predominance of investments coming from the public sector. Most of this financial support derives from initiatives performed by Municipalities and Local Governments, [10, 15, 18, 9, 21]. The RECs addressed in articles [23] and [20] also account for Municipality investments, however [23] equally relies on funding from '*Parceria Local de Telheiras*', which is a non-profit community web composed by public and private entities who aim to support local initiatives, while [20] can similarly rely on '*Coopérnico*' for additional funding, which is a Portuguese Renewable Energy Cooperative. In the case of article [19], financial aid is provided by EEA Grants, which accepts donations from Iceland, Liechtenstein and Norway as to reduce social and economic disparities in Europe. In [17], the investment is covered by the proposed public building and the non-vulnerable consumers, according to the respective consumption. Aside from investments, article [14] remarks that many ECs are taking up additional services as a way to keep funding the community, namely energy distribution (through the management of local and smart grids), a range of ancillary services (such as energy upgrading services, consumption monitoring, auditing and financial services), micro-mobility services (car sharing or carpooling), as well as other additional services (consulting, communication and awareness campaigns).

In regard to the vulnerable consumer entry fee, article [17] took a monthly fee approach, where the VC has a monthly expense of:

$$\frac{77\% \times TotalInvestment}{PybackTime(months) \times VulnerableHouseholds} \tag{2.5}$$

where 77% is the percentage of the total investment covered by the non-vulnerable households (since the public building only consumes around 23% of the generated energy). This translates in a 5.30€ monthly fee for vulnerable consumers throughout a 15 year period. Now in article [23], a yearly quote approach is applied where, for vulnerable consumers, translates in a yearly expense of simply 1€.

2.6.4 Modeling Aspects

In this section, the focus is shifted towards the modelling of an energy community, centering the discussion around optimization models and business approaches regarding the energy/profit distribution system among EC members.

Of the reviewed articles, purely 4 reports fully addressed this topic, [16, 18, 9, 22], and solely 3 of these are incorporated in the energy vulnerability context, [16, 18, 9].

Document [16] explores the modelling of an energy community that focuses on user's goals and preferences, generating a Pareto front that showcases the trade-offs between two conflicting objectives of minimizing costs and discomfort. The first objective, minimizing user's energy bills, is achieved through the minimization of the net power requested to the grid (NPR_t) and the maxi-

mization of power sold to the grid (PS_t):

$$min \sum_{t=1}^{T} \left(NPR_t . \frac{BP_t}{1000} . \Delta t - PS_t . \frac{SP_t}{1000} . \Delta t \right) \quad [€] \tag{2.6}$$

where BP_t and BP_t are the energy buying and selling prices, respectively.

In regards to the opposite front, discomfort is modelled as penalties that the algorithm aims to minimize. These penalties are modelled as:

$$min \sum_{t=1}^{T} \left(\sum_{j=1}^{n} \frac{TSP_{jt} . Y_{jt}}{100} + \sum_{b=1}^{m} \frac{TVP_{bt}}{1000} \right) + \sum_{e=1}^{v} \frac{max(0, IFC_e - SoC_e)}{10} \tag{2.7}$$

Where TSP_{jt} represents a time slot penalty for the late/early start of shiftable loads, TVP_{bt} stands for a temperature variation penalty accounting for the temperature difference between the desired and real temperatures, while the last term symbolizes a penalty for the postponement/advancement of EV charging, being IFC_e and SoC_e the ideal and real states of charge, respectively. In document [24], of the same authors from [16], it's possible to clarify how these penalties are defined:

$$D_{it} = \begin{cases} \frac{T_{b,t} - HRT_b}{e^{HRT_b} - LRT_b} - 1, & \text{if } T_{b,t} > HRT_b \\ \frac{LRT_b - T_{b,t}}{e^{HRT_b} - LRT_b} - 1, & \text{if } T_{b,t} < LRT_b \end{cases} \tag{2.8}$$

$$\begin{cases} \frac{LRT_b - T_{b,t}}{e^{HRT_b} - LRT_b} - 1, & \text{if } T_{b,t} < LRT_b \\ 0, & \text{otherwise} \end{cases} . \tag{2.9}$$

Where $T_{b,t}$ represents the thermostatically controllable load's (TCL) temperature, while LHR_b and HRT_b stand for the minimum and maximum reference temperatures of said TCL.

Alongside this optimization, article [16] proposes an individual goal-oriented approach, where each EC member chooses whether they are a cost-driven member (would sacrifice comfort over higher costs), a comfort-driven member (the opposite), or balanced, which assumes an equal relevance over both terms of the bi-objective function. Under this regime, vulnerable consumers are always placed as cost-driven members. Lastly, document [16] ensures that the community manager, which schedules the energy transactions between consumers, must prioritize energy transactions involving vulnerable consumers.

Article [18] proposes an optimization model that handles the energy sharing task through the implementation of sharing coefficients. The model's overall objective is to minimize the community's energy costs, through minimizing the power requested to the grid and maximizing its energy surplus sales. The decision variables, on the other hand, are a set of sharing coefficients assigned to each member $\beta_{i,t}$ indicating the share of energy directed towards them in each time step. With vulnerable consumers in mind, document [18] presents the three following energy sharing strategies:

- **Equal Beta -** all vulnerable consumers are assigned the same energy share at any given time step:

$$\beta_{i,t} = \beta_{i+1,t} \tag{2.10}$$

- **Equal Savings -** the sharing coefficients assigned to each vulnerable consumer must result in equal monthly savings for all:

$$C^{buy}_{i,t}.p^{demand}_{i,t} - (C^{buy}_{i,t}.p^{buy}_{i,t} - C^{sell}_{i,t}.z^{sell}_{i,t}) = C^{buy}_{i+1,t}.p^{demand}_{i+1,t} - (C^{buy}_{i+1,t}.p^{buy}_{i+1,t} - C^{sell}_{i+1,t}.z^{sell}_{i+1,t}) \tag{2.11}$$

- **Equal Energy -** all vulnerable consumer's sharing coefficients are assigned so that they all receive the same energy amount, yearly:

$$\sum_{t\in T} \beta_{Nhouseholds}.(PV_t + P^{dch}_{es,t} - P^{ch}_{es,t}) = \sum_{t\in T} \beta_{N_{nouseholds+1}}.(PV_t + P^{dch}_{es,t} - P^{ch}_{es,t}) \tag{2.12}$$

Along with that, the authors in [18] also provide three time frame options for the set of sharing coefficients, as these can be fixed throughout the whole year, or can be updated monthly and even hourly. To conclude the revision on this article, two important formulations were added to the model: one that imposes a threshold of 70% on the energy that is allocated to non-residential buildings (equation 2.13) and a second one ensuring that the EV charging station covers all its energy costs as to provide its service to all EC members, free of charge (equation 2.14).

$$\sum_{n\in I_{non-residential}} \beta_{n,t} \leq \lambda_p \tag{2.13}$$

$$\sum_{t\in T} C^{buy}_{ev,t}.p^{buy}_{ev,t} - C^{sell}_{ev,t}.z^{sell}_{ev,t} \tag{2.14}$$

Continuing on, the last article specifically aimed at inclusive RECs, [9], proposes several algorithms and consequent combinations to tackle the energy sharing optimization problem in ECs.

The first algorithm presented, distributes ECs profits according to each member's ownership share of the RES installation.

$$Profit_{i,d,h} = \frac{contribution_i}{totalinvestment} * Profit_{CER,d,h} \tag{2.15}$$

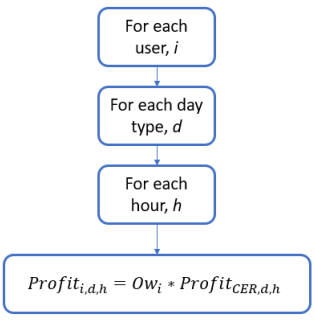


Figure 2.7: Owner's Algorithm, [9]

Assuming an equivalent simplicity, another algorithm is proposed, where benefits are allocated proportionally to consumption.

$$Profit_{i,d,h} = \frac{Load_{i,d,h}}{Load}_{CER,d,h} * Profit_{CER,d,h} \quad (2.16)$$

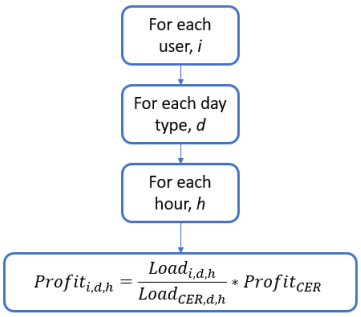


Figure 2.8: Proportional Algorithm, [9]

Next is presented an iterative approach which solves the energy allocation task through the delivery of individual 'packets' of energy to each member in every iteration. These packets assume a value of L_{min}, representing the lowest quantity within an array L accounting for all member's power demand (kWh) in that time step. This cycle is performed until the shared energy is completely allocated. [9]

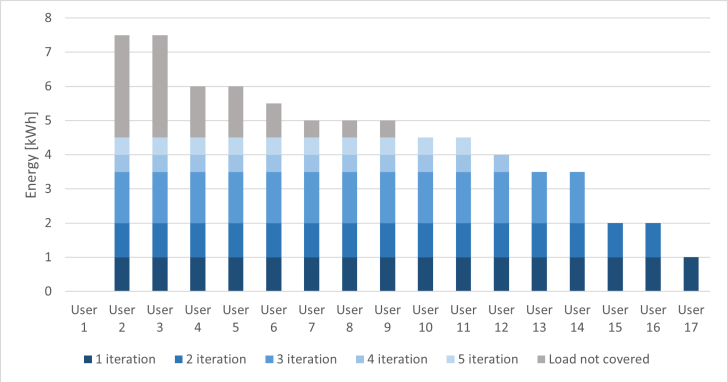


Figure 2.9: Packets Algorithm, [9]

Further on, a Shapley value Algorithm is suggested, which defines, in mathematical terms, the contribution of an individual within a coalition. For each coalition, the ECs profit with and without the member is calculated through the *Compute Value* function, which computes the gains of the REC by taking in this coalition. In order to distribute this value among the users in a fair manner, the Shapley value is used, which calculates the marginal contribution of each 'player' [9]:

$$\Phi_i = \sum_{S \subseteq N\{i\}} \frac{|S|!(n-|S|-1)!}{n!}.(\upsilon(S \vee \{i\} - \vee(S))) \quad (2.17)$$

Where the left term represents a weighted factor that takes into account every possible order in which user i can join the coalition S, and the term on the right considers the added value that each member brings into the said coalition. Figure 2.10 ilustrates this algorithm:

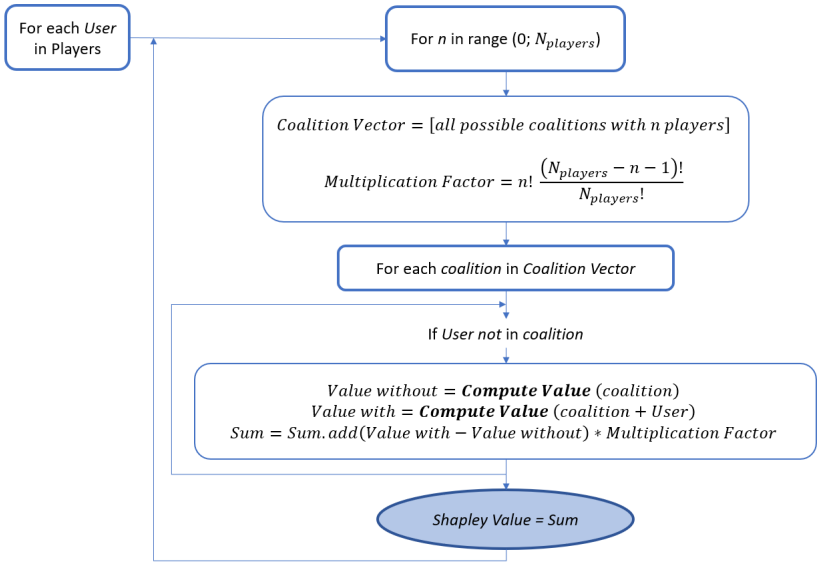


Figure 2.10: Shapley Value Algorithm, [9]

The economic benefits inside the EC would then be distributed according to the value each member brings to the community itself.

From this point on, the author of [9] begins to build more complex algorithms through a combination of the previous simpler ones.
Firstly, a bi-level algorithm is proposed, which imposes a first level of profit distribution through the proportional method, and a second one according to the owner's method.

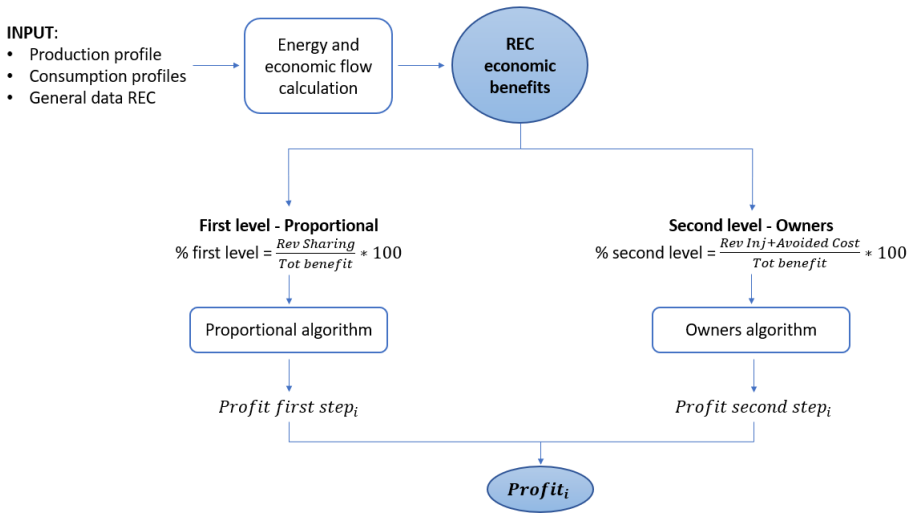


Figure 2.11: Bi-Level Algorithm: Proportional and Owners, [9]

The economic benefits allocated in the first level derive from the energy sharing revenues within the EC, i.e, the profits associated to the selling of energy through peer to peer transactions

in the LEM, while the ones allocated in the second level of the algorithm rely on economic benefits derived from feed-in of surplus energy and avoided cost due to self-consumption.

Still within the bi-level structure, an Energy Poverty Algorithm is proposed, based on the LIHC index described in Section 2.4. These algorithms combine the Energy Poverty approach with either the Owners or Proportional Algorithms, as shown in Figures 2.12 and 2.13.

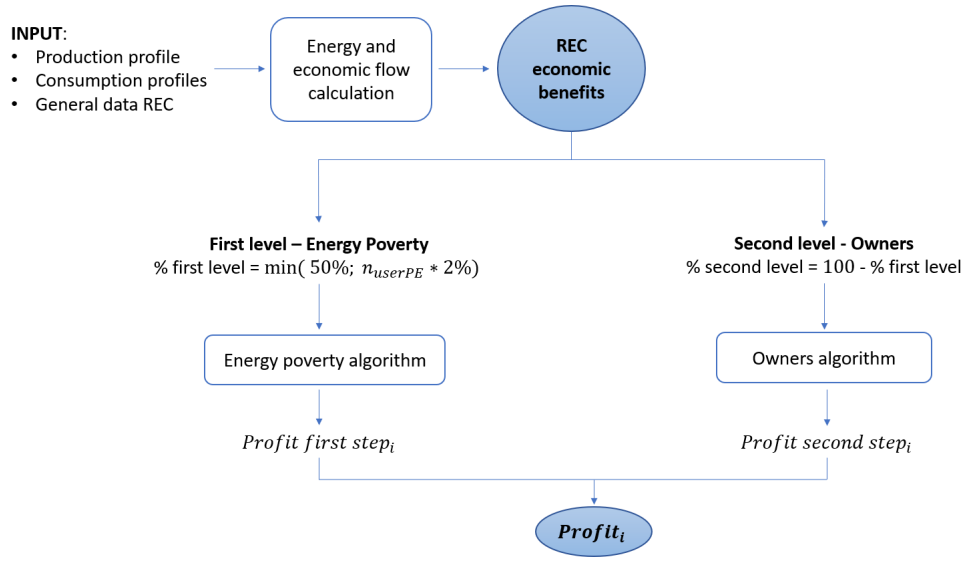


Figure 2.12: Bi-Level Algorithm: Energy Poverty and Owners, [9]

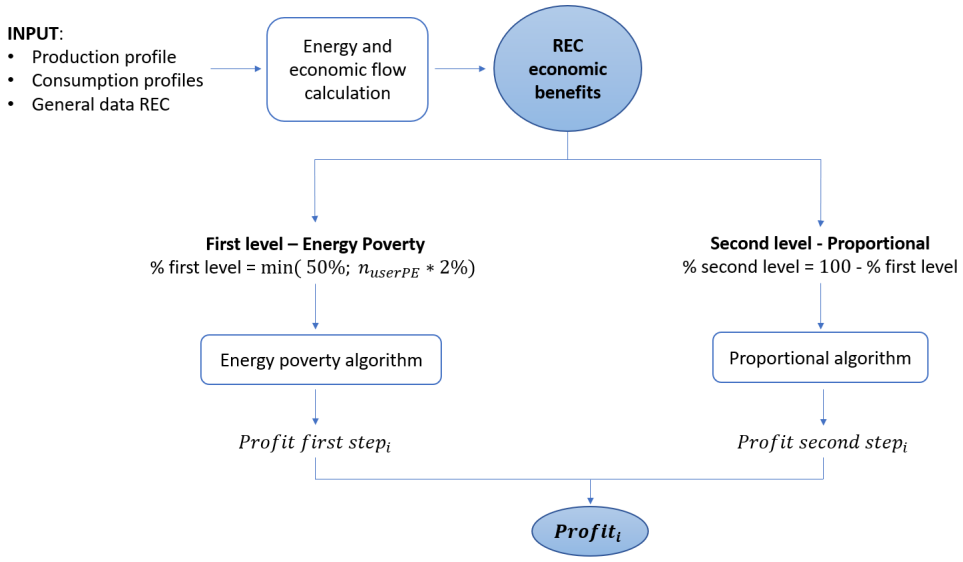


Figure 2.13: Bi-Level Algorithm: Energy Poverty and Proportional, [9]

In regards to the first level of these algorithms, it's presupposed an allocation of 2% of economic benefits per vulnerable consumer (up to a threshold of 50%), which are then distributed in accordance to the continuous version of the vulnerability index LIHC. As for the second level,

the remaining economic benefits are then distributed either accordingly to the Owner's Algorithm (Figure 2.12) or the to Proportional Algorithm (Figure 2.13).

Finally, the author in [9] culminates its proposals by building a Tri-Level Algorithm which incorporates the three previously mentioned Energy Poverty, Proportional and Owner's methods, in the following manner:

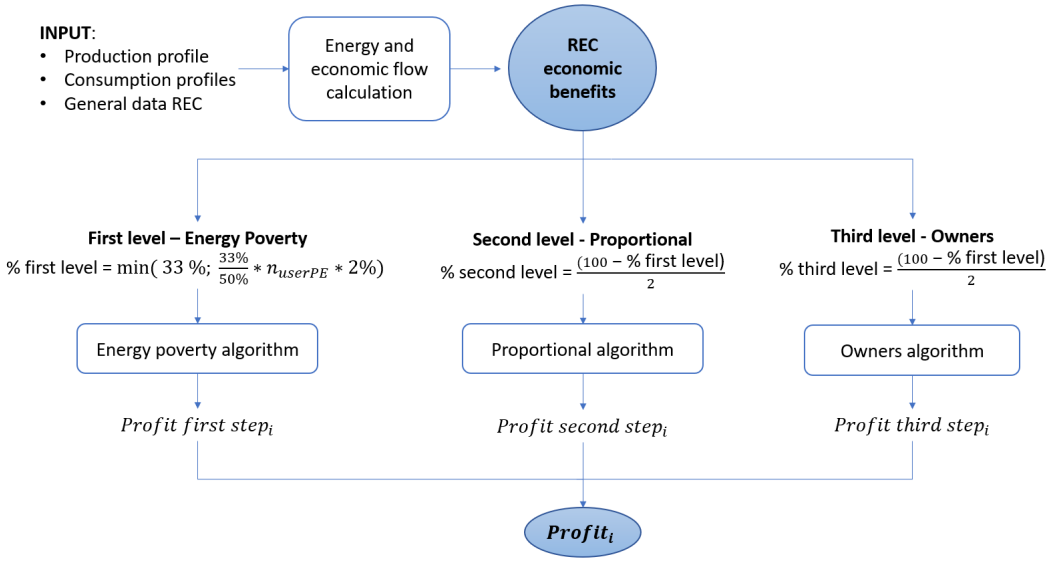


Figure 2.14: Tri-Level Algorithm, [9]

Each vulnerable consumer contributes to an allocation of $2\% * \frac{33\%}{50\%}$ of economic benefits up to a threshold of 33%, which are then distributed according to the Energy Poverty algorithm, while the remaining profits are equally divided between the Proportional and Owner's methods and shared among EC members accordingly.

To conclude this section, reviewed article [22] advocates a two-stage mechanism, enabling EC members to participate in a day-ahead market during the first stage, through an iterative bidding mechanism, that allows consumers to update their energy demand according to the prices indicated by the community operator. In this first stage the objective should be to minimize the ECs energy costs by minimizing the power requested to the grid.

Proceeding to the second stage, consumers are able to adjust their commitments in the previous phase by trading energy with other EC members, through a one-shot bidding process in the real-time market. The model's overall objective is to reduce the total operational cost of the community. Figure 2.15, taken from [22], illustrates this two-stage mechanism:

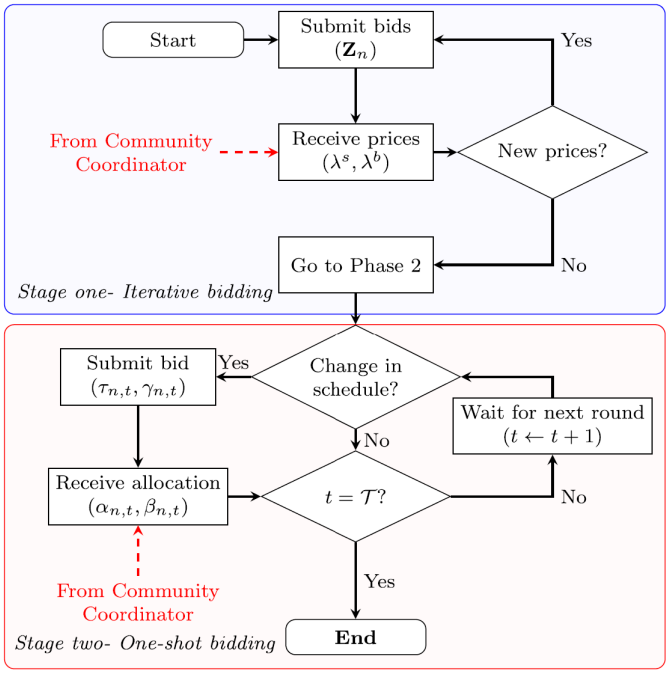


Figure 2.15: Two-Stage Mechanism, [22]

Apart from the articles displayed in Table 2.7, further research was conducted on the topic of EC modeling.

The author of report [25] develops an post-delivery electricity allocation algorithm based on EC member's preferences. In fact, an energy allocation is performed prior to this one, in order to fulfill the consumer's demands. This distribution is conveyed attending to two actions: maximizing self-consumption of members who own generation and the sharing of surplus power through static coefficients. The outputs from this allocation (load covered within EC & generation consumed within EC per member) are used as inputs for the ex-post electricity allocation, as presented in figure 2.16. Here, each consumer is allowed to state its preference regarding the favoured member to purchase power from. Subsequently, the 'preferred' amounts are firstly (re-)allocated, followed by the 'non-preferred' amounts.

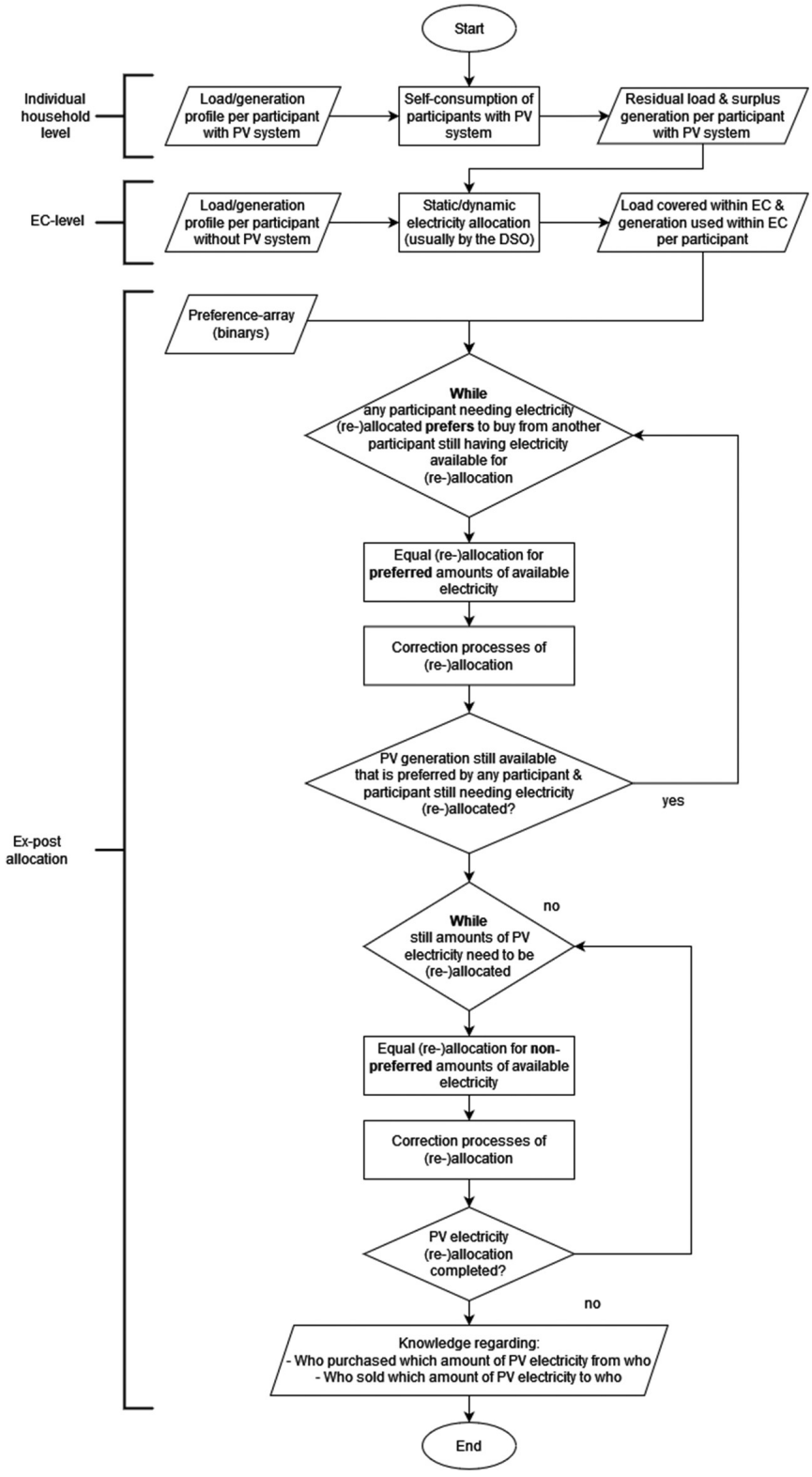


Figure 2.16: Ex-post allocation algorithm, [25]

Within the topic of post-delivery markets, article [26] discusses the impact of bidding behaviour and proposes three different bidding strategies. The first one comprises a Random Bid-

ding process, where the bidding prices are generated randomly according to a uniform law, within set bounds, and depend on the import/export status of the each user. Secondly, a Constant Bids method is suggested, where the bidding prices are settled at the average value between the retail selling and purchasing prices (Mid-Market Rate). The author in [26] lastly presents a Proportional Bids strategy, where the bidding prices are generated proportionally to the meter value and normalized by the maximum value.

As some final notes, document [27] reports its view on several value sharing methods in a context of energy communities, some of them being methods already reviewed in articles [9], [18] and [26] (such as fixed coefficients, ownership, proportional and shapley value), and thoroughly discusses the different approaches' fairness and stability, as well as the simplicity and intellectual accessibility of these methods.

Longing on the fairness subject, paper [28] introduces three distinct facets regarding the energy justice topic: a Procedural Justice dimension, aiming to ensure an equitable, non-discriminatory engagement procedure for all stakeholders [28], a Distributional Justice perspective, granting access to both consumption and production related activities/services, and lastly a Recognitional Justice facet, acknowledging misrepresented and overlooked social groups [28].

Table 2.8 presented below aggregates some indicators belonging to the three dimensions identified.

Justice Tenet	Indicators
Procedural Justice	Overcoming barriers for participation: - Reduced membership fees - Lower share prices for vulnerable groups - Targeted information & engagement activities
Distributional Justice	Member diversity Services offered: - Energy efficiency services targeted at vulnerable groups - Lower energy tariffs for vulnerable groups
Recognitional Justice	Level of knowledge about: - Energy vulnerability & poverty, the preferences, needs & living situation of vulnerable & energy-poor households Engagement with energy vulnerable & poor householdsAddressing energy poverty in the organisational statutes

Table 2.8: Indicators for elements of energy justice, [28]

To conclude this section, in regard to an ECs energy distributing system, article [14] mentions

a change on the traditional grid network and refers the implementation of community batteries with their own independent mini network, where each household is offered a certain amount of storage. The author in [14] states that this approach is more suitable for remote and small communities and would help to ease the weight on overloaded national grids.

2.7 Business Model's Frameworks in Energy Communities

The decentralization of energy sources is reshaping the way energy is produced, distributed and managed, which, naturally and rightfully so, has a great impact on how business models within the energy sector are structured. The energy market, previously ruled by large-scale facilities mainly owned by large utilities and government entities, is now integrating smaller and local energy sources, often providing green energy, which can be owned by private, individual or collective, entities, cooperatives and communities. Through their production and storage assets, passive consumers become active agents in the electricity market, as they're able to compete against traditional energy providers, offering services to other consumers, [29] and therefore extending the market scope.

In this light, peer-to-peer (P2P) business models gained significant relevance, as they provide an alternative and allow consumers to switch energy supplier on a minute-by-minute timeframe [29]. Chiara D'Alpaos and Francesca Andreolli identified three main innovative P2P market structures in [29] based on the literature thus far reviewed. The first market structure is presented as a 'Full P2P' model, where negotiations are carried out directly between peers, as free and autonomous agents, although recognizing a crucial stability problem in regards to the model's scalability. Subsequently, a 'community-based' model was introduced, where prosumers are connected within a community, and trading actions are regulated by the respective manager. The third model assumes a 'Hybrid' structure, combining the two previous ones. At the upper level, peers directly negotiate among them and with existing markets, while at the bottom level, community trading takes place.

Similarly, articles [26] and [30] seem to address this characterization in quite a complementary way. The latter, states that EC frameworks can be roughly divided into market-based models and cost or benefit sharing models [30]. Steffen Limmer claims that market-based models presuppose a local energy market (LEM) within the community, where members trade energy with each other, that can vary on aspects such as time of trading (day-ahead/real-time), level of centralization

(P2P/centralized) and the criteria used to define the associated LEM transaction prices. The author defines this market-based model as a non-cooperative approach, where users are purely self-driven and act solely to maximize their own profit. On the other hand, [30] classifies cost/benefit sharing models as a much more collaborative approach, where users cooperate in order to maximize the community's profit, which is then distributed among members. It also recognizes the mix of these two models as a viable work route, where LEM prices are determined centrally and not by users' influence.

Anchoring on that level of centralization, paper [26] distinguishes two main types of organizations regarding ECs: a centralized framework, and a decentralized one.

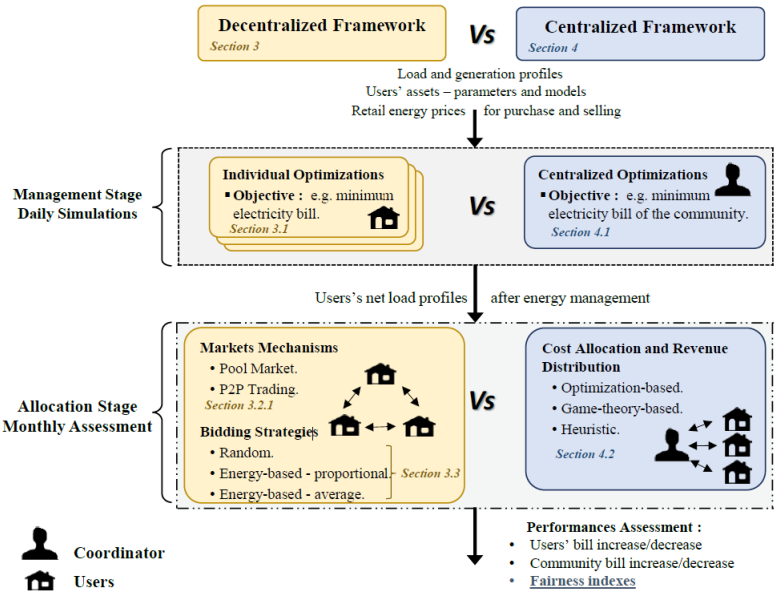


Figure 2.17: Centralized and Decentralized Frameworks, [26]

The authors describe the decentralized framework as a goal-oriented model acting individually on each peer, with no coordination on a community perspective. Transactions between peers are ruled by a local energy market and the model's results strongly rely on user's bidding strategies. On the contrary, [26] refers to centralized organizations as a collective resource management, where the community is seen as a singular entity. It points out the model's main challenge comprises of the cost/revenue distribution that follows the operational phase.

This defines two distinct dimensions within the EC business model: the operational, and the revenue allocation side [26]. This bi-level approach allows strategies such as the cooperative scheduling of energy transactions, so as to minimize the community's energy bill, followed by a revenue/cost allocation stage, keeping in mind the subsequent cost/revenue streams:

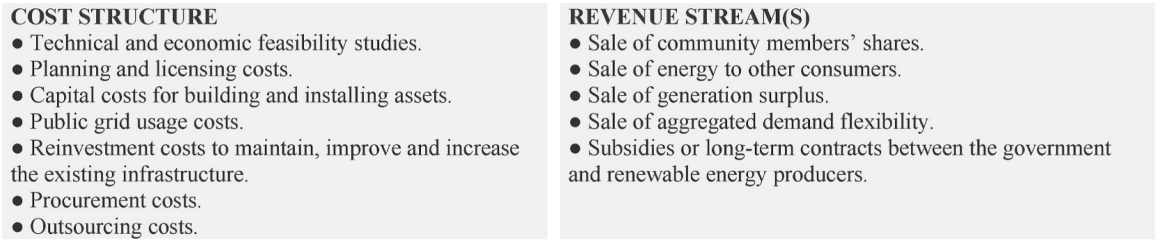


Figure 2.18: Cost/Revenue Streams, [31]

This distribution poses a complex challenge, particularly when vulnerability comes into play, since finding a stable and fair allocation method that takes into account each user's socio-economic settings is not easy to accomplish.

Chapter 3

Work Methodology

3.1 Introduction

Indisputably, having followed a critical and synthetized literature review, eased the way into a much clearer and better contextualized background, together with more solidified perspectives on how to attain viable alternatives, ensuring the desired outcome.

This chapter transitions the study into a more convergent, pinpointed approach, as to introduce this dissertation's work methodology, reliant on an INESC TEC optimization module for energy communities.

3.2 INESC TEC Optimization Software

As mentioned, the business models to be proposed will be implemented by modifying an optimization module for EC planning and resource sizing, previously developed by INESC TEC. Thus being, this section is fully dedicated to presenting and explaining the given base structure.

This module comprises a python library entitled 'rec_op_lem_prices' (Renewable Energy Community Operation and Local Energy Market Pricing) which provides two types of functions:

- **Optimization Functions**, which call to a MILP module for individual and collective optimal management of a REC with stationary storage, PV generation and inflexible loads (all assets behind-the-meter)
- **Pricing Mechanisms Functions**, consisting of various algorithms for defining LEM tariffs' pricing

These functions allow the scheduling of controllable assets, as well as, alternatively or concurrently, the optimal internal exchanges to be performed within a REC, according to the optimization model described in [32]. This model assumes a three-stage framework, however, in the referred python library, only stage 1 and 2 are implemented.

The first stage aims to minimize each member's individual energy bill, through the optimal scheduling of batteries (if owned), taking into account the user's consumption, generation and

supply/feed-in tariffs [32]. Once concluded, C_n^{ind} is returned, as being the minimum energy bill of consumer n. The stage 1 objective function is then:

$$min \sum_{t \in T} (E_{n,t}^{SUP}.\lambda_{n,t}^{buy} - E_{n,t}^{SUR}.\lambda_{n,t}^{sell} + \sum_{s \in S} E_{n,s,t}^{BD}.\lambda_{deg}^{n,s}) \tag{3.1}$$

Where $E_{n,t}^{SUP}$ [kWh] is the energy supplied to member n by its retailer at time t and $E_{n,t}^{SUR}$ is the energy sold to its retailer at time t, each of them multiplied by the respective retailer tariffs [€/kWh]. $E_{n,s,t}^{BD}$ symbolizes the discharged energy from battery s, while $\lambda_{s,t}^{deg}$ represents the degradation cost of said battery.

Subsequently, if intended, one can perform a second stage, which offers a community-level optimization, where the goal shifts to the minimization of the collective energy bill, through the scheduling of internal transactions with surplus energy, while ensuring that each member's individual cost does not surpass the value computed in stage 1 [32]. Hence, the objective function is converted to:

$$min \sum_{t \in T} \left(\sum_{n \in N} (E_{n,t}^{SUP}.\lambda_{n,t}^{buy} - E_{n,t}^{SUR}.\lambda_{n,t}^{sell} + E_{n,t}^{SC}.\lambda_t^{grid} + \sum_{s \in S} E_{n,s,t}^{BD}.\lambda_{deg}^{n,s}) \right) \tag{3.2}$$

Where $E_{n,t}^{SC}$ [kWh] is the energy self-consumed by meter n at time t and λ_t^{grid} [€/kWh] is the grid access tariff.

The constraint accountable for certifying that the individual cost of stage 2 does not surpass the individual cost computed in stage 1 is the following:

$$\sum_{t \in T} \left(E_{n,t}^{SUP}.\lambda_{n,t}^{buy} - E_{n,t}^{SUR}.\lambda_{n,t}^{sell} + E_{n,t}^{SC}.\lambda_t^{grid} + (E_{n,t}^{PUR} - E_{n,t}^{SALE}).\lambda_t^{p2p} + \sum_{s \in S} E_{n,s,t}^{BD}.\lambda_{deg}^{n,s} \right) \leq C_n^{ind} \tag{3.3}$$

Where $E_{n,t}^{PUR}$ and $E_{n,t}^{SALE}$ are the locally purchased and sold amounts of energy, respectively, with $lambda_t^{p2p}$ being the LEM tariff for energy transactions between peers. C_n^{ind} symbolizes the individual cost computed in stage 1 (individual optimization).

Therefore, the user is allowed to:

- perform an individual asset optimization of any REC member
- perform a collective asset optimization of all REC members
- perform the same collective optimization, while guaranteeing that no member's cost is penalized for incorporating the REC

Regarding the Pricing Mechanisms Functions, local energy market prices can be determined in relation to different timeframes - a post and a pre delivery timeframe - depending if the goal is set on maximizing internal transactions or on the scheduling of the most advantageous transactions for all members, before communicating the share coefficients to the DSO. Hence, the algorithm could be implemented in a pre-delivery timeframe, as shown in Figure 3.1 below presented.

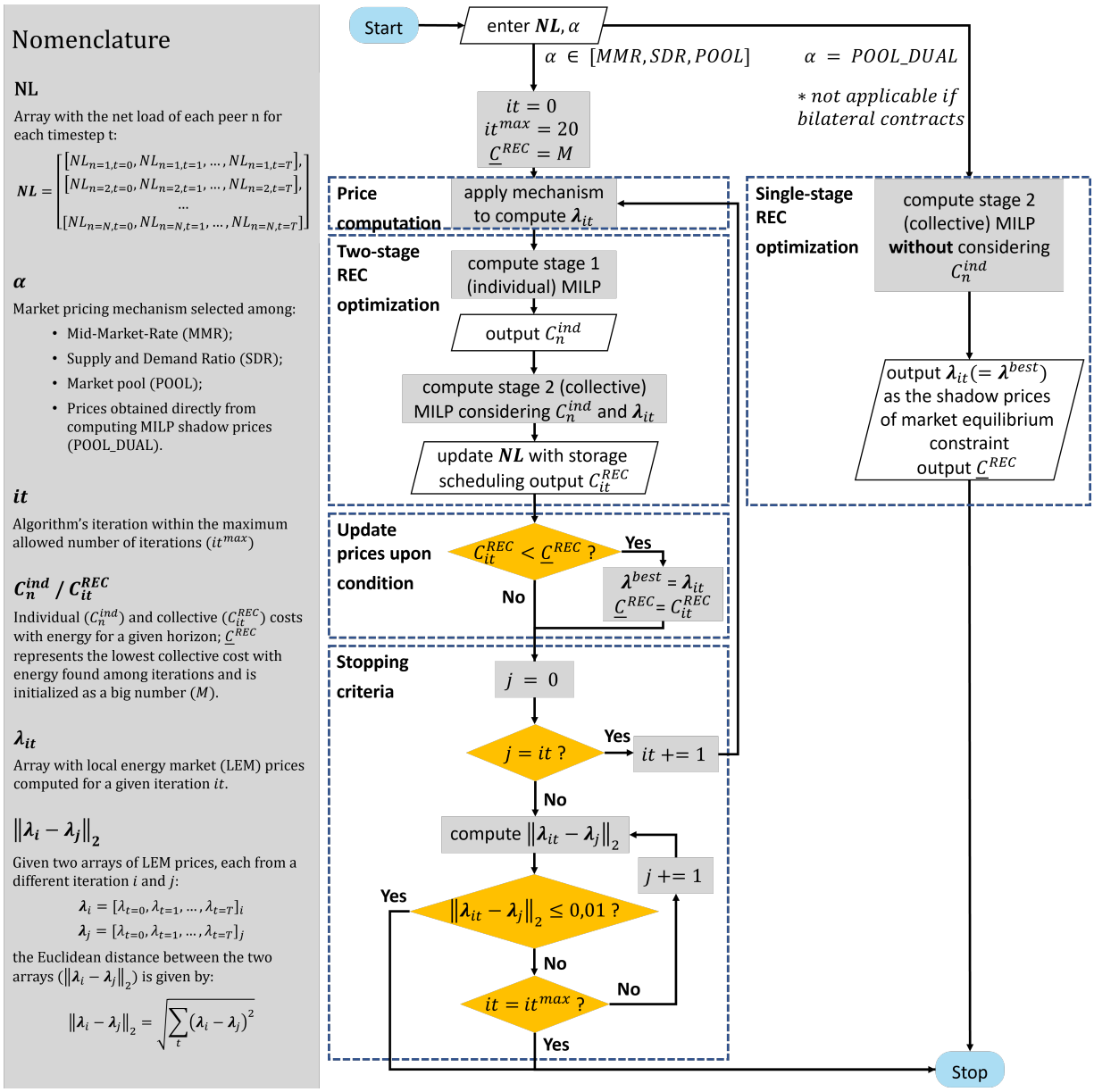


Figure 3.1: Overarching Algorithm for price computation, in the pre-delivery timeframe

Conversely, this algorithm could also be implemented attending to a post-delivery timeframe, as illustrated in Figure 3.2, where the LEM tariff price can be computed according to various mechanisms, later described.

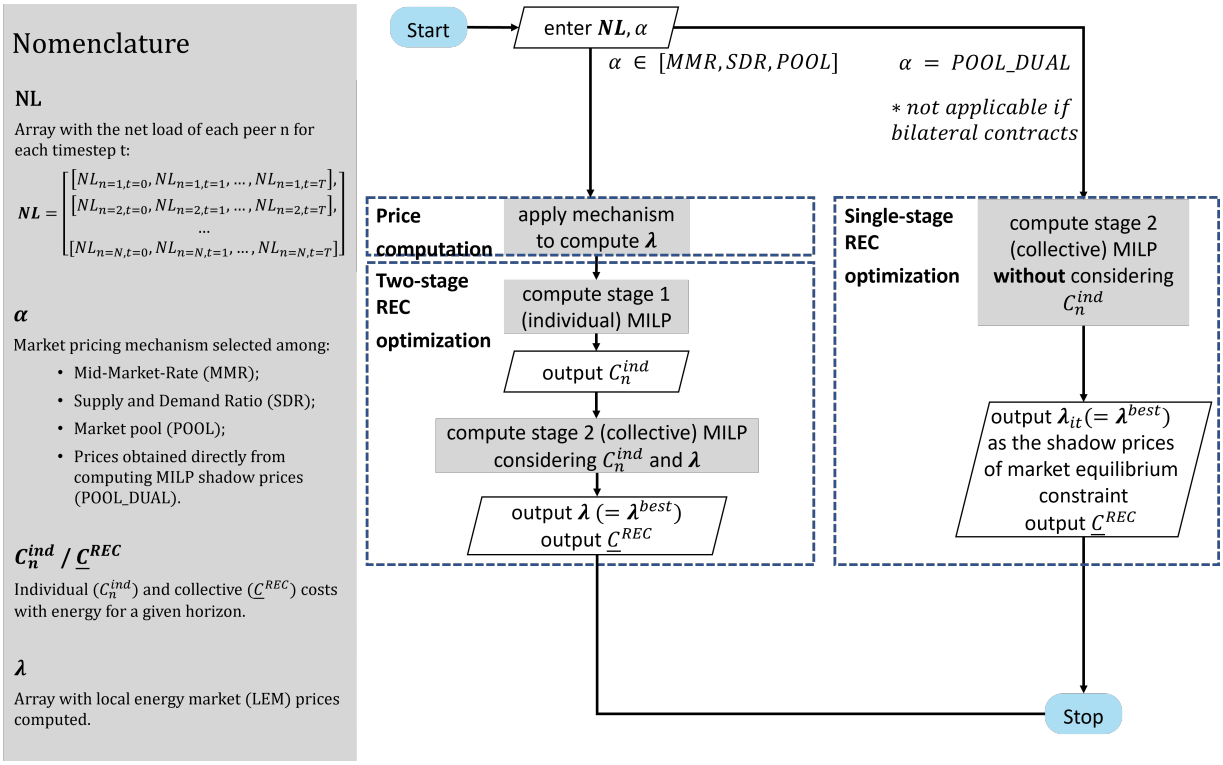


Figure 3.2: Overarching Algorithm for price computation, in the post-delivery timeframe

Additionally, the module provides the choice concerning the market paradigm, being able to opt between:

- a **True Pool**, where, for each member, is solely established the transacted energy (bought/sold)

- a **Bilateral Contract** market, where peer-to-peer transactions are carried out

The following table synthesizes the application scope of combinations between timeframes and market models:

Time frame	Market paradigm	Application
Pre-delivery	Pool	✓ Storage assets' scheduling; ✓ Schedule of internal transactions per peer (i.e., total energy to buy and sell at the local energy market that can minimize REC costs) – implies that public grid usage tariffs are socialized and can't be minimized; ✓ Compute the optimal energy price for those local transactions.
	Bilateral contracts	✓ Storage assets' scheduling; ✓ Schedule of P2P bilateral contracts (i.e., the scheduled energy transactions between peers that can minimize REC costs) – public grid usage tariffs are considered and can be minimized; ✓ Compute the optimal energy price for those local transactions.
Post-delivery	Pool	✓ Definition of internal transactions per peer that minimize REC costs based on their metered net load (i.e., total energy bought and sold at the local energy market) – implies that public grid usage tariffs are socialized and can't be minimized; ✓ Compute the optimal energy price for those local transactions.
	Bilateral contracts	✓ Definition of P2P bilateral contracts that minimize REC costs based on their metered net load (i.e., the effectively established energy transactions between peers that can minimize REC costs) – public grid usage tariffs are considered and can be minimized; ✓ Compute the optimal energy price for those local transactions.

Table 3.1: Combination scope of algorithms

Finally, the pricing mechanisms available are listed below:

- **Mid-market rate** (MMR), which sets the price at the midpoint between the buying and selling offers

$$\frac{min \text{ buying offer } + \ max \text{ selling offer}}{divisor} \tag{3.4}$$

where the *divisor* establishes how close the price is set to either the least valuable buying offer or to the most valuable selling offer. The value is set to 2.0, by default, placing the LEM tariff as equidistant form both offers.

- **Supply and demand ratio** (SDR), as the name implies, the ratio between the energy supply and demand is computed:

$$sdr = \frac{\text{total amount of offered energy}}{\text{total amount of requested energy}} \tag{3.5}$$

Consequently, the LEM tariff price is determined according to:

$$\begin{cases} max \text{ selling offer}, & \text{if } sdr \geq 1 \\ \frac{min \text{ buying offer} * max \text{ selling offer}}{(min \text{ buying offer} - max \text{ selling offer}) * sdr + max \text{ selling offer}}, & \text{if } 0 < sdr \leq 1 \end{cases} \tag{3.6}$$

Assuming the value of the most valuable selling offer in the event of the energy supply surpassing/matching the demand. On the other side of the spectrum, if the demand is greater

than the available energy, the LEM tariff then consists of the least valuable buying offer increased by $\frac{max \text{ selling offer}}{(min \text{ buying offer} - max \text{ selling offer}) * sdr + max \text{ selling offer}}$, a factor which drops in value proportionally to the rise of both the supply/demand ratio and the discrepancy between minimum and maximum buying and selling offers, respectively.

- **Compensated supply and demand ratio** (CSDR), which follows a similar approach to the one previously described, though with the addition of a compensation factor (*comp*). The LEM tariff is hence computed as:

$$\begin{cases} max \text{ selling offer } + \frac{comp}{sdr}, & \text{if } sdr \geq 1 \\ \\ \frac{min \text{ buying offer} * (max \text{ selling offer} + comp)}{(min \text{ buying offer} - max \text{ selling offer} - comp) * sdr + max \text{ selling offer} + comp}, & \text{if } 0 < sdr \leq 1 \end{cases} \tag{3.7}$$

  where the compensation is defined as:

$$comp = (min \text{ buying offer} - max \text{ selling offer}) * \delta^{compensation} \tag{3.8}$$

  with $\delta^{compensation}$ being a *float* between 1.0 and 0.0, which establishes the relative compensation.

- **Pool equilibrium**

The first three mechanisms, MMR, SDR and SDRC, are made available in two forms: a "complete" form, where all potential buying and selling offers are considered for computing the prices at each time step, and a "partial" form, where the only offers considered are the ones that would be accepted if they were made under a pool equilibrium mechanism.

In the event of any selling offer surpassing a buying offer, the pool crossing value (interception between buying and selling offers) is returned.

Chapter 4

Adapting Energy Sharing Models for Vulnerable Consumers

4.1 Introduction

Building upon the insights previously discussed, this chapter delves into a more creative thinking process, so to explore further perks and possibilities under the reviewed frameworks, while promoting a just and comprehensive energy transition.

4.2 Identifying and Quantifying Vulnerabilities

Prior to any hypothesis formulation, it is important to analyze and understand any given EC context, in order to quickly identify potential vulnerabilities. For this purpose, it is likely that some additional information, personal to each member, is to be required. Under these circumstances, it's advisable a fair degree of consciousness and apprehension, as to not only avoid an invasive approach, but also, in regards to the quantity and accessibility of the requested data, aim to minimize any additional required time/effort on the consumer side (as advised in [11]).

4.2.1 Vulnerability Index

In this sense, it was developed a Vulnerability Index (VI) as a way to recognize vulnerabilities within the energy poverty scope, that could easily be implemented in a REC context. Thus, with the sole purpose of identifying vulnerable consumers in a setting of potential EC members, the following logical proposition is presented (equation 4.1), defining a boolean variable, VI_n, which assumes the value 1 if both conditions are True, and 0 in any other case:

$$VI_n = \left\{ \left[\frac{exp_n}{inc_n} > ref1 \right] \cap \left[\frac{inc_n}{N_n^{inc}} - N_n^{dep} * ref3 < ref2 \right] \right\} \tag{4.1}$$

The first condition of the proposed boolean expression relates the annual amount of energy expenses of each household n, exp_n [€], with the respective household's annual income, inc_n

[€], and compares it with a set reference value, $ref1$ (set at 10%). This allows to easily identify potential vulnerabilities within the energy sector, since typically low-income households suffer a much greater impact on their earnings due to energy bills, as previously shown in Table 2.2.

The second condition evaluates a household's annual income per resident that benefits or is in a position to benefit from a salary, N_n^{inc}. Subtracted to this, is a conservatively estimated annual expenditure (so to blend in under a vulnerable setting) accounting for household members who are not in a position to benefit from a salary (N_n^{dep}), such as children, elderly, people with disabilities, etc, and are therefore dependent on the income of N_n^{inc} (it was assumed a monthly expense of 150€, resulting in a 1800€ value attributed to $ref3$). Lastly this expression is compared with a set income threshold placed at 7000€ ($ref2$).

4.2.2 Continuous Vulnerability Index

Subsequent to the identification of vulnerable consumers, it is just as relevant to apply criteria that assists in quantifying said vulnerability, easing the way into a more fair and adaptable business model.

To achieve this, three distinct indicators were defined:

$$indicator_{1,n} = \begin{cases} \left(\frac{exp_n}{inc_n}\right) * 2, & \text{if } 0.12 < \frac{exp_n}{inc_n} < 0.14 \\ \left(\frac{exp_n}{inc_n}\right) * 3, & \text{if } \frac{exp_n}{inc_n} > 0.14 \\ \frac{exp_n}{inc_n}, & \text{otherwise} \end{cases} \tag{4.2}$$

which relates a household's annual energy expenses to its annual income, in a way that a **higher value** symbolizes a **higher vulnerability**; this indicator **doubles** in value in case the member's energy expense is higher than **12%** of its income, and **triples** in value if higher than **14%**.

$$indicator_{2,n} = ref2 - \frac{inc_n}{N_n^{inc}} \tag{4.3}$$

which evaluates a household's earnings per source of income (active or not), in a way that a **higher value** symbolizes a **higher vulnerability**.

$$indicator_{3,n} = \begin{cases} \left(\frac{N_n^{dep}}{N_n^{inc}}\right) * 2, & \text{if } N_n^{inc} = 1 \cap N_n^{dep} \neq 0 \\ \frac{N_n^{dep}}{N_n^{inc}}, & \text{otherwise} \end{cases} \tag{4.4}$$

which relates the number of sources of income (active or not) with the number of residents dependent on those sources, in a way that a **higher value** symbolizes a **higher vulnerability**; this

indicator **doubles** in value in the event of a household solely accounting for a single source of income, with dependent residents ($\mathbf{N_n^{inc}} = \mathbf{1} \cap \mathbf{N_n^{dep}} \neq \mathbf{0}$), such as, for instance, the case of a single parent.

Once computed, all three indicators are normalized in accordance to the EC context, returning, for each member, three values between 0 and 1 to help place the consumer in a vulnerability spectrum. This normalization is performed according to:

$$indicator_{i,n}^{norm} = \frac{indicator_{i,n}}{\sum_{n \in N} indicator_{i,n}}, \quad for \ \ i = 1,2,3 \tag{4.5}$$

In a way that a value closer to zero symbolizes a less vulnerable consumer, while a value closer to 1 relates to a higher vulnerability. Lastly, a weighted average is calculated, taking into account all three indicators, which returns the continuous Vulnerability Index, VI^{cont}:

$$VI_n^{cont} = 0.20 * indicator_{1,n}^{norm} + 0.60 * indicator_{2,n}^{norm} + 0.20 * indicator_{3,n}^{norm} \tag{4.6}$$

This index inputs an additional relevance over the income indicator, as it plays the major role when it comes to evaluating an energy poverty scenario. Refraining from a higher weight, indicators 2 and 3 assume more of a 'tie breaker' role and are not intended to neglect vulnerabilities impacting individuals, for instance, living alone (which can even add severity to the case), or individuals sacrificing comfort to save on energy bills.

On the other hand, it is intended to address and grant due credibility to certain situations that strongly affect a household's susceptibility, and for that reason the third indicator suffers a 100% increase in the case of a single source of income supporting one or more dependent household members. Similarly, the implementation with regard to doubling/tripling indicator 1, once it reaches a 12%/14% threshold, serves the purpose of distancing the user's values, inducing a stronger impact over the vulnerability index in more severe cases.

This index is only calculated for vulnerable consumers, and a higher index value relates to a higher vulnerability.

4.3 Approach Development

The present section begins to elucidate the proposed strategies comprising goal number 2 of section 1.2.

4.3.1 LEM tariff Discount

Revisiting the energy justice subject briefly brushed upon in subsection 2.6.4, Table 2.8 presents as one of the indicators pertaining to Distributional Justice, the implementation of lower energy tariffs for vulnerable groups. Furthermore, article [28] states that 19 of the RECs that took part in

the study (corresponding to 27%) offer either reduced membership fees or energy sharing prices as a way to combat energy poverty, placing this suggestion as a feasible and rather appealing approach.

4.3.1.1 How to implement lower LEM tariffs for Vulnerable Consumers?

Implementing lower tariffs for selected consumers will be achieved through personal discounts. As explained in section 3.2, the INESC TEC optimization model comprises a second stage where a collective optimization is performed, assuring that each member's individual cost does not surpass the value computed in stage 1. This restriction is applied through equation 4.7:

$$\sum_{t \in T} \left(E_{n,t}^{SUP} . \lambda_{n,t}^{buy} - E_{n,t}^{SUR} . \lambda_{n,t}^{sell} + E_{n,t}^{SC} . \lambda_{t}^{grid} + (E_{n,t}^{PUR} - E_{n,t}^{SALE}) . \lambda_{t}^{p2p} \right) \leq C_{n}^{ind,\ stage1} \tag{4.7}$$

Therefore, in order to apply the intended discounts, the value of λ_t^{p2p} is to be altered. Hence, equation 4.7 becomes:

$$\sum_{t \in T} \left(E_{n,t}^{SUP} . \lambda_{n,t}^{buy} - E_{n,t}^{SUR} . \lambda_{n,t}^{sell} + E_{n,t}^{SC} . \lambda_{t}^{grid} + (E_{n,t}^{PUR} - E_{n,t}^{SALE}) . \lambda_{t}^{p2p} * (1 - \delta_n) \right) \leq C_{n}^{ind,\ stage1} \tag{4.8}$$

Where δ_n is the discount defined for each consumer (being 0 for non-vulnerable consumers).

The associated cost increment over the non-vulnerable portion of EC members is soon to be addressed.

Regarding this implementation, there are a few aspects to be noted:

– **Will the discount also impact the LEM tariff when locally selling energy?**

In fact, the discount is applied over the difference between the locally bought and sold amounts ($E_{n,t}^{PUR} - E_{n,t}^{SALE}$). However, this model assumes that vulnerable consumers do not own any generation assets, and therefore $E_{n,t}^{SALE}$ (with n being a VC) is always zero.

– **Who will cover the costs associated to this lower LEM tariff?**

In practice, equation 4.8 only applies a discount over VCs' LEM tariff and does not apply that discount over on the seller side, so the optimization is performed not considering the profit cut imposed when selling energy to a vulnerable consumer. This was implemented in this manner, for a few reasons:

1. $\boldsymbol{\lambda_t^{p2p}}$ **only dependent on time**, hindering the discount application over the locally sold energy, $E_{n,t}^{SALE}$, on the seller side.

2. **possibly counter-productive approach**, since applying the discount through the seller's point of view indicates that energy sold to a VC translates in a lower profit, being less advantageous for the consumer selling the energy, which could compromise the model's main

goal; in another perspective, solely placing the discount on the VC side might actually serve a dual purpose, since the collective optimization in stage 2 should prioritize energy transactions whose end consumers are vulnerable, as to minimize the collective cost, refining the model into an even more inclusive approach; however, this should not be seen as a granted feature of the proposed model, since the optimization is a complex process influenced by a vast array of factors, and such characteristic cannot be confirmed with no proper testing;

Nonetheless, the cost associated to this concession still has to be supported by non-vulnerable consumers; however, that topic will only be discussed later on.

4.3.1.2 What discounts will be implemented?

As a way of promoting Recognitional Justice [28], the discounts were defined for each vulnerable consumer in accordance to the continuous Vulnerability Index (VI_n^{cont}), in such way:

$$\delta_n = \begin{cases} 0.20, & \text{if } VI_n^{cont} > \overline{VI^{cont}} + 15\% \\ 0.10, & \text{if } VI_n^{cont} < \overline{VI^{cont}} - 15\% \\ 0.15, & \text{otherwise} \end{cases} \tag{4.9}$$

This implies that a vulnerable consumer with an index value at least 15% below average will benefit from a 20% discount over the LEM tariff price, a VC with an index value at least 15% higher than average will benefit from a 10% discount, and a value in between will lead to a 15% discount.

4.3.1.3 Social Energy Tariff

Back in 2.3.2, it was referenced that energy consumers under a certain degree of vulnerability may benefit from a Social Energy Tariff that imposes a 33.8% discount over the distribution grid access tariffs, when buying energy from retailers. Since the criteria for this benefit is quite strict and selects highly vulnerable consumers, it was feared that, in the event of a user who benefits from this tariff joining an EC, the lower LEM prices might still not represent a profitable situation in comparison to buying from a retailer with the Social Tariff applied.

In order to avoid this scenario, the same concept was implemented in the proposed model, by applying a social discount of 33.8% over the distribution grid access tariff, solely for EC members that benefit from the Social Energy Tariff outside the community.

Equation 4.8 then becomes:

$$\sum_{t \in T} \left(E_{n,t}^{SUP} . \lambda_{n,t}^{buy} - E_{n,t}^{SUR} . \lambda_{n,t}^{sell} + E_{n,t}^{SC} . \lambda_t^{grid} * (1 - \delta_n^{social}) + (E_{n,t}^{PUR} - E_{n,t}^{SALE}) . \lambda_t^{p2p} * (1 - \delta_n) \right) \leq C_n^{ind,\ stage1} \tag{4.10}$$

The same methodology adopted in 4.3.1.1 was assumed here, with the discount only being implemented over the locally bought energy on the VC side.

4.3.1.4 Distribution of Costs associated to the Discount Implementation

Like earlier outlined, the profit cut associated to the discounts is not accounted for within the optimization algorithm and, thereby, a post-delivery distribution of costs must be performed.

As a way to promote energy justice also among the non-vulnerable members, it was imposed that all non-vulnerable consumers (NVC) must support the associated cost, as opposed to only the consumer selling the energy, reinforcing a community spirit when embracing vulnerability.

Under this framework, two methods were suggested as a distribution strategy:

- **Method 1: Equal Distribution**, where the given cost penalty:

$$\sum_{t\in T}\Big(\sum_{n\in VC}\big(E_{n,t}^{PUR}*\lambda_t^{p2p}*\delta_n+E_{n,t}^{SLC}*\lambda_t^{grid}*\delta_n^{social}\big)\Big) \tag{4.11}$$

  is equally distributed among all NVCs

- **Method 2: According to a Non-Vulnerability Index**, where the same given penalty is distributed according to a developed continuous non-vulnerability index, calculated for each NVC.

  In order to implement this method, the following Non-Vulnerability Index was developed:

→ **Non-Vulnerability Index**

The proposed Non-Vulnerability Index (NVI_n) is computed attending to the three indicators, similar to the ones defined in 4.2.1 for the Vulnerability Index. However, it is intended that a higher NVI value relates to a higher non-vulnerability, hence symbolizing a consumer that is able to support a higher percentage of costs. In order to achieve these, the three previous indicators are now computed as:

$$indicator_{1,n}=\begin{cases}\left(1-\frac{exp_n}{inc_n}\right)*1.5, & \text{if } \frac{exp_n}{inc_n}<0.04\\ 1-\frac{exp_n}{inc_n}, & \text{otherwise}\end{cases} \tag{4.12}$$

where a **higher value** symbolizes a **higher non-vulnerability**; this indicator **doubles** in value in case the member's energy expenses represent less than **4%** of its income.

$$indicator_{2,n} = \begin{cases} \left(\frac{inc_n}{N_n^{inc}}\right) * 1.15, & \text{if } St_n = 1 \\ \left(\frac{inc_n}{N_n^{inc}}\right) * 1.35, & \text{if } RES_n = 1 \\ \frac{inc_n}{N_n^{inc}}, & \text{otherwise} \end{cases} \tag{4.13}$$

in a way that a **higher value** symbolizes a **higher non-vulnerability**; this value suffers a **15%** increase in value in the event of an EC member owning **storage assets**, and an additional **35%** in the case of owning any **generation assets** (resulting in a 50% increase in value when owning both).

$$indicator_{3,n} = \begin{cases} \left(\frac{N_n^{inc}}{N_n^{dep}}\right) * 0.5, & \text{if } N_n^{inc} = 1 \cap N_n^{dep} \neq 0 \\ N_n^{inc}, & \text{if } N_n^{dep} = 0 \\ \frac{N_n^{inc}}{N_n^{dep}}, & \text{otherwise} \end{cases} \tag{4.14}$$

where a **higher value** translates to a **higher non-vulnerability**; this indicator suffers a **50% reduction** in value in the event of a household solely accounting for a single source of income, with dependent residents ($\mathbf{N_n^{inc} = 1 \cap N_n^{dep} \neq 0}$), such as, for instance, the case of a single parent.

Regarding this index, an even higher relevance was added to the second indicator. For this reason, the conditional increases/decreases over the indicator's values are much more abrupt in the case of indicators 1 and 3, as they assume a much lower relevance within the NVI and thus require a much more noticeable change in value in order to have a proper influence over the continuous index.

Once computed, all three indicators are normalized in accordance to the EC context, returning, for each member, three values between 0 and 1 to help place the consumer within a non-vulnerability spectrum. This normalization is performed according to:

$$indicator_{i,n}^{norm} = \frac{indicator_{i,n}}{\sum_{n \in N} indicator_{i,n}}, \quad for \ i = 1,2,3 \tag{4.15}$$

The weighted average for NVI_n^{cont} is then computed as:

$$NVI_n^{cont} = 0.10 * indicator_{1,n}^{norm} + 0.80 * indicator_{2,n}^{norm} + 0.10 * indicator_{3,n}^{norm} \tag{4.16}$$

This index returns values between 0 and 1 which correspond to the penalty percentage each non-vulnerable consumer has to account for.

4.3.1.5 Individual Cost constraint

As previously explained in section 3.2, the optimization module performs the collective optimization in stage 2, while restraining the individual cost of each consumer under a threshold set by the individual cost of stage 1. However, when redistributing costs after the optimization is performed, this constraint is no longer active. In order to avoid any non-vulnerable consumer to shift into an unprofitable scenario, the algorithm presented in Figure 4.1 was implemented.

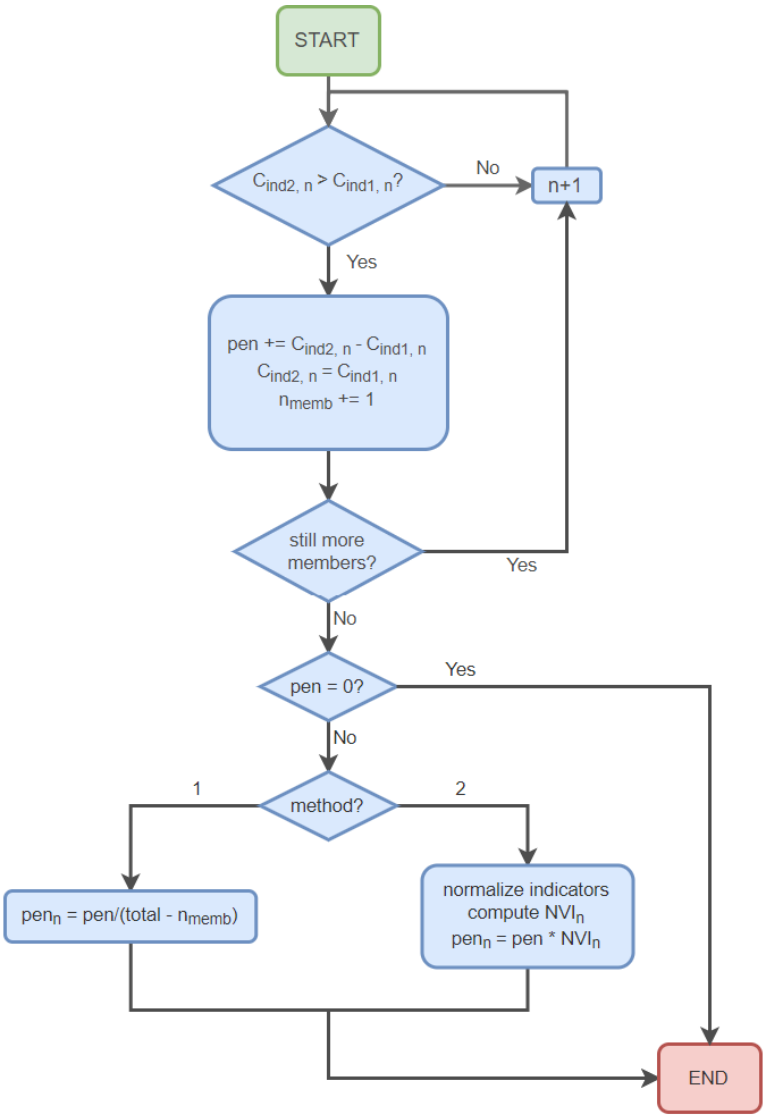


Figure 4.1: Algorithm accounting for the individual cost constraint when distributing penalties

This implementation checks whether any of the user's individual cost surpasses the value from stage 1 and, in case it does, resets $C_{2,n}^{ind}$ back to the value from stage 1 and redistributes the difference among the remaining non-vulnerable consumers, according to the preferred method. If the chosen method is number 2, then the non-vulnerability indexes must be re-normalized, solely accounting for the NVCs whose individual cost did not surpass the set threshold.

4.3.2 Post-Delivery Benefit Allocation

Facing away from the discount proposal, this paper now leans more into a benefit sharing framework, as opposed to a model focused on the share of energy directed towards VCs.

Thus, aiming to not interfere in the optimization process, a profit allocation approach is proposed, where a post-delivery distribution of economic benefits/costs takes place.

4.3.2.1 What benefits are to be allocated?

When approaching this subject, a very critical and comprehensive awareness is necessary, as to not indulge in a purely 'vulnerable' point of view over the energy justice concept. Truly, a fair and balanced methodology on the non-vulnerable side of the community is just as important, ensuring non-vulnerable consumers are valued and respected within the environment they built and still support.

Under this light, an economic benefit allocation for VCs that takes into account the community's overall revenues appears to be somewhat of a fanciful idea, which would translate in a significant and direct financial impact over any community behaviour.

In order to alleviate this financial load, the selection of a profitability source is imperative. Article [9] divides the concept of 'REC's economic benefits' into three categories:

- **Revenues from feed-in tariffs**, due to the sale of surplus energy to retailers. Within the INESC TEC optimization model, this accounts for:

$$\sum_{t \in T} \left(\sum_{n \in N} \left(E_{n,t}^{SUP} . \lambda_{n,t}^{buy} \right) \right) \tag{4.17}$$

- **Revenues from energy sharing**, due to the sale of energy through P2P transactions in the local energy market. Referencing the INESC TEC model, these account for:

$$\sum_{t \in T} \left(\sum_{n \in N} \left(E_{n,t}^{SALE} . \lambda_{t}^{p2p} \right) \right) \tag{4.18}$$

- **Avoided cost due to self-consumption**, derived from the energy consumption of personally owned, local generation assets, as opposed to buying from a retailer.

Taking into account these revenue streams, one can identify two scalability strategies for EC economic returns:

- a **community-based** route, where profit increase is mainly due to a growing community, hosting a diversity of generation and consumption profiles; in this perspective, revenues from energy sharing classify as a community-based profit, once they benefit from the arrival of new members with new offers and demands, that play as potential sellers/buyers in the local energy market.

- an **investment-based** route, where profit increase is mainly due to monetary investments in the community, such as the acquisition of extra generation/storage assets; given these terms, avoided cost due to self-consumption and revenues from feed-in tariffs classify as investment-based profits, once they increase with the augmentation of the installed power and/or installed batteries.

Attending to these definitions, it was imposed, as also suggested in [9], that the profit allocation for vulnerable consumers should solely rely on community-based profits, and hence the revenues from energy sharing. This was implemented in this way due to:

1. **Scalability:** as the benefits derived from energy sharing are strongly influenced by the composition of the community, it tends to rise along with the rise in EC members with new production and demand profiles; this behaviour plays in favour of the proposed model, in a way that a higher revenue allocation for the vulnerable side of the community usually comes along with a bigger support system on the non-vulnerable side, with more members to sustain the resulting cost and hence refrain from a much heavier financial impact over the non-vulnerable consumers.

2. **Investment sources:** when it comes to investing in additional generation/storage assets, it is very unlikely that any vulnerable consumer will be able to participate and contribute to those upgrades and, therefore, it would not be a fair and balanced approach if investment-based benefits were also allocated to vulnerable members.

3. **Economic impact over non-vulnerable consumers:** although investing in a REC has a strong positive influence on avoided costs and feed-in returns, it naturally also acts as a booster on energy sharing revenues, since more energy generation results in more available energy to be shared among members (and typically LEM tariffs translate in a larger revenue stream when compared to retail selling tariffs); from this perspective, wouldn't the allocation of energy-sharing profits for VCs also pose as an unfair and unbalanced methodology for the non-vulnerable side of the community? Article [9] addresses this exact concern, and presents the following graph (Figure 4.2) showing the evolution of all three revenue categories under different 'installed power' scenarios, for their study case:

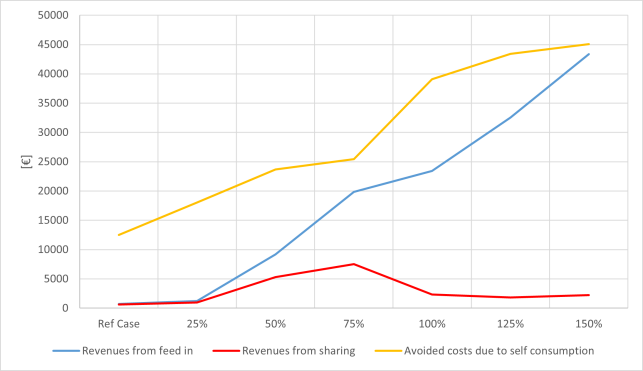


Figure 4.2: Economic returns under different power installation scenarios, [9]

Figure 4.2 reveals that investments on additional renewable energy sources have a much more significant impact on investment-based returns, and not so much on community-based revenues, placing the proposed methodology as a viable and appealing approach.

4.3.2.2 How much profit will be allocated?

In the proposed approach, the optimization process, comprising the scheduling of energy transactions, is performed with no special regard to user's vulnerabilities. Instead, a post-delivery profit redistribution is performed as a way to assess said vulnerabilities. It was already stated that the economic benefits to be allocated to vulnerable consumers are those related to energy sharing within the community. In the INESC TEC optimization model, this refers to:

$$\sum_{n \in N} (E_{n,t}^{SALE} . \lambda_t^{p2p}) \tag{4.19}$$

However, this revenue still represents a considerable amount of economic benefits and, therefore, its entirety should not be allocated to vulnerable consumers.

Instead, it was decided that a percentage of 4% of energy sharing revenues should be allocated per vulnerable consumer, up to a threshold of 33.3%:

$$min\Big(\sum_{n \in N} (E_{n,t}^{SALE} . \lambda_t^{p2p}) * 0.04 * N^{vuln}, \sum_{n \in N} (E_{n,t}^{SALE} . \lambda_t^{p2p}) * 0.333 \Big) \tag{4.20}$$

4.3.2.3 How will the profit be distributed?

In the defined approach, a percentage of 4% of energy sharing revenues is allocated per vulnerable consumer belonging to the EC. However, those 4% are not directly allocated to each VC, they simply represent the benefit percentage allocated to the vulnerable group, and therefore it is necessary to define a method to distribute those economic benefits among VCs in a fair manner.

Revisiting subsection 4.2.2, a continuous vulnerability index was defined, under a normalized scale ranging from 0 to 1, where a higher index value relates to a higher vulnerability, and hence, the profit share allocated per vulnerable consumer can now be expressed as:

$$\text{profit allocated to n} = \text{total allocated profit} * VI_n^{cont} \tag{4.21}$$

4.3.2.4 How will it impact non-vulnerable members?

In a post-optimization process, if economic benefits are relocated to a certain set of consumers, they naturally have to be taken away from the consumers who previously owned them. In this sense, who will support this 'cost'?

Inherently, these allocations will have to be sustained by the non-vulnerable members of the community, although, not every member should be charged equally.

Returning to subsection 4.3.1.4, a continuous non-vulnerability index was defined, which returns normalized values ranging from 0 to 1, where a higher index value relates to a higher non-vulnerability. Given this context, the associated cost can be distributed proportionally to the continuous NVI, as it would result in a higher profit cut for consumers who present themselves in less vulnerable conditions. Thus, for NVCs:

$$\text{cost allocated to n} = \text{total cost} * NVI_n^{cont} \tag{4.22}$$

Chapter 5

Model's Testing and Result Analysis

The present chapter follows the implementation of the two developed approaches, and, therefore, the focus is shifted towards the test and approval of both models, according to the theoretic background thus far presented.

In a first assessment, prior to any optimization, both the Vulnerability and Non-Vulnerability Indexes are to be computed for a set of consumers with various socio-economic characteristics, as to verify if they're behaving in accordance to what is intended.

Subsequent to that, the overall approaches are tested under selected scenarios, which aim to explore and compare each model's characteristics

5.1 Testing Scenario

As previously introduced, a basic testing scenario was put together, as a way to easily observe the models' behaviour under different sets of inputs.

The reference scenario comprises 6 EC members, of which the first three resemble non-vulnerable consumers, while the remaining three are assumed to be vulnerable.

In order to compute both the vulnerability and non-vulnerability indexes, some extra data, personal to each member, is required, namely the annual income, annual energy expenses, number of household members benefiting, or in a position to benefit, from a salary, and lastly the number of household members who are not in a position to benefit from a salary. Besides, other aspects to be considered rely on the ownership of any storage or generation assets, and finally if any of the members benefits from the Social Energy Tariff.

Thus being, Table 5.1 gathers all this required information:

consumers	vulnerable?	annual income	energy expense	nº inc	nº no inc	PV?	Storage?	Social Tariff?
Meter#1	no	134 000.00 €	4 550.00 €	2	2	yes	yes	no
Meter#2	no	49 000.00 €	2 200.00 €	1	0	no	no	no
Meter#3	no	102 500.00 €	4 300.00 €	2	3	yes	no	no
Meter#4	yes	13 100.00 €	1 500.00 €	2	2	no	no	no
Meter#5	yes	5 500.00 €	760.00 €	1	0	no	no	yes
Meter#6	yes	6 630.00 €	800.00 €	1	1	no	no	no

Table 5.1: Extra required data for testing scenario

From here, it's possible to infer that Meter#1 stands at a higher level of non-vulnerability, as it holds the highest salary per source of income and owns both storage and generation assets. On top of that, this user's energy expenses represent less than 4% of its income.

On the other side of the spectrum, Meter#5 poses as the most vulnerable consumer of this scenario, accounting for the lowest income source, along with the highest percentage of energy related expenses. Additionally, this consumer benefits from the Social Energy tariff.

Another important aspect to be noted is the composition of household #6, comprising a single source of income and a dependent resident.

Moving on to the remaining sets of data, Figures 5.1 and 5.2 gather the generation and consumption profiles of all six meters. A small horizon of 5 hours is assumed, with time steps of 1 hour each, as a way to simplify and quicken the testing process, once it reduces the amount of necessary inputs/outputs and, consequently, the simulation time and computational weight.

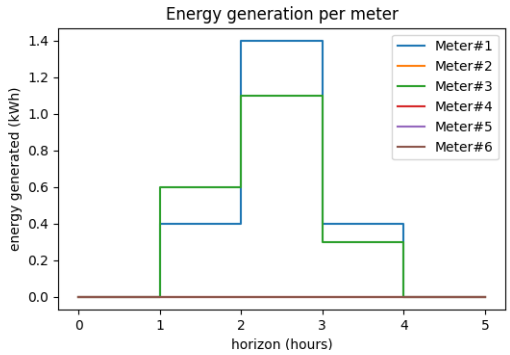


Figure 5.1: Generation profiles of testing scenario

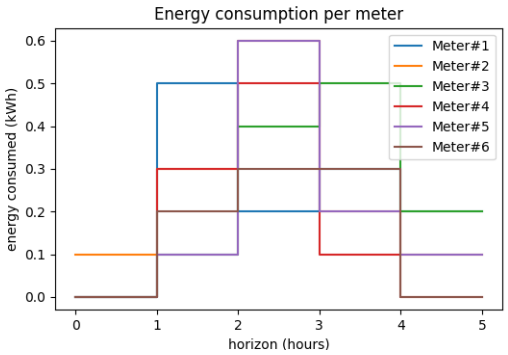


Figure 5.2: Consumption profiles of testing scenario

Where solely meters #1 and #3 provide generation data.

Finally, the buying and selling energy retail tariffs of each meter are presented below:

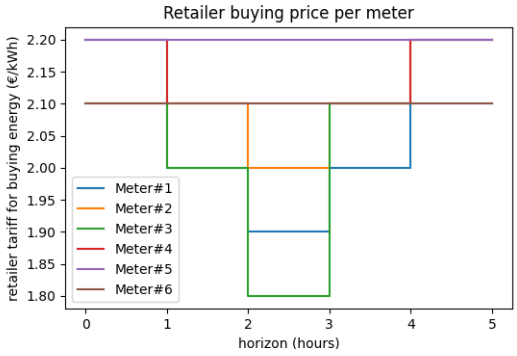


Figure 5.3: Energy retailer buying tariffs of testing scenario

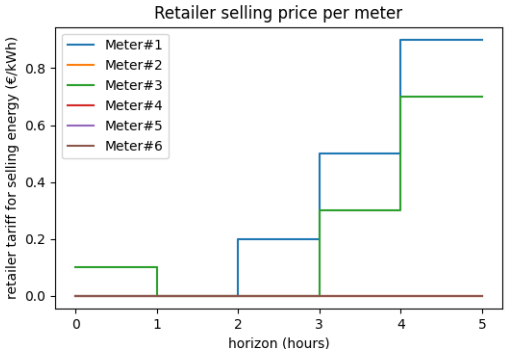


Figure 5.4: Energy retailer selling tariff of testing scenario

With meters #4, #5 and #6 always positioned at the top of the chart in Figure 5.3, symbolizing more expensive energy prices.

5.2 Testing Vulnerability and Non-Vulnerability Indexes

These indexes, proposed in the previous chapter, influence the computation of individual costs over both the vulnerable and non-vulnerable side of the community.

The VI, in the case of the first strategy, decides the LEM discount applied to each consumer, whereas in the second strategy, decides what percentage of the allocated benefits belongs to each VC. In both of these approaches a **higher VI value symbolizes a higher vulnerability**.

The NVI symbolizes the percentage of costs (due to the financial relief applied over the VCs) that is charged to each NVC. Consequently, a **higher NVI value symbolizes a higher non-vulnerability**.

5.2.1 Vulnerability Index

With the aim of following the developed Vulnerability Index's behaviour to certain inputs, the presented scenarios were put together:

	alteration				
scenario	description	annual income	energy expense	nº inc	nº no inc
1	none - base case	-	-	-	-
2	all equal (controlo)	12 000.00 €	1 440.00 €	2	1
3	#4 as single parent	6 000.00 €	720.00 €	1	1
4	#5 w/ higher + #4 w/ lower energy expenses	12 000.00 €	1700€ / 1320€	2	1
5	#6 w/ higher + #4 w/ lower incomes	13000€ / 11000€	1560€ / 1320€	2	1

Table 5.2: Scenarios for VI testing

In scenario 1, the base case is tested, with the inputs exposed in the previous section (Table 5.1).

Scenario 2 introduces a control group, where all VCs account for an annual income of 12.000€, along with annual energy expenses of 1.440€ and a household composition of two sources of income and one dependent resident. The following scenarios (3, 4 and 5) are **altered according to this control group**.

These alterations, in scenario 3, consist of placing consumer #4 as a single parent, in order to visualize the relevance given to this factor.

In scenario 4 the energy expenses of consumer #5 are set to a higher value of 1700€, whereas for consumer #4 these were lowered to 1320€. In this way, #4 accounts for energy expenses that represent less than 12% of its income, #5 will have expenses symbolizing over 14%, while consumer #6 is placed in between.

Alternatively, in scenario 5, the annual incomes of consumers #6 and #4 are set to a higher value of 13000€ and a lower value of 11000€, respectively. The energy expense values are adjusted accordingly in order to preserve the ratio between income and energy expenditures, and avoid altering the index in that sense.

The Vulnerability Indexes of each consumer in each of these scenarios are revealed in table 5.3 below. It is to be reminded that, for any non-vulnerable consumer, the Vulnerability Index is always 0.

	VI					
scenario	Meter#1	Meter#2	Meter#3	Meter#4	Meter#5	Meter#6
1	0.0%	0.0%	0.0%	21.9%	47.5%	30.5%
2	0.0%	0.0%	0.0%	33.3%	33.3%	33.3%
3	0.0%	0.0%	0.0%	40.0%	30.0%	30.0%
4	0.0%	0.0%	0.0%	29.5%	37.6%	32.9%
5	0.0%	0.0%	0.0%	43.3%	33.3%	23.3%

Table 5.3: Vulnerability Index values for scenarios of Table 5.2

In the base case (scenario 1), Meter#5 is placed as the most vulnerable consumer, since it accounts for the lowest source of income along with the highest percentage of energy expenses, followed by #6 and lastly #4, which differ in indicators 1 and 2.

Scenario 2, naturally, returns equal percentages for all VCs (control group).

Moving on to the cases altered according to 2, scenario 3 gives due consideration to the vulnerable circumstances applied to Meter#4, confirming that a single source of income, responsible for one or more dependent residents, will benefit from a notable rise in its vulnerability index.

Scenario 4 places a higher percentage over Meter#5, since this consumer is viewed as the most critical situation (regarding indicator 1), where its ratio between energy expenses and income surpasses the 14% threshold. Meter#6 is not considered as critical, but still suffers a slight VI increase (in comparison to #4), as its second indicator still surpasses the 12% threshold.

Finally, in scenario 5, a greater variation of values between meters is noticeable, as this case alters sources of income (indicator 2), which carries the highest relevance when computing the developed index.

5.2.2 Non-Vulnerability Index

While testing the non-vulnerability index, a similar approach was taken.

First, a set of scenarios are introduced:

	alteration				
scenario	description	annual income	energy expense	nº inc	nº no inc
1	none - base case	-	-	-	-
2	all equal (controlo)	90 000.00 €	4 050.00 €	2	1
3	#3 as a single parent	45 000.00 €	2 025.00 €	1	1
4	#2 w/ lower energy expenses	90 000.00 €	3 000.00 €	2	1

Table 5.4: Scenarios for NVI testing

Just like before, scenario 1 assumes the base scenario described in section 5.2, while scenario 2 assumes the control group, where all NVCs account for an annual income of 90.000€, annual energy related expenditures of 4.050€ and a household composition of two sources of income and 1 dependent resident. However, in this control group, the generation and storage assets were not taken away, meaning that Meter#1 still owns a battery, and both #1 and Meter#3 still own PV panels. The following scenarios (3 and 4), were **altered in regard to the control group**.

Scenario #3, as implemented earlier, accounts for the event of a household comprising a single source of income along with at least one dependent resident (in this case, Meter#3).

Alternatively, scenario 4 lowers the energy expenses of Meter#2, in order to observe the index's behaviour when the user's energy expenses represent less than 4% of its income.

The Non-Vulnerability Index values under these scenarios, for each meter, are presented in Table 5.5:

	NVI					
scenario	Meter#1	Meter#2	Meter#3	Meter#4	Meter#5	Meter#6
1	49.1%	19.2%	31.7%	0.0%	0.0%	0.0%
2	37.3%	28.2%	34.5%	0.0%	0.0%	0.0%
3	38.9%	29.8%	31.2%	0.0%	0.0%	0.0%
4	35.8%	31.1%	33.1%	0.0%	0.0%	0.0%

Figure 5.5: Non-Vulnerability Index values for scenarios of Table 5.4

Regarding scenario 1, Meter#1 is placed at a higher level of non-vulnerability, evidently, mainly due to its storage + generation assets that lead to a boosting effect over the already high value of the income indicator (indicator 2), which plays the biggest role when computing the NVI.

The control group (scenario 2), in this case, does not retrieve equal percentages for all meters. Instead, it's possible to verify the impact of asset's ownership over the developed index, with Meter#2 not owning any, Meter#3 owning generation assets and #1 both storage and generation.

In scenario 3, it's possible to identify a slight decrease over Meter#3's NVI, due to portraying a scenario of, for example, a single parent. However, this variation isn't as strong as the one observed in the VI testing, as this condition is not considered as critical under a 'non-vulnerable' setting, which led to the income indicator holding an even higher relevance for this index.

To finalize, scenario 4 results in a 3% increase of Meter2's NVI, as a consequence of their extremely low ratio of energy expenses and income (<4%).

5.3 Testing the developed models

After confirming that the developed indexes are behaving as intended, the present section proceeds with the testing of the models exposed in chapter 4.

Firstly, the tests are focused towards observing how the models react to the addition of non-vulnerable consumers, and later the focus is shifted towards their behaviour when adding vulnerable consumers. Initially, the results will be presented individually for each approach (in tables with precise values), and later compared (through charts).

5.3.1 Adding Non-Vulnerable Consumers

The goal of this test relies on following how the models behave with the addition of non-vulnerable consumers to the community, and observing how it may impact a vulnerable consumer already within the EC.

In order to achieve this, five different scenarios will be tested, where the only vulnerable consumer is Meter#4. The scenarios will start solely with Meter#4 and Meter#1, while the remaining 4 meters will be added one by one, composing, therefore, the five different sets of inputs. For this purpose, the annual incomes and energy expenses of Meters #5 and #6 were altered (Table 5.5), in a way that they no longer play a vulnerable role, and naturally, Meter#5 will no longer benefit from the energy social tariff.

Meter	income	expense
#5*	35 000 €	1 650 €
#6*	41 500 €	2 050 €

Table 5.5: Altered data of Meters #5 and #6

5.3.1.1 Approach 1 - LEM tariff Discounts

In regard to approach 1, where discounts are applied over the local energy market tariffs for VCs, the following results were obtained:

	Not in EC	#1#4			#1#2#4			#1#2#3#4			#1#2#3#4#5*			#1#2#3#4#5*#6*		
Meter	Cind	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI
#1	-0.6	-1.0455	0	100%	-1.3299	0	72.42%	-1.3406	0	49.06%	-1.2721	0	43.13%	-1.1493	0	36.14%
#2	2.68	-	-	-	2.4864	0.4	27.58%	2.1579	1	19.22%	2.3408	0.6	16.39%	2.3308	0.6	14.03%
#3	0.74	-	-	-	-	-	-	-1.1328	0.4	31.72%	-1.0349	0.2	27.99%	-1.0526	0.2	23.46%
#4	2.1	1.5285	0.7	-	1.5285	0.7	-	1.3655	0.9	0.00%	1.5285	0.7	-	1.6915	0.5	-
#5	2.2	-	-	-	-	-	-	-	-	-	1.5253	1	12.50%	1.5176	1	10.69%
#6	1.68	-	-	-	-	-	-	-	-	-	-	-	-	1.4016	0.5	15.68%
penalty	-	0.1575			0.1575			0.2025			0.1575			0.1125		

Table 5.6: Testing addition of NVCs - Approach 1

Referencing Table 5.6, the first scenario 'Not in EC' reveals the individual cost of each consumer, had they not joined the energy community in the first place. The subsequent columns account for the previously described scenarios, where, for each one, the individual cost ('Cind' [€/kWh]), the locally purchased energy ('e_pur' [kWh]) and the Non-Vulnerability Index ('NVI' [%]) are presented for each meter. At the bottom of the table, the last row gathers the total cost penalties [€/kWh] of each scenario, derived from the discount application, which are distributed according to the computed NVI.

Paying now attention to the highlighted values, which correspond to the individual cost of Meter#4 under the different testing inputs, it's possible to verify that the addition of non-vulnerable consumers who don't own any assets tends to have a not so favourable impact over a pre-existing EC vulnerable consumer.

From scenario '#1#4' to scenario '#1#2#4', that impact is null, since Meter#1 still has enough surplus energy to locally sell to both consumers, in a way that the new "competition" does not affect the total energy allocated to the VC, and thus its individual cost remains the same.

From scenario '#1#2#4' to '#1#2#3#4', the individual cost of Meter#4 now decreases. Although, this relief is solely due to the generation assets now introduced by Meter#3, which boost the available energy to share, and hence increase the VC's locally purchased energy ('e_pur').

The last two scenarios suffer a cost increase (in comparison to the respective previous one) over the individual cost of Meter#4, which derives from the inclusion of non-vulnerable consumers who do not own any generation assets, and solely pose as 'competition' for the VC, resulting in a decrease over the meter's locally purchased energy, and, as a consequence, the total cost penalty.

5.3.1.2 Approach 2 - Economic Benefits Allocation

Regarding the second developed strategy, Table 5.7, arranged in the same manner as the previous one, gathers the resulting optimization outputs:

	Not in EC	#1#4			#1#2#4			#1#2#3#4			#1#2#3#4#5*			#1#2#3#4#5*#6*		
Meter	Cind	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI	Cind	e_pur	NVI
#1	-0.6	-1.1610	0	100%	-1.3962	0	72.42%	-1.3723	0	49.06%	-1.2753	0	43.13%	-1.1293	0	36.14%
#2	2.68	-	-	-	2.4612	0.4	27.58%	2.2045	0.9	19.22%	2.3396	0.6	16.39%	2.5156	0.3	14.03%
#3	0.74	-	-	-	-	-	-	-1.1532	0.4	31.72%	-1.0370	0.2	27.99%	-1.0396	0.2	23.46%
#4	2.1	1.6440	0.7	-	1.6200	0.7	-	1.3710	1	-	1.5360	0.7	-	1.5180	0.7	-
#5	2.2	-	-	-	-	-	-	-	-	-	1.5278	1	12.50%	1.5270	1	10.69%
#6	1.68	-	-	-	-	-	-	-	-	-	-	-	-	1.3513	0.6	15.68%
penalty	-	0.042			0.066			0.138			0.15			0.168		

Table 5.7: Testing addition of NVCs - Approach 2

The displayed results show that, from scenario '#1#4' to scenario '#1#2#4', the individual cost of Meter#4 suffers a slight decrease in value. Such is due to the inclusion of Meter#2, which raises the total locally purchased energy and, therefore, the resultant economic benefits, of which 4% are redirected towards the vulnerable consumer.

Transitioning to the third scenario, the individual cost of Meter#4 suffers an abrupt curtail, as Meter#3 joins the community and introduces additional generation assets. The introduction of this new generation profile, provides more local energy to be shared within the community, which can naturally increase the amount of allocated energy towards the vulnerable consumer, and thus reduce its individual cost.

On top of that, this rise in surplus energy also benefits other consumers, as seen in the case of Meter#2, where its locally purchased energy suffers a generous increase.

Apart from the new generation profile, Meter#3 also introduces a new consumption profile, which translates in new sale opportunities for other consumers with available surpluses.

Both of these factors (rise in allocated energy to #2 and locally sold energy to #3), increase the EC's economic benefits due to the share of energy, contributing to an even more enhanced curtailment over the individual cost of vulnerable consumer #4, who benefits from 4% of these profits.

Shifting to scenario 4, the vulnerable consumer's individual cost now goes up, even though the associated penalty is higher than the one in the previous scenario. In fact, despite the rise in allocated economic benefits, Meter#4 still holds a higher cost due to the consequent rise in demand, hindering the energy allocation process, and cancelling that immediate financial relief observed in scenario 3.

Finally, in the last scenario, the individual cost of Meter#4 is slightly lowered, as a result of the shown increase over the penalty cost, derived again from the rise in demand.

5.3.1.3 Comparing the two approaches

An analysis is now performed in the sense of exploring each model's perks and applicability.

- **Individual Cost Comparison**

To begin with, Figures 5.6 and 5.7 showcase the individual cost of each meter under all the mentioned scenarios, for approach 1 and 2, respectively.

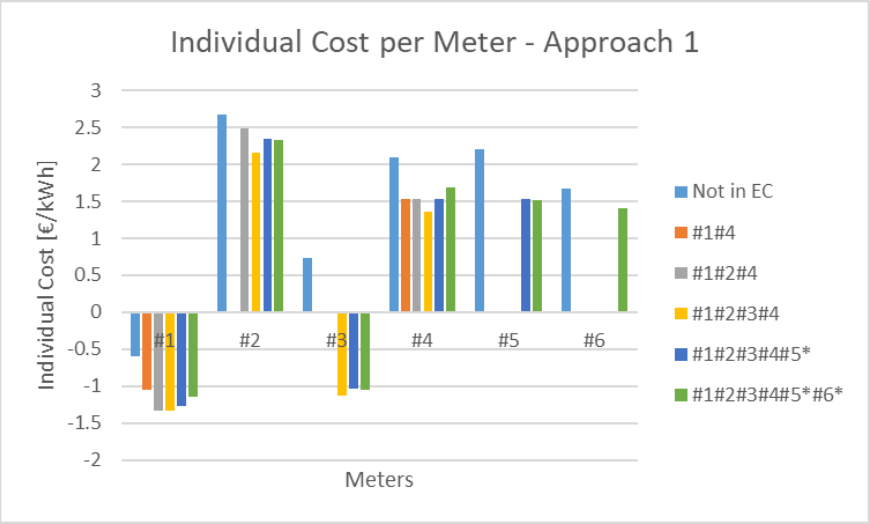


Figure 5.6: Test 1: Individual Cost of each meter under each scenario - Approach 1

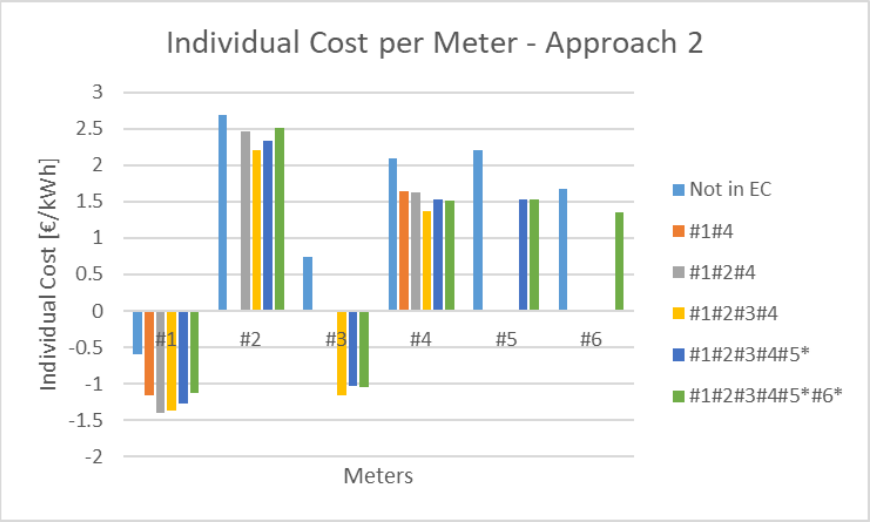


Figure 5.7: Test 1: Individual Cost of each meter under each scenario - Approach 2

When comparing both models, it's important to note how, for Meter#4 (VC), the most favourable outcome is firstly through approach 1 (scenarios 1, 2 and 3) and gradually transitions to approach 2 (scenarios 4 and 5). This is due to the fact that, for smaller communities, the revenues from energy sharing aren't as significant, hence the share of economic benefits allocated to the vulnerable consumer does not portray a scenario as advantageous as a 15% discount over their locally bought energy. However, once the community starts growing, this allocation overpowers the discount approach, returning lower individual costs.

The most noticeable disparity is observed in the last scenario, where approach 1 returns an individual cost of 1.6915 €/kWh for Meter#4, while approach 2 reports a cost of 1.518 €/kWh, assuming a variation of almost 20 cents per kilowatt hour. These results confirm the scalability

issue reflected upon in 4.3.2, showing that the second approach is less hostile for VCs within energy communities that incorporate a fair amount of NVCs without any assets.

In spite of that, approach 1 depicts a much more desirable outcome for VCs in scenarios '#1#4' and '#1#2#4', accounting for a cost difference going up to 0.1155 €/kWh, when compared to the second model. This may suggest that approach 1 is more suitable for smaller communities with fewer VCs and NVCs without assets, while approach 2 thrives more under a diverse EC setting with a vaster array of profiles.

- **Penalty Comparison**

Figures 5.8 and 5.9 aim to compare the overall cost penalty, resultant from the 15% discount application over the VC's locally purchased energy (approach 1) or from the 4% of energy sharing benefits allocated to the VC (approach 2), in each scenario:

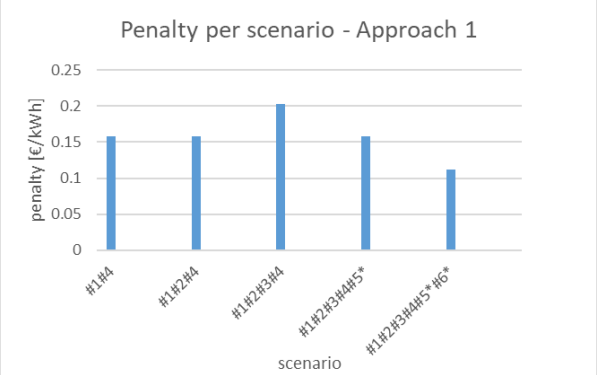


Figure 5.8: Test 1: Penalty per scenario - Approach 1

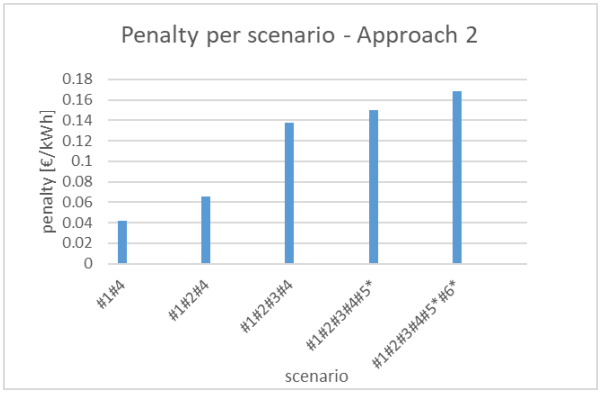


Figure 5.9: Test 1: Penalty per scenario - Approach 2

Figure 5.9 illustrates a much more predictable and linear progression, whereas Figure 5.8 portrays a rather volatile approach.

In this sense, the second model seems to provide a more stable and reliable environment for the inclusion of vulnerable consumers.

- **Locally Purchased Energy Comparison**

To conclude this set of tests, Figures 5.10 and 5.11 refer to the locally purchased energy of each meter, for each scenario, under approaches 1 and 2, respectively:

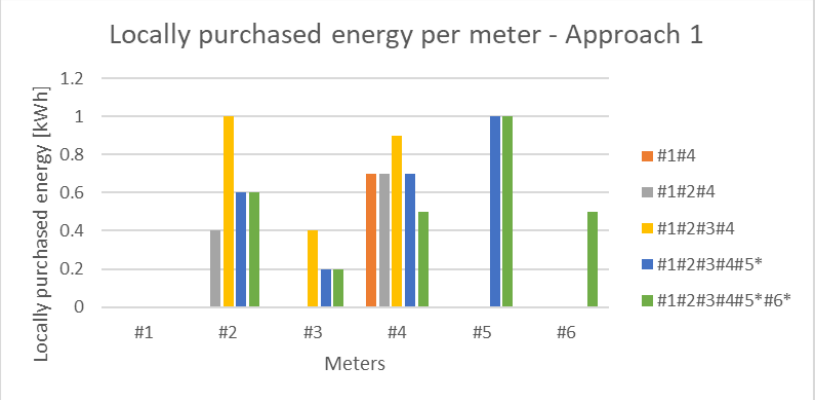


Figure 5.10: Test 1: Locally purchased energy by each meter under each scenario - Approach 1

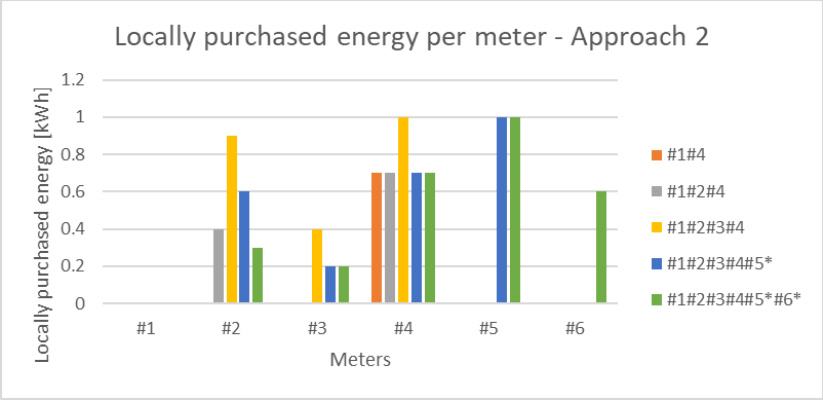


Figure 5.11: Test 1: Locally purchased energy by each meter under each scenario - Approach 2

Indubitably, the discount application over the LEM tariff in the individual cost constraint (equation 4.8) has an influence over the optimization process. However, it is not clear in what way exactly it impacts the returned outputs, due to the complexity involved. In order to retrieve credible and reliable information on this topic, a much more oriented set of tests would have to be ran.

In this manner, one cannot affirm that approach 1 prioritizes energy transactions towards vulnerable consumers, as speculated in 4.3.1.1.

5.3.2 Adding Vulnerable Consumers

In this segment, a set of scenarios are run, in order to observe how differently both models perform when facing a vulnerable consumer, as opposed to a non-vulnerable one. For this purpose, two sets of scenarios are introduced:

- the **base set**, where the first scenario comprises the non-vulnerable group of consumers plus Meter#4, while the remaining VCs (#5 and #6) are added one by one, thus forming the other two scenarios

- an **all non-vulnerable case**, where the same scenarios as before are built, though with meters #4, #5 and #6 as NVCs. In this sense, the annual incomes and energy expenses of these consumers are altered to:

Meter	income	expense
#4*	74000	2700
#5*	35000	1650
#6*	41500	2050

Table 5.8: Alterations made to the annual incomes and energy expenses of meters #4, #5 and #6

5.3.2.1 Approach 1 - LEM tariff Discounts

The obtained results for the first developed model are presented below:

all non-vulnerable						
	#1#2#3#4*		#1#2#3#4*#5*		#1#2#3#4*#5*#6*	
Meter	Cind	e_pur	Cind	e_pur	Cind	e_pur
#1	-1.4400	0	-1.3400	0	-1.1900	0
#2	2.1780	0.9	2.3150	0.6	2.4920	0.3
#3	-1.1970	0.4	-1.0790	0.2	-1.0790	0.2
#4	1.5090	1	1.6860	0.7	1.6860	0.7
#5	-	-	1.5090	1	1.5090	1
#6	-	-	-	-	1.3250	0.6

base case									
	#1#2#3#4			#1#2#3#4#5			#1#2#3#4#5#6		
Meter	Cind	e_pur	discount	Cind	e_pur	discount	Cind	e_pur	discount
#1	-1.3406	0	-	-1.1249	0	-	-0.9164	0	-
#2	2.1579	1	-	2.5173	0.4	-	2.5992	0.3	-
#3	-1.1328	0.4	15%	-0.9400	0.2	-	-0.9021	0.2	-
#4	1.3655	0.9	-	1.4330	0.9	10%	1.7290	0.5	10%
#5	-	-	-	1.2056	1	20%	1.2090	1	20%
#6	-	-	-	-	-	-	1.0243	0.8	15%
penalty	0.2025			0.4384			0.5577		

Table 5.9: Testing addition of VCs - Approach 1

Referencing the first scenario of each set ('#1#2#3#4*' and '#1#2#3#4'), it's possible to note that the individual cost of Meter#4 as a vulnerable consumer is, in fact, lower when compared to the same scenario as a NVC, despite the fact that its total allocated energy does diminish when running the base case, yet it's still uncertain why.

However, in the following scenarios, the model does seem to favour sharing energy among VCs. When adding consumer 5, first of all, is to be noted the change in the discount percentage of Meter#4. In fact, consumer #5 presents a notably more vulnerable profile in comparison to #4, which puts in perspective the pressing need of each consumer. Due to this relativization, Meter#5 is now granted the highest discount (20%), whereas for #4 it is lowered to 10%. Looking over at the 'e_pur' quantities, the model does now seem to prioritize the needs of Meter#4 as it refrains from allocating the total 0.6 kWh to Meter#2 and, instead, redirects 0.2 kWh towards the VC.

Likewise, the last scenario of each set does appear to give due credibility to vulnerabilities, though now the model refrains from allocating larger quantities to a less vulnerable consumer (#4)

and focuses on supplying Meter#6, which accounts for a higher discount and, hence, a more 'urgent' situation. Thus being, this prioritization does negatively impact Meter#4, who now holds a higher individual cost than in the one in the 'all non-vulnerable' case.

5.3.2.2 Approach 2 - Economic Benefits Allocation

Carrying on to the second approach, the same testing method was put to practice, returning the following results:

all non-vulnerable						
	#1#2#3#4*		#1#2#3#4*#5*		#1#2#3#4*#5*#6*	
Meter	Cind	e_pur	Cind	e_pur	Cind	e_pur
#1	-1.44	0	-1.34	0	-1.19	0
#2	2.178	0.9	2.315	0.6	2.492	0.3
#3	-1.197	0.4	-1.079	0.2	-1.079	0.2
#4	1.509	1	1.686	0.7	1.686	0.7
#5	-	-	1.509	1	1.509	1
#6	-	-	-	-	1.325	0.6
base case						
	#1#2#3#4		#1#2#3#4#5		#1#2#3#4#5#6	
Meter	Cind	e_pur	Cind	e_pur	Cind	e_pur
#1	-1.3723	0	-1.193	0	-0.9427	0
#2	2.20452	0.9	2.3727	0.6	2.5889	0.3
#3	-1.1532	0.4	-0.984	0.2	-0.9191	0.2
#4	1.371	1	1.5669	0.7	1.5755	0.7
#5	-	-	1.3281	1	1.2694	1
#6	-	-	-	-	1.1711	0.6
penalty	0.138		0.3		0.504	

Table 5.10: Testing addition of VCs - Approach 2

Examining Table 5.10, attention is first brought over to the amounts of shared energy directed towards each consumer, which remain the same for both sets of testing scenarios. This is expected, as this approach does not interfere in the optimization process and is solely tasked with the redistribution of economic benefits.

In regard to the individual costs of meters #4, #5, and #6, one can note a decrease in value for all vulnerable consumers when compared to the 'all non-vulnerable' set, for every scenario.

5.3.2.3 Comparing the two approaches

- **Individual Cost Comparison**

Firstly, the individual costs per consumer of each approach are presented:

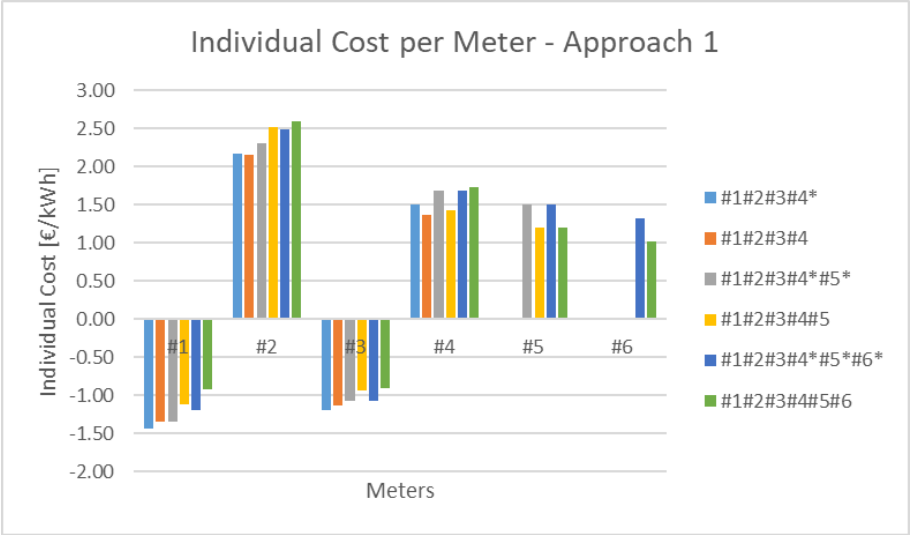


Figure 5.12: Test 2: Individual Cost of each meter under each scenario - Approach 1

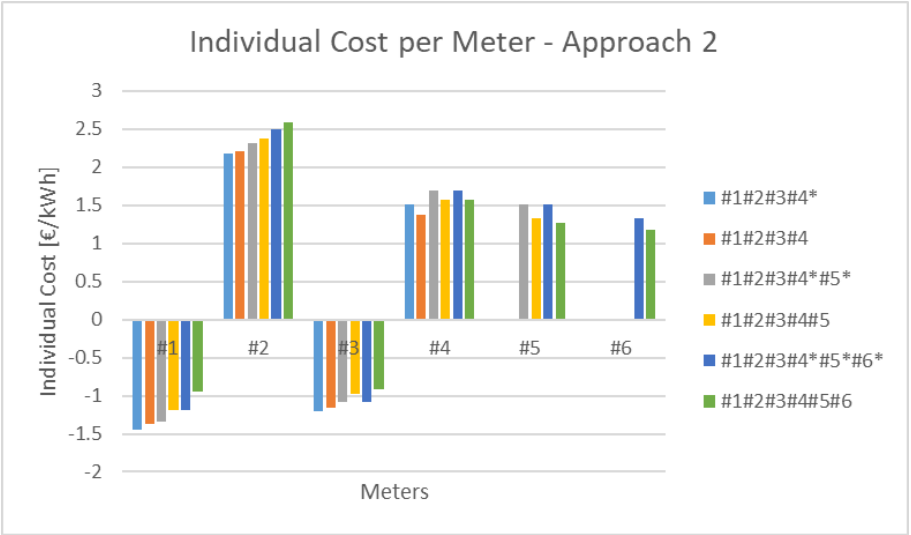


Figure 5.13: Test 2: Individual Cost of each meter under each scenario - Approach 2

The discount application model shows to have a rather drastic approach, strongly focusing over the most vulnerable cases of the group and often neglecting the less, yet still vulnerable ones. This can be observed looking at the green and blue bars in charts 5.12 and 5.13, which, in the first approach, suffer much a more abrupt reduction (meters #5 and #6) and reveals a less predictable behaviour (rising cost of Meter#4).

- **Penalty Comparison**

Next, Figures 5.14 and 5.15 display the cost penalties for each scenario of the base set, regarding approaches 1 and 2, respectively:

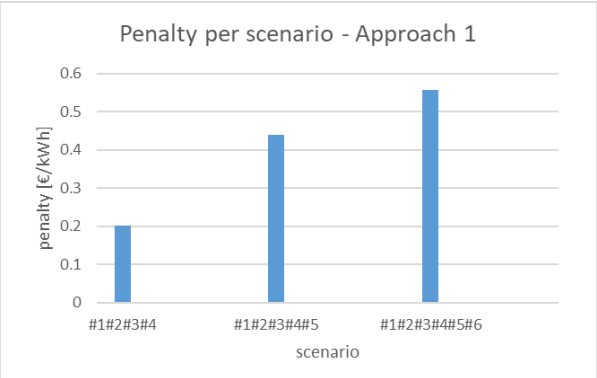


Figure 5.14: Test 1: Penalty per scenario - Approach 1

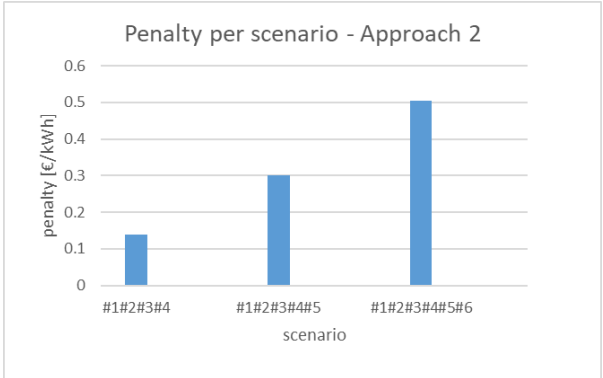


Figure 5.15: Test 1: Penalty per scenario - Approach 2

In this case, both approaches' penalties rise as the scenerios progress, however model number 1 reaches higher costs, which does not necessarily mean a more profitable situation for all VCs, yet it does mean a less profitable situation for all NVCs.

Chapter 6

Conclusions and Future Work

In this final chapter, the intention lays on concisely reuniting the main conclusions found in the course of this dissertation, as well as address any limitations and suggest future work routes to further explore the presented challenge.

6.1 Conclusions

In a first assessment, some conclusions are gathered in regard to the main challenges and concerns when approaching the topic of Inclusive Renewable Energy Communities:

- **Available literature**: as the topic of energy communities is still a recent concept, introduced in the European Union legislation in 2019 and solely in 2022 in the Portuguese legislation, the amount of literature on this subject is still not very abundant. Moreover, inclusive RECs represent a very niche portion of this subject, further hindering the literature research, which provides few real scenarios of such ECs and, hence, still lacks much research over the operational and ethical sides of this matter.
- **Acknowledging Vulnerabilities**: one of the main challenges regarding inclusive RECs is understanding consumer's vulnerabilities in the energy sector. In order to formulate business models that are able to adapt to any community, especially ones with multiple vulnerable consumers, a great understanding of these susceptibilities is crucial. Naturally, low incomes and high energy expenses pose as the main drivers of energy poverty, however if a more flexible and comprehensive model is intended, a broader analysis is required, willing to evaluate factors such as household composition, education levels, infrastructural vulnerabilities, etc. Thus being, such a subjective and wide evaluation is prone to cause many challenges and doubts regarding the operational and ethical side of the community.
- **Acceptance and solidarity towards vulnerable groups**: just as important as the understanding of vulnerabilities is the consideration and respect given to the non-vulnerable side of the community. In fact, these consumers built and sustain these communities and thus deserve equal acknowledgement. Vulnerable consumers will most likely integrate ECs at

other member's expense, and hence an acceptance and willingness to help is necessary on their behalf, which can always lead to disagreements within the community. Therefore, a balanced approach is necessary in order to have a social impact without disregarding or jeopardizing the non-vulnerable members. This includes building a business model that runs smoothly and does not require any additional time/effort on behalf of consumers.

With the concluded implementation and testing of the two developed models, it is believed that both approaches pose as viable and worthwhile strategies for Inclusive RECs.

However, as the result analysis showed, they do behave and react differently under certain scenarios. From these observations, the main conclusions and findings of this work are presented below:

- **Discount Approach more suitable for ECs comprising smaller and less heterogeneous vulnerable groups**: as seen in chapter 5, the growing energy demand and the defined hierarchy levels within the vulnerable group of the EC, did generate some unwanted inequalities which lead to a certain neglect towards vulnerable consumers considered to be in less of a critical situation. For this purpose, this approach is believed to be more suitable for EC settings comprised of VCs standing at similar degrees of energy poverty, or with a certain consumption profile compatibility, as to not cultivate such competitiveness under an inclusive environment.

- **Economic Benefits Allocation Approach more stable and scalable**: as also observed in chapter 5, the second approach seems to provide more stability for EC members, as it does not interfere in the optimization process, avoiding hard to predict behaviours that might not be seen as the most fair and suitable solution. Similarly, it was observed that the associated cost penalty of this approach tends to rise along with the growth of the community (or, at least, does not lower), creating a more easily predictable and moldable strategy, which reinforces the model's stability and allows the continuous integration of VCs, as long as it follows a proportional growth on the non-vulnerable side of the community.

6.2 Future Work

It goes without saying, that though this paper is concluded, the proposal it relies on still holds an immense amount of possibilities that are worth pursuing.

In this section, it is intended to lay out a few suggestions and set some starting points, related to this line of work, that hold the potential of further exploring and elucidating on the Inclusive REC's scope of opportunities:

- **Testing and comprehending the influence of discounts over the optimization process**: as the prioritization of energy transactions towards vulnerable consumers did not pose as an

initial requirement of the first developed approach, and was solely introduced as a speculation of how the model may react to a discount implementation within vulnerable consumers' individual cost computation, the topic was never really deeply discussed. However, the observed impact over the transacted energy amounts does arise a fair degree of curiosity and it is believed to be a topic worth delving into, so to further explore ways of orienting the optimization goal towards defined preferences.

- **Discount application in a post-optimization process**: due to the lack of knowledge in regard to the previous topic, the first developed approach demonstrated a rather unpredictable behaviour that can compromise any community's stability and goals. On account of this, it is believed that a discount application in a post-optimization process, following the same methodology as the second approach, may pose as more appealing and reliable offer regarding EC sharing strategies.

- **Continuous discounts**: as seen in the first approach's results, a discrete discount implementation creates a certain hierarchy within the community that does not enroll as smoothly when discrete values based on set thresholds are implied. In order to avoid such a discrepant scenarios, and as to not disregard any vulnerabilities, a continuous discount, under a defined range, based on the Vulnerability Index, could deliver more balanced and fair outcomes.

The next few topics consist of some additional small suggestions that could help to further improve and/or help to explore other perks within the proposed models:

- **Non-Vulnerability Index also dependent on installed power of each NVC**: in fact, the proposed models to already define non-vulnerability in accordance to the ownership of any generation assets; although it is believed that the installed power of each consumer (though it would have to be somehow normalized relatively to its consumption) plays a big role, naturally, when accounting for EC personal profits; because of this, an NVI attending to this factor, poses as a promising adjustment to the income indicator.

- **Vulnerability Index also dependent on retail buying tariffs**: in the same way, retail buying prices stand as relevant criterion when defining an energy poverty related vulnerability, since they pose as a significant barrier to lowering energy expenses; to this regard, the first indicator could be modified in order to account for consumer's price range of energy buying retail tariffs.

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