FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

# Repartition Algorithms in Energy Communities

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# Resumo

Ao introduzir a Diretiva (UE) n.º 2018/2001, o Parlamento Europeu e o Conselho deram o primeiro passo para o avanço da utilização de energia proveniente de fontes renováveis, tendo a ideia de uma comunidade de energia renovável (CER) surgido como um auxílio a esta transição. A escolha da forma de repartição da energia gerada nas CER é uma questão crucial a abordar aquando da implementação de uma, daí a importância do estudo de algoritmos de repartição em CER.

O principal objetivo desta dissertação é estudar, simular e comparar diferentes algoritmos de repartição em CER, identificando o melhor algoritmo de repartição, bem como caraterizar os diferentes coeficientes de repartição, avaliar a influência do momento em que ocorre a repartição e o impacto da isenção de tarifas para os consumidores.

Tendo em conta estes objetivos, foram desenvolvidas três metodologias para os atingir. A primeira consistiu em efetuar a repartição através de diferentes coeficientes de repartição, em que a repartição ocorria de 15 em 15 minutos, mantendo-se os coeficientes iguais ao longo do ano. A segunda metodologia implicava efetuar a repartição de 15 em 15 minutos, sendo que os coeficientes variavam todos os meses. A última metodologia implicava efetuar a repartição através de diferentes coeficientes de repartição, em que a repartição ocorria no final de cada mês, mantendo-se os coeficientes iguais ao longo do ano.

Os dados utilizados para caraterizar o caso de estudo sobre o qual se aplicou as metodologias acima referida dizem respeito aos dados de produção e consumo para o período de um ano, de 29 de setembro de 2020 a 29 de setembro de 2021, de quatro produtores e quatro consumidores pertencentes a uma CER.

As principais conclusões que se podem retirar do trabalho desenvolvido nesta dissertação são que a escolha correta do algoritmo de repartição a implementar numa CER pode significar uma redução significativa de custos para os consumidores e que o algoritmo de repartição através de coeficientes dinâmicos proporcionais ao consumo apresenta os melhores resultados. Por outro lado, a alteração mensal dos coeficientes só traz alterações significativas nos custos se os perfis de consumo dos consumidores se alterarem drasticamente ao longo de um ano. Além disso, a agregação de dados por mês e por período horário é uma solução muito interessante a explorar na tentativa de reduzir os custos dos consumidores e simplificar o processo de repartição. Por fim, a isenção de pagamento de CIEG é essencial para não inviabilizar a participação de consumidores numa CER.

Finalmente, as conclusões retiradas desta dissertação podem ser úteis para os países que ainda não têm um enquadramento legal para as CER e para a forma como a energia pode ser repartida, para decidirem qual a melhor forma de formularem a sua regulamentação sobre as CER. Este trabalho é também útil para as entidades gestoras das comunidades decidirem qual o tipo de repartição mais adequado às características dessa CER.

**Palavras-chave:** comunidade de energia renovável, algoritmos de repartição, coeficientes de repartição

# Abstract

By introducing Directive (EU) No. 2018/2001, the European Parliament and Council took the first step toward advancing the use of energy from renewable sources, and the idea of a renewable energy community (REC) emerged as an aid to this transition. Choosing how to repartition the energy generated in RECs is a crucial issue to address when implementing one, hence the importance of the study of repartition algorithms in RECs.

The main objective of this dissertation is to study, simulate and compare different repartition algorithms in RECs, identifying the best repartition algorithm as well as characterize the different repartition coefficients, evaluate the influence of the moment where the repartition occurs and the impact of tariffs exemption for consumers.

Having in mind these goals, three methodologies were developed to accomplish them. The first entailed performing repartition through different repartition coefficients, where the repartition happened every 15 minutes, with the coefficients remaining the same throughout the year. The second methodology involved performing repartition every 15 minutes, with the coefficients changing each month. The final methodology implicated performing repartition through different repartition coefficients, where the repartition happened at the end of every month, with the coefficients remaining the same throughout the year.

The data used to characterize the case study on which the above-mentioned methodology was applied concerned the production and consumption data for a one-year period, from September 29, 2020, to September 29, 2021, of four producers and four consumers belonging to a REC.

The major conclusions that can be drawn from the work developed in this dissertation are that the correct choice of repartition algorithm to implement in a REC can mean a significant reduction in costs for consumers and that the repartition algorithm through dynamic coefficients proportional to consumption yields the best results. Moreover, changing coefficients monthly only brings significant changes in costs if consumers' consumption profiles change drastically over a year. Furthermore, aggregation of data by month and hourly period is a very interesting solution to explore in the quest to reduce consumer costs and simplify the repartition process. Finally, the exemption of CIEG payments is essential not to render the participation of consumers in a REC unfeasible.

Finally, the conclusions drawn from this dissertation can be useful for countries that still do not have a legal framework for REC and for how energy can be repartitioned to decide the best way to formulate their regulations on RECs. This work is also useful for the community management entities to decide which type of repartition is best suitable for the characteristics of that REC.

**Keywords:** renewable energy community, repartition algorithms, repartition coefficients

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A todos, muito obrigado.

Danilo Pinto

*“Science can amuse and fascinate us all,*
*but it is engineering that changes the world.”*

Isaac Asimov

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# Abbreviations

| | |
|---|---|
| CIEG | *Custo de Interesse Económico Geral* |
| CME | Community Management Entity |
| DSO | Distribution System Operator |
| DGEG | *Direção-Geral de Energia e Geologia* |
| EHV | Extra High Voltage |
| ERSE | *Entidade Reguladora dos Serviços Energéticos* |
| EU | European Union |
| HV | High Voltage |
| LV | Low Voltage |
| MV | Medium Voltage |
| NAT | Network Acess Tariff |
| NES | National Electric System |
| P2P | Peer-to-peer |
| PV | Photovoltaic |
| PUSC | Production Units for Self-Consumption |
| REC | Renewable Energy Community |
| RSC | Renewables Self-Consumer |
| SLV | Special Low Voltage |
| UI | Usage Installation |

# Symbols

| | |
|---|---|
| $\alpha_i^{15min}$ | Consumption factor for a 15-minute interval for Consumer *i* |
| $\beta_{15min}$ | Production factor for a 15 minute interval |
| $CC_i$ | Consumer Coefficient assigned to Consumer *i* |
| $E_{C_i}$ | Energy consumed by Consumer *i* |
| $E_{C_i}^{15min,j}$ | Energy consumption in each 15-minute interval by Consumer *i* |
| $E_{C_i,ave}$ | Average energy consumption throughout a year by Consumer *i* |
| $E_{C_i,max}^{15min}$ | Maximum energy consumed among the 15-minute intervals in one year by Consumer *i* |
| $E_{Prod}$ | Total Energy Produced in the REC |
| $E_{Prod}^{15min}$ | Energy production in a 15 minute interval |
| $E_{Prod,Max}^{15min}$ | Maximum energy that could be produced in a 15-minute interval |
| $EA_{C,i}$ | Energy Allocated to Consumer *i* |
| $N$ | Number of 15-minute intervals |
| $N_c$ | Total number of consumers |

# Chapter 1

# Introduction

The present chapter introduces the subject of this dissertation giving its context and presenting its legal framework, as well as providing the motivation that leads to the need to study renewable energy communities and the repartition algorithms used in them. This chapter also presents the main objectives of this dissertation and the research questions it tries to answer. Finally, it exposes the methodology that was followed, the case studies analyzed, and the document's structure.

## 1.1 Context and motivation

The European Parliament and Council, on December 11, 2018, introduced Directive (EU) No. 2018/2001 [1] with the purpose of promoting the use of energy from renewable sources having in mind the target set by the Union where the Member States shall collectively ensure that the share of energy from renewable sources in the Union's gross final consumption of energy in 2030 is at least 32%. Furthermore, this directive introduces the definition of concepts such as renewables self-consumer (RSC), jointly acting renewables self-consumers, renewable energy community (REC) and peer-to-peer (P2P) trading.

In 2016, Portugal committed to the goal of reaching carbon neutrality by 2050 [2] and, in 2019, the Council of Ministers Resolution No. 107/2019 [3] approved the *Roteiro para a Neutralidade Carbónica 2050*. Additionally, in 2020, the Council of Ministers Resolution No. 53/2020 [4] approved the *Plano Nacional Energia e Clima 2030*, which reinforces the objective to increase the production of energy from renewable sources.

The approval of both plans meant that a legal framework needed to be established, and in 2019, the first Portuguese legislation on RECs was approved in the Decree-Law No. 162/2019 [5] and, most recently, the previous mention decree was revoked and replaced by Decree-Law No. 15/2022 [2] that legislates on the updated organization and operation of the National Electric System (NES). This last one has in account the Regulation No. 373/2021 [6] on the self-consumption of energy approved by *Entidade Reguladora dos Serviços Energéticos* (ERSE), the Portuguese regulatory entity of energy services, on May 5, 2021.

These decisions lead to the change of role of the consumer in the NES allowing them to become active agents that are able to produce electricity for self-consumption and even sell the surplus [7]. One of the ways that the consumer can do this is by becoming a member of a renewable energy community where the main objective of the REC is to provide its members with environmental, economic, and social benefits. According to [2], a REC is considered a collective person that allows members to join having the REC capacity to produce, consume, store, sell, and buy renewable energy between its members or with others outside of the community.

In a REC, the energy generated through renewable energy sources is aggregated and then shared with its members. However, the repartition of the produced energy isn´t physical but instead virtual, where the energy is shared by means of repartition keys that are imported into mathematical algorithms that later impose the proportion of total local electricity produced within the REC to allocate to each community consumer [8].

The process of managing RECs can be quite complex because in them might have to coexist multiple producers and consumers. Also, some members can have priority in the allocation process, or the REC management entity can set several rules and restrictions within the community resulting in numerous variations in repartition algorithms. The possibility of storage inside the REC and the possibility of production at different voltage levels increases the management complexity [9, 10]. Because of this, various models can be implemented, leading to the possibility that different models may be adopted in the same country. Furthermore, given that every country has its own legislation and regulatory entities, each one has its own models and variations [11].

The constitution of RECs brings huge transformations for the electrical system in terms of data acquisition and management of power flows. Effectively, it´s expected a change in the role of the electrical grid, becoming a service that allows energy exchanges between REC members and provides a balancing of energy in the system. Moreover, RECs originate new scenarios that can mean different billing of electricity for the members of the community, such as the possibility of a single consumer being able to have multiple suppliers or the costs associated with the use of the grid.

The implementation of RECs can be beneficial for both consumers and electrical grid operators. From the perspective of the consumer, the major advantage of being a member of a REC is to have access to electricity at a lower cost than the electricity provided by the electrical grid. This happens because the REC uses its own production resources and infrastructures, avoiding the need to resort to services provided by companies external to the community. On the other hand, for the electrical system, the implementation of RECs means that the production is closer to the consumption site resulting in a decrease in energy losses, the decrease of need to reinforce the electrical grid at different voltage levels, and the decrease in the need to expand the production capacity. These reasons lead to the reduction of costs associated with the management of the electrical system and, consequently, the reduction of costs for the consumer [2, 12].

To summarize, the main motivation for the development of this dissertation is to study various repartition models and evaluate them in terms of technical and economic benefits for the electrical system and the consumers since the implementation of different repartition algorithms in RECs has implications not only on costs involving the management of the electrical system but also on the price of the electricity for consumers.

## 1.2 Research questions

This dissertation has the intention to answer the following research questions:

- What are the different repartition algorithms that can be implemented?
- How can the fixed repartition coefficients be defined?
- Is it possible to assign multiple coefficients broken down by hourly periods to the same consumer?
- Which is the best repartition algorithm through fixed coefficients?
- Is there an advantage to changing the coefficients monthly instead of keeping them all year round?
- Is it possible for the repartition to be done only at the end of each month, considering the different hourly periods?
- What is the influence of exempting consumers from paying certain grid tariffs?

## 1.3 Objectives

The main objective of this dissertation is to study, simulate and compare different repartition algorithms in energy communities. Thus, it is intended to achieve the following specific objectives:

- Identify the best repartition algorithm;
- Characterize the different repartition coefficients;
- Evaluate the advantages of changing the repartition coefficients monthly;
- Evaluate the advantages of performing the repartition at the end of each month, considering the different hourly periods;
- Evaluate the impact of tariffs exemption for consumers.

## 1.4 Methodology and tools

The methodology developed involved the application of different repartition algorithms and evaluating them on the energy balances they yield and the resulting electricity bill based on in-force tariffs in Portugal.

The first repartition entailed performing repartition through different coefficients, where the repartition happened every 15 minutes, with the coefficients remaining the same throughout a year. The second repartition involved performing repartition through different repartition coefficients, where the repartition happened every 15 minutes, with the coefficients changing each month. The final one entangled performing repartition through different repartition coefficients, where the repartition happened at the end of every month, with the coefficients remaining the same throughout the year.

The calculation tool used in the different studies performed was *Microsoft Excel*, including its optimization problem-solving tool, *Solver*.

## 1.5 Case study and data used

The data used to characterize the case study on which the above-mentioned methodology was applied was extracted from [13]. It concerns the production and consumption data for a one-year period, from September 29, 2020, to September 29, 2021, of four producers and four consumers.

## 1.6 Structure of the dissertation

This dissertation is organized into 5 chapters.

In chapter 1 is made an introduction to the subject of this dissertation by presenting its context and motivation. Additionally, the main objectives and research questions are presented, the methodology followed, and the case studies considered. Lastly, the structure of the dissertation is presented by explaining each chapter's content.

In chapter 2 is done a literature review of the subject of this dissertation where is presented the state of the art involving renewable energy communities and the repartition algorithms used in them.

In chapter 3 is presented the methodology followed in the study of different repartition algorithms in renewable energy communities with the purpose of answering the research questions raised.

In chapter 4 is presented the characterization of the case study where the methodology described in the previous chapter was applied in order to draw conclusions that allow answering the research questions that this dissertation proposes to answer.

In chapter 5 is presented the major conclusions that were possible to draw from the work developed as well as the answers to the research questions and possible future utility of the work done in this dissertation.

# Chapter 2

# State of the Art

The present chapter aims to present a literature review of the most relevant topics involving RECs and whose understanding is important for comprehending the work developed in this dissertation.

In section 2.1 is presented an overview of the concepts related to RECs from an EU perspective, followed by the identification of the current state of the legal framework and regulation of RECs in some EU Member States with a more detailed analysis involving the Portuguese legislation.

In section 2.2 are proposed different business models that may be implemented in RECs.

In section 2.3 is presented the different aspects that one can encounter when studying repartition algorithms in renewable energy communities, with special attention to the repartition algorithm currently implemented in Portugal.

## 2.1 Renewable Energy Communities

### 2.1.1 Renewable Energy Community in a European Union perspective

The definition of a REC was first introduced, in the European Union context, in 2018 by Directive (EU) 2018/2001, on December 11. The structure and composition of RECs as well as the rules applicable to them, are different depending on the legislation of each EU Member State. However, that legislation has to transpose said EU directive, meaning that the general concepts involving REC are the same for every member.

A REC is a legal entity based on open and voluntary participation, where the participants are shareholders or members. The shareholders or members are natural persons, micro, small or medium-sized enterprises, or even local authorities like municipalities, and it is them that effectively control the REC [1, Art. 2]. Due to the characteristics of the participants, it is possible to state that the membership is limited since shareholders or members do not include large enterprises [14]. The participants in RECs are in proximity to each other and in proximity to renewable energy sources that are owned and developed by the REC. It is up to each EU member to define, in its own legal framework, the value of the proximity criteria [1, Art. 2].

The primary purpose of a REC is to provide environmental, economic, or social community benefits for its shareholders or members or for the local areas where is implemented, rather than financial profits. REC participants, in particular household customers, are entitled to maintain their rights and obligations as final customers and have the guarantee that they won't be subject to discriminatory conditions because they are REC participants [1, Art. 2].

Thus, a REC and, consequently, its shareholders or members, according to [1, Art. 22] are entitled to:

- Produce, consume, store, and sell renewable energy, including through renewables power purchase agreements;
- Share, within the REC, renewable energy that is produced by the production units owned by that REC, maintaining the rights and obligations of the renewable energy community members as customers;
- Access all suitable energy markets both directly or through aggregation in a non-discriminatory manner.

Based on the information present in [1], EU countries have the flexibility to decide on numerous criteria involving RECs. Later in this chapter is presented the specificities for the Portuguese context, but, firstly, it is important to detail the different participants/agents and entities involved in the process of a REC implementation.

The first agent worth mentioning is the REC itself. The term REC refers to a legal entity where participants can join voluntarily and are referred to as members or shareholders. Thus, with this definition, legal entities that can represent RECs can be condominiums, consumer associations, cooperatives, autarchy or parish, building owners, developer companies, management companies, and investment companies, for example. It is the responsibility of each EU member to legislate on this matter.

Additionally, there are the members who are the participants in a REC and fit into three major categories: producer, consumer, and prosumer (producer and consumers at the same time). A producer is a member that owns renewable energy production units, and supplies said energy to the REC consumers. A producer can interact within the community with the role of only producer, not being obliged to be a consumer. Although it is not restricted to this form of generation, renewable energy production in REC is most commonly obtained through photovoltaic (PV) energy, according to [10]. A consumer is a member that uses energy produced within the REC to satisfy its needs. However, they also have access to external energy suppliers to complement their energy needs when the energy produced in the REC it is not enough. Finally, a member can be a prosumer which consists in a consumer that uses energy produced within the REC but also owns energy production units.

Another agent present in a REC is the community management entity (CME) which is an entity nominated by the REC to represent it. It is its job to manage the community in terms of energy shared between the members as well as its financial management and, depending on the national legislation of countries, it can assume other roles.

The distribution system operator (DSO) is responsible for the electrical grid operation, management, and maintenance. This entity might also assume the role of the entity responsible for measurement acquisition and information management involving data related to the consumption and production of REC members. This job can also be deferred to a dedicated company.

The energy suppliers are also entities that interact with a REC, whose activity involves the purchase and sale of energy.

Depending on the REC organization and promotor, other entities that may be involved are aggregators, which are the entities that aggregate the energy production within the REC, and investment entities that are responsible for the financial investment of the REC.

These are the major agents involved in the REC. It is possible to exist other entities or some variations of those entities indicated attending to each country's legislation concerning the role of different entities in a REC.

### 2.1.2 European Legislation and Regulation

The first piece of legislation mentioning RECs was introduced in 2018, the year in which the European Parliament and Council approved the Directive (EU) No. 2018/2001 [1] on December 11, where it established a common framework for the production of energy from renewable sources. In this directive, the concept of a renewable energy community is introduced. The definition of REC presented in this directive was already exposed in the previous section. However, this piece of legislation also gives a set of instructions on how Member States should proceed when it comes to RECs. The Member States, as indicated in [1, Art. 22], must ensure that customers that are members of RECs are not subject to discriminatory conditions that prevent their participation in RECs. The Member States are obligated to carry out an assessment in order to find possible obstacles that prevent the implementation of RECs as well as provide an enabling framework that allows the development of RECs. This framework must ensure that unjustified administrative barriers are removed, the distribution system operator cooperates with RECs, allowing a smooth process involving energy transfers, and RECs are treated fairly when it comes to the registration and licensing processes and network usage costs. Finally, Member States shall ensure tools that facilitate access to finance and information on RECs. This framework must take into consideration Regulation (EU) No. 2018/1999 [15], of the European Parliament and Council, of December 11, 2018, that determined that all Member States should draw up a national energy and climate plan for the 2021-2030 horizon. This regulation also requires members to take measures to promote energy communities in their plans.

Therefore, with the approval of the referred legislation, each Member State had to create a legal framework for RECs, resulting in different countries having distinct laws when it comes to these communities.

### 2.1.3 Comparison of RECs legal frameworks in EU Member States

Given that the European directive was introduced in 2018, most EU Member States already have legal frameworks for RECs or at least a draft [11]. Table 2.1 compiles the progress of different EU countries concerning legislation involving RECs as of May 2022. It is important to state that is considered an implemented framework legislation that ranges between complex frameworks or only simple definitions introduced into law.

Table 2.1: RECs Legal Frameworks in EU Members. Source: [16].

| **EU Member State** | **Renewable Energy Communities Legal Framework?** |
|---|---|
| Austria | YES |
| Belgium: Wallonia | YES |
| Belgium: Flanders | YES |
| Czech Republic | NO |
| Croatia | DRAFT |
| Denmark | YES |
| Estonia | DRAFT |
| Finland | YES |
| France | YES |
| Greece | YES |
| Hungary | DRAFT |
| Ireland | DRAFT |
| Italy | YES |
| Lithuania | YES |
| Luxemburg | YES |
| Portugal | YES |
| Poland | DRAFT |
| Romania | NO |
| Slovenia | YES |
| Spain | DRAFT |
| Sweden | DRAFT |

The ways in which Member States transpose the EU directive rules vary greatly, and consequently, the level of detail of their legislation differs across member states. [16] Hence, it is important to analyze in more detail form the legal framework of different EU Member States. Due to difficulties encountered during this analysis, a deep study of legislation involving RECs was only done for Portugal.

#### 2.1.3.1 Legislation and Regulation in Portugal

The first Portuguese legislation on RECs was approved in the Decree-Law No. 162/2019 [5] and, most recently, the previous mention decree was revoked and replaced by Decree-Law No. 15/2022 [2] that legislates on the updated organization and operation of the National Electric System, where one of its objectives is to partially transpose of Directive 2018/2001.

The referred decree-law provides several pieces of legislation involving RECs in the Portuguese context. The definition of REC is very similar to the one in [1]. In Portuguese legislation, a renewable energy community is a legal entity, established through open and voluntary membership of its members, partners, or shareholders, who may be individuals or legal entities, of public or private nature, including, in particular, small and medium-sized enterprises or local authorities, controlled by them and which, cumulatively [2]:

- Members or participants are located in the vicinity of renewable energy projects or develop activities related to the renewable energy projects of their energy community, including necessarily Production Units for Self-Consumption (PUSC);
- Said projects are owned and developed by the REC or by third parties, provided that they benefit and serve the REC;
- The REC has as its main objective to provide environmental, economic, and social benefits to its members or to the localities where the community operates, instead of financial profits

In Portugal, legal entities, which also can be referred to as collective persons, are social organisms endowed with legal personality and constituted to pursue common or collective interests, which may be public or private [17, 18]. According to [17, 18], these entities are of the following types:

- Public: for example, commissions created by the State itself, to ensure the pursuit of public interests and, therefore, endowed with authority prerogatives (that is, public powers and duties).
- Public Utility: for example, municipal entities responsible for the supply and distribution of water, which are private legal entities without profit (associations, foundations, or certain cooperatives), which pursue general interest goals in cooperation with the central or local Administration.
- Private: In terms of private, they can be:
  - Associations that aim at non-profit goals and can be of cultural, social, or other nature. An example of this is a neighborhood association;
  - Foundations which are legal entities that manage a set of assets for the pursuit of a lasting and socially relevant purpose, whether religious, moral, cultural, or assistance-related;
  - Civil or commercial companies (in collective name, by quotas or anonymous);
  - Cooperatives (in collective name, by quotas).

According to Portuguese legislation, [2, Art. 189], a REC has the ability:

- To produce, consume, store, purchase, and sell renewable energy with its members or with third parties;
- To share and trade among its members the renewable energy produced by PUSC serving the community while observing the other requirements provided, without prejudice to the members of the REC maintaining their rights and obligations as consumers;
- To access all energy markets, including system services, both directly and through aggregation.

Furthermore, a REC must have an entity responsible for its management, designated as *Entidade Gestora do Autoconsumo* (EGAC), which corresponds to the community management entity. This is a singular or collective person, that can be a REC member or not, designated by all members to represent the community with specific activities such as [2, Art. 86]:

- Practice of operational management acts of current activity, including the management of the internal network, when it exists;
- Articulation with the electronic platform provided for in [2, Art. 15];
- The connection with the public grid and articulation with the respective operators, namely in terms of production sharing and respective coefficients;
- The commercial relationship to be adopted for surpluses, as well as others committed by members.

In Portugal, it is the DSO, *E-Redes*, responsible for the monitorization of production and consumption of energy by REC members. They do this using smartmeters and the data collection is done depending on the repartition algorithm adopted in the community, but, by default, is collected in the time period of 15 minutes [17].

RECs are subject to grid tariffs defined by the energy services regulatory entity, ERSE.

The use of the public networks to transport energy between PUSC and the Usage Installations (UI) is subject to Network Access Tariff (NAT) applicable to consumption at the IUs connection voltage level. These tariffs are paid by the communities and are derived from:

a) Tariffs for the use of networks of voltage levels upstream of the voltage level of the PUSC connection when there is energy injection from the public network from a higher voltage level that the PUSC is connected;

b) Tariffs for the use of the networks of the voltage levels upstream of the level PUSC connection voltage, in the amount to be defined by ERSE, when there is an inversion of the energy flow in the public network for upstream of the voltage level connection to the PUSC.

The Network Access Tariff is paid by all consumers and reflects the cost of infrastructures and services used by all consumers in a shared. This tariff results from the sum of the tariffs for the Global Use of the System, the Use of the Transport Network, the Use of the Distribution Network, and the Logistics Operation of the Change of Supplier, all fixed by ERSE [17].

The CME is the entity responsible for the payment of the NAT to the DSO. For this purpose, CME will have to establish a network use contract with the DSO when the configuration of installations participating in a REC result in the possibility of self-consumption occurring through public networks.

The use of internal networks that do not involve the use of public networks to transmit electricity between the PUSC and IUs is not subject to any tariff.

The tariffs for access to the networks to be applied to self-consumption through the public grid are composed of the following prices:

a) Power prices in peak hours, defined in Euros per kW, per month;

b) Active energy prices, defined in Euros per kWh.

Furthermore, as part of the NAT, there is a charge designated as *Custo de Interesse Económico Geral* (CIEG), in English, costs of general economic interest, and projects such as RECs that use public networks may benefit from an exemption. It is incumbent upon the *Direção-Geral de Energia e Geologia* (DGEG), in English, Directorate-General of Energy and Geology, to verify the eligibility conditions of installations entitled to apply for the exemption from CIEG charges. The exemption may be 100% of the CIEG in the case of REC.

The Portuguese legislation does not impose restrictions in terms of the dimension of the REC when it comes to the number of members or power. However, there is a proximity criterion that must be met in order for a REC to be constituted. This criterion is divided by voltage levels [17]:

- **Low Voltage (LV):** The distance between the PUSC and the usage installation must be less than 2km apart or be connected to the same LV transformer;
- **Medium Voltage (MV):** Members must be connected to the same substation, and the distance between the PUSC and the UI must be less than 4km apart;
- **High Voltage (HV):** Members must be connected to the same substation, and the distance between the PUSC and the UI must be less than 10km apart;
- **Extra High Voltage (EHV):** Members must be connected to the same substation, and the distance between the PUSC and the UI must be less than 20km apart;
- Special cases analyzed by *Direção-Geral de Energia e Geologia*.

The energy produced within the REC has its origin in self-production from members, autonomous power plants, or storage units belonging to the REC, and the producers must be REC members even if they do not consume any energy. The CME is not allowed to buy energy that comes from the public electrical grid and, later, sell it directly to consumers. However, members with their own storage units or a REC with collectively owned storage units can use energy that comes from the public electric grid to change their batteries and later share that energy with the community members.

Finally, a REC can sell its energy surplus. The CME is responsible for the commercial relationship with other agents in order to sell the REC energy surplus. The trade of energy surplus may be [19]:

- In an organized or bilateral market, including through a renewable power purchase contract;
- Through a market participant against payment of a price agreed between the parties;
- Through a market facilitator, subject to an acquisition obligation with market remuneration.

Table 2.2 compiles the most relevant information involving the Portuguese legislation on RECs.

Table 2.2: REC's Legislation and Regulation in Portugal.

| | **Portugal** |
|---|---|
| **Latest Legislation (Year)** | Decree-Law No. 15/2022 (2022) |
| **REC Representative Entity** | Legal entity open to voluntary adhesion. |
| **REC Members** | Members or shareholders can be singular or collective person of public or private nature. |
| **REC Producers** | Producers must be a member of the REC. |
| **REC Management Entity** | The entity responsible is EGAC. It's a singular or collective person that can be a REC member or not, designated by all members to represent the community with specific activities. |
| **Production and Consumption Monitorization** | The DSO, E-Redes, is responsible for monitoring production units and consumption data. |
| **Measureament System** | The measurement instrument used are smartmeters with a time period of 15 minutes. |
| **Grid Tariffs** | Grid tariffs defined by ERSE, energy services regulation entity. REC is subject to the following tariffs involving public grid usage corresponding to the grid voltage levels that are used due to injection or power flow inversion. REC internal networks that don´t use the public grid aren´t subject to a tariff. |
| **REC Dimension** | There are no restrictions in the dimension of a REC in terms of the number of members or power. However, there is a proximity criterion that must be met. |
| **Proximity Criteria** | Low Voltage: PUSC and UI less than 2km apart or connected to the same LV transformer;<br>Medium Voltage: connected to the same substation and PUSC and UI less than 4km apart;<br>High Voltage: connected to the same substation and PUSC and UI less than 10km apart;<br>Extra Hight Voltage: connected to the same substation and PUSC and UI less than 20km apart;<br>Special cases analyzed by DGEG. |
| **Energy Origin** | The energy produced within the REC has its origin in self-production from members, autonomous power plant, or storage units belonging to the REC. |
| **REC Energy Surplus** | REC can sell its energy surplus. EGAC is responsible for the commercial relationship to adopt for energy surplus. |

## 2.2 Business Models

The present concept of RECs at the European level enables the different agents involved to have various types of relations. These different relations originate mainly because of who is promoting the implementation of the REC, which, consequently, influences who are the producers and who are the consumers. However, at this time, there are no defined specific business models for REC leading to the creation of different business models. The following business models proposed for REC are the result of the analysis of the business models proposed by [20, 21, 22].

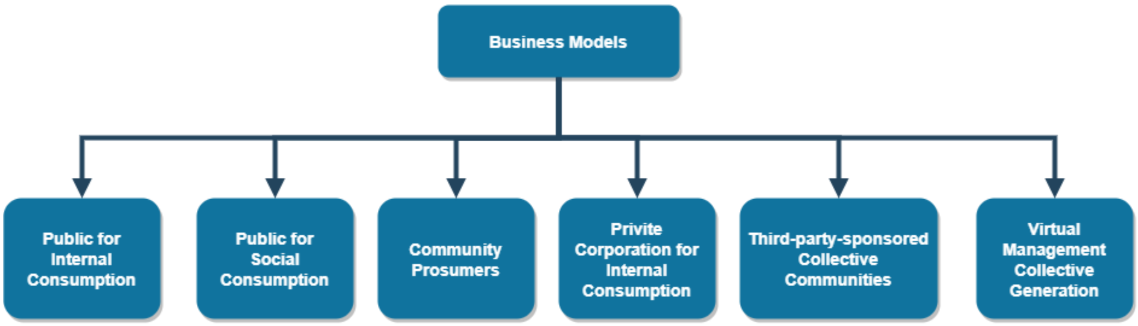


Figure 2.1: Proposed Business Models.

The first proposed business model is **Public for Internal Consumption**, which consists of a REC created by a public institution with the objective of sharing the produced renewable energy with facilities belonging to that same public institution. Therefore, the promotors of this kind of business model are large public institutions such as municipalities or parishes buildings. The production of energy comes from large production units in small numbers, and the consumers are also considered big consumers (large buildings) but exist in small numbers.

The second proposed business model is **Public for Social Consumption**. Similarly to the previous model, the REC in this model is also created by a public institution but has a different goal, which consists in sharing the produced local renewable energy with facilities that may belong or not to the same public institution. Therefore, the promotors of this kind of business model are large public institutions such as municipalities or parishes buildings. The production of energy comes from large production units in small numbers, and the consumers are considered small consumers but in large numbers. A situation where this type of model can be implemented is in social projects promoted by municipalities or parishes to provide cheaper energy to vulnerable consumers living in social buildings [21].

The third proposed business model is **Privite Corporation for Internal Consumption**. This model is comparable to the first model with the major difference being the promotor. Indeed, in this model, the promotors are private companies, where the production of energy comes from large production units in small numbers, and the consumers are also considered big consumers but exist in small numbers. This business model is mainly aimed at REC where the members are large industries or large-scale commerce parks.

The fourth proposed business model is **Community Prosumers**. This model is a result not of an individual enterprise but instead of an association of prosumers. The REC promotor can be an association, cooperative, or foundation. This type is the most common because the REC members are regular household consumers. The renewable energy production of the REC comes from a large number of small production units owned by various members and the consumers are a large number of small household consumers.

The fifth proposed model is **Third-party-sponsored Collective Communities**. In this business model, the promoting entity owns the total or partial REC assets such as production units, and supports the associated costs involving the REC. The promotor is the main producer that shares the energy with the REC consumers. This model results in a smaller number of large production units that provide energy to a large number of small consumers. Examples of entities that could promote this type of business model are energy suppliers, energy services companies, or production energy companies.

The final proposed business model is **Virtual Management Collective Generation**. This business model consists of private corporations acting as the managing entity of the REC. These companies are responsible for sharing, expediting, and facilitating the REC energy surplus by neighbors consumers, or other renewable energy communities. So, in this model, the promoters are private companies, the production is a result of a large number of small production units and the consumers are a large number of small consumers. Similar to the previous model, examples of entities that could promote this type of business model are energy suppliers, energy services companies, or production energy companies.

The following table compiles the proposed business models, emphasizing the main characteristics of each one.

Table 2.3: Business Models for RECs.

| Business Model | Who is the REC promoter? | What are the characteristics of the production? | What are the characteristics of the consumption? | What are the main objectives? |
|---|---|---|---|---|
| **Public for Internal Consumption** | Public institutions | • Large production units<br>• Small number of units | • Large consumers<br>• Small numbers of consumers | Share local energy production with the facilities that belong to the promotor |
| **Public for Social Consumption** | Public institutions | • Large production units<br>• Small number of units | • Small consumers<br>• Large numbers of consumers | Share local energy production with the facilities that belong or not to the promotor |
| **Privite Corporation for Internal Consumption** | Privite companies | • Large production units<br>• Small number of units | • Large consumers<br>• Small numbers of consumers | Share local energy production with the facilities that belong to the promotor |
| **Community Prosumers** | Consumers association | • Small production units<br>• Large numbers of units | • Small consumers<br>• Large numbers of consumers | Share local production energy with the members |
| **Third-party-sponsored Collective Generation** | Privite companies | • Large production units<br>• Small number of units | • Small consumers<br>• Large numbers of consumers | Share local production energy with the members |
| **Virtual Management Collective Generation** | Privite companies | • Large production units<br>• Small number of units | • Small consumers<br>• Large numbers of consumers | Share local production energy with the members |

## 2.3 Repartition algorithms in renewable energy communities

The repartition of the energy produced by renewable energy production units within the REC must be shared with the REC members. This repartition is done by the means of repartition keys that impose the proportion of the produced energy that is shared with each member [8]. However, the repartition process depends on the REC organization, on how the is REC managed and what rules are imposed by the REC management entity. Therefore, this subsection pretends to characterize the different aspects that one might encounter when overseeing the repartition process in a REC.

For the repartition process in a REC is essential that production sites, consumption sites, and storage units be equipped with an energy meter or smartmeter, depending on the repartition algorithm used. This requirement is important to secure the correct data management that allows the tracking of the energy produced and consumed by each REC member as well as the energy stored in storage units that may exist.

### 2.3.1 Dynamic of the repartition process

The characteristic of dynamic comes as a result of the different composition, production, and storage units, rules, and interests of each community. As a result, the repartition process is quite dynamic to ensure that the different rules in the internal regulation of a REC can be fulfilled.

This dynamic is verified due to the ability to update the repartition coefficients several times. The coefficients can be associated with different variables such as consumption, production, or hourly periods allowing this process to be dynamic.

Additionally, decisions involving priorities in the repartition as well as the production aggregation also affect the repartition coefficients.

Finally, the repartition process has to be dynamic due to the possibility of new members joining, whether as a consumer, a producer, or a prosumer, which alters the configuration and the coefficients of the repartition used.

### 2.3.2 Temporal granularity and information update of the repartition

The ability to introduce dynamic coefficients (explained later in this chapter) in the repartition algorithms is dependent on the use of intelligent smartmeters that allow the constant monitorization of the production and consumption data by the responsible entity. With this monitorization capacity, another important aspect of the repartition process is the time granularity and the update of the information of the repartition. These two characteristics relate to the time frame that the responsible entity collects data regarding consumption and production and the time frame that the responsible entity sends that data. These time frames can be, for example, every 15 minutes, hourly, weekly, or monthly [14].

### 2.3.3 Production characteristics

The energy produced within a REC to be shared with the members can have different origins and varies in dimensions and location [23]. The different sources of that energy are the ones depicted in figure 2.2.

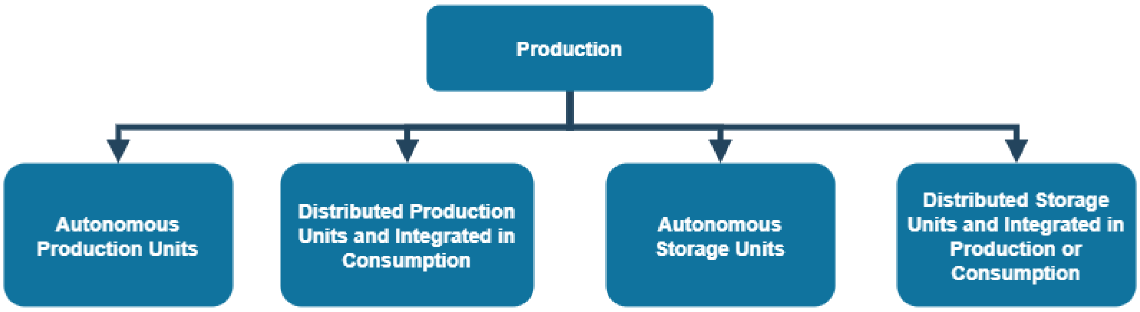


Figure 2.2: Production Characteristics.

The origin of energy of a REC comes from two major forms: production units and storage units.

The production units normally only inject energy into the grid, but in special situations might also have internal consumption. They are equipped with a production meter to measure the energy produced.

Storage units can work as a load, consuming energy when charging, or work as production units when injecting energy into the grid. This means that these units are normally equipped with a bidirectional meter to be able to count as a consumer when charging and as a producer when it is injecting. The storage energy itself does not produce or consume any energy, and their charging can be done by using the energy from the REC or from the electrical grid.

These production and storage units can be divided into autonomous units or distributed units. The characteristics that differentiate these two are the dimension and their location. Autonomous units are typically of a medium to large dimension and may be several in a community.

The distributed production and storage units are typically of a smaller dimension when compared to the autonomous ones. They are normally integrated in locations of consumption or production, and the facilities are equipped with bidirectional meters.

In summary, the produced energy may result from autonomous production units, which consist of a large production site solely dedicated to production where the REC members can share all energy generated. The energy production in a REC may also originate from small distributed production units that are incorporated in consumption locations. Finally, the energy made available for the REC to share can come from large autonomous storage units or, similarly to production units, can come from small distributed storage units integrated into production or consumption locations.

### 2.3.4 Allocation (priority) of distribution of production

The allocation of the energy produced to each consumer and the priorities in the repartition process define how the energy is aggregated. Depending on the priorities defined in the REC, three types of production aggregation can be found: total aggregation, aggregation by internal networks, and total disaggregation.

The first option is total aggregation, where the total energy produced is aggregated before the repartition process occurs. This happens when there is no priority in allocating energy to REC members.

The produced energy can also be aggregated by internal networks where the energy produced by a certain production unit is first allocated to the consumers that integrate the same internal network, and if there is a surplus of energy after this first allocation, then the energy that remains is allocated to other members. This is a very interesting solution because it minimizes the possibility of unnecessary use of public networks and the consequence payment of the associated tariffs, which the previous option does not take into account.

Finally, the energy can be totally disaggregated. This happens when is done an individual allocation to each consumer, i.e., the consumer chooses from which production unit wants its allocated energy to come.

Figure 2.3 presents the different priorities that can exist in a REC in terms of repartition.

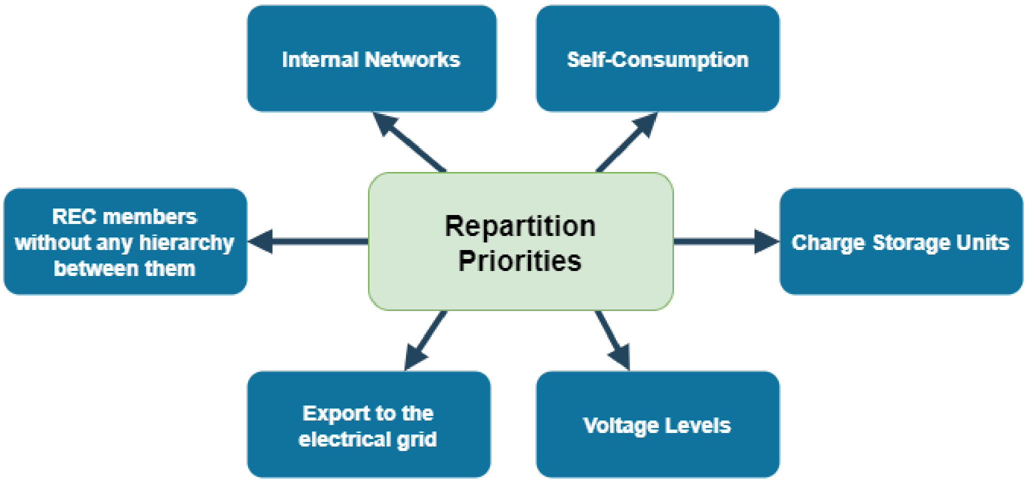


Figure 2.3: Repartition Priorities

The energy produced within the REC can be prioritized to be shared first with the REC members without any type of hierarchy between them, meaning that no member has priority over another when the repartition process takes place. If there is no hierarchy, the energy production can be totally aggregated and then shared.

Another priority that can be implemented is to organize the sharing of energy by internal networks. In this case, the members that belong to the same internal network where the production or storage unit is located have priority over other members. The energy is first allocated to them, and then the surplus, if there is any, is shared with the rest of the REC. Take as an example the REC structure presented in figure 2.4, where the REC is constituted by two internal networks connected through the public grid. In this case, if it is chosen allocation by internal networks, the energy produced on the rooftop of building 1 is firstly shared with the households belonging to that building and the same happens in building 2. Only after, if there is any, is shared the surplus with the rest of the members.

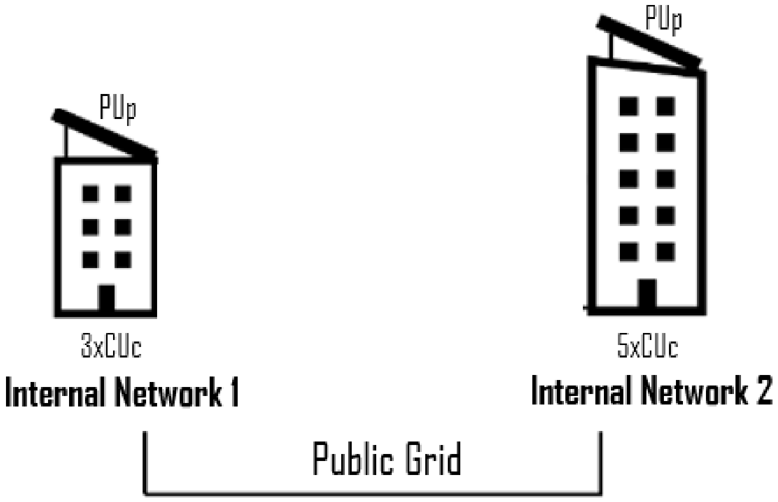


Figure 2.4: REC constituted by two internal networks. Adapted from [24].

Additionally, if a REC member owns its production unit, it can have priority to meet its energy needs first, through self-consumption, and only after, share with the rest of the REC the surplus to be repartitioned.

Furthermore, the energy produced can be prioritized to charge storage units owned by the REC. Note that this prioritization to charge the storage units depends on the strategy chosen for managing these units. Important to note that nothing prohibits charging the storage units with energy from the grid instead of using energy produced within the REC.

The repartition can also prioritize the allocation of energy by voltage levels. This type of priority is mostly considered by the entities responsible for the power flow management in the REC. Prioritizing the allocation of energy by voltage levels may prevent unnecessary inversion of power flows, leading to better and more efficient management.

Finally, another option for prioritization can be to export energy to the grid when market prices are high. Assuming that the REC consumers have a fixed cost for the energy consumed and the origin of that energy is irrelevant, the CME can decide to sell the REC energy directly to the grid in exchange for financial profits. It is important to emphasize that this latest type of prioritization is only a suggestion. The European directive [1] does not allow the constitution of REC with the goal of financial profits. However, no physical impediment would prevent this from being accomplished.

### 2.3.5 Repartition coefficients

The repartition algorithms are defined by the repartition coefficients used in them. The literature involving the repartition coefficients used in the algorithms for energy allocation in RECs is quite superficial, leaving much room for improvement [25]. This subsection presents some of the most common and introduces possible new ones.

The repartition algorithms can be divided into two groups: fixed and dynamic repartition coefficients [25, 26]. In both cases, the coefficients define how much energy production is allocated to each consumer.

Figure 2.5 presents the various types of repartition coefficients that are considered interesting to be explored within the scope of this dissertation.

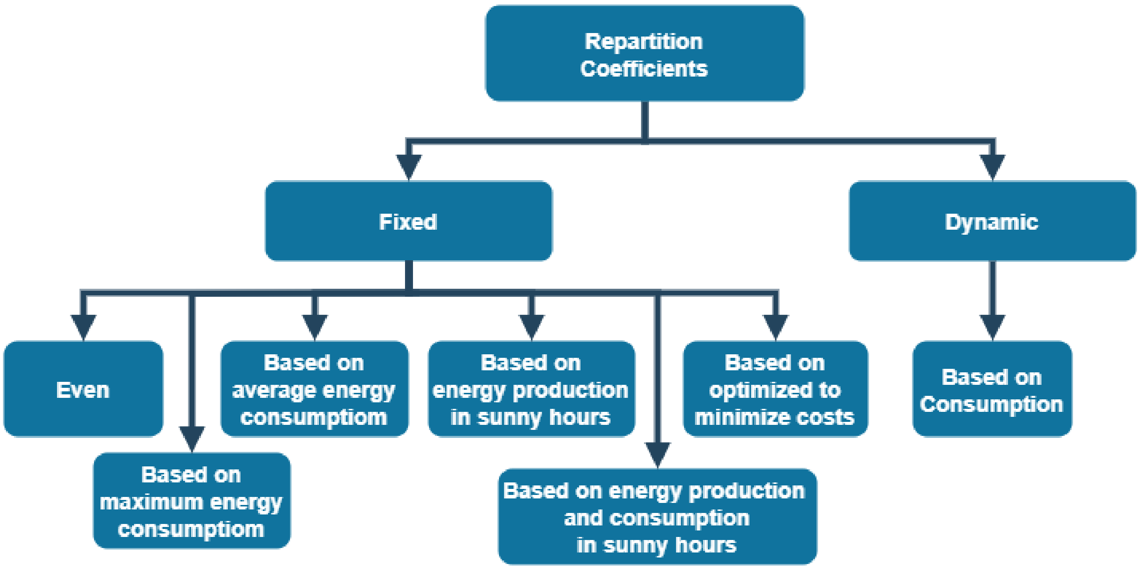


Figure 2.5: Repartition Coefficients.

The repartition of energy produced in a REC happens in a specified time frame, for example, every 15 minutes. Fixed coefficients are values that remain the same throughout the repartition process, meaning that in every 15-minute interval, the coefficient assigned to a consumer is the same [26]. This kind of coefficient may be affected by different variables. The consumers may have their coefficient assigned based on the number of members where all received the same energy (even coefficients), based on maximum energy consumption from the consumers, based on the average consumption of the consumers, based on the energy produced in the REC in sunny hours, based on the energy produced and consumed in sunny hours or optimize coefficients to reduce costs [27]. Although they are referred to as fixed coefficients, they can be updated at a constant rate, such as daily, monthly, or annual, depending on the rules set by the CME or if REC composition changes with the addition of new members (producers or consumers).

The dynamic coefficients differ from the fixed coefficients in that they can be updated at each repartition moment, and, right now, the dynamic coefficients are based on consumption [26]. Therefore, the coefficients based on consumption are dynamic coefficients because they change every time the repartition occurs, such as in 15-minute time periods.

### 2.3.6 Repartition algorithms in Portugal

According to Portuguese legislation, the repartition of energy can occur in the following ways [2, Art. 87]:

a) In fixed coefficients differentiated, among others, by working days and holidays or weekends that may or may not take into account the seasons of the year;

b) In variable coefficients defined based on criteria, in the hierarchy, in the consumption measured in each period in the time period defined in the ERSE regulations;

c) In the combination of any of the modalities referred to in the previous paragraphs under the terms of ERSE regulations.

Therefore, in Portugal, the two types of repartition algorithms previously mentioned, repartition algorithms through fixed or dynamic coefficients, may be implemented [28].

## 2.4 Conclusive summary of the State of the Art

In section 2.1 was done a review of EU legislation on RECs, namely Directive (EU) 2001/2018 which introduced this concept as one of the solutions to promote the use of energy from renewable sources having in mind the target set by the Union where the Member States shall collectively ensure that the share of energy from renewable sources in the Union's gross final consumption of energy in 2030 is at least 32%. It was also found that, even though the mentioned directive was approved in 2018, several EU still did not have in place legislation and regulation for RECs in their national laws. Looking particularly at Portuguese legislation and regulation, RECs have had a legal framework since 2019, with a recent update in Decree-Law No. 15/2022 from 2022.

In section 2.2, after conducting a review of business models for RECs it was concluded that this issue was not well defined in the existing literature. So, it was considered that the better approach for this dissertation was to propose its own business models, considering the scarce amount of information available. The business models proposed some are new and others present slight differences from some existing ones.

Finally, in section 2.3 are presented the different aspects that influence the repartition algorithms such as the dynamic of the repartition process, the temporal granularity and information update of the repartition, production characteristics, priorities in the distribution process and the repartition coefficients. Once more, the amount of information regarding this subject was quite low.

# Chapter 3

# Repartition Algorithms

This chapter presents the methodology followed in the study of repartition algorithms in renewable energy communities, and that pretends to answer the research questions raised.

Initially, some technical assumptions considered in the methodology followed are detailed.

Next, is explained the methodology followed and to be applied in the case study. This concerns the way the different coefficients were obtained and applied in the repartition algorithms is described in detail.

The calculation tool developed to implement this methodology was Microsoft Excel, with a resort to several of its functionalities, namely the integrated optimization tool, Solver.

## 3.1 Technical assumptions adopted for the case study

The study and analysis of different repartition models are based on some technical assumptions that are important to state for the understanding of the methodology presented in the following sections.

First, it is assumed that the available consumption and production data are in 15-minute intervals and for a period of one year, and the consumers for which the energy produced will be allocated are all in LV as well as the production units. Furthermore, the repartition algorithms implemented assume that all energy production of the REC members is aggregated, and only then does the distribution according to the different models start. The goal of the algorithm is always to try to allocate the most possible energy produced within the REC.

The repartition coefficients obtained are based on historical data, that is, they are extrapolated from past production and consumption data. Also, their application will be on the data from which they were obtained to test the different repartition algorithms.

After these conditions are met, the repartition algorithm is similar for all types of coefficients. In effect, the repartition algorithms studied follow a similar energy distribution algorithm based on coefficients, where these coefficients define the percentage of the REC energy production that is allocated to each consumer. In this way, each repartition algorithm studied differs in the way these coefficients are affected by different variables.

Finally, even though this dissertation has as one of its purposes the fact that the different repartition algorithms can be applied in different countries with different legislations, in order to carry out an economic evaluation of each algorithm, the electricity bill was calculated based on the energy tariffs applied in the Portuguese legislation. Also, the cost of installing the PV was not taken into account when evaluating the repartition algorithms.

## 3.2 Implementation of the repartition algorithm

The different repartition algorithms implemented are quite similar and based on the flowchart shown in figure 3.1. In fact, for the different algorithms, the change is in the definition of the repartition coefficients that are associated with different variables.

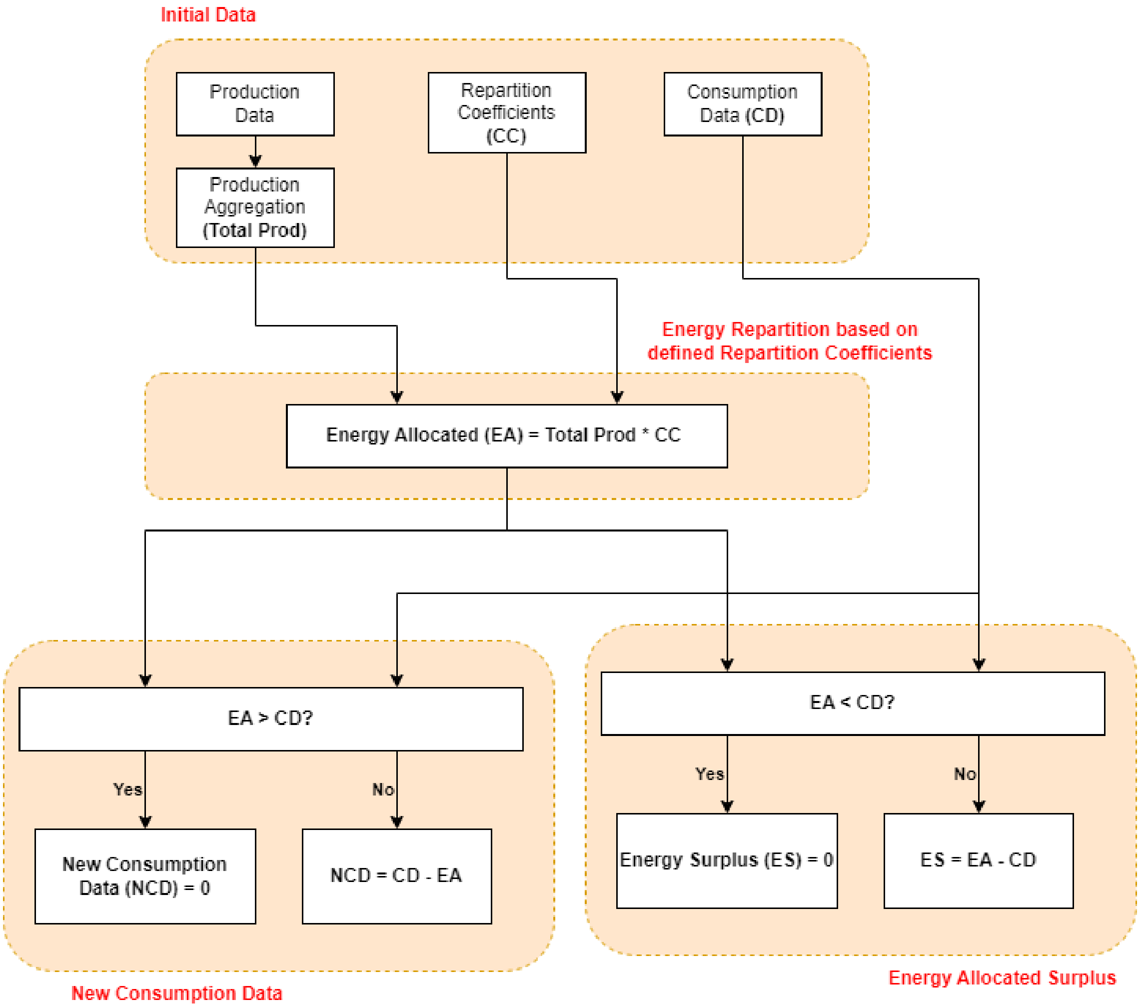


Figure 3.1: Repartition algorithm implemented.

Analyzing the flowchart in more detail, one can observe that the initial data comprises three elements: production data, consumption data, and the definition of the repartition coefficients. Next, the aggregation of production is performed.

Then, with these data available, the distribution process begins, where the coefficients assigned for a given consumer are multiplied by the production of the REC.

Finally, two verifications are carried out: one to determine the new consumption of a given consumer after the allocation of distributed energy and the other to determine the excess energy that might have been allocated. In the first verification, if the initial consumption is greater than the allocated energy, the new consumption value becomes the difference between the initial consumption and the allocated energy, and if the opposite occurs, that is, the allocated energy is greater than the consumption, the new consumption value is zero. In the second verification, if the energy allocated is greater than the consumption, the excess energy will be the difference between the energy allocated and the consumption, and zero otherwise. Note that the consumption per satisfy will be supplied by the electrical grid.

## 3.3 Repartition through coefficients indexed to different variables

In this dissertation, the coefficients considered for the studies performed are of two types, fixed and dynamic. It is important to emphasize again that the fixed coefficients come from the fact that they remain the same for a certain period of time, while the dynamic ones are constantly updated for each energy repartition moment.

Putting these two types of coefficients in mathematical terms, for the case of fixed repartition coefficients, we have that the energy allocated in the repartition process is given by the expression 3.1. On the other hand, the dynamic repartition process based on consumer consumption is given by the mathematical expression 3.2. It should be noted that in both cases, the application of these expressions results in the allocation, to a given consumer, of a percentage of the total energy produced by the REC in the period where the repartition happens.

$$EA_{C,i} = CC_i \cdot E_{Prod} \tag{3.1}$$

Where:

$EA_{C,i}$ - Energy Allocated to Consumer $i$;

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$E_{Prod}$ - Total Energy Produced in the REC.

$$EA_{C,i} = \frac{E_{C_i}}{\sum_{i=1}^{N_c} E_{C_i}} \cdot E_{Prod} \tag{3.2}$$

Where:

$EA_{C,i}$ - Energy Allocated to Consumer $i$;

$E_{C_i}$ - Energy consumed by Consumer $i$;

$E_{Prod}$ - Total Energy Produced in the REC;

$N_c$ - Total number of consumers.

In order to study different repartition algorithms, eight different coefficients were tested to conclude which one would be the best, in economic terms, for the individual consumers and the community as a whole. Of these eight types of coefficients, seven are fixed coefficients, and one is a dynamic consumption-based coefficient. Thus, the following fixed coefficients were analyzed:

- Even;
- Proportional to annual maximum energy consumption;
- Proportional to annual average energy consumption;
- Proportional to energy production in sunny hours;
- Proportional to energy production and consumption in sunny hours;
- Optimized coefficients to minimize total costs;
- Optimized coefficients indexed to hourly periods to minimize total costs.

In terms of dynamic coefficients, we have one being consumption-based coefficients.

Below are the mathematical expressions to obtain the consumer coefficients that allow these different repartition algorithms. It is important to highlight that, as already mentioned, these expressions assume that consumption and production data are available at 15-minute intervals for a period of one year.

### 3.3.1 Repartition through even coefficients

The first algorithm analyzed is based on even coefficients. The consumer coefficients in this case, as the name suggests, are the same for all consumers in the REC and are obtained by expression 3.3.

$$CC_i = \frac{1}{N_c} \tag{3.3}$$

Where:

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

### 3.3.2 Repartition through coefficients proportional to the annual maximum energy consumption

The second repartition algorithm is based on the maximum consumption energy of each consumer belonging to the REC. Thus, initially, the maximum consumption value of each consumer among all 15-minute periods is identified. Next, the consumer coefficient is obtained by normalizing the maximum consumption of a given consumer relative to the maximum individual consumption of the total of consumers as shown in equation 3.4.

$$CC_i = \frac{E^{15min}_{C_i,max}}{\sum\limits_{i=1}^{N_c} E^{15min}_{C_i,max}} \tag{3.4}$$

Where:

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$E^{15min}_{C_i,max}$ - Maximum energy consumed among the 15-minute intervals in one year by Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

### 3.3.3 Repartition through coefficients proportional to annual average energy consumption

This repartition algorithm is based on the average energy consumed over a year. First, the average value is obtained using expression 3.5. The consumer coefficient is obtained by normalizing the average consumption of a given consumer relative to the average individual consumption of the total of consumers, as presented by 3.6.

$$E_{C_i,ave} = \frac{\sum\limits_{j=1}^{N} E^{15min,j}_{C_i}}{N} \tag{3.5}$$

$$CC_i = \frac{E_{C_i,ave}}{\sum\limits_{i=1}^{N_c} E_{C_i,ave}} \tag{3.6}$$

Where:

$E_{C_i,ave}$ - Average energy consumption throughout a year by Consumer $i$;

$E^{15min,j}_{C_i}$ - Energy consumption in each 15-minute interval by Consumer $i$;

$N$ - Number of 15-minute intervals;

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

### 3.3.4 Repartition through coefficients proportional to energy production in sunny hours

This repartition algorithm is based on an energy distribution that considers the individual consumption of each consumer during the hours of sunshine, that is to say, the hours when there is energy production by the REC power plants. The objective of this algorithm is to proportionally distribute the energy produced to the consumers who consume the most during this period. Initially, the production factor is determined, which is a representative indicator of the percentage of production in a 15-minute interval in relation to the maximum that the power plants could be producing, as shown in equation 3.7. The consumer coefficient is obtained by multiplying the production factor by the consumption in each 15-minute interval and dividing by the sum of the result obtained by performing the same procedure as in the numerator for the total of consumers as shown in expression 3.8.

$$\beta_{15min} = \frac{E^{15min}_{Prod}}{E^{15min}_{Prod,Max}} \tag{3.7}$$

$$CC_i = \frac{\sum\limits_{j=1}^{N} \beta \cdot E^{15min,j}_{C_i}}{\sum\limits_{i=1}^{N_c}\sum\limits_{j=1}^{N} \beta \cdot E^{15min,j}_{C_i}} \tag{3.8}$$

$\beta_{15min}$ - Production factor for a 15 minute interval;

$E^{15min}_{Prod}$ - Energy production in a 15 minute interval;

$E^{15min}_{Prod,Max}$ - Maximum energy that could be produced in a 15-minute interval;

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N$ - Number of 15-minute intervals;

$E^{15min,j}_{C_i}$ - Energy consumption in each 15-minute interval by Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

### 3.3.5 Repartition through coefficients proportional to energy production and consumption in sunny hours

The repartition algorithm based on coefficients proportional to production and consumption in sunny hours is quite similar to the previous one but now includes a consumption factor. Like the previous one, it starts by calculating the production factor as indicated by the expression 3.7. Next, the consumption factor is calculated using the equation 3.9, which checks what percentage of consumption a given consumer has in relation to the total consumption in a 15-minute interval. Then the sum of the product between these two factors is calculated for each 15-minute interval divided by the sum of the production factor, expression 3.10. The coefficient for a given consumer is obtained by normalizing the value obtained by the previous expression for the total of all consumers as shown by equation 3.11.

$$\alpha_i^{15min} = \frac{E_{C_i}^{15min}}{\sum\limits_{i=1}^{N_c} E_{C_i}^{15min}} \tag{3.9}$$

$$\gamma_i = \frac{\sum\limits_{j=1}^{N} \beta_{15min,j} \cdot \alpha_i^{15min,j}}{\sum\limits_{j=1}^{N} \beta_{15min,j}} \tag{3.10}$$

$$CC_i = \frac{\gamma_i}{\sum\limits_{i=1}^{N_c} \gamma_i} \tag{3.11}$$

Where:

$\alpha_i^{15min}$ - Consumption factor for a 15-minute interval for Consumer $i$;

$E_{C_i}^{15min}$ - Energy consumption in each 15-minute interval by Consumer $i$;

$\beta_{15min,j}$ - Production factor for a 15-minute interval;

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N$ - Number of 15-minute intervals;

$N_c$ - Total number of consumers belonging to the REC;

### 3.3.6 Repartition through optimized coefficients to minimize total cost

This algorithm differs from those previously presented in that the consumer repartition coefficients result from solving the optimization problem shown below.

- **Decision Variables**

$$CC_1, CC_2, \ldots, CC_{Nc}$$

- **Objective Function**

$$\min \quad \text{Total Cost} = \text{Electricity Bill From REC} + \text{Electricity Bill From Supplier}$$

- **Constrains**

$$CC_i \geq 0 \tag{3.12}$$

$$\sum_{i=1}^{N_c} CC_i = 1 \tag{3.13}$$

Where:

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

The decision variables, which are the target of optimization, are the consumer repartition coefficients. The objective function is to minimize the total cost of the electricity bill for the set of consumers. Note that the decision variables do not appear directly in the objective function. However, this function comprises two parts: the community's electricity bill and the supplier's electricity bill. The first depends directly on the energy distributed among the community's consumers, therefore depending on the decision variables, that is, the consumer repartition coefficients. The way of calculating the community and supplier electricity bills is demonstrated in section 3.6. Finally, the solution of the optimization problem is subject to the constraints, 3.12 and 3.13, where the first defines that the coefficients must take a non-negative value and the second ensures that the sum of all coefficients is equal to one.

### 3.3.7 Repartition through optimized coefficients indexed to hourly periods to minimize total costs

This algorithm is similar to the one presented in the previous subsection in that the consumer coefficients are also the result of solving an optimization problem. However, in this case, each consumer has an associated coefficient for the different hourly periods of the energy tariffs. Thus, instead of optimizing one coefficient per consumer, a matrix of coefficients is optimized as shown in table 3.1. Note that hourly periods use Portuguese terms. In section 3.6 it is explained what each one refers to.

- **Decision Variables**

Table 3.1: Coefficients Matrix to Optimize.

|  | **Consumers** |  |  |  |
|---|---|---|---|---|
| **Hourly Periods** | **$C_1$** | **$C_2$** | **...** | **$C_{Nc}$** |
| ***Super Vazio*** | $CC_{1,SV}$ | $CC_{2,SV}$ | ... | $CC_{Nc,SV}$ |
| ***Vazio*** | $CC_{1,V}$ | $CC_{2,V}$ | ... | $CC_{Nc,V}$ |
| ***Cheia*** | $CC_{1,C}$ | $CC_{2,C}$ | ... | $CC_{Nc,C}$ |
| ***Ponta*** | $CC_{1,P}$ | $CC_{2,P}$ | ... | $CC_{Nc,P}$ |

- **Objective Function**

$$\min \quad \text{Total Costs} = \text{Electricity Bill From REC} + \text{Electricity Bill From Supplier}$$

- **Constrains**

$$CC_i \geq 0 \tag{3.14}$$

$$\sum_{i=1}^{N_c} CC_i = 1 \tag{3.15}$$

Where:

$CC_i$ - Consumer Coefficient assigned to Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

In terms of the objective function and constraints to which the solutions of the optimization problem are subject, the same statements as in the previous optimization problem apply here as well.

### 3.3.8 Repartition through coefficients proportional to consumption

The last repartition algorithm is simply based on the consumers' consumption, with the particularity that the coefficients, unlike those presented above, are updated at each energy repartition moment, that is, in this case, every 15 minutes. The way to obtain the consumer coefficient for a given 15-minute interval is simply to divide the consumption of a consumer in that interval by the consumption of all consumers. The mathematical expression for obtaining the coefficients is given by 3.16.

$$CC_i^{15min} = \frac{E_{C_i}^{15min}}{\sum_{i=1}^{N_c} E_{C_i}^{15min}} \tag{3.16}$$

Where:

$CC_i^{15min}$ - Consumer Coefficient assigned to Consumer $i$ for a 15-minute interval;

$E_{C_i}^{15min}$ - Energy consumption in a 15-minute interval by Consumer $i$;

$N_c$ - Total number of consumers belonging to the REC;

## 3.4 Repartition through coefficients that change monthly

In order to find out the influence of the possibility of changing the consumer repartition coefficients in a shorter time period than a year, a methodology was developed in which the coefficients are updated on a monthly basis. This study, where the coefficients change monthly, is similar to that presented in section 3.3. In fact, the only relevant change to mention is that, in the mathematical expressions presented above, the consumer repartition coefficients are determined from 15-minute data each month instead of the 15-minute data at the end of the year.

## 3.5 Repartition through coefficients where the data is aggregated by months and hourly periods

To investigate the necessity or not of using smartmeters to measure every 15 minutes the production and consumption in a REC, a study was conducted in which consumption and production data are aggregated by monthly and hourly tariff periods. Thus, it is possible to conclude whether a repartition only at the end of each month using a meter that measures energy consumed by hourly tariff periods is feasible or whether the current solution where the repartition is done every 15 minutes using smartmeters is the best. The previous expressions for different repartition coefficients still apply here, the only difference being that the data is not in 15-minute intervals.

## 3.6 Electricity bill calculation for the repartition algorithm

After applying the different repartition algorithms, the electricity bill was calculated for each individual consumer, for the community, and for the community management entity. The electricity bills were calculated taking into account tariffs in force in Portugal.

To calculate the bills, it is necessary to consider energy prices according to the tariffs in force. These vary according to legal time periods, winter time and summer time, quarterly periods (I, II, III, IV), and hourly periods (*Super Vazio*, *Vazio*, *Cheia* and *Ponta*). Note that the hourly periods are in Portuguese. These will be the terms used in the dissertation. Translating to English these terms mean super off-peak hours, off-peak hours, flood hours, and peak hours, respectively. Consumers in Special Low Voltage (SLV) have the possibility to choose whether they want the daily cycle or the weekly cycle. The structure of each one is present in appendix C.

The consumers' electricity bill, as mentioned above, is composed of two parts: the community's electricity bill and the supplier's electricity bill. The first concerns the payment for REC energy that is shared among the consumers, and the second concerns the payment for the energy provided by the supplier to consumers to meet their energy needs when the energy shared by the community is not enough.

The community's electricity bill comprises two major portions: the price of energy sold by the community and the network access tariff for self-consumption through the public network. Acceptable values for the sale of energy by the CME to consumers could be between 0,05€/kWh and 0,15€/kWh. For the case study later analyzed, the sale of energy by the CME to consumers was fixed at 0,10€/kWh. Regarding the network access tariffs, these are composed of a power tariff at peak hours and an active energy tariff.

These costs associated with the NAT can differ if an exemption from the payment of CIEG is applied or not. Appendix B contains the tabulated values for this situation, but since this is the specific case where the generation facilities are in LV, and the customers are in SLV, the tabulated values are compiled in tables 3.2 and 3.3. It is important to highlight that these are the tabulated values for 2021. The decision was made to use the tabulated values for that year since the tabulated values for 2022 and 2023 take a negative value. This trend is expected to be temporary, and, as such, it was considered more interesting for this study to use the tariffs from the most recent year when they were positive.

Table 3.2: Network Acess Tariff for Self-Consumption through the Public Network - Without CIEG Exemption for 2021. Source: [29].

| TARIFA DE ACESSO ÀS REDES DO AUTOCONSUMO ATRAVÉS DA RESP - SEM ISENÇÃO DE CIEG | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Níveis de tensão e opções tarifárias da IU | Níveis de tensão da UPAC | Potência em horas de ponta | | Energia ativa (EUR/kWh) | | | | | | | |
| | | | | Períodos I e IV | | | | Períodos II e III | | | |
| | | [EUR /(kW.mês)] | [EUR /(kW.dia)]* | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio |
| BTE | BT | 6,65 | 0,2186 | 0,0866 | 0,0559 | 0,0184 | 0,0169 | 0,0862 | 0,0556 | 0,0182 | 0,0169 |

Table 3.3: Network Acess Tariff for Self-Consumption through the Public Network - With 100% CIEG Exemption for 2021. Source: [29]

| TARIFA DE ACESSO ÀS REDES DO AUTOCONSUMO ATRAVÉS DA RESP - ISENÇÃO 100% DE CIEG | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Níveis de tensão e opções tarifárias da IU | Níveis de tensão da UPAC | Potência em horas de ponta | | Energia ativa (EUR/kWh) | | | | | | | |
| | | | | Períodos I e IV | | | | Períodos II e III | | | |
| | | [EUR /(kW.mês)] | [EUR /(kW.dia)]* | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio |
| BTE | BT | 6,65 | 0,2186 | 0,0092 | 0,0082 | 0,0069 | 0,0054 | 0,0088 | 0,0079 | 0,0067 | 0,0054 |

The electricity bill for grid-sourced power comprises three components: an energy tariff, a contracted power tariff, and a peak-hour power tariff. These values are tabulated and are shown in table 3.4 for the year 2022.

Table 3.4: Transitory Sales Tariff to End Costumers in SLV for 2022. Source: [30].

| **TARIFA TRANSITÓRIA DE VENDA A CLIENTES FINAIS EM BTE** | | | **PREÇOS** | |
|---|---|---|---|---|
| | | | | |
| **Termo tarifário fixo** | | | **(EUR/mês)** | **(EUR/dia) *** |
| | | | 22,89 | 0,7525 |
| **Potência** | | | **(EUR/kW.mês)** | **(EUR/kW.dia) *** |
| Tarifa de médias utilizações | | Horas de ponta | 15,374 | 0,5054 |
| | | Contratada | 0,797 | 0,0262 |
| Tarifa de longas utilizações | | Horas de ponta | 20,514 | 0,6744 |
| | | Contratada | 1,503 | 0,0494 |
| **Energia ativa** | | | **(EUR/kWh)** | |
| Tarifa de médias utilizações | Períodos I, IV | Horas de ponta | 0,2072 | |
| | | Horas cheias | 0,1297 | |
| | | Horas de vazio normal | 0,0847 | |
| | | Horas de super vazio | 0,0736 | |
| | Períodos II, III | Horas de ponta | 0,2062 | |
| | | Horas cheias | 0,1267 | |
| | | Horas de vazio normal | 0,0842 | |
| | | Horas de super vazio | 0,0742 | |
| Tarifa de longas utilizações | Períodos I, IV | Horas de ponta | 0,1599 | |
| | | Horas cheias | 0,1263 | |
| | | Horas de vazio normal | 0,0808 | |
| | | Horas de super vazio | 0,0697 | |
| | Períodos II, III | Horas de ponta | 0,1583 | |
| | | Horas cheias | 0,1251 | |
| | | Horas de vazio normal | 0,0793 | |
| | | Horas de super vazio | 0,0710 | |
| **Energia reativa** | | | **(EUR/kvarh)** | |
| | | Indutiva | 0,0318 | |
| | | Capacitiva | 0,0243 | |

As already indicated, the final bill for each consumer is given by the sum of the two resulting electricity bills.

It is important to analyze the price of the energy for the different repartition algorithms. The price of electricity of the energy, in €/kWh, coming from the REC, from the grid, and as a whole is given by 3.17, 3.18 and 3.19, respectively.

$$\text{REC Energy Price}_{\text{€/kWh}} = \frac{\text{Electrical Bill from REC Energy}}{\text{Energy from REC}} \tag{3.17}$$

$$\text{Supplier Energy Price}_{\text{€/kWh}} = \frac{\text{Electrical Bill from Energy Supplier}}{\text{Energy from Supplier}} \tag{3.18}$$

$$\text{Total}_{\text{€/kWh}} = \frac{\text{Total Electrical Bill}}{\text{Total Energy Consumption}} \tag{3.19}$$

Finally, in terms of profits for the CME, it is considered that these can have two origins: the sale of the energy produced in the REC to the consumers, which, as mentioned, was fixed at 0,10€/kWh, and the sale of surplus energy after the repartition process whose price was fixed at 0,05€/kWh. The sum of these parcels dictates the profit of the CME. It also considered that the cost of energy production by the REC was null.

# Chapter 4

# Simulation of Repartition Models

This chapter presents a case study where the methodology described in the previous chapter is applied in order to draw conclusions that allow answering the research questions that this dissertation proposes to answer.

Initially, the characteristics of the case study in terms of production data, consumption data, and consumer characteristics are detailed.

Next, the results of the application of different repartition algorithms are presented, as well as the conclusions that can be drawn.

Finally, it is presented the evaluation of the repartition through coefficients that change monthly, the repartition that happens only at the end of the month as well the influence of exemption of CIEG payment.

## 4.1 Characterization of the case study

The case study analyzed represents an energy community composed of four consumers and four producers for a total of eight members belonging to the REC. The data was extracted from [13]. It is considered that all energy flows between the production and consumption facilities occur through the use of the public electrical grid.

The four production units belonging to the energy community are producers of solar photovoltaic energy. Overall, they total 239 solar panels and an installed power of 73.3 kWp, and the peak power installed at each plant is detailed in table 4.1.

Table 4.1: Producers' Characteristics.

| Producers | PV Modules Pmax STC (W) | Number of modules | Peak Power Installed (kWp) |
|---|---|---|---|
| P1 | 300 | 33 | 9,9 |
| P2 | 320 | 78 | 25 |
| P3 | 300 | 60 | 18 |
| P4 | 300 | 68 | 20,4 |

Regarding consumption installations, all of them have a contracted power of 41.4kW in the Special Low Voltage regime. It should also be noted that all consumers have tetra-hourly tariffs (*Super Vazio, Vazio, Cheia* and *Ponta*), with consumers C1 and C2 opting for daily cycles and consumers C3 and C4 for weekly cycles. This information is detailed in table 4.2.

Table 4.2: Consumers' Characteristics.

| **Consumers** | **Contrated Power (kVA)** | **Voltage Level and Tariff Option of the Consumption Installation** | **Number of Time Periods** | **Cycle** |
|---|---|---|---|---|
| C1 | 41,4 | SLV | Tetra-Hourly | Daily |
| C2 | 41,4 | SLV | Tetra-Hourly | Daily |
| C3 | 41,4 | SLV | Tetra-Hourly | Weekly |
| C4 | 41,4 | SLV | Tetra-Hourly | Weekly |

## 4.2 Production and consumption data of the case study

The data used to perform the analyses in this dissertation correspond to production and consumption data for a one-year period from September 29, 2020, to September 29, 2021. The production and consumption data were collected in 15-minute intervals, and for each interval, eight measures were available together with timestamps, four referring to production and the other four to consumption. As an example, table 4.3 shows a small fraction of the data used, and table 4.4 the annual production and consumption.

Table 4.3: Production and Consumption Data.

| **Date** | **C1 (kW)** | **C2 (kW)** | **C3 (kW)** | **C4 (kW)** | **P1 (kW)** | **P2 (kW)** | **P3 (kW)** | **P4 (kW)** |
|---|---|---|---|---|---|---|---|---|
| ... | ... | ... | ... | ... | ... | ... | ... | ... |
| 30/9/20 6:00 | 1,6 | 3,2 | 3,2 | 5,6 | 0 | 0 | 0 | 0 |
| 30/9/20 6:15 | 2 | 3,6 | 4,8 | 5,2 | 0 | 0 | 0 | 0 |
| 30/9/20 6:30 | 2,8 | 3,6 | 4,8 | 6 | 0 | 0 | 0 | 0 |
| 30/9/20 6:45 | 1,8 | 4,6 | 10 | 5,8 | 1 | 1 | 0 | 1 |
| 30/9/20 7:00 | 1,6 | 4,4 | 5,6 | 6,4 | 0 | 2 | 2 | 2 |
| 30/9/20 7:15 | 18,6 | 6 | 5,4 | 10,2 | 1 | 4 | 3 | 3 |
| 30/9/20 7:30 | 14 | 4,8 | 8,2 | 16,4 | 2 | 4 | 5 | 4 |
| 30/9/20 7:45 | 3,8 | 5,2 | 7,8 | 10,2 | 1 | 6 | 7 | 5 |
| 30/9/20 8:00 | 9,8 | 6,4 | 5,2 | 7,2 | 3 | 8 | 8 | 6 |
| 30/9/20 8:15 | 16,6 | 7,4 | 5,8 | 5,8 | 3 | 9 | 9 | 7 |
| 30/9/20 8:30 | 11 | 6 | 15,2 | 14,2 | 3 | 10 | 10 | 9 |
| 30/9/20 8:45 | 14,8 | 6 | 15,6 | 17 | 4 | 12 | 10 | 9 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... |

Table 4.4: Annual Production and Consumption.

| | |
|---|---|
| **Production (MWh)** | 106,667 |
| **Consumption (MWh)** | 166,782 |

For a better understanding of the dynamics of the repartition mechanisms to be studied and the draw of conclusions, an initial analysis of the production and consumption profiles is important.

Figure 4.1 presents the average of the different production units throughout the day. Given, as already mentioned, that the production comes from photovoltaic plants, the observable curves are within expectations. Observing figure 4.1, it can be seen that there is energy production between 6h30 and 19h30, with peak production between 10h and 16h.

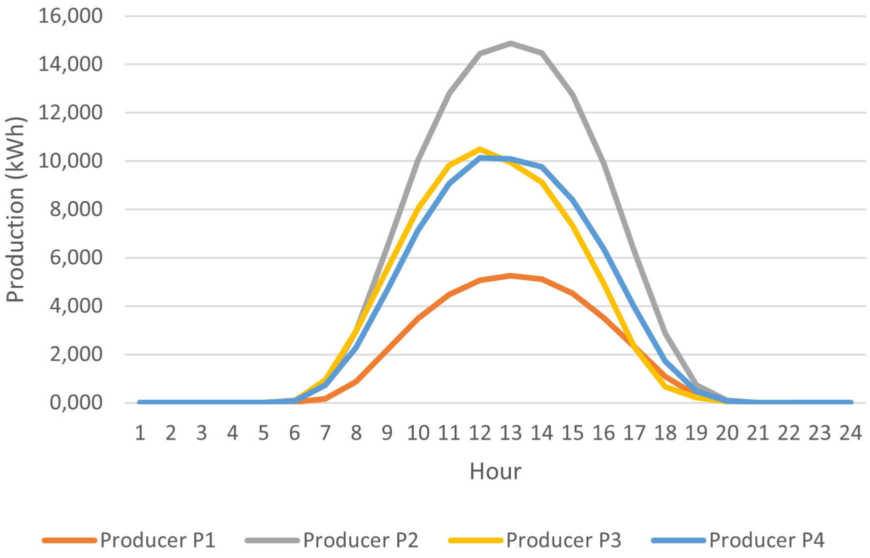


Figure 4.1: Average Hourly Production.

Analyzing now in monthly periods, the production is higher in the months of May, June, July, and August, corresponding to the months of greater solar irradiation. In turn, it can be seen that in the months of November, December, January, and February, the production is lower because it is a period when solar irradiation is lower.

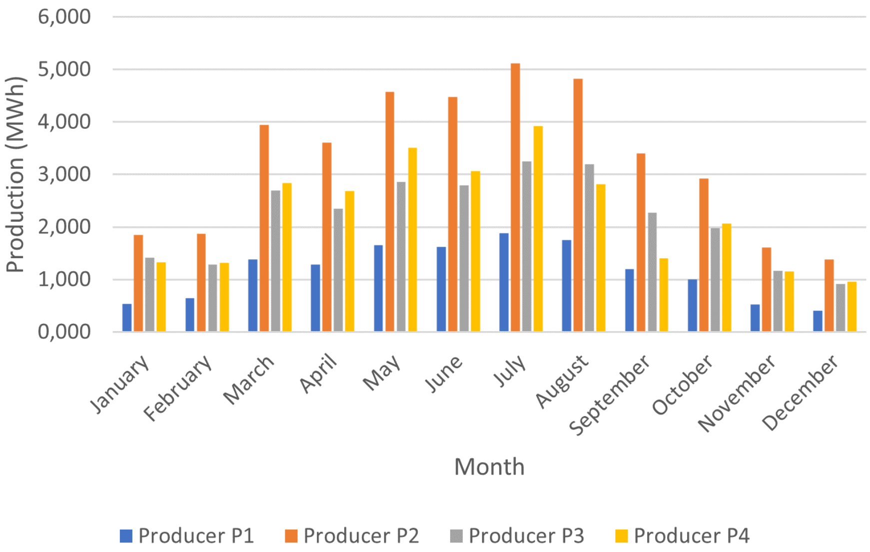


Figure 4.2: Total Monthy Production.

Finally, but very important to analyze, is energy production by hourly period tariffs associated with consumers. Now, in economic terms, higher production in certain hourly periods, when compared to others, can lead to a significant difference in the consumer's electricity bill. Thus, visualizing figure 4.3, it can be seen that most of the energy production occurs in the periods of *Cheia* and *Ponta*, with a very small production in the *Vazio* period, around 5%, and less than 1% in the *Super Vazio* period.

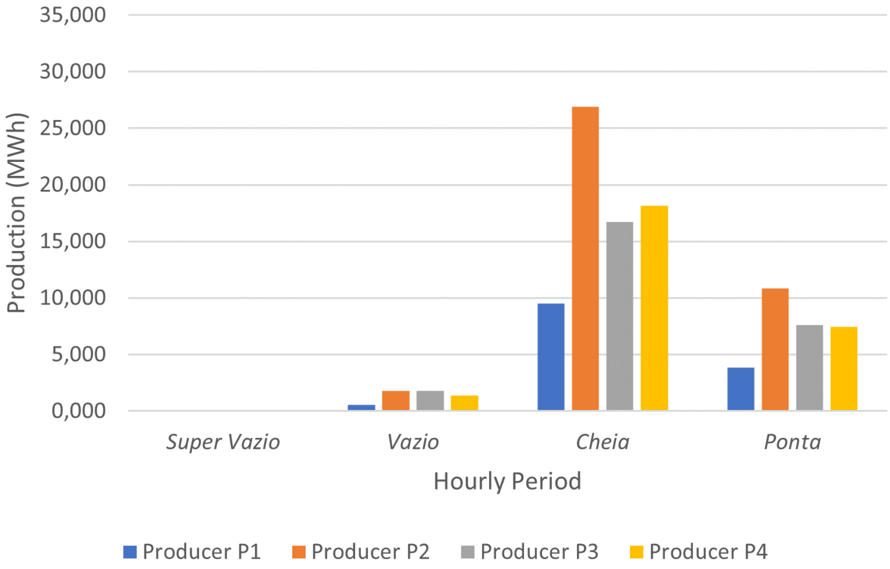


Figure 4.3: Total Annual Production by Hourly Periods.

Similar to what was analyzed for production, it is important to know the consumption profile of the different consumers. Starting with the daily consumption profile, presented in figure 4.4, it is possible to observe two consumption trends. On the one hand, it can be seen that consumer C1 is the one with the highest consumption during the day, coinciding with the hours when there is higher solar production, figure 4.1. On the other hand, the consumption profiles of consumers C2, C3, and C4, although distinct, present a similar trend: a higher consumption during the first and last hours of the day, with the minimum consumption occurring during the midday hours. Thus, unlike consumer C1, the latter have a consumption profile almost antagonistic to that of production.

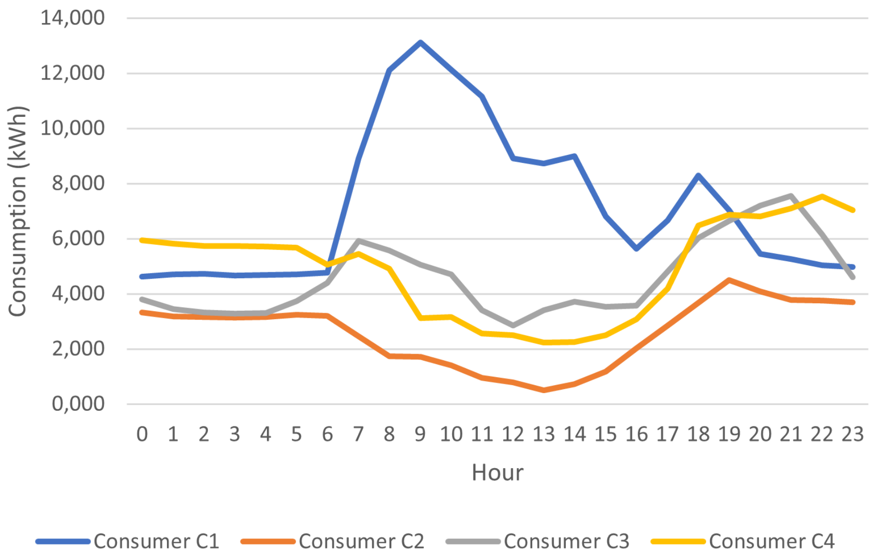


Figure 4.4: Average Hourly Consumption.

Looking at figure 4.5, we can see an opposite trend to that of production, that is, consumption is higher in the winter months and lower in the summer months. Taking a closer look at individual consumptions, it can be seen that consumer C1 is the largest being responsible for 37.3% of the annual consumption of the REC, followed by consumers C3 and C4, which are equivalent to 23.8% and 25.2%, respectively, of the annual consumption of the community. Consumer C2 is the consumer that consumes the least, being responsible for 13.5% of the total annual consumption of the REC.

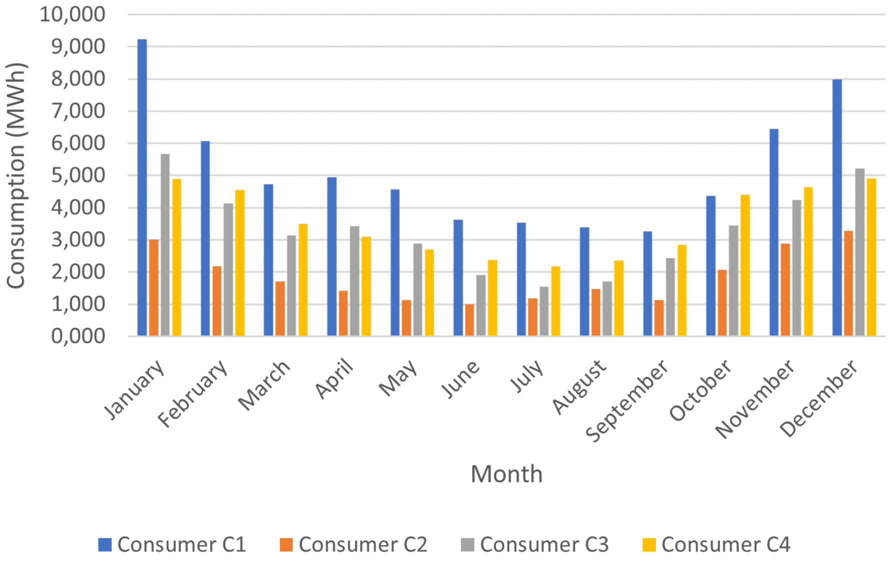


Figure 4.5: Total Monthy Consumption.

Finally, observing figure 4.6, we can see that consumers consume more in the *Cheia* period, followed by the *Vazio* and *Ponta* periods. The *Super Vazio* period is when the lowest consumption is observed. Comparing the graph relative to the consumption of figure 4.6 and the production of figure 4.3, it is clear that in the *Super Vazio* and *Vazio* periods the consumers' consumption needs will have to be satisfied by the grid because REC production is very small.

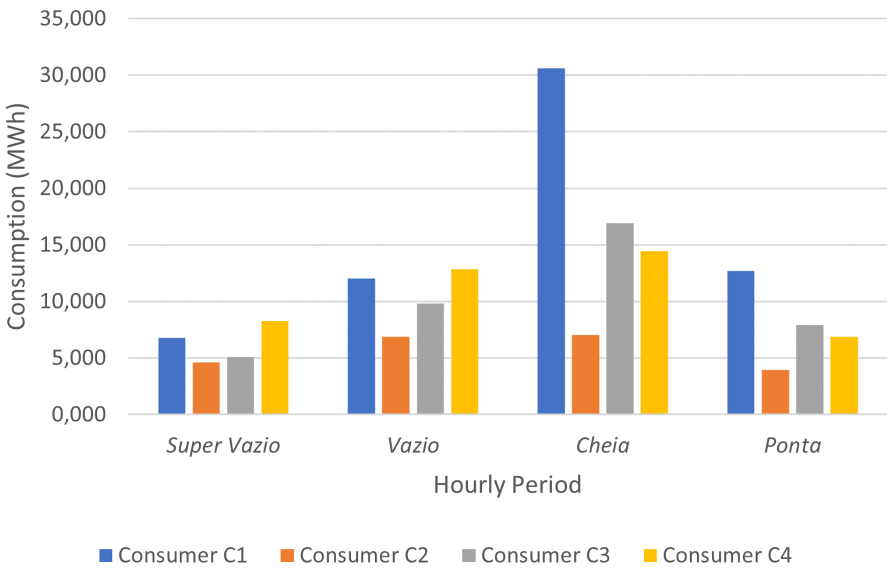


Figure 4.6: Total Consumption by Hourly Periods.

In order to have a benchmark to compare results and verify possible economic savings for consumers after applying each repartition algorithm, the REC electricity bill was calculated before any energy allocation from REC´s production units. It is considered for this case study that the sale of the energy produced in the REC to the consumers is fixed at 0,10 €/kWh, and the sale of surplus energy after the repartition process is fixed at 0,05 €/kWh.

The bill was calculated according to the information set out in section 3.6. Table 4.5 shows the electricity bill composed of two parts: an electricity bill from REC energy and an electricity bill from energy supplier. The first component is divided into two parts: energy component and grid usage, where the energy component refers to the actual cost of the energy that comes from the REC, and grid usage to the cost of using the public grid to receive said energy. The cost for each individual consumer is present in the sub-total line and results from the sum of the mentioned parcels. The total represents the sum of the costs of all consumers.

Note that in this case, consumers will only have one part of the bill, which will be the bill referring to the energy from the grid since none will come from the REC. The electricity bill is shown in table 4.5.

Table 4.5: Consumers' Electricity Bill without REC Energy.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electricity Bill from REC Energy** | **Energy Component** | 0,00 € | 0,00 € | 0,00 € | 0,00 € |
| | **Grid Usage** | 0,00 € | 0,00 € | 0,00 € | 0,00 € |
| **Electricity Bill from Energy Supplier** | | 10 094,41 € | 3 535,42 € | 5 930,68 € | 5 787,37 € |
| **Sub-Total** | | 10 094,41 € | 3 535,42 € | 5 930,68 € | 5 787,37 € |
| **Total** | | 25 347,88 € | | | |

Examining the results from table 4.5, it can be observed that consumer C1 is one that pays the highest bill, followed by consumer C3 and C4, and, lastly, consumer C2, which makes sense given the consumption of each one previously mentioned.

## 4.3 Application of different repartition algorithms for the case study

This section will present the results of applying the different repartition algorithms exposed in the previous chapter. For each, the energy balance, electricity bill amount, and CME's profit are analyzed. It should be noted that, for the calculation of the electricity bill, it was considered that consumers have 100% exemption from CIEG payment.

### 4.3.1 Scenario 1 - Repartition through even coefficients

The first repartition algorithm is based on even coefficients, and since there are four consumers, the resulting repartition coefficients are shown in table 4.6.

Table 4.6: Repartition coefficients for scenario 1.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |

This algorithm distributes a total of 29,50 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 137,28 MWh, coming from the grid. A total of 77,17 MWh of energy produced by the REC is not allocated, being sold to the grid.

Note that although the coefficients are equal, the value of the energy allocated is not the same for all consumers, as can be seen in Figure 4.7. This is due to the fact that, in certain 15-minute intervals, the energy that the consumer should receive is superior to the consumption in those 15 minutes, being then allocated only the value corresponding to the consumption. Consumer C1 is the one that receives more, given that a major part of his consumption happens during hours of energy production, as seen in figures 4.1 and 4.4.

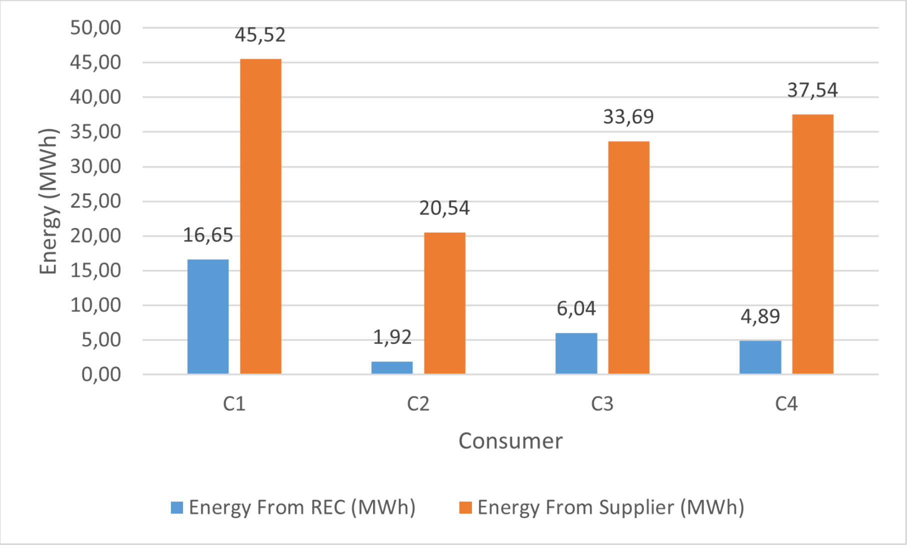


Figure 4.7: Energy Balance resulting from repartition through even coefficients.

This type of repartition coefficient does not consider the weight of each consumer's consumption resulting in the allocation of energy to consumers that do not need it. Figure 4.8 represents the percentage of energy surplus (difference between possible energy allocated and energy consumption) and energy allocated in relation to the possible allocated energy that each consumer had the right to. It can be seen that consumer C1 uses 62% of the possible allocated energy, but consumers C2, C3, and C4 only use 7%, 23%, and 18%, respectively, meaning that most of the energy is sold to the grid instead of being repartitioned. Also important to note that, as previously shown, peak production and peak consumption for consumers C2, C3, and C4 do not coincide.

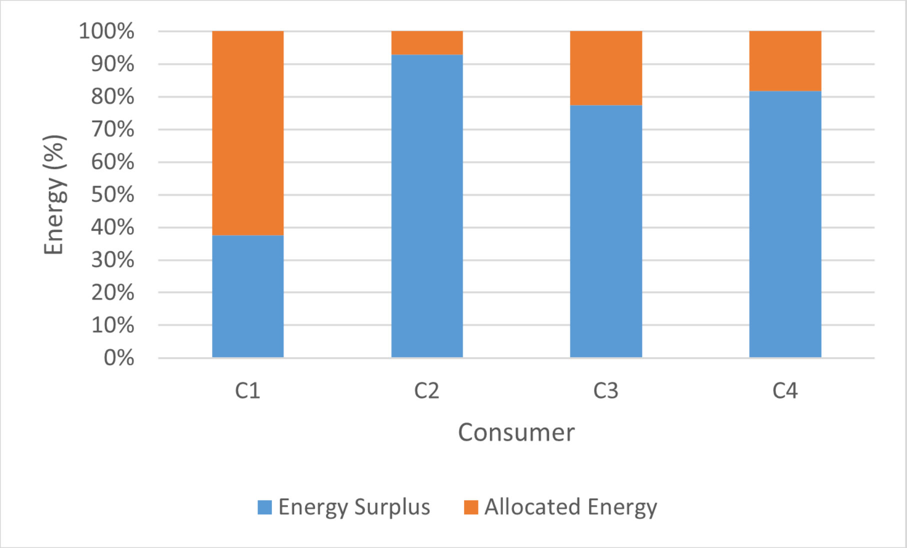


Figure 4.8: Energy surplus for repartition through even coefficients.

Table 4.7 shows the consumers' electricity bill. For consumer C1, the REC bill represents 20% of the final invoice value, while for consumers C2, C3, and C4, it represents 6%, 12%, 10%, respectively, this being a consequence of the quantities of REC energy allocated. In terms of consumer aggregate, there is a saving of 7.3% compared to the value of the electricity bill before the existence of the REC energy, table 4.5.

The profit for the community management entity from selling the REC energy to consumers and selling the excess energy is set at 6 808,35 €, as shown in table 4.8.

Table 4.7: Consumers' electricity bill for repartition through even coefficients.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electricity Bill from REC Energy** | **Energy Component** | 1 664,98 € | 191,97 € | 604,11 € | 488,94 € |
| | **Grid Usage** | 135,82 € | 15,39 € | 48,03 € | 38,70 € |
| **Electricity Bill from Energy Supplier** | | 7 195,49 € | 3 233,83 € | 4 906,31 € | 4 984,23 € |
| **Sub-Total** | | 8 996,29 € | 3 441,19 € | 5 558,44 € | 5 511,86 € |
| **Total** | | 23 507,78 € | | | |

Table 4.8: CME profits for repartition through even coefficients.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 2 950,00 € | 3 858,36 € | 6 808,35 € |

### 4.3.2 Scenario 2 - Repartition through coefficients proportional to the annual maximum energy consumption

The repartition through coefficients proportional to the annual maximum energy consumption results in the repartition coefficients shown in table 4.9. The coefficients were obtained by applying equation 3.4, previously presented. Consumer C1 registers the highest maximum consumption in a 15-minute interval among all consumers, followed by consumers C3, C4, and lastly C2.

Table 4.9: Repartition coefficients for scenario 2.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,3695 | 0,1186 | 0,2915 | 0,2203 |

This algorithm distributes a total of 32,67 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 134,11 MWh, coming from the grid. A total of 74,00 MWh of energy produced by the REC is not allocated, being sold to the grid. Compared to scenario 1, this algorithm allows the distribution of more 3,17 MWh.

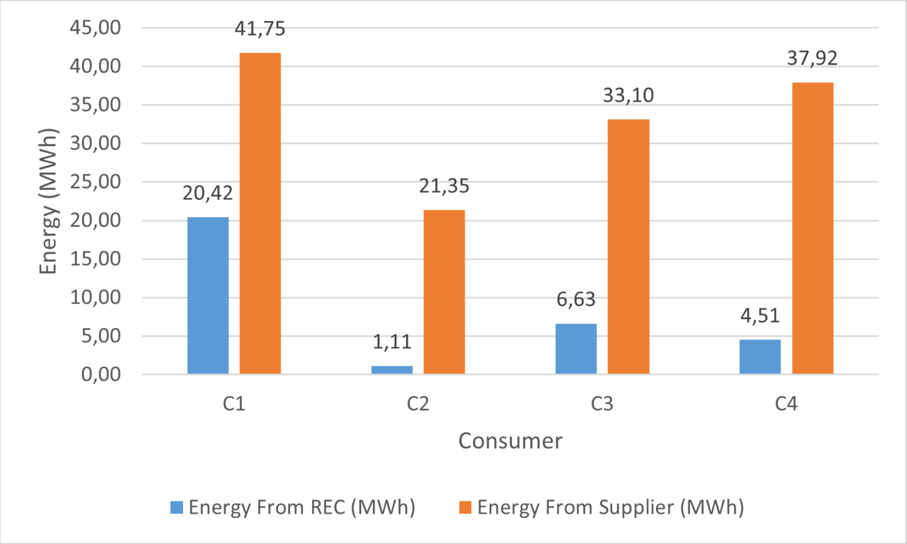


Figure 4.9: Energy Balance resulting from repartition through coefficients proportional to the annual maximum energy consumption.

This type of repartition only makes sense if the maximum energy consumption is representative of the percentage of each consumer's consumption in the aggregate consumption. In this case, consumers C1, C2, C3, and C4 represent 37,3%, 13,5%, 23,8%, and 25,2%, respectively, of the total consumption, as already mentioned. But, as seen in table 4.9, the coefficient for C3 is higher than the coefficient for C4 even though the last has a bigger weight on the percentage of total consumption. Therefore, the success of the application of this type of repartition algorithm is dependent on the premise that the highest maximum consumption represents well the consumption throughout the time period in analyses. If that is not the case, this repartition may not yield good results.

Analyzing the consumers' electricity bill for this scenario, table 4.10, it can be concluded that this repartition results in an 8,0% savings when compared with the bill from the scenario without REC energy, table 4.5. Confronting the results of the CME profit from the current scenario with scenario 1, an increase in the profit is observable. Given that this repartition algorithm managed to allocate slightly more REC energy to the consumers, and the price of energy fixed to sell to consumers is higher than the one fixed to sell to the grid, this yields a higher profit.

Table 4.10: Consumers' electricity bill for repartition through coefficients proportional to the annual maximum energy consumption.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electricity Bill from REC Energy** | **Energy Component** | 1 664,98 € | 191,97 € | 604,11 € | 488,94 € |
| | **Grid Usage** | 135,82 € | 15,39 € | 48,03 € | 38,70 € |
| **Electricity Bill from Energy Supplier** | | 7 195,49 € | 3 233,83 € | 4 906,31 € | 4 984,23 € |
| **Sub-Total** | | 8 996,29 € | 3 441,19 € | 5 558,44 € | 5 511,86 € |
| **Total** | | 23 507,78 € | | | |

Table 4.11: CME profits for repartition through coefficients proportional to the annual maximum energy consumption.

| Energy Sold to Consumers | Sold Energy Surplus | Total |
|---|---|---|
| 3 267,05 € | 3 699,83 € | 6 966,88 € |

### 4.3.3 Scenario 3 - Repartition through coefficients proportional to annual average energy consumption

The repartition through coefficients proportional to annual average energy consumption results in the repartition coefficients shown in table 4.12. The coefficients were obtained by using mathematical expressions 3.5 and 3.6.

Table 4.12: Repartition coefficients for scenario 3.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,3727 | 0,1347 | 0,2382 | 0,2544 |

Observing figure 4.10, it can be seen that this algorithm distributes a total of 32,54 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 134,25 MWh, coming from the grid. A total of 74,13 MWh of energy produced by the REC is not allocated, being sold to the grid.

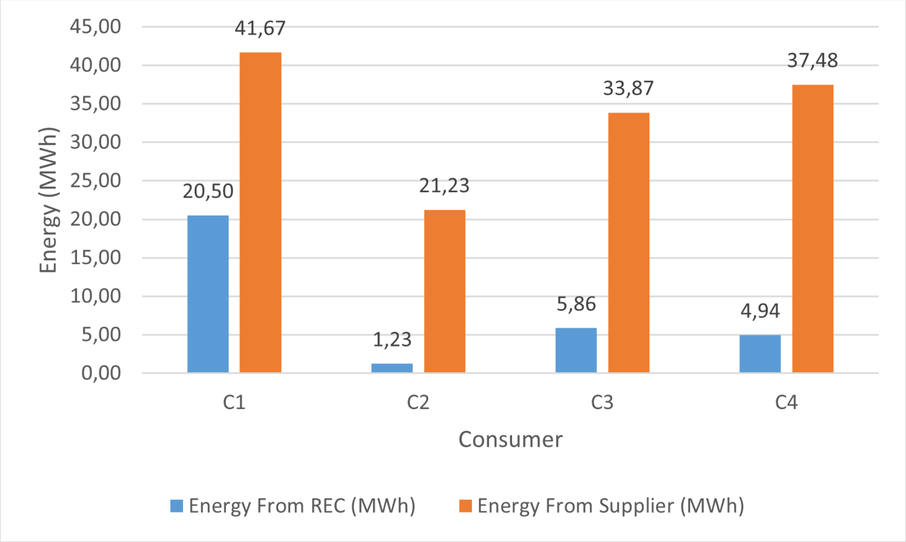


Figure 4.10: Energy Balance resulting from repartition through coefficients proportional to annual average energy consumption.

Compared to scenario 2, this repartition algorithm allocates less energy to consumers, although, at first instance, it would be expected to present better results. Figure 4.11 presents the average hourly consumption before the repartition and the average hourly production. Note that consumption and production have a different Y axis. Looking at this figure, it can be seen that consumers C2, C3, and C4 consume very little during the hours of solar production, C1 being the outcast because it has its peak consumption during those hours. Observing now figure 4.12, it can be concluded that C1 actually sees its consumption significantly reduced after repartition. Therefore, this type of repartition could result in better outcomes in terms of more energy allocated if all consumers presented their peak consumption during solar production hours.

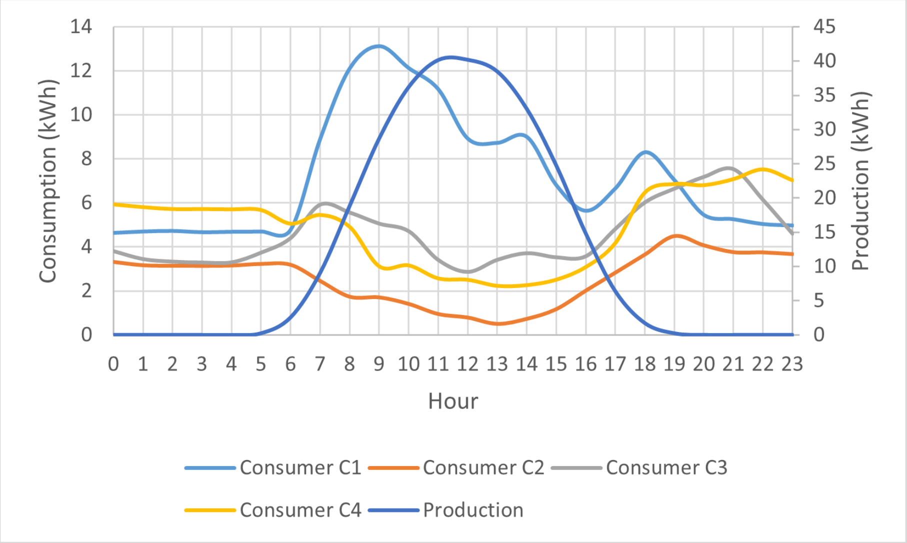


Figure 4.11: Average hourly production and consumption.

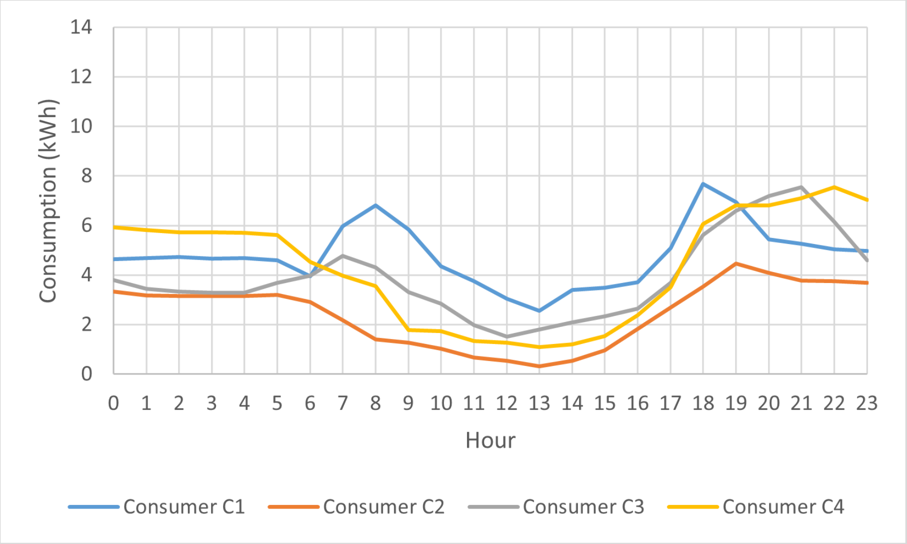


Figure 4.12: Average hourly consumption after repartition.

Analyzing the consumers' electricity bill for this scenario, table 4.13, it can be concluded that this repartition results in an 8,0% savings when compared with the bill from the scenario without REC energy, table 4.5. Confronting the results of the CME profit from the current scenario with scenario 2, a slight decrease in the profit is noticeable.

Table 4.13: Consumers' electricity bill for repartition through coefficients proportional to annual average energy consumption.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 050,08 € | 123,09 € | 586,08 € | 494,34 € |
| | **Grid Usage** | 167,09 € | 9,86 € | 46,60 € | 39,13 € |
| **Electrical Bill from Energy Supplier** | | 6 558,34 € | 3 342,55 € | 4 935,66 € | 4 975,70 € |
| **Sub-Total** | | 8 775,51 € | 3 475,51 € | 5 568,34 € | 5 509,16 € |
| **Total** | | 23 328,53 € | | | |

Table 4.14: CME profits for repartition through coefficients proportional to annual average energy consumption.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 253,59 € | 3 706,56 € | 6 960,15 € |

### 4.3.4 Scenario 4 - Repartition through coefficients proportional to energy production in sunny hours

The repartition through coefficients proportional to energy production in sunny hours results in the repartition coefficients shown in table 4.15. The coefficients were obtained by using the mathematical expressions 3.7 and 3.8.

Table 4.15: Repartition coefficients for scenario 4.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,6814 | 0,0284 | 0,1697 | 0,1205 |

Given what was explained about this repartition algorithm in section 3.3 and figure 4.11 presented above, it can be said that these coefficients do what they were designed to do, that is, observing the hours where there is solar production, C1 is the one that consumes the most followed by C3, C4 and finally C2. Looking at the coefficients presented in table 4.15, the degree of magnitude of the coefficients follows the same order.

Observing figure 4.13, it can be seen that this algorithm distributes a total of 33,50 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 132,28 MWh, coming from the grid. A total of 73,17 MWh of energy produced by the REC is not allocated, being sold to the grid.

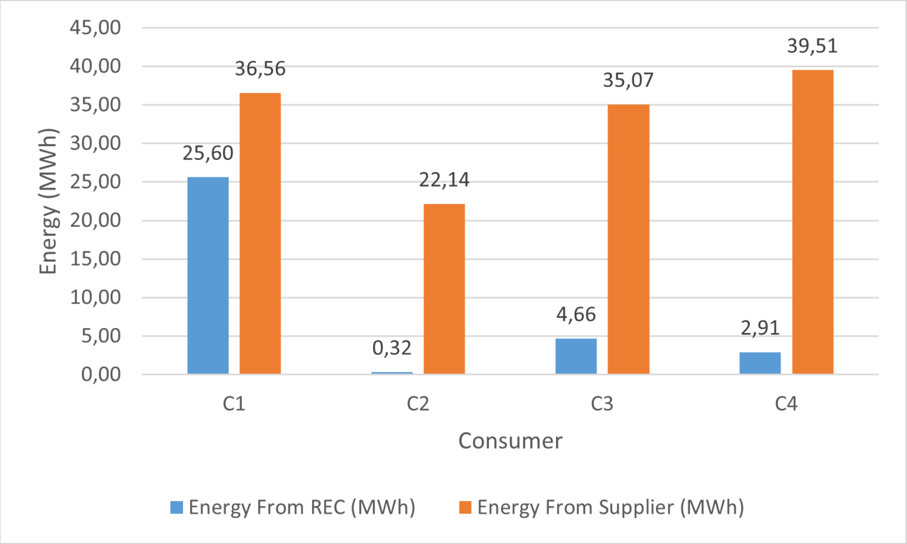


Figure 4.13: Energy Balance resulting from repartition through coefficients proportional to energy production in sunny hours.

From the different scenarios studied so far, this is the one that results in the allocation of more energy. Effectively, this repartition algorithm, by considering which consumers consume during production hours, allows more energy to be allocated to those consumers, as has been proven in this scenario.

Table 4.16 shows the electricity bill for this scenario and it can be concluded that this repartition results in an 8,2% savings when compared with the bill from the scenario without REC energy, table 4.5. Confronting the results of the CME profit from the current scenario, table 4.17, with ones already studied, this is the one that yields a higher profit.

Table 4.16: Consumers' electricity bill for repartition through coefficients proportional to energy production in sunny hours.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 560,37 € | 31,74 € | 466,46 € | 291,50 € |
| | **Grid Usage** | 208,37 € | 2,54 € | 37,12 € | 23,12 € |
| **Electrical Bill from Energy Supplier** | | 5 739,00 € | 3 485,84 € | 5 132,59 € | 5 299,30 € |
| **Sub-Total** | | 8 507,74 € | 3 520,12 € | 5 636,16 € | 5 613,92 € |
| **Total** | | 23 277,94 € | | | |

Table 4.17: CME profits for repartition through coefficients proportional to energy production in sunny hours.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 350,07 € | 3 658,32 € | 7 008,39 € |

### 4.3.5 Scenario 5 - Repartition through coefficients proportional to energy production and consumption in sunny hours

The repartition through coefficients proportional to energy production and consumption in sunny hours results in the repartition coefficients shown in table 4.18. The coefficients were obtained by using the mathematical expressions 3.9, 3.10, and 3.11.

Table 4.18: Repartition coefficients for scenario 5.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,7848 | 0,0134 | 0,1232 | 0,0786 |

Observing figure 4.14, it can be seen that this algorithm distributes a total of 32,50 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 134,22 MWh, coming from the grid. A total of 74,11 MWh of energy produced by the REC is not allocated, being sold to the grid.

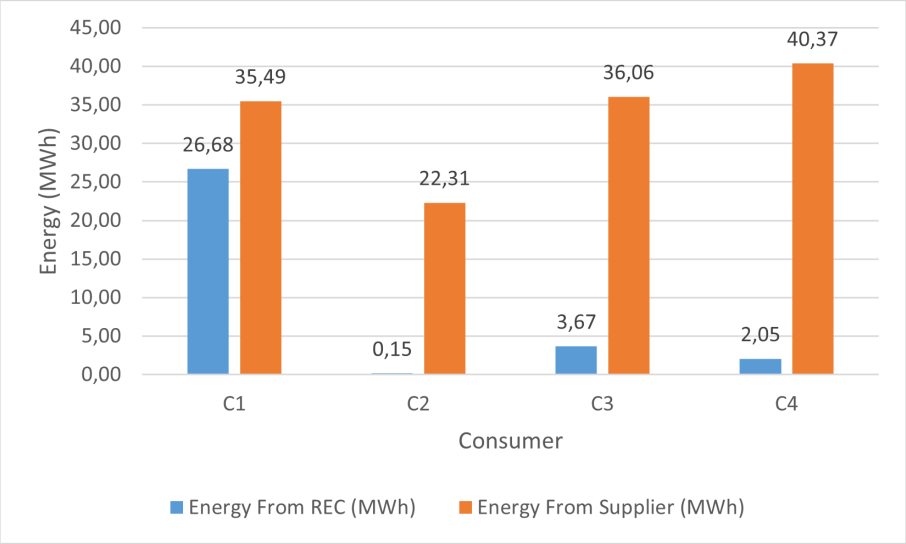


Figure 4.14: Energy Balance resulting from repartition through coefficients proportional to energy production and consumption in sunny hours.

Table 4.19 shows the electricity bill for this scenario, and it can be concluded that this repartition results in a 7,9% savings when compared with the bill from the scenario without REC energy, table 4.5. Confronting the results of the CME profit from the current scenario, table 4.20, with the previous one it produces a lower profit.

Table 4.19: Consumers' electricity bill for repartition through coefficients proportional to energy production and consumption in sunny hours.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 667,87 € | 15,30 € | 367,34 € | 205,32 € |
| | **Grid Usage** | 217,06 € | 1,23 € | 29,24 € | 16,30 € |
| **Electrical Bill from Energy Supplier** | | 5 567,68 € | 3 511,51 € | 5 299,36 € | 5 440,54 € |
| **Sub-Total** | | 8 452,61 € | 3 528,04 € | 5 695,95 € | 5 662,15 € |
| **Total** | | 23 338,75 € | | | |

Table 4.20: CME profits for repartition through coefficients proportional to energy production and consumption in sunny hours.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 255,83 € | 3 705,44 € | 6 961,27 € |

### 4.3.6 Scenario 6 - Repartition through optimized coefficients to minimize total costs

The repartition through optimized coefficients to minimize total costs results in the repartition coefficients shown in table 4.21. The coefficients were obtained by solving the optimization problem presented in subsection 3.3.6, using the Excel Solver.

Table 4.21: Repartition coefficients for scenario 6.

| **Consumer** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| **Coefficient** | 0,5403 | 0,0000 | 0,2759 | 0,1838 |

Even though the optimization was solved successfully, with all constraints being respected, in reality, this is not a viable solution given that consumer C2 does not receive any energy. Nevertheless, is important to analyze these results.

Observing figure 4.15, it can be seen that this algorithm distributes a total of 34,16 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 132,62 MWh, coming from the grid. A total of 72,51 MWh of energy produced by the REC is not allocated, being sold to the grid.

Of all the studies conducted until this moment, this repartition through optimized coefficients is the one that is able to allocate the most amount of energy.

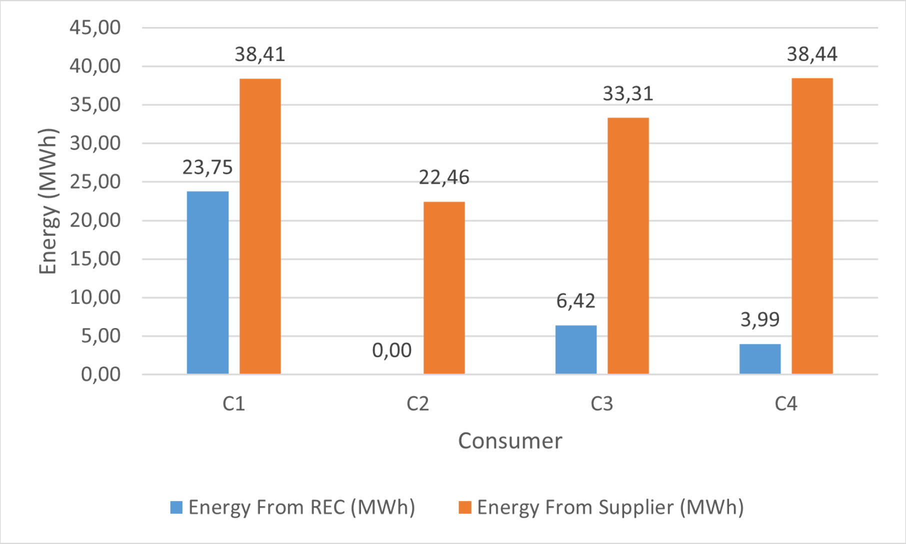


Figure 4.15: Energy Balance resulting from repartition through optimized coefficients to minimize total costs.

Table 4.22 shows the electricity bill for this scenario, and it can be concluded that this repartition results in an 8,3% savings when compared with the bill from the scenario without REC energy, table 4.5. Regarding the CME profit, the current scenario,table 4.23, produces highest profit among the previous scenarios analyzed.

Table 4.22: Consumers' electricity bill for repartition through optimized coefficients to minimize total costs.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 242,25 € | 63,75 € | 447,69 € | 264,71 € |
| | **Grid Usage** | 185,42 € | 4,26 € | 37,41 € | 22,16 € |
| **Electrical Bill from Energy Supplier** | | 6 129,94 € | 3 482,10 € | 5 014,78 € | 5 242,92 € |
| **Sub-Total** | | 8 557,61 € | 3 550,11 € | 5 499,88 € | 5 529,79 € |
| **Total** | | 23 137,39 € | | | |

Table 4.23: CME profits for repartition through optimized coefficients to minimize total costs.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 415,78 € | 3 625,47 € | 7 041,24 € |

### 4.3.7 Scenario 7 - Repartition through optimized coefficients indexed to hourly periods to minimize total costs

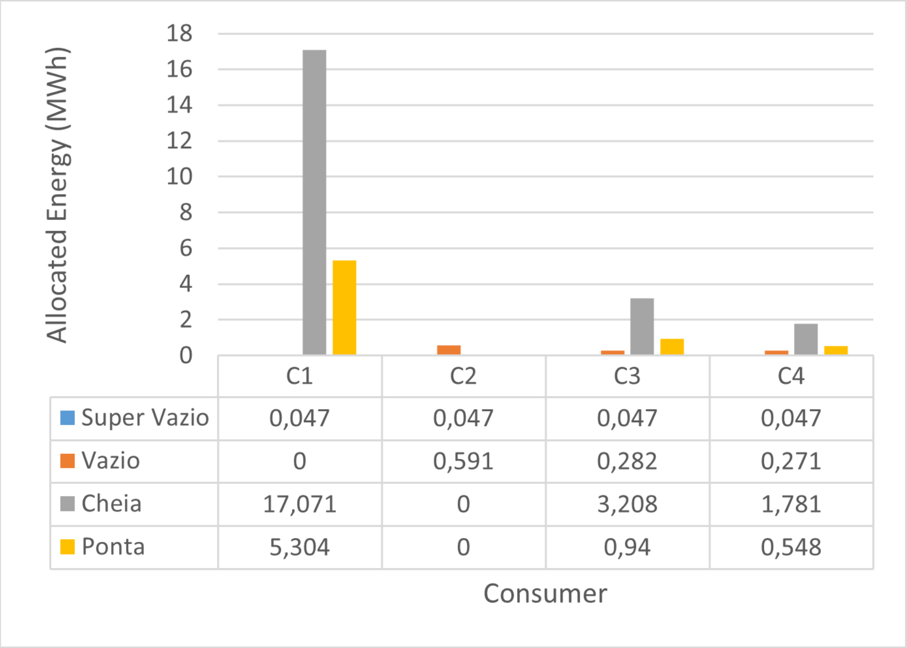
The repartition through optimized coefficients indexed to hourly periods to minimize total costs results in the repartition coefficients shown in table 4.24. The coefficients were obtained by solving the optimization problem presented in subsection 3.3.7, using the Excel Solver.

Table 4.24: Repartition coefficients for scenario 7.

| **Hourly Period** | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|
| ***Super Vazio*** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| ***Vazio*** | 0,0000 | 1,0000 | 0,0000 | 0,0000 |
| ***Cheia*** | 0,6222 | 0,0000 | 0,2285 | 0,1493 |
| ***Ponta*** | 0,5128 | 0,0000 | 0,2904 | 0,1968 |

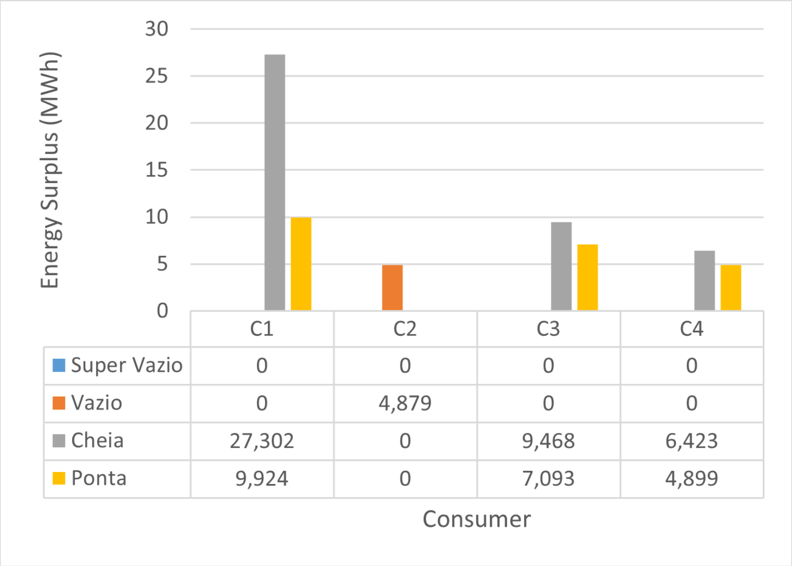
To understand better the results of the optimization, figures 4.16, and 4.17 should be analyzed. The first represents the energy allocated by hourly period for repartition through optimized coefficients indexed to hourly periods to minimize total costs for each consumer, and the second, the energy surplus by hourly period for repartition through optimized coefficients indexed to hourly periods to minimize total costs for each consumer. Once again, this surplus refers to the difference between the possible energy allocation and the consumption value.

For the *Super Vazio* period, the coefficients are even for all consumers. This is because the production in this period is so little that the energy allocated will always be used no matter the consumer, and none will be sold to the grid, as shown in figure 4.17. For the *Vazio* period, only consumer C2 receives energy which contrasts with the fact that it does not receive any in the *Cheia* and *Ponta* periods. In said periods, consumer C1 receives the most, given that it is the one that consumes the most, followed by consumers C3 and C4.



| | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| 🟦 Super Vazio | 0,047 | 0,047 | 0,047 | 0,047 |
| 🟧 Vazio | 0 | 0,591 | 0,282 | 0,271 |
| ◼ Cheia | 17,071 | 0 | 3,208 | 1,781 |
| 🟨 Ponta | 5,304 | 0 | 0,94 | 0,548 |

Figure 4.16: Energy Allocated by Hourly Period for repartition through optimized coefficients indexed to hourly periods to minimize total costs.



| | C1 | C2 | C3 | C4 |
|---|---|---|---|---|
| Super Vazio | 0 | 0 | 0 | 0 |
| Vazio | 0 | 4,879 | 0 | 0 |
| Cheia | 27,302 | 0 | 9,468 | 6,423 |
| Ponta | 9,924 | 0 | 7,093 | 4,899 |

Figure 4.17: Energy surplus by Hourly Period for repartition through optimized coefficients indexed to hourly periods to minimize total costs.

Observing figure 4.18, it can be seen that this algorithm distributes a total of 30,16 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 132,62 MWh, coming from the grid. A total of 69,99 MWh of energy produced by the REC is not allocated, being sold to the grid.

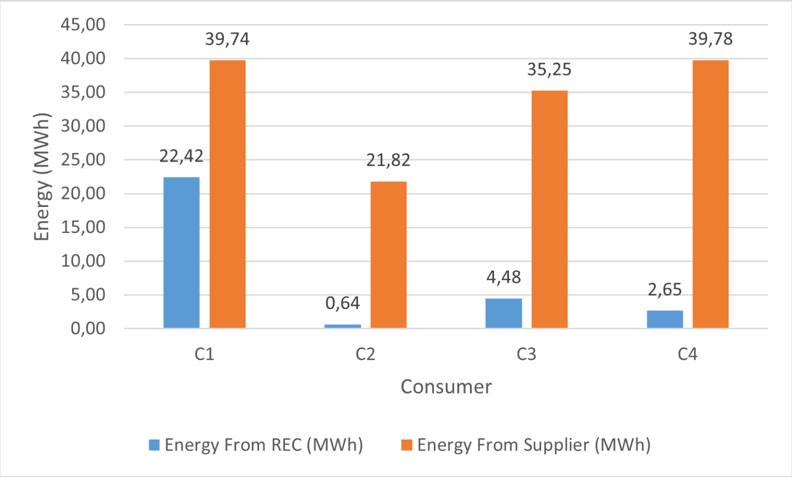


Figure 4.18: Energy Balance resulting from repartition through optimized coefficients indexed to hourly periods to minimize total costs.

Table 4.25 shows the electricity bill for this scenario, and it can be concluded that this repartition results in an 8,7% savings when compared with the bill from the scenario without REC energy, table 4.5. In terms of CME profit, the current scenario presents a profit of 6 517,75 €, table 4.20.

Table 4.25: Consumers' electricity bill for repartition through optimized coefficients indexed to hourly periods to minimize total costs.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 242,25 € | 63,75 € | 447,69 € | 264,71 € |
| | **Grid Usage** | 185,42 € | 4,26 € | 37,41 € | 22,16 € |
| **Electrical Bill from Energy Supplier** | | 6 129,94 € | 3 482,10 € | 5 014,78 € | 5 242,92 € |
| **Sub-Total** | | 8 557,61 € | 3 550,11 € | 5 499,88 € | 5 529,79 € |
| **Total** | | 23 137,39 € | | | |

Table 4.26: CME profits for repartition through optimized coefficients indexed to hourly periods to minimize total costs.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 018,40 € | 3 499,36 € | 6 517,75 € |

### 4.3.8 Scenario 8 - Repartition through coefficients proportional to consumption

This last repartition algorithm differs from the previous ones in that there is not a single coefficient for the consumer that is applied in all the intervals in which energy is repartitioned. In effect, at each 15-minute interval, a different coefficient is applied based on consumer consumption, as shown in expression 3.2, presented in the previous chapter.

Observing figure 4.19, it can be seen that this algorithm distributes a total of 36,26 MWh among the consumers, with the rest of the energy required to meet their needs, corresponding to 130,52 MWh, coming from the grid. A total of 61,40 MWh of energy produced by the REC is not allocated, being sold to the grid. This algorithm is the one that is able to allocate the most REC energy to consumers from the ones analyzed.

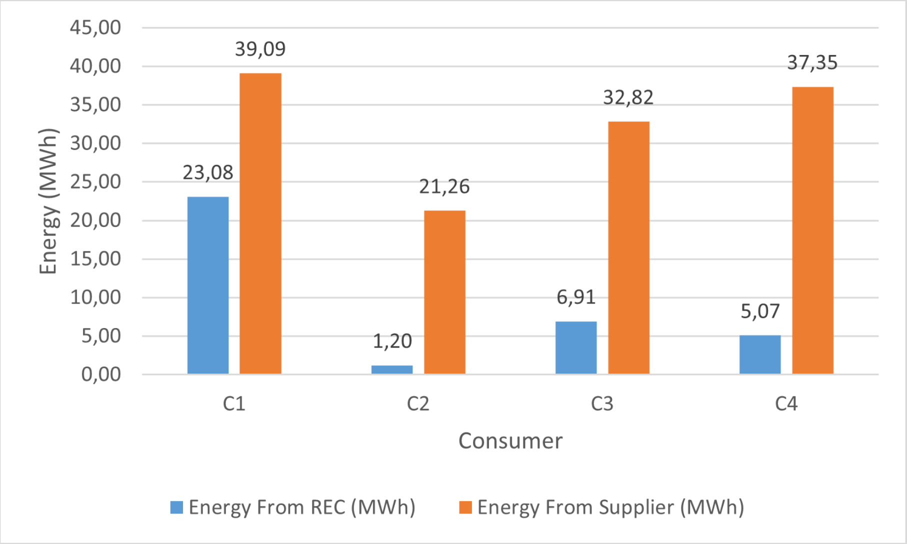


Figure 4.19: Energy Balance resulting from repartition through coefficients proportional to consumption.

Table 4.27 shows the electricity bill for this scenario, and it can be concluded that this repartition results in an 8,7% savings when compared with the bill from the scenario without REC energy, table 4.5. In terms of CME profit, the current scenario presents a profit of 6 517,75 €, table 4.28.

Table 4.27: Consumers' electricity bill for repartition through coefficients proportional to consumption.

| **Consumer** | | **C1** | **C2** | **C3** | **C4** |
|---|---|---|---|---|---|
| **Electrical Bill from REC Energy** | **Energy Component** | 2 307,70 € | 119,96 € | 691,01 € | 507,28 € |
| | **Grid Usage** | 188,19 € | 9,57 € | 54,81 € | 40,00 € |
| **Electrical Bill from Energy Supplier** | | 6 120,01 € | 3 348,75 € | 4 773,32 € | 4 967,88 € |
| **Sub-Total** | | 8 615,91 € | 3 478,29 € | 5 519,14 € | 5 515,16 € |
| **Total** | | 23 128,49 € | | | |

Table 4.28: CME profits for repartition through coefficients proportional to consumption.

| **Energy Sold to Consumers** | **Sold Energy Surplus** | **Total** |
|---|---|---|
| 3 625,95 € | 3 069,78 € | 6 695,73 € |

## 4.4 Comparison between the different repartition algorithms

This section pretends to compile the results of all repartition algorithms studied and identify which one benefits each consumer the most and the one that benefits the aggregate of consumers.

Initially, it is important to examine the price of electricity for each repartition algorithm. Based on the electricity bill presented for each algorithm in the previous section, the price of REC energy, supplier energy, and the total was calculated using the mathematical expression 3.17, 3.18, and 3.19 presented in chapter 3. The results of this study are compiled in table 4.29. The column named Total(€/kWh) has a color scale, with green for the lower (better) price and escalating to red for the highest (worse) price.

Table 4.29: Energy price for different repartition algorithms.

| **Type of Coefficients** | **REC Energy Price (€/kWh)** | **Supplier Energy Price (€/kWh)** | **Total (€/kWh)** |
|---|---|---|---|
| **Even** | 0,10807 | 0,14802 | 0,14095 |
| **Proportional to Maximum Energy Consumption** | 0,10807 | 0,14755 | 0,13981 |
| **Proportional to Average Energy Consumption** | 0,10807 | 0,14758 | 0,13987 |
| **Proportional to Energy Production in Sunny Hours** | 0,10809 | 0,14748 | 0,13957 |
| **Proportional to Energy Consumption and Production in Sunny Hours** | 0,10810 | 0,14766 | 0,13994 |
| **Optimized to Minimize Total Cost** | 0,10808 | 0,14734 | 0,13930 |
| **Optimized and Indexed to Hourly Periods to Minimize Total Cost** | 0,10826 | 0,14546 | 0,13873 |
| **Proportional to Consumption** | 0,10807 | 0,14718 | 0,13867 |

It can be seen that repartition proportional to consumption presents the lower energy price, in €/kWh, and the repartition through even coefficients presents the worse. Given that the first is the one that allocates more REC energy to consumers and the second the least, this conclusion was expected.

Next, it is important to evaluate the electricity bill for each consumer for the different repartition algorithms.

Figure 4.20 presents the cost of the electricity bill for consumer C1. The difference between the repartition algorithms where C1 pays more and pays less is 6,04%. For this consumer, the best algorithm is the repartition through coefficients proportional to energy production and consumption in sunny hours. This consumer benefits the most from this type of repartition because he has the highest percentage of consumption among all consumers when the solar production is at its highest, being assigned to him a coefficient where he has the right to 78,48% of the production. The repartition through even coefficients is the one where he pays more because it is the one when he has the right to the least energy between all repartition algorithms.

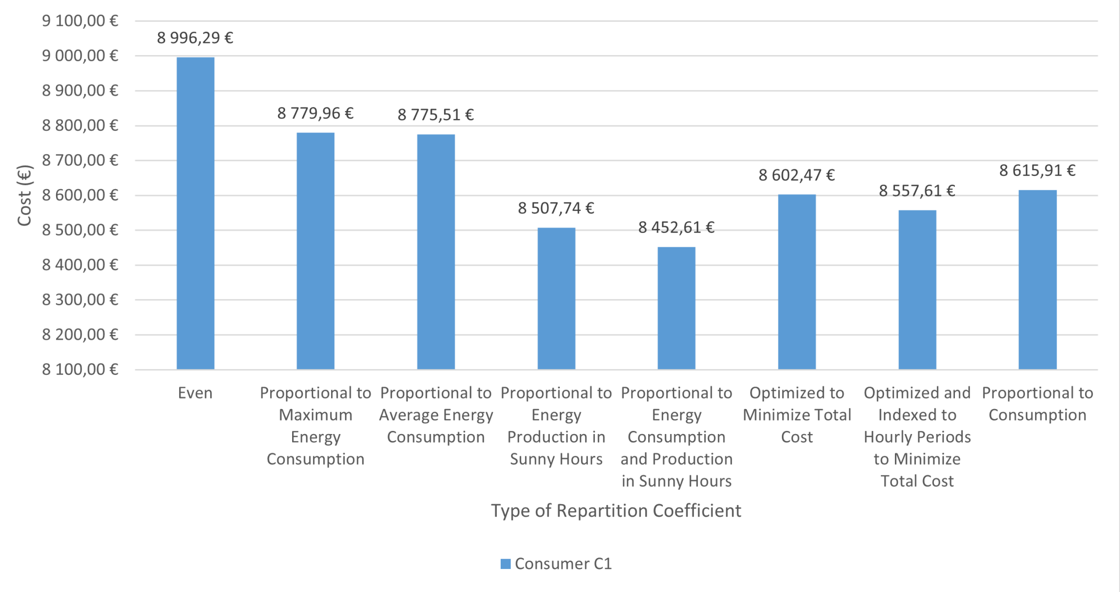


Figure 4.20: Costs for Consumer C1 for different repartition algorithms.

Figure 4.21 presents the cost of the electricity bill for consumer C2. The difference between the repartition algorithms where C2 pays more and pays less is 3,07%. The best repartition for consumer C2 is the repartition through even coefficients. Consumer C2 is the one that consumes the least throughout the day, meaning that repartition coefficients that have into consideration the general consumption and consumption during solar production hours will always prejudicate this consumer.

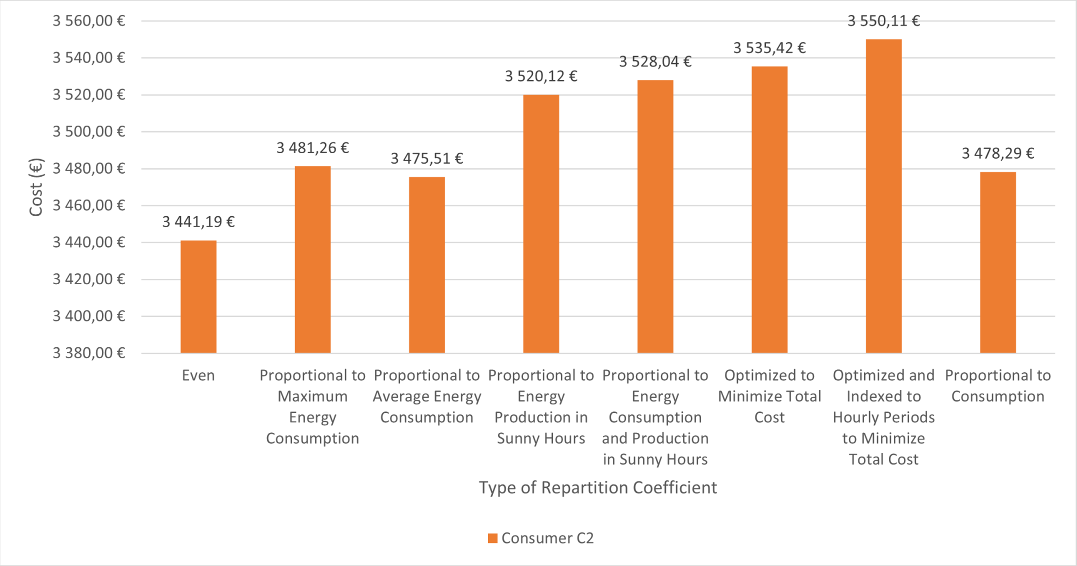


Figure 4.21: Costs for Consumer C2 for different repartition algorithms.

Figure 4.22 presents the cost of the electricity bill for consumer C3. The difference between the repartition algorithms where C3 pays more and pays less is 3,44%. The best repartition for consumer C3 is the repartition through optimized coefficients indexed to hourly periods to minimize total cost, and the one where he pays more is the repartition through coefficients proportional to average consumption and production in sunny hours.

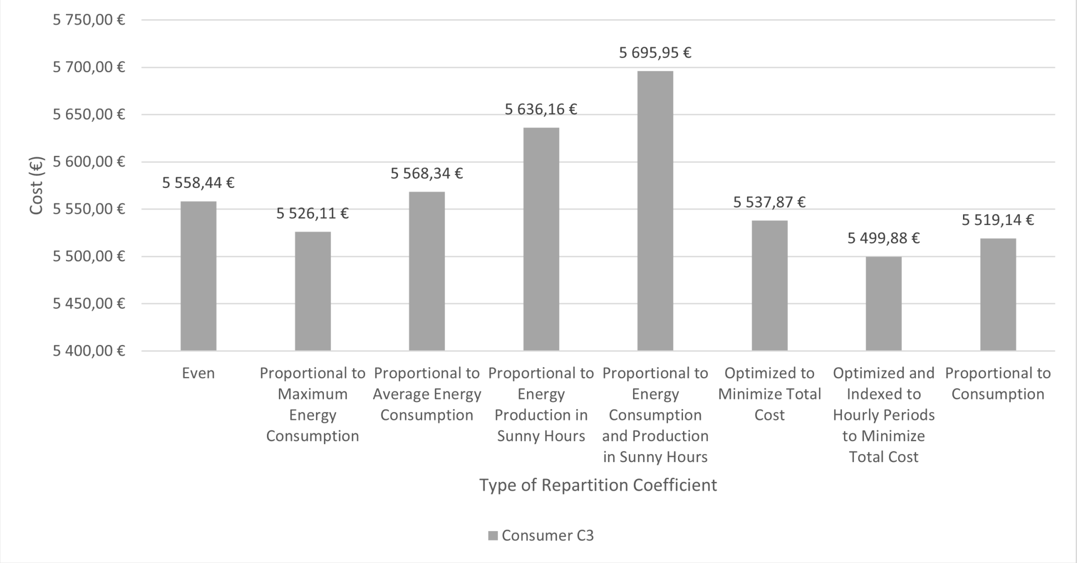


Figure 4.22: Costs for Consumer C3 for different repartition algorithms.

Figure 4.23 presents the cost of the electricity bill for consumer C4. The difference between the repartition algorithms where C4 pays more and pays less is 2,70%. The best repartition for consumer C4 is the repartition through coefficients proportional to average energy consumption, and the one where he pays more is the repartition through coefficients proportional to energy production and consumption in sunny hours.

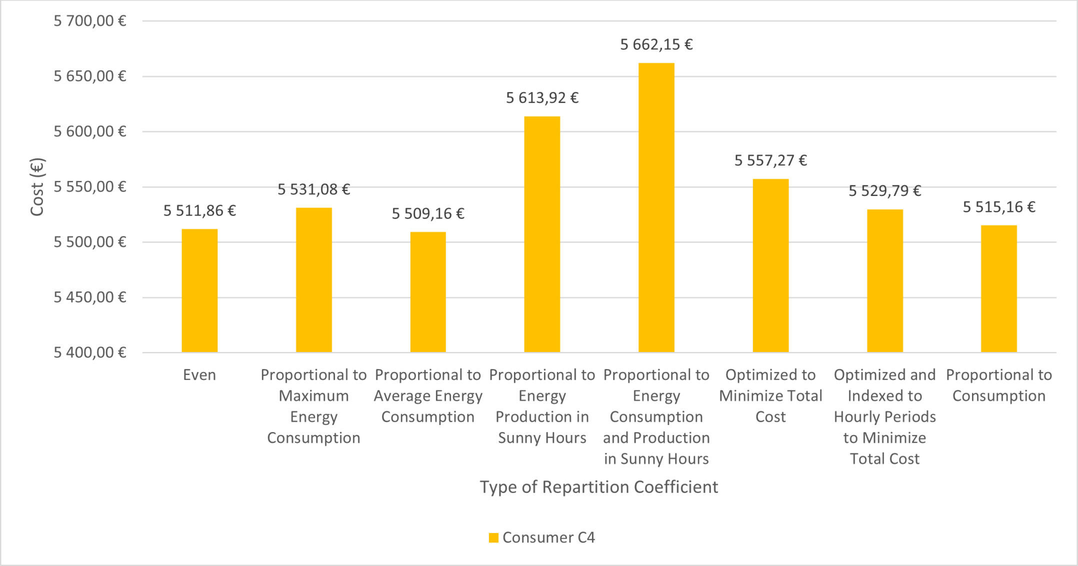


Figure 4.23: Costs for Consumer C4 for different repartition algorithms.

Finally, evaluating the cost of the electricity bill for the aggregate of the consumers, it can be seen that, by observing figure 4.24, the difference between the repartition algorithms where the consumers pay more and pay less is 2%. The repartition algorithm that results in a lower cost for the consumers as a whole is repartition proportional to the consumption. The ability for the coefficients to change in every repartition moment according to the consumers' consumption allows a larger amount of REC energy to be allocated compared to the other repartition algorithms.

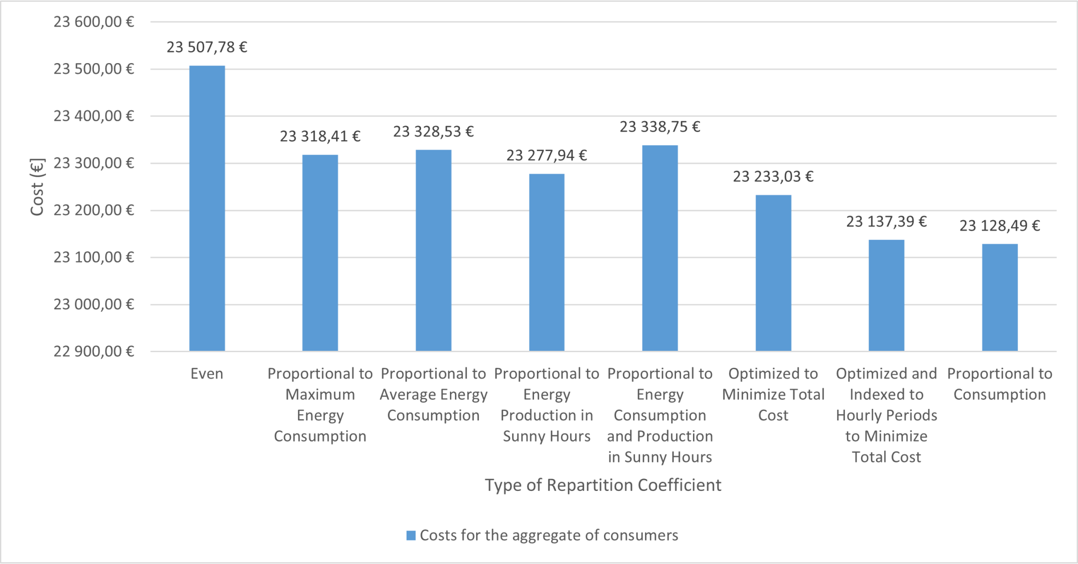


Figure 4.24: Costs for the aggregate of consumers for different repartition algorithms.

In short, table 4.30 compiles the most cost-effective algorithm for each consumer and the aggregate of consumers. It is interesting to see all consumers have a different algorithm when they are the most benefited in terms of cost, and none of them corresponds to the repartition algorithm that renders the lower cost for the consumers as an aggregate.

Table 4.30: Most cost-effective Repartition Algorithm for each Consumer and the aggregate.

| Consumer | Most Cost-effective Repartition Algorithm |
|---|---|
| **C1** | Proportional to Energy Consumption and Production in Sunny Hours |
| **C2** | Even |
| **C3** | Optimized and Indexed to Time Periods to Minimize Total Cost |
| **C4** | Proportional to Average Power Consumption |
| **Aggregate of consumers** | Proportional to Consumption |

Finally, to end this analysis on the differents repartition algorithms, table 4.25 presents the profit for CME for each one of them. The difference between the repartition algorithms that yield the most profit and the less is 7,4%. The repartition that results in the greater profit is the repartition through optimized coefficients to minimize total cost and the least the repartition through optimized indexed to hourly periods coefficients to minimize total cost.

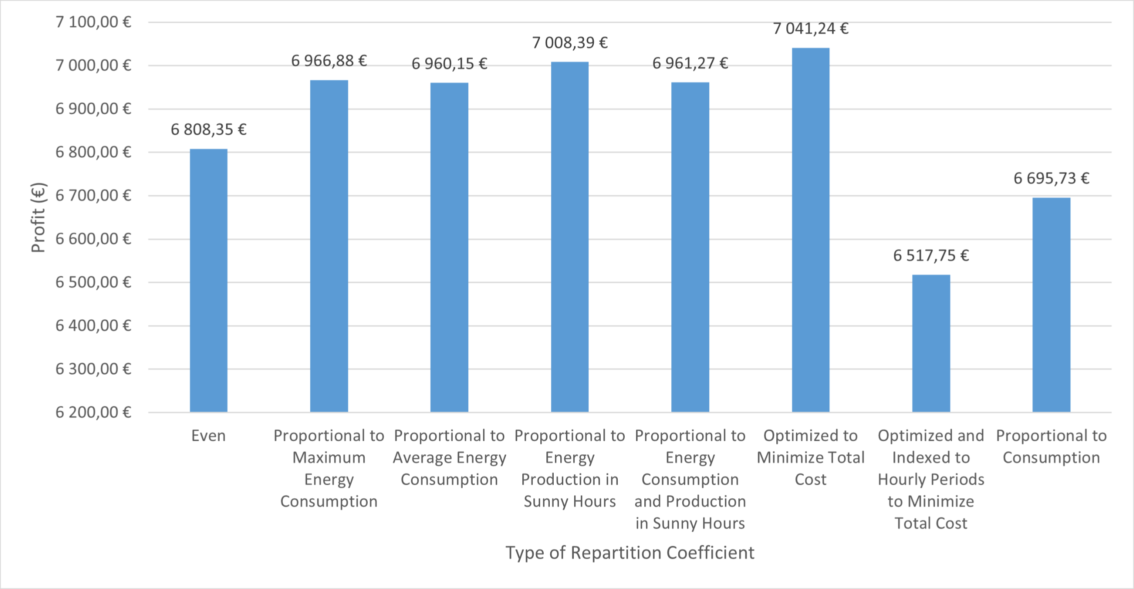


Figure 4.25: CME profit for different repartition algorithms.

## 4.5 Influence of CIEG payment exemption on the total cost for consumers

At the beginning of section 4.3, it was stated that the electricity bill was calculated considering that the consumer had 100% exemption of CIEG payment. This section pretends to demonstrate what is the influence on the total cost of the electricity bill for each repartition algorithm if the consumers were obliged to pay CIEG.

Figure 4.26 presents the total cost of the electricity bill with and without CIEG exemption for each repartition algorithm and table 4.31 the difference, in percentage, between them.

The exemption of payment of CIEG is essential to increase the savings to the consumers by belonging to a REC. The difference among the electricity bill for the different repartition algorithms with or without CIEG exemption can vary between 5,92% and 7,28%.

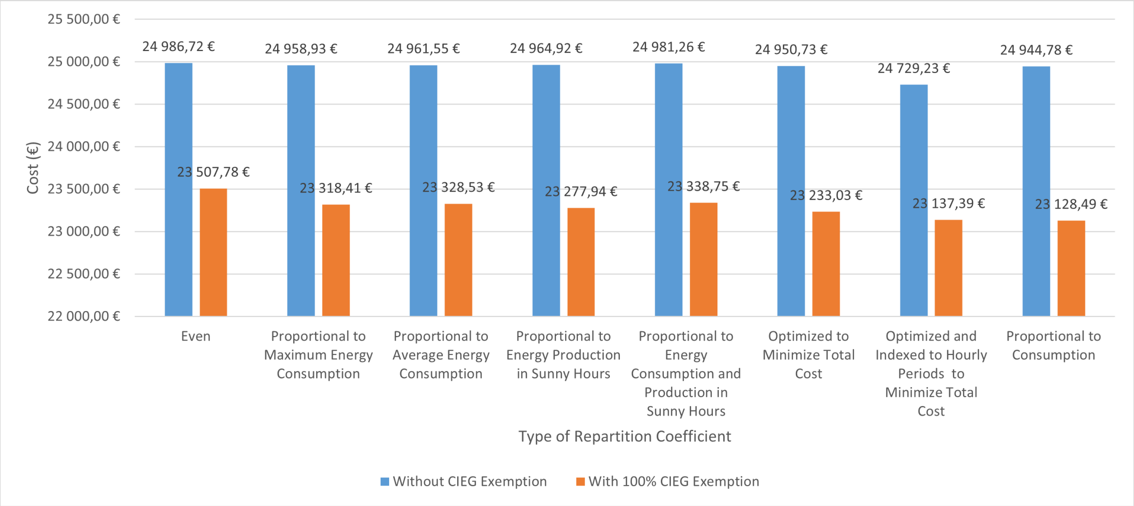


Figure 4.26: Difference in total cost between with and without 100% CIEG exemption.

Table 4.31: Difference between with and without 100% CIEG exemption.

| Type of Coefficients | Difference between with and without 100% CIEG Exemption |
|---|---|
| **Even** | 5,92% |
| **Proportional to Maximum Energy Consumption** | 6,57% |
| **Proportional to Average Energy Consumption** | 6,54% |
| **Proportional to Energy Production in Sunny Hourss** | 6,76% |
| **Proportional to Energy Consumption and Production in Sunny Hours** | 6,57% |
| **Optimized to Minimize Total Cost** | 6,88% |
| **Optimized and Indexed to Time Periods to Minimize Total Cost** | 6,44% |
| **Proportional to Consumption** | 7,28% |

Table 4.32 presents the energy price for the repartition algorithms without CIEG exemption. It can be seen that the REC energy price, in €/kWh, is actually higher than the price of the energy coming from the grid. Therefore, it can be concluded that if the consumers do not dispose of the exemption of paying CIEG, participating in a REC is not beneficial, given that they will be paying a higher price for REC energy than grid energy.

Table 4.32: Energy price for different repartition algorithms without CIEG exemption.

| **Type of Coefficients** | **REC Energy Price (€/kWh)** | **Supplier Energy Price (€/kWh)** | **Total (€/kWh)** |
|---|---|---|---|
| **Even** | 0,15820 | 0,14802 | 0,14982 |
| **Proportional to Maximum Energy Consumption** | 0,15829 | 0,14755 | 0,14965 |
| **Proportional to Average Energy Consumption** | 0,15826 | 0,14758 | 0,14967 |
| **Proportional to Energy Production in Sunny Hours** | 0,15845 | 0,14748 | 0,14969 |
| **Proportional to Energy Consumption and Production in Sunny Hours** | 0,15855 | 0,14766 | 0,14978 |
| **Optimized to Minimize Total Cost** | 0,15837 | 0,14734 | 0,14960 |
| **Optimized and Indexed to Hourly Periods to Minimize Total Cost** | 0,16100 | 0,14546 | 0,14827 |
| **Proportional to Consumption** | 0,15816 | 0,14718 | 0,14957 |

## 4.6 Repartition through coefficients that change monthy

For the study conducted in section 4.3 it was considered that the repartition coefficients remain the same during the entire year. Here it was analyzed what gain the consumers would have if those coefficients could be updated monthly. Only a few repartitions presented earlier were tested. Below are listed the repartition algorithms considered and the reason why they were chosen:

- Even coefficients;
- Proportional to energy production in sunny hours;
- Optimized coefficients to minimize total cost ;
- Proportional to consumption.

These repartition algorithms were chosen because, for even coefficients, they presented the worse result. The repartition through proportional to energy production in sunny hours was also tested because it presented the best result among fixed coefficients, not including the optimized ones. The repartition through optimized coefficients to minimize total cost was also included in this analysis since it had the best of the fixed coefficients, not including the optimized coefficients indexed to hourly periods. Finally, the repartition through proportional coefficients was studied as well, given that it was determined to be the best.

The repartition coefficients obtained for each algorithm are presented in appendix D.

Figure 4.27 shows the energy allocated for both kinds of repartition. The repartition through coefficients proportional to average energy production in sunny hours allocates slightly less energy when coefficients change monthly and, for the repartition through optimized coefficients to minimize total cost the opposite happens, where it is allocated slightly more energy when the coefficients change monthly. Note that, for the repartition through even coefficients and proportional to consumption, the results obtained earlier do not change. In the first case, the coefficients are not affected by consumption or production data for each month but instead by the number of consumers that remains the same. In the second case, the coefficients continue to be updated in every repartition moment (15-minute intervals), independently from the month.

Even though that are observable differences, they are almost negligible, given that the discrepancies in energy allocated between both kinds of repartition are less than 0,5%

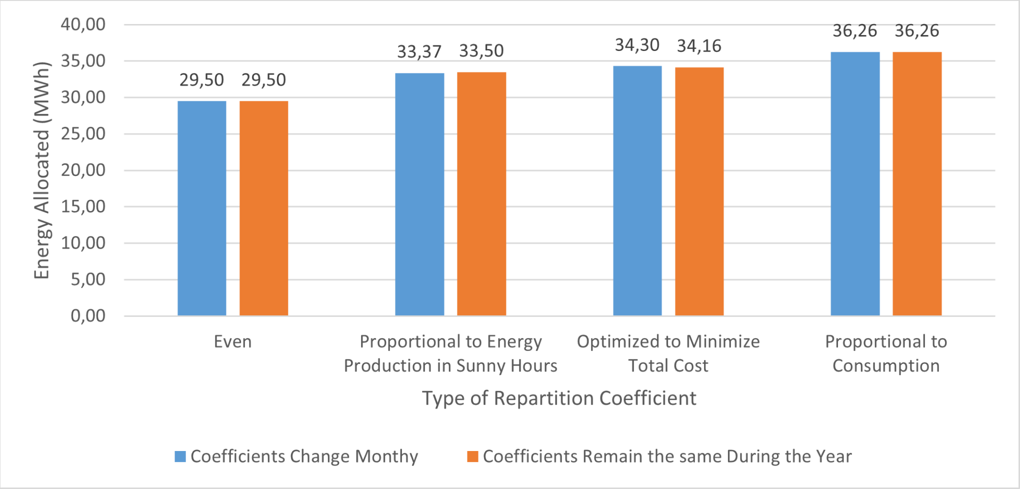


Figure 4.27: Comparison in energy allocated between repartition through coefficients that remain the same vs change monthy.

Figures 4.28, 4.29, 4.30, and 4.31 show the cost of electricity for each consumer for the two kinds of repartition. The electricity bill was calculated in the same condition in both repartitions, where the consumers disposed of 100% CIEG exemption.

Starting with consumer C1, as seen in figure 4.28, he ends up paying more if the coefficients change monthly for repartition through coefficients proportional to average energy production in sunny hours and less in the repartition through optimized coefficients to minimize total cost. But the difference for both cases is less than 1%.

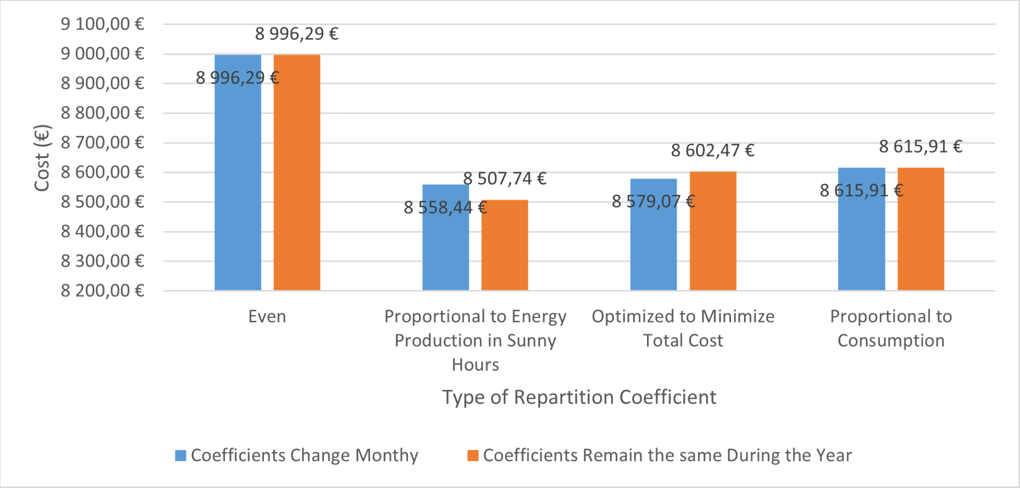


Figure 4.28: Comparison in cost for consumer C1 between repartition through coefficients that remain the same vs change monthy.

For consumer C2, as seen in figure 4.29, he ends up paying more if the coefficients change monthly for repartition through optimized coefficients to minimize total cost (but only 0,01€) and less in the repartition through coefficients proportional to average energy production in sunny hours, but the difference is less than 0,3%.

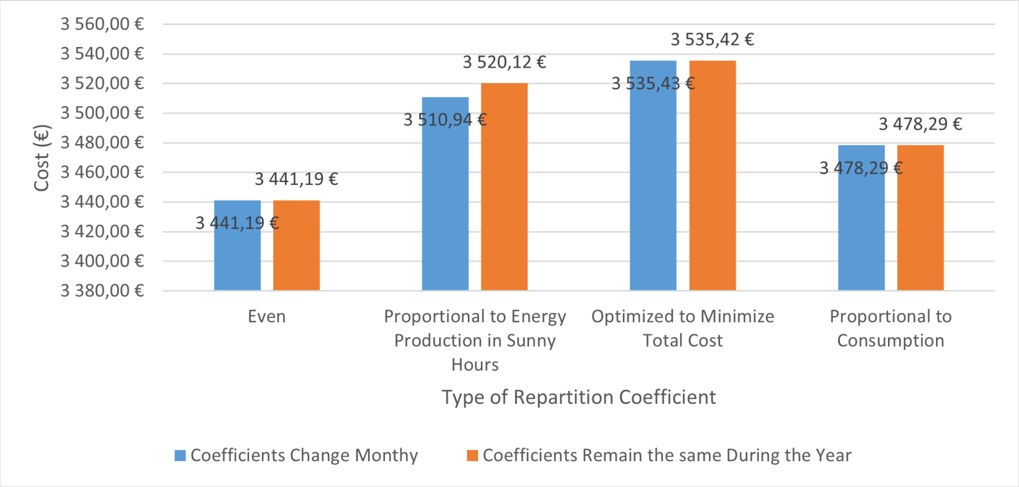


Figure 4.29: Comparison in cost for consumer C2 between repartition through coefficients that remain the same vs change monthy.

For consumer C3, as seen in figure 4.30, he ends up paying more if the coefficients change monthly for repartition through optimized coefficients to minimize total cost and less in the repartition through coefficients proportional to average energy production in sunny hours. Once again, the difference in both cases is less than 0,5%.

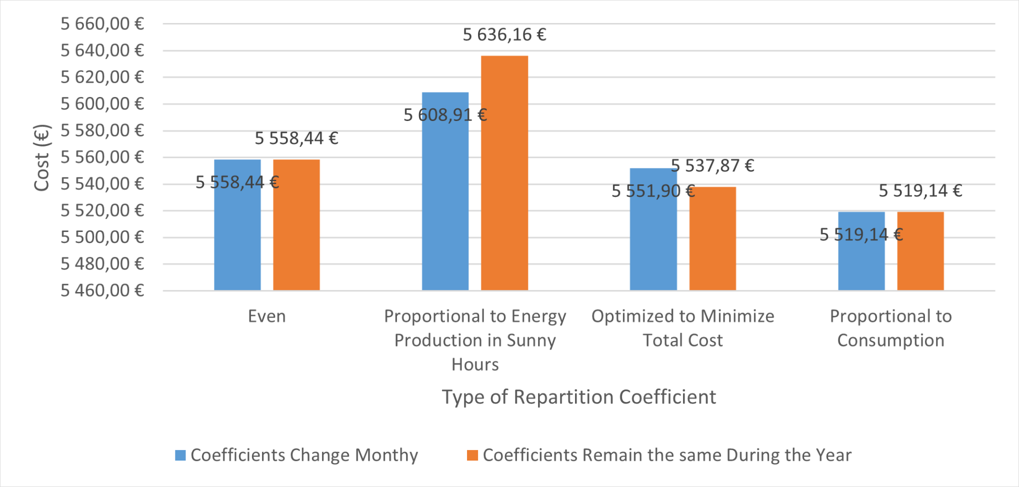


Figure 4.30: Comparison in cost for consumer C3 between repartition through coefficients that remain the same vs change monthy.

For consumer C4, as seen in figure 4.30, he ends up paying less if the coefficients change monthly for both repartitions through optimized coefficients to minimize total cost and repartition through coefficients proportional to average energy production in sunny hours. Once again, the difference in both cases is less than 0,5%.

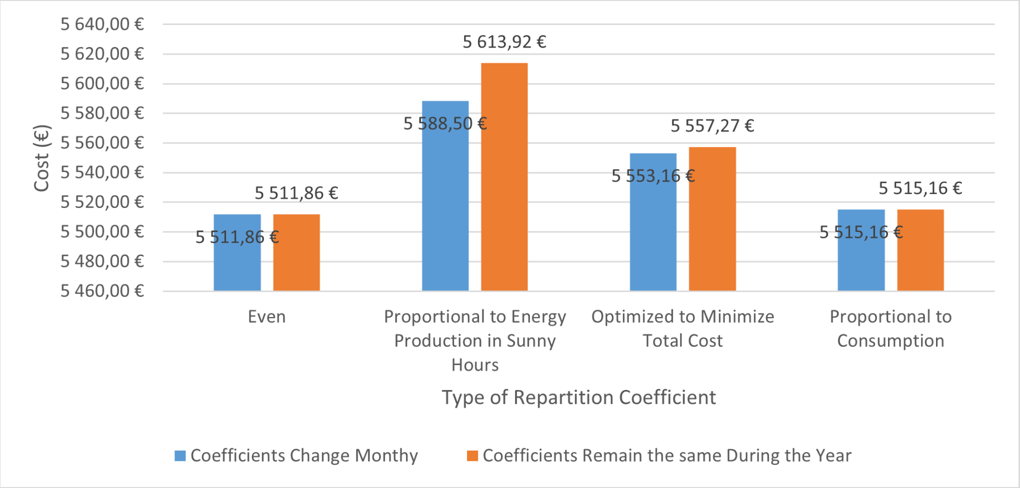


Figure 4.31: Comparison in cost for consumer C4 between repartition through coefficients that remain the same vs change monthy.

Finally, analyzing the cost for the aggregate of the consumers, as seen in figure 4.32, they end up paying less if the coefficients change monthly for both repartitions through optimized coefficients to minimize total cost and repartition through coefficients proportional to average energy production in sunny hours. However, the difference in both cases is less than 0,5%.

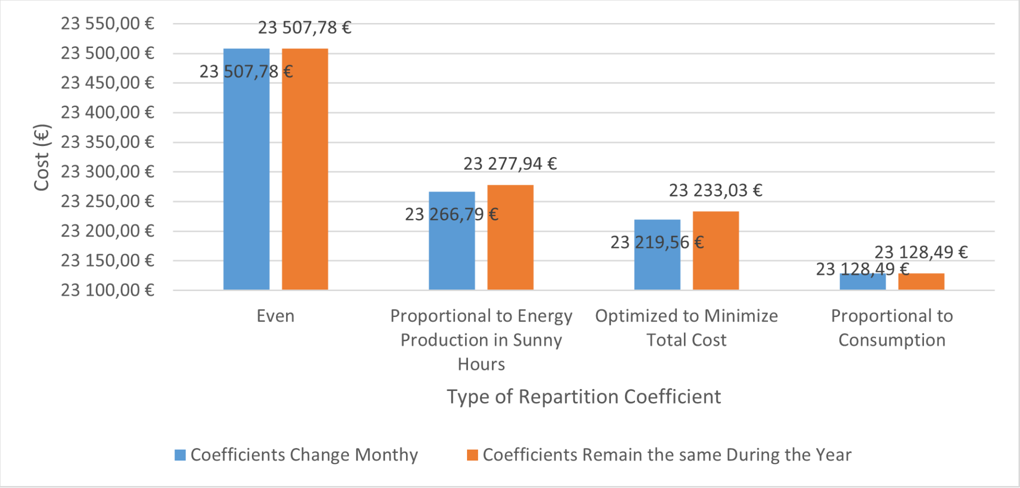


Figure 4.32: Comparison in cost for the aggregate of consumers between repartition through coefficients that remain the same vs change monthy.

After these analyses, it can be concluded that changing the coefficients monthly does not bring a big improvement to the situation where they remain the same throughout the year.

However, to try to understand why the ability to change the coefficients monthly did not bring big advantages, table 4.33 presents the percentage of consumption in relation to total consumption for each consumer for every month. Each month, there is a color scale where green is the highest percentage, escalating until red for the lowest percentage. Note that for every month except October, consumer C1 is the one that consumes the most and C2 the least, and C3 and C4 trade places but with always similar percentages.

Therefore, it can be said that the consumption profile between the consumer does not present significant differences throughout the year, which results that changing the coefficients monthly does not bring a big change compared to the ones that remain the same throughout a year.

Table 4.33: Percentage of consumption in relation to total consumption for each consumer for every month.

| Month | Consumer C1 | Consumer C2 | Consumer C3 | Consumer C4 |
|---|---|---|---|---|
| **January** | 40,47% | 13,23% | 24,89% | 21,41% |
| **February** | 35,84% | 12,88% | 24,40% | 26,88% |
| **March** | 36,17% | 13,07% | 24,03% | 26,73% |
| **April** | 38,37% | 10,98% | 26,66% | 23,99% |
| **May** | 40,50% | 10,00% | 25,51% | 23,98% |
| **June** | 40,70% | 11,22% | 21,40% | 26,68% |
| **July** | 41,93% | 14,06% | 18,24% | 25,77% |
| **August** | 38,03% | 16,49% | 19,04% | 26,44% |
| **September** | 33,78% | 11,59% | 25,13% | 29,49% |
| **October** | 30,61% | 14,46% | 24,15% | 30,78% |
| **November** | 35,44% | 15,86% | 23,25% | 25,45% |
| **December** | 37,32% | 15,34% | 24,38% | 22,96% |

## 4.7 Repartition where data production and consumption are aggregated by months and hourly periods

In the previous two sections, it was shown two kinds of repartitions: one where the coefficients remain the same during a year and the other where the coefficients change monthly. Despite this difference in both, the repartition process happens every 15 minutes, which is the time the data is available. In this section, it is attempted to conclude if aggregating the data by month and hourly periods and performing the repartition at the end of each one is beneficial to the consumer from an economic perspective.

To clarify what is meant by stating that the data is aggregated by month and hourly periods, table 4.34 shows a small fraction of said data.

Table 4.34: Aggregated consumption and production data by month and hourly periods.

| Month | Hourly Period | C1 (kW) | C2 (kW) | C3 (kW) | C4 (kW) | P1 (kW) | P2 (kW) | P3 (kW) | P4 (kW) |
|---|---|---|---|---|---|---|---|---|---|
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |
| **March** | ***Super Vazio*** | 2370 | 1666 | 1764,4 | 2991,2 | 0 | 0 | 0 | 0 |
| | ***Vazio*** | 3712 | 2427,2 | 3587,6 | 4698,8 | 133 | 438 | 460 | 376 |
| | ***Cheia*** | 8532 | 1331,6 | 4634,4 | 3866,4 | 4422 | 12512,6 | 8066,8 | 8827,4 |
| | ***Ponta*** | 4283,2 | 1402 | 2569,2 | 2410,4 | 973 | 2810,2 | 2262 | 2142 |
| **April** | ***Super Vazio*** | 2016 | 1450,4 | 1946 | 2722 | 2 | 11 | 11 | 6 |
| | ***Vazio*** | 4039,6 | 1995,2 | 3908,4 | 4314,4 | 213 | 641 | 682 | 583 |
| | ***Cheia*** | 9607,2 | 1518 | 5337,6 | 3551,2 | 3293 | 9170 | 5496,6 | 6673,8 |
| | ***Ponta*** | 4107,2 | 694 | 2541,2 | 1773,2 | 1645 | 4621,2 | 3182 | 3474 |
| **May** | ***Super Vazio*** | 1758,8 | 1378,8 | 1950,8 | 2760,8 | 19 | 69 | 66 | 67 |
| | ***Vazio*** | 3816,8 | 1645,2 | 3190,4 | 3930 | 356 | 1184,2 | 1192 | 1101 |
| | ***Cheia*** | 8542,8 | 896 | 4054,8 | 2580 | 4282 | 11549 | 6635,4 | 8769,6 |
| | ***Ponta*** | 4158 | 592,4 | 2315,6 | 1551,2 | 1970 | 5489 | 3554,8 | 4117,2 |
| **June** | ***Super Vazio*** | 1492,4 | 1198,8 | 1646,4 | 2384 | 16 | 75 | 89 | 71 |
| | ***Vazio*** | 3140 | 1450 | 2238 | 3223,6 | 354 | 1207,2 | 1233 | 1036 |
| | ***Cheia*** | 7308,8 | 833,2 | 2626,8 | 2636,8 | 4095 | 11047,6 | 6199,6 | 7448,6 |
| | ***Ponta*** | 2562,4 | 515,2 | 1114,8 | 1261,2 | 2022 | 5570,4 | 3631,2 | 3689 |
| ... | ... | ... | ... | ... | ... | ... | ... | ... | ... |

The repartition algorithms tested are those presented below. These were the ones considered based on the same reasons already stated in the previous study. The repartition coefficients obtained for each one are present in appendix E.

- Even coefficients;
- Proportional to energy production in sunny hours;
- Optimized coefficients to minimize total cost ;
- Proportional to consumption.

The results obtained in the first study, that is, repartition through coefficients that remain the throughout a year, will be the benchmark to which the results of the current study will be compared.

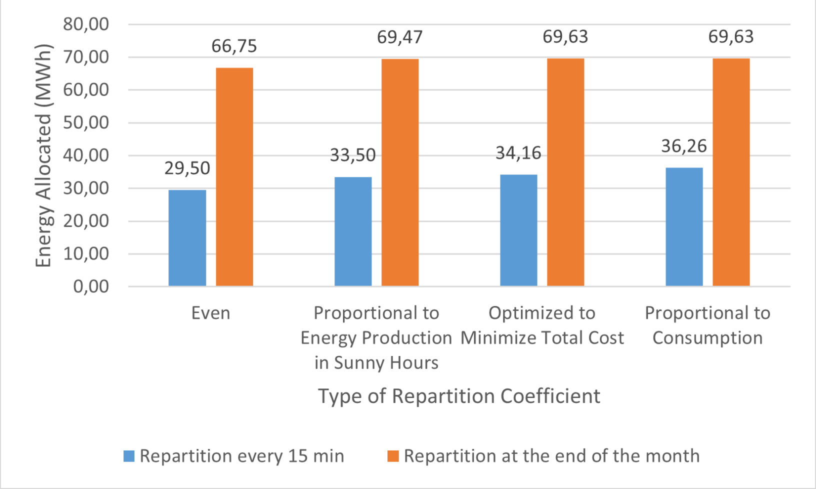


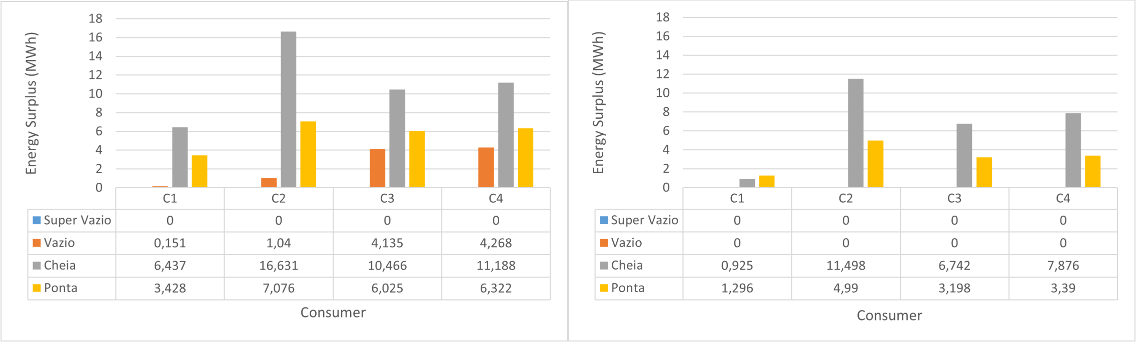
Figure 4.33: Difference in energy allocated between repartition every 15 minutes vs repartition at the end of each month.

Figure 4.33 demonstrates the energy allocated between repartition every 15 minutes and repartition at the end of each month for different repartition algorithms considered. It can be seen a tremendous increase of energy allocated in the repartition at the end of the month, where for all, except repartition through proportional to consumption, the value actually surpasses the double of the energy allocated in the repartition every 15 minutes.

It can be stated that, based on the results, data aggregation allows a higher allocation because it is no longer mandatory for consumers to consume the energy in that 15 min interval. Aggregation allows energy transfer between 15-minute intervals or even the transfer of energy from one day to another as long as it belongs to the same hourly period and to the same month. This flexibility of not obliging the consumers to use the allocated energy in those 15 minutes results in advantageous energy management for them.

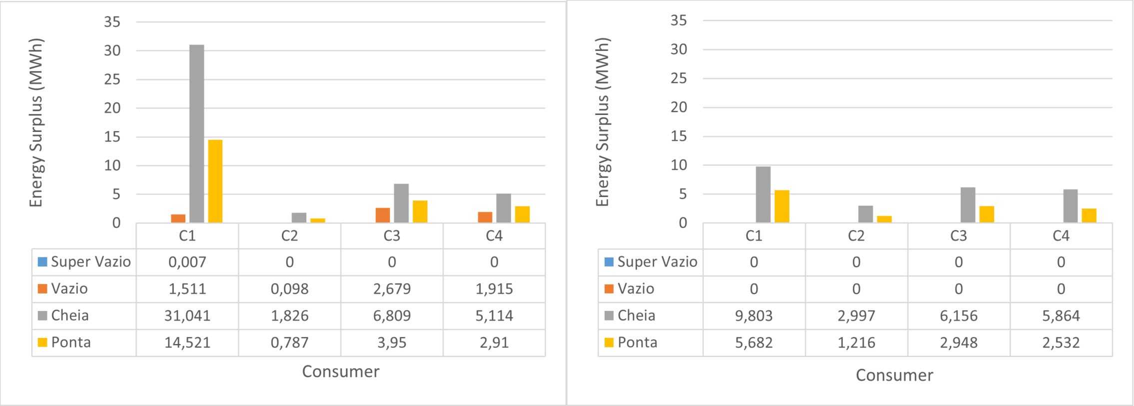
To try to explain in which hourly period this aggregation has the most effect, figures 4.34, 4.35, 4.36 and 4.37, present the energy surplus for the repartition every 15 minutes and the repartition at the end of each for the repartitions algorithms analyzed. It can be seen that, for both kinds of repartitions, there is no energy surplus for the *Super Vazio* period. However, the same is not true for the *Vazio* period. On the one hand, the repartition every 15 minutes presents energy surplus for all four repartitions algorithms studied. On the other hand, for repartition at the end of each month, all four repartition algorithms register zero energy surplus for that period.

For the *Cheia* and *Ponta* periods, in both kinds of repartition, there is a surplus of energy, but it should be noted that for all four repartition algorithms, the repartition every 15 minutes presented a higher value than the repartition at the end of each month.



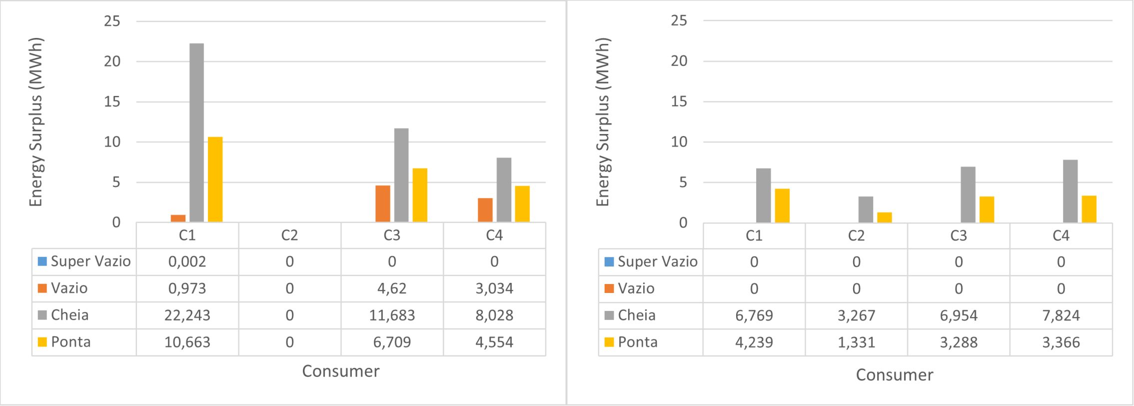
(a) Repartition every 15 minutes. (b) Repartition at the end of each month.

Figure 4.34: Energy Surplus for repartition every 15 minutes vs repartition at the end of each month for repartition through even coefficients.



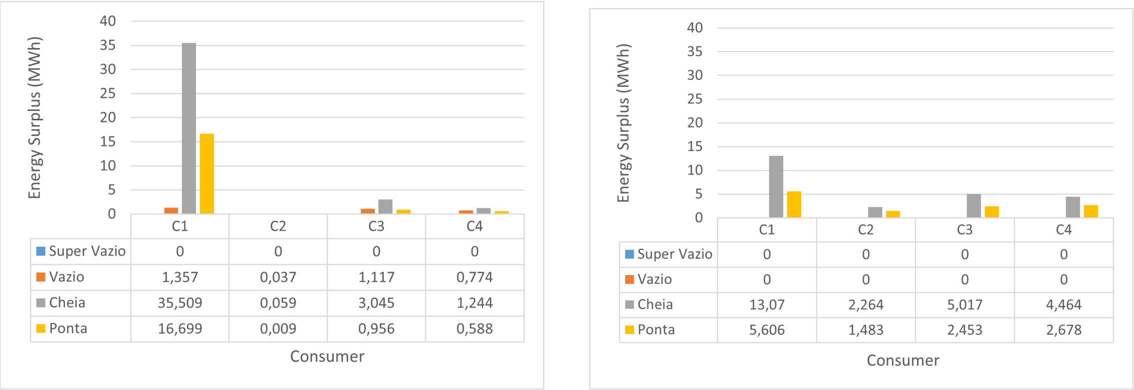
(a) Repartition every 15 minutes. (b) Repartition at the end of each month.

Figure 4.35: Energy Surplus for repartition every 15 minutes vs repartition at the end of each month for repartition through coefficients proportional to energy production in sunny hours



(a) Repartition every 15 minutes. (b) Repartition at the end of each month.

Figure 4.36: Energy Surplus for repartition every 15 minutes vs repartition at the end of each month for repartition through optimized coefficients to minimize total cost.



(a) Repartition every 15 minutes. (b) Repartition at the end of each month.

Figure 4.37: Energy Surplus for repartition every 15 minutes vs repartition at the end of each month for repartition through coefficients proportional to consumption.

Next, figure 4.38 shows the electricity bill for the aggregate of consumers for repartition every 15 minutes and repartition at the end of each month. It is clear that a significant reduction in cost for the consumers happens. The savings for consumers could reach values up to 7,33% between the two kinds of repartition for the different algorithms as shown in table 4.35.

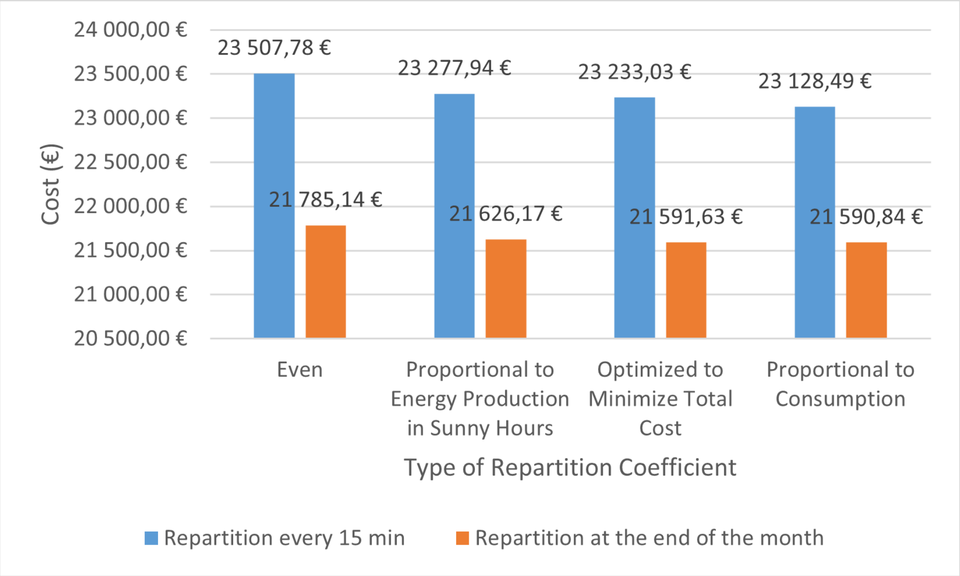


Figure 4.38: Difference in cost for the aggregate of consumers between repartition every 15 minutes vs repartition at the end of each month.

Table 4.35: The difference in Total Cost between repartition every 15 minutes and at the end of each month.

| **Type of Coefficients** | **The difference in Total Cost between repartition every 15 minutes and at the end of each month** |
|---|---|
| **Even** | -7,33% |
| **Proportional to Energy Production in Sunny Hours** | -7,10% |
| **Optimized to Minimize Total Cost** | -7,06% |
| **Proportional to Consumption** | -6,65% |

The aggregation results in a 14% to 15% decrease in the electricity bill compared to the electricity bill for the consumers before joining the REC, table 4.5.

Finally, looking at the profit for the CME, table 4.36, it can be seen that they can go up, and some can reach gains up to 24% in some algorithms. Note that, given the prices fixed for selling energy to consumers and to the grid, it is more profitable to sell energy to consumers. Therefore, since this kind of repartition allocates more REC energy, the profits are bigger.

Table 4.36: CME profits for repartition every 15 minutes vs repartition at the end of each month.

| **Type of Coefficients** | **Repartition every 15 minutes** | **Repartition at the end of each month** | **Difference** |
|---|---|---|---|
| **Equatitive** | 6 808,35 € | 8 670,98 € | 21,48% |
| **Proportional to Energy Production in Sunny Hours** | 7 008,39 € | 8 806,76 € | 20,42% |
| **Optimized to Minimize Final Cost** | 7 041,24 € | 8 814,77 € | 20,12% |
| **Proportional to Consumption** | 6 695,73 € | 8 814,95 € | 24,04% |

# Chapter 5

# Conclusions and Future Usefulness

This chapter presents the major conclusions obtained from the studies conducted in this dissertation. It also presents the answers to the research question this dissertation proposed responding to. Finally, it is discussed the future application of the developed.

## 5.1 Conclusions

The main goals of the present dissertation were to study different repartition algorithms in energy communities and analyze the economic benefits of each one for the consumers and the community as a whole.

The energy sector is undergoing a profound change to promote a transition to energy consumption from renewable sources. The European Parliament and Council took that first step by introducing Directive (EU) No. 2018/2001, with the intention of promoting the use of energy from renewable sources while keeping in mind the Union's target, which calls for the Member States to work together to ensure that the share of energy from renewable sources in the Union's gross final energy consumption is at least 32% in 2030. As part of this transition, the concept of a renewable energy community emerged as one of the solutions to help this process. A key problem to solve when implementing a REC is deciding how the energy produced in them should be distributed by its consumers, hence the importance of the studies conducted in this dissertation.

In chapter 3 was presented the different repartition algorithms elected to be studied in this work. In total, it was examined eight different types of repartition algorithms that fitted into two major categories: fixed coefficients and dynamic coefficients. There was also presented the different mathematical expressions for each one of them. The eight different repartition algorithms tested were those presented below. The first seven are classified as fixed coefficients, and the last one as dynamic.

- Repartition through even coefficients;
- Repartition through coefficients proportional to annual maximum energy consumption;
- Repartition through coefficients proportional to annual average energy consumption;

- Repartition through coefficients proportional to energy production in sunny hours;
- Repartition through coefficients proportional to energy production and consumption in sunny hours;
- Repartition through optimized coefficients to minimize total costs;
- Repartition through optimized coefficients indexed to hourly periods to minimize total costs;
- Repartition through coefficients proportional to consumption.

Chapter 4, started by presenting the community on which the proposed repartition algorithms were implemented to draw conclusions about each of them. Four major studies were conducted: the first was the one where the repartition was done every 15 minutes with the coefficients being maintained throughout a year. The second was the evaluation of CIEG payment exemption in the previously obtained results. The third study was the one in which the repartition was done every 15 minutes, but the coefficients changed for each month of the year. Finally, the fourth study was the one where the production and consumption data was aggregated by months and hourly periods, and repartition happened at the end of each month, and the coefficients remained the same throughout the year.

From the first study conducted, where the repartition was done every 15 minutes with the coefficients being maintained throughout a year, the repartition algorithm that presented the best performance by leading to a lower total cost for the community is the repartition through coefficients proportional to consumption. The dynamic of this algorithm allows the allocation of more energy to consumers and, consequently, to a lower energy price in €/kWh. The repartition through even coefficients yields the worse result from the analyzed algorithms, with the total cost being the highest. Looking only between the algorithm with fixed coefficients, the repartition through optimized coefficients indexed to hourly periods to minimize total costs resulted in the lower cost, and, if overlooking the optimized coefficients, the repartition through coefficients proportional to energy production in sunny hours was the one that presented the best results. However, it was interesting to conclude that, even though the repartition through coefficients proportional to consumption was best for the community, for the individual consumers, this last one was not the most cost-effect for any of them. Finally, in terms of profits for the community management entity, the repartition through optimized coefficients indexed to hourly periods to minimize total costs was the one that yielded the highest profit.

Other conclusions that could be drawn were that it is important to be considered in the algorithm what periods of the day are the production and consumption happening. Repartition through coefficients proportional to annual maximum energy consumption or coefficients proportional to annual average energy consumption do not take this fact into account. Assuming the production through solar energy and the consequent production profile during the day and consumers that have high consumption but it happens during nighttime, it will happen that it will be allocated a lot of the energy produced to those consumers, and if they do not have consumption during the day, that energy will always be sold to the grid, and that is not the goal.

The second study evaluated the importance of CIEG payment exemption in the previously obtained results. It was concluded that the exemption was, in fact, very important. All the previous tested repartitions presented a significant increase in the total cost when the consumers were not exempted from CIEG payment. For the repartition algorithm that presented the best result, repartition through coefficients proportional to consumption, the savings for the community reached 7,28%. By analyzing the prices of energy, it was concluded that the REC energy price was actually higher than the price of energy from the grid in the consumers did not dispose of the exemption of CIEG payment, meaning it would not be in the consumers' best interests to join a REC.

The third study was the repartition every 15 minutes, but the coefficients changed for each month of the year to see if an improvement of the total cost for consumers was registered. For this study, only four of the initial eight repartition coefficients were analyzed, and they were repartition through even coefficients, repartition through coefficients proportional to energy production in sunny hours, repartition through optimized coefficients to minimize total costs, and repartition through coefficients proportional to consumption. Due to the nature of the repartition through even coefficients and repartition through coefficients proportional to consumption, they presented the exact same result as expected. When it comes to repartition through coefficients proportional to energy production in sunny hours and repartition through optimized coefficients to minimize total costs, they, in fact, a lower price for the aggregate of consumers, but this difference was smaller than initially anticipated, less than 0,5% when comparing the two kinds of repartitions. The major conclusion that can be drawn is that if the consumers' consumption profile does not change from month to month, being able to change the coefficients each month does not bring any big advantages, and if the change of the coefficients monthly entails significant extra costs for consumers, this should not be applied.

The final study conducted was the one where production and consumption data were aggregated by months and hourly periods, and the repartition happened at the end of each month, and the coefficients remained the same throughout the year. The same four repartition algorithms were analyzed. It was seen a massive increase of energy allocated in this kind of repartition compared to the results obtained in the initial study. All, except repartition through proportional to consumption, presented more than doubled the energy allocated, and consequently, the total cost for the aggregate of consumers registered significant decreases, reaching 6,65% for the repartition through proportional to consumption.

This kind of repartition allows energy transfer between 15-minute intervals or even the transfer of energy from one day to another as long as it belongs to the same hourly period and to the same month. This flexibility of not obliging the consumers to use the allocated energy in those 15 minutes results in advantageous energy management for them. Note that, by considering the different hourly periods, the consumers will still pay the correct associated tariffs to the various hourly periods.

Summarizing, the major conclusions that can be drawn from the work developed in this dissertation are that the correct choice of repartition algorithm to implement in a REC can mean a significant reduction in costs for consumers. The repartition through dynamic coefficients proportional to consumption presented better results among those analyzed. Furthermore, the exemption of CIEG payments is essential for the participation of consumers in RECs to be feasible. Moreover, changing coefficients monthly only brings significant changes in costs when consumers' consumption profiles change drastically over the course of a year. And finally, aggregation of data by month and hourly period could be a very interesting solution to explore in the quest to reduce consumer costs.

## 5.2 Answers to the research questions

In chapter 1 it was stated the different research questions this dissertation proposed to answer. Therefore, in this section, it will be presented succinct answers to those questions based on the research performed and the conclusions drawn from the studies conducted.

- What are the different repartition algorithms that can be implemented?

After the research conducted in the elaboration of the state of the art on the subject of REC and repartition algorithms as well as the case studies carried out, it was possible to conclude that exist two major repartitions algorithms: the first is repartition algorithms through fixed coefficients and repartition algorithms through dynamic coefficients. In both cases, the algorithm is based on repartition coefficients that determine the percentage of REC energy production allocated to a certain consumer. In the case of the repartition through fixed coefficients, these coefficients are pre-defined before the repartition process and are not updated in each repartition moment, and can be affected by different variables to assist in their assignment to each consumer. In the case of the repartition algorithm through dynamic coefficients, the repartition coefficients are updated in every repartition moment, meaning that they can not be pre-defined, unlike the fixed ones. The only dynamic repartition coefficient identified is the repartition proportional to consumption.

- How can the fixed repartition coefficients be defined?

The fixed repartition coefficients can be defined by using consumption statistics, production statistics, or benchmarks. This dissertation explored seven types of fixed repartition coefficients that fit into the above-mentioned categories. Note that this production and consumption data, to define the repartition coefficients, can be from the previous year, if available, or from forecasting studies of production and consumers´ consumption.

The repartitions through coefficients proportional to the maximum energy consumption and through coefficients proportional to the average annual energy consumption are defined based on consumption statistics. The repartition through coefficients proportional to energy production in sunny hours is based on production statistics, and the repartition through coefficients proportional to energy production and consumption in sunny hours fits in both categories.

Finally, the fixed repartition coefficients can be defined by benchmarks, and, in this work, two kinds were explored: the first was even coefficients that only depend on the number of consumers, and the other was optimized coefficient to minimize the total cost for the aggregate of consumers.

- Is it possible to assign multiple coefficients broken down by hourly periods to the same consumer?

In the first case study, it was proven that assigning multiple repartition coefficients to the same consumer was viable. The repartition through coefficients indexed to hourly periods to minimize total cost yielded satisfactory outcomes, resulting in the lowest cost for the aggregate of consumers compared to the rest of the fixed coefficients with only a single repartition coefficient assigned to each consumer. Therefore, although it is not currently used under the present Portuguese legislation, assigning multiple coefficients broken down by hourly periods to the same consumer is achievable.

- Which is the best repartition algorithm through fixed coefficients?

The case studies carried out showed that the repartition through dynamic coefficients was the best, giving the lowest cost for the aggregate of consumers, leaving the question of which of the fixed coefficients was the best.

The first case study demonstrated that the repartition through coefficients proportional to the energy produced in sunny hours was the one that yielded the better cost for the aggregate of consumers. Effectively, it proves that taking into account the hours in which there is energy being produced allows better management and repartition of energy. The optimized coefficients were not considered in this evaluation because they are only optimal for the data they were optimized for.

- Is there an advantage to changing the coefficients monthly instead of keeping them all year round?

The third study demonstrated that changing the coefficients monthly instead of keeping them all year round did not bring big advantages for consumers, given that difference in total costs between the situations was very small.

It was concluded that if the consumers' consumption profile does not change from month to month, that is, the consumers maintained the same approximate percentage of consumption in relation to the total consumers' consumption, being able to change the coefficients each month does not bring any big advantages, and if the change of the coefficients monthly entails significant extra costs for consumers, this might not bring any advantages at all.

- Is it possible for the repartition to be done only at the end of each month, considering the different hourly periods?

The fourth study performed tested if it was possible for the repartition to be done only at the end of each month, considering the different hourly periods and it was concluded that it was possible. Not only that, this repartition allows more allocation of energy than the repartition every 15 minutes, which means a reduction in the total cost for the aggregate of the consumers. This repartition is advantageous to the consumers and also to the entity responsible for allocating the energy to the consumer because they only have to do it 12 times a year simplifying the process. Also, as long as the data is also aggregated by hourly periods, the energy suppliers will not be prejudicated because the consumers will pay the correspondent energy tariffs of each hourly period regarding the energy that comes from the grid.

- What is the influence of exempting consumers from paying certain grid tariffs?

In this dissertation was proven that the exemption of CIEG payment is essential for the consumers to be able to participate in a REC. Effectively, the cost for the consumers could increase up to 7% depending on the repartition coefficient. Furthermore, it was concluded that it would be unfeasible for consumers to participate in RECs if they did not dispose of CIEG payment exemption because the price of REC energy is higher than the price of the energy originating from the electrical grid.

## 5.3 Verification of dissertation objectives

Similar to the research questions, in chapter 1, it was stated the objectives of this dissertation, and in this section, a verification is performed to check if those defined goals.

The work developed in this dissertation allowed the achievement of all the objectives stated initially. The first study permitted the characterization of different repartition coefficients and the identification of the repartition through dynamic coefficients proportional to consumption as the one that resulted in the best outcome for the community.

Moreover, the study on the change of repartition coefficients every month enabled the evaluation of the advantages that this situation might bring to consumers, and the study of repartition at the end of each month, considering the different hourly periods, also allowed the evaluation of this particular repartition method.

Finally, the verification of the influence of CIEG payment exemption permitted the evaluation of the impact of exempting REC consumers from certain grid tariffs.

## 5.4 Future usefulness of the work developed

The conclusions drawn from this dissertation can be useful for countries that still do not have a legal framework for REC and how energy can be repartitioned. Effectively, based on the information exposed in this work, those countries can decide the best way to formulate their regulations on RECs, specifically on how to share the energy produced.

In countries that already have their legislation in place, such as Portugal, this dissertation may be useful for the CME to decide which type of repartition, through fixed or dynamic coefficients, is best suitable for the characteristics of that REC and how to define those coefficients.

Finally, specifically for Portugal, if the current legislation is revised, introducing the possibility of assigning multiple coefficients to the same consumer should be something to consider concerning the repartition of energy.

# Appendix A

# Glossary

For the purposes of this dissertation, it is defined:

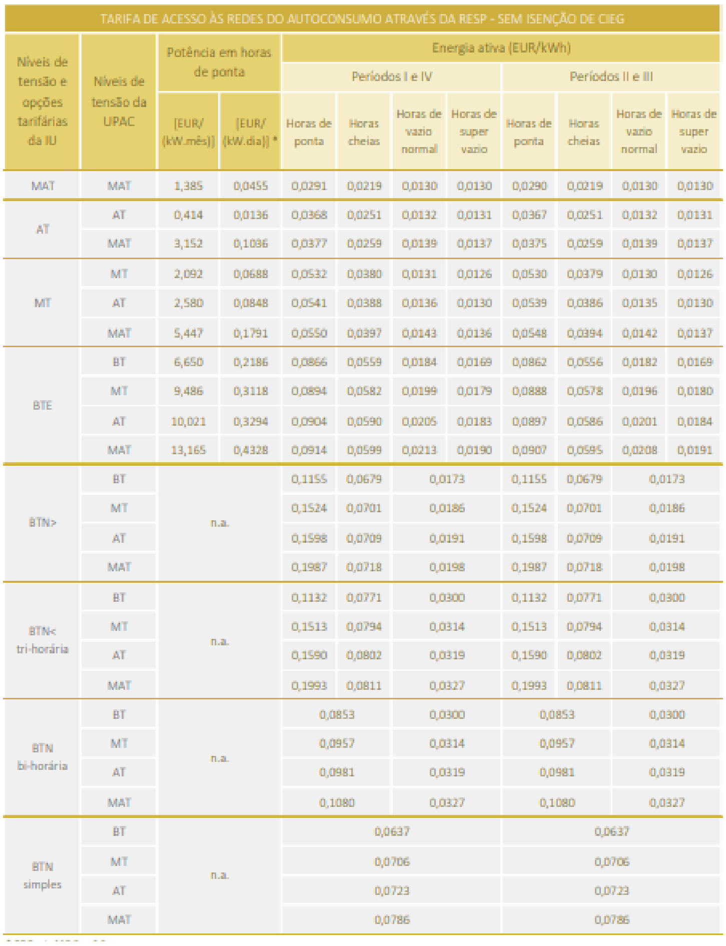
- **Aggregator:** It is the entity that aggregates the energy production within the REC.
- **Community Management Entity (CME):** It is the is the entity nominated by the REC to represent it. It is its job to manage the community in terms of energy shared between the members as well as its financial management.
- **Distribution System Operator:** It is responsible for the electrical grid operation, management, and maintenance. This entity might also assume the role of the entity responsible for measurement acquisition and information management involving data related to the consumption and production of REC members. This job can also be deferred to a dedicated company.
- **Energy Allocated:** It refers to the energy produced within the REC and that is shared with its members.
- **Energy Suppliers:** Entities whose activity involves the purchase and sale of energy, taking here the role of complementary suppliers in addition to the local energy. They supply any deficit and absorb any surplus of REC energy.
- **Energy Surplus:** Sometimes referred to as REC energy surplus and it should be understood as the energy produced within the REC and that is not shared with REC members, and is sold to the grid.
- **Investement Entities:** It is an entity that is responsible for the financial investment of the REC.
- **Internal Networks:** It refers to REC members that are connected to each other through privately own electrical networks, without the need to resort to the public grid.
- **Members:** Fit into three major categories: producer, consumer, and prosumer (producer and consumers at the same time). A producer is a member that owns renewable energy

production units and supplies said energy to the REC consumers. A producer can interact within the community with the role of only producer, not being obliged to be a consumer. A consumer is a member that uses energy produced within the REC to satisfy its needs. However, they also have access to external energy suppliers to complement their energy needs when the energy produced in the REC it is not enough. Finally, a member can be a prosumer, consisting of a consumer that uses energy produced within the REC but also owns energy production units.

- **REC:** Stands for renewable energy community and it can be refered in some occasions only as energy community. It is an entity where participants can join voluntarily and are referred to as members or shareholders. Legal entities that can represent RECs can be condominiums, consumer associations, cooperatives, autarchy or parish, building owners, developer companies, management companies, and investment companies, for example.
- **REC Energy:** It refers to the energy produced within the REC by member owned production units.

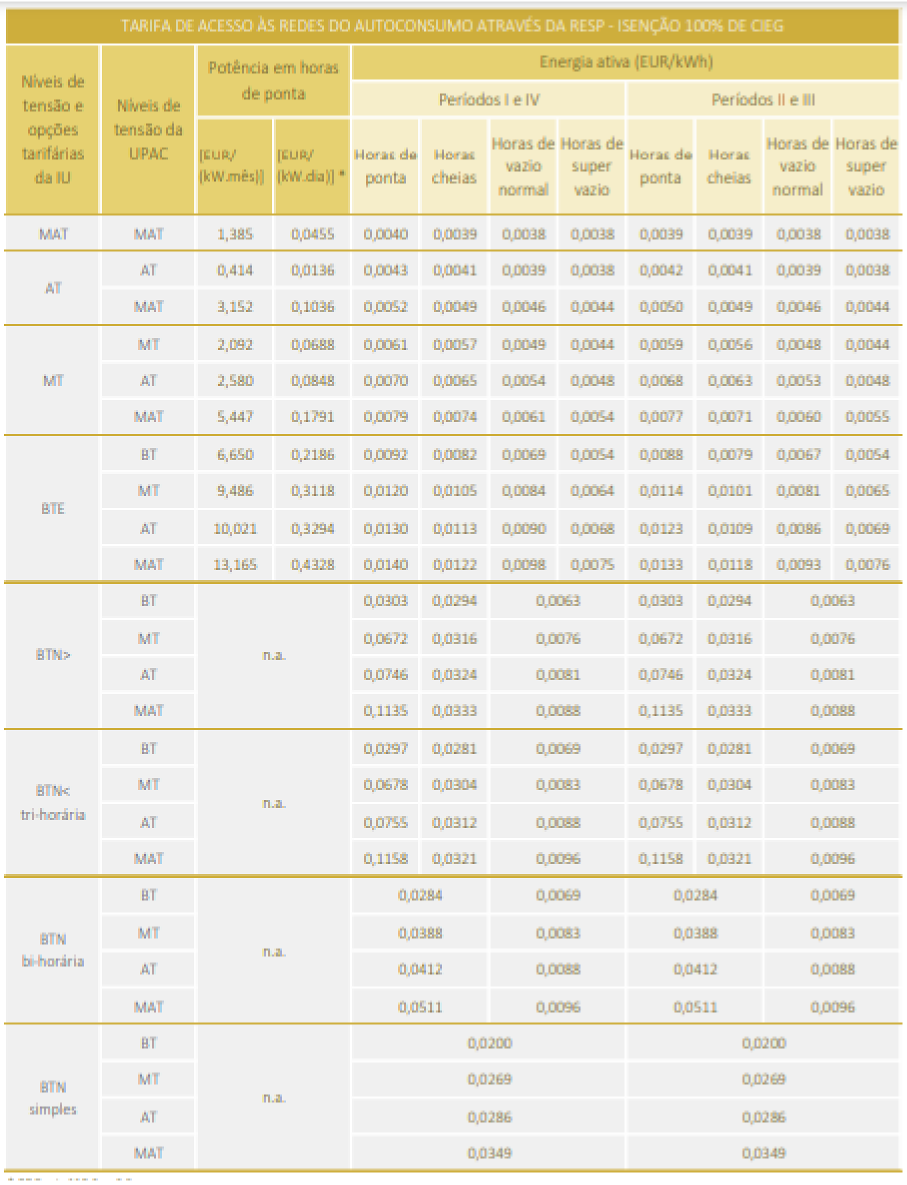
# Appendix B

# Network Access Tariff for Self-Consumption through the Public Network



| TARIFA DE ACESSO ÀS REDES DO AUTOCONSUMO ATRAVÉS DA RESP - SEM ISENÇÃO DE CIEG | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Níveis de tensão e opções tarifárias da IU | Níveis de tensão da UPAC | Potência em horas de ponta | | Energia ativa (EUR/kWh) | | | | | | | |
| | | | | Períodos I e IV | | | | Períodos II e III | | | |
| | | [EUR/(kW.mês)] | [EUR/(kW.dia)] * | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio |
| MAT | MAT | 1,385 | 0,0455 | 0,0291 | 0,0219 | 0,0130 | 0,0130 | 0,0290 | 0,0219 | 0,0130 | 0,0130 |
| AT | AT | 0,414 | 0,0136 | 0,0368 | 0,0251 | 0,0132 | 0,0131 | 0,0367 | 0,0251 | 0,0132 | 0,0131 |
| | MAT | 3,152 | 0,1036 | 0,0377 | 0,0259 | 0,0139 | 0,0137 | 0,0375 | 0,0259 | 0,0139 | 0,0137 |
| MT | MT | 2,092 | 0,0688 | 0,0532 | 0,0380 | 0,0131 | 0,0126 | 0,0530 | 0,0379 | 0,0130 | 0,0126 |
| | AT | 2,580 | 0,0848 | 0,0541 | 0,0388 | 0,0136 | 0,0130 | 0,0539 | 0,0386 | 0,0135 | 0,0130 |
| | MAT | 5,447 | 0,1791 | 0,0550 | 0,0397 | 0,0143 | 0,0136 | 0,0548 | 0,0394 | 0,0142 | 0,0137 |
| BTE | BT | 6,650 | 0,2186 | 0,0866 | 0,0559 | 0,0184 | 0,0169 | 0,0862 | 0,0556 | 0,0182 | 0,0169 |
| | MT | 9,486 | 0,3118 | 0,0894 | 0,0582 | 0,0199 | 0,0179 | 0,0888 | 0,0578 | 0,0196 | 0,0180 |
| | AT | 10,021 | 0,3294 | 0,0904 | 0,0590 | 0,0205 | 0,0183 | 0,0897 | 0,0586 | 0,0201 | 0,0184 |
| | MAT | 13,165 | 0,4328 | 0,0914 | 0,0599 | 0,0213 | 0,0190 | 0,0907 | 0,0595 | 0,0208 | 0,0191 |
| BTN> | BT | n.a. | | 0,1155 | 0,0679 | 0,0173 | | 0,1155 | 0,0679 | 0,0173 | |
| | MT | | | 0,1524 | 0,0701 | 0,0186 | | 0,1524 | 0,0701 | 0,0186 | |
| | AT | | | 0,1598 | 0,0709 | 0,0191 | | 0,1598 | 0,0709 | 0,0191 | |
| | MAT | | | 0,1987 | 0,0718 | 0,0198 | | 0,1987 | 0,0718 | 0,0198 | |
| BTN< tri-horária | BT | n.a. | | 0,1132 | 0,0771 | 0,0300 | | 0,1132 | 0,0771 | 0,0300 | |
| | MT | | | 0,1513 | 0,0794 | 0,0314 | | 0,1513 | 0,0794 | 0,0314 | |
| | AT | | | 0,1590 | 0,0802 | 0,0319 | | 0,1590 | 0,0802 | 0,0319 | |
| | MAT | | | 0,1993 | 0,0811 | 0,0327 | | 0,1993 | 0,0811 | 0,0327 | |
| BTN bi-horária | BT | n.a. | | 0,0853 | | 0,0300 | | 0,0853 | | 0,0300 | |
| | MT | | | 0,0957 | | 0,0314 | | 0,0957 | | 0,0314 | |
| | AT | | | 0,0981 | | 0,0319 | | 0,0981 | | 0,0319 | |
| | MAT | | | 0,1080 | | 0,0327 | | 0,1080 | | 0,0327 | |
| BTN simples | BT | n.a. | | 0,0637 | | | | 0,0637 | | | |
| | MT | | | 0,0706 | | | | 0,0706 | | | |
| | AT | | | 0,0723 | | | | 0,0723 | | | |
| | MAT | | | 0,0786 | | | | 0,0786 | | | |

Figure B.1: Network Acess Tariff for Self-Consumption through the Public Network - Without CIEG Exemption. Source: [29].



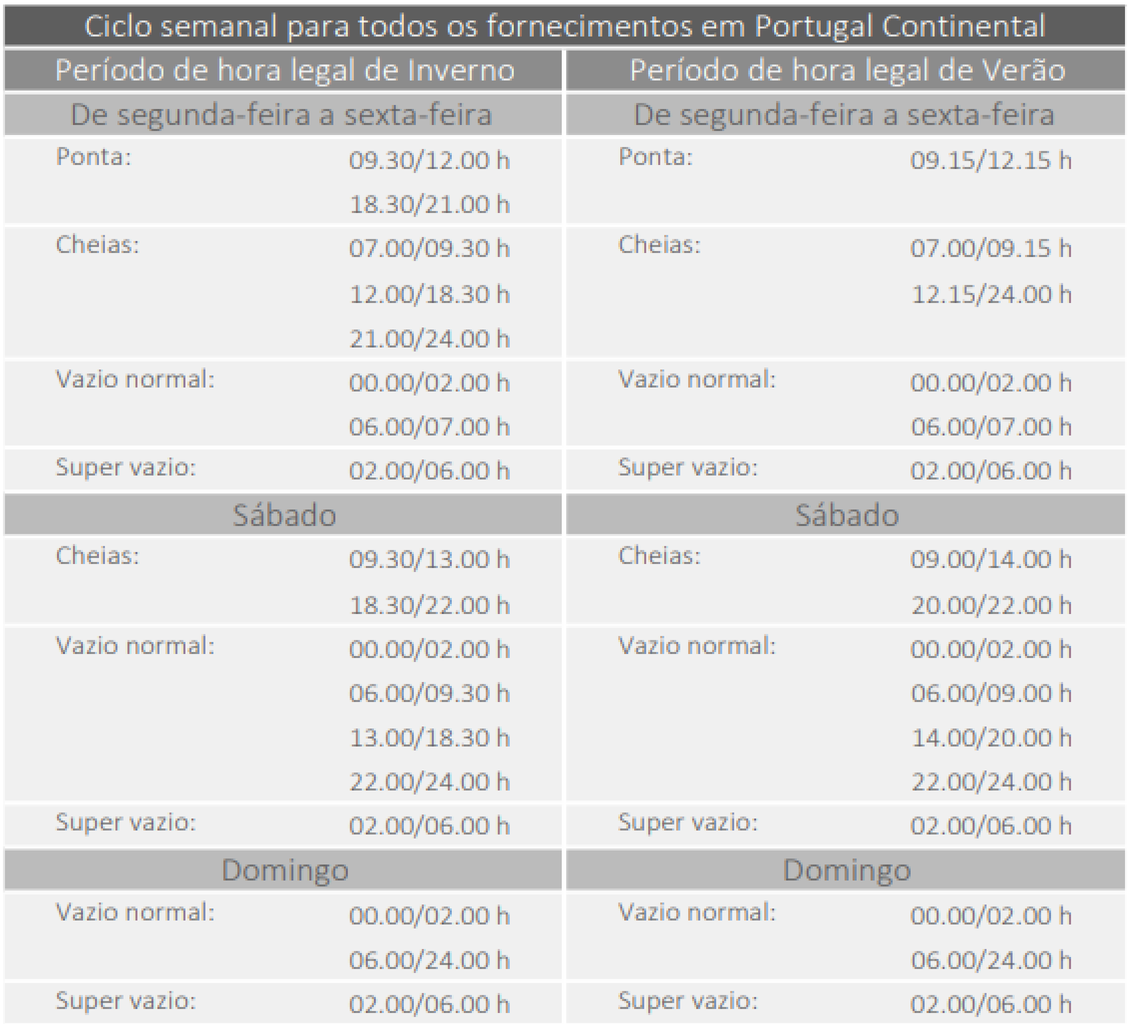
TARIFA DE ACESSO ÀS REDES DO AUTOCONSUMO ATRAVÉS DA RESP - ISENÇÃO 100% DE CIEG

| Níveis de tensão e opções tarifárias da IU | Níveis de tensão da UPAC | Potência em horas de ponta | | Energia ativa (EUR/kWh) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Períodos I e IV | | | | Períodos II e III | | | |
| | | [EUR/(kW.mês)] | [EUR/(kW.dia)] * | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio | Horas de ponta | Horas cheias | Horas de vazio normal | Horas de super vazio |
| MAT | MAT | 1,385 | 0,0455 | 0,0040 | 0,0039 | 0,0038 | 0,0038 | 0,0039 | 0,0039 | 0,0038 | 0,0038 |
| AT | AT | 0,414 | 0,0136 | 0,0043 | 0,0041 | 0,0039 | 0,0038 | 0,0042 | 0,0041 | 0,0039 | 0,0038 |
| | MAT | 3,152 | 0,1036 | 0,0052 | 0,0049 | 0,0046 | 0,0044 | 0,0050 | 0,0049 | 0,0046 | 0,0044 |
| MT | MT | 2,092 | 0,0688 | 0,0061 | 0,0057 | 0,0049 | 0,0044 | 0,0059 | 0,0056 | 0,0048 | 0,0044 |
| | AT | 2,580 | 0,0848 | 0,0070 | 0,0065 | 0,0054 | 0,0048 | 0,0068 | 0,0063 | 0,0053 | 0,0048 |
| | MAT | 5,447 | 0,1791 | 0,0079 | 0,0074 | 0,0061 | 0,0054 | 0,0077 | 0,0071 | 0,0060 | 0,0055 |
| BTE | BT | 6,650 | 0,2186 | 0,0092 | 0,0082 | 0,0069 | 0,0054 | 0,0088 | 0,0079 | 0,0067 | 0,0054 |
| | MT | 9,486 | 0,3118 | 0,0120 | 0,0105 | 0,0084 | 0,0064 | 0,0114 | 0,0101 | 0,0081 | 0,0065 |
| | AT | 10,021 | 0,3294 | 0,0130 | 0,0113 | 0,0090 | 0,0068 | 0,0123 | 0,0109 | 0,0086 | 0,0069 |
| | MAT | 13,165 | 0,4328 | 0,0140 | 0,0122 | 0,0098 | 0,0075 | 0,0133 | 0,0118 | 0,0093 | 0,0076 |
| BTN> | BT | n.a. | | 0,0303 | 0,0294 | 0,0063 | | 0,0303 | 0,0294 | 0,0063 | |
| | MT | | | 0,0672 | 0,0316 | 0,0076 | | 0,0672 | 0,0316 | 0,0076 | |
| | AT | | | 0,0746 | 0,0324 | 0,0081 | | 0,0746 | 0,0324 | 0,0081 | |
| | MAT | | | 0,1135 | 0,0333 | 0,0088 | | 0,1135 | 0,0333 | 0,0088 | |
| BTN< tri-horária | BT | n.a. | | 0,0297 | 0,0281 | 0,0069 | | 0,0297 | 0,0281 | 0,0069 | |
| | MT | | | 0,0678 | 0,0304 | 0,0083 | | 0,0678 | 0,0304 | 0,0083 | |
| | AT | | | 0,0755 | 0,0312 | 0,0088 | | 0,0755 | 0,0312 | 0,0088 | |
| | MAT | | | 0,1158 | 0,0321 | 0,0096 | | 0,1158 | 0,0321 | 0,0096 | |
| BTN bi-horária | BT | n.a. | | 0,0284 | | 0,0069 | | 0,0284 | | 0,0069 | |
| | MT | | | 0,0388 | | 0,0083 | | 0,0388 | | 0,0083 | |
| | AT | | | 0,0412 | | 0,0088 | | 0,0412 | | 0,0088 | |
| | MAT | | | 0,0511 | | 0,0096 | | 0,0511 | | 0,0096 | |
| BTN simples | BT | n.a. | | 0,0200 | | | | 0,0200 | | | |
| | MT | | | 0,0269 | | | | 0,0269 | | | |
| | AT | | | 0,0286 | | | | 0,0286 | | | |
| | MAT | | | 0,0349 | | | | 0,0349 | | | |

Figure B.2: Network Acess Tariff for Self-Consumption through the Public Network - With 100% CIEG Exemption. Souce: [29].

# Appendix C

# Daily and Weekly Cycles



| Ciclo semanal para todos os fornecimentos em Portugal Continental | | | |
|---|---|---|---|
| Período de hora legal de Inverno | | Período de hora legal de Verão | |
| De segunda-feira a sexta-feira | | De segunda-feira a sexta-feira | |
| Ponta: | 09.30/12.00 h<br>18.30/21.00 h | Ponta: | 09.15/12.15 h |
| Cheias: | 07.00/09.30 h<br>12.00/18.30 h<br>21.00/24.00 h | Cheias: | 07.00/09.15 h<br>12.15/24.00 h |
| Vazio normal: | 00.00/02.00 h<br>06.00/07.00 h | Vazio normal: | 00.00/02.00 h<br>06.00/07.00 h |
| Super vazio: | 02.00/06.00 h | Super vazio: | 02.00/06.00 h |
| Sábado | | Sábado | |
| Cheias: | 09.30/13.00 h<br>18.30/22.00 h | Cheias: | 09.00/14.00 h<br>20.00/22.00 h |
| Vazio normal: | 00.00/02.00 h<br>06.00/09.30 h<br>13.00/18.30 h<br>22.00/24.00 h | Vazio normal: | 00.00/02.00 h<br>06.00/09.00 h<br>14.00/20.00 h<br>22.00/24.00 h |
| Super vazio: | 02.00/06.00 h | Super vazio: | 02.00/06.00 h |
| Domingo | | Domingo | |
| Vazio normal: | 00.00/02.00 h<br>06.00/24.00 h | Vazio normal: | 00.00/02.00 h<br>06.00/24.00 h |
| Super vazio: | 02.00/06.00 h | Super vazio: | 02.00/06.00 h |

Figure C.1: Weekly Cycle fo BTE and BTN in mainland Portugal in 2023. Source: [31].

Ciclo diário para BTE e BTN em Portugal Continental

| Período de hora legal de Inverno | | Período de hora legal de Verão | |
|---|---|---|---|
| Ponta: | 09.00/10.30 h | Ponta: | 10.30/13.00 h |
| | 18.00/20.30 h | | 19.30/21.00 h |
| Cheias: | 08.00/09.00 h | Cheias: | 08.00/10.30 h |
| | 10.30/18.00 h | | 13.00/19.30 h |
| | 20.30/22.00 h | | 21.00/22.00 h |
| Vazio normal: | 06.00/08.00 h | Vazio normal: | 06.00/08.00 h |
| | 22.00/02.00 h | | 22.00/02.00 h |
| Super vazio: | 02.00/06.00 h | Super vazio: | 02.00/06.00 h |

Figure C.2: Weekly Cycle fo BTE and BTN in mainland Portugal in 2023. Source: [31].

# Appendix D

# Repartition coefficients that change monthly

Table D.1: Repartition coefficients for even coefficients

| Month | Consumer C1 | Consumer C2 | Consumer C3 | Consumer C4 |
|---|---|---|---|---|
| **January** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **February** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **March** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **April** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **May** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **June** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **July** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **August** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **Spetember** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **October** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **November** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **December** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |

Table D.2: Repartition coefficients proportional to energy production in sunny hours

| Month | Consumer C1 | Consumer C2 | Consumer C3 | Consumer C4 |
|---|---|---|---|---|
| **January** | 0,5966 | 0,0522 | 0,2070 | 0,1441 |
| **February** | 0,5347 | 0,0434 | 0,2126 | 0,2093 |
| **March** | 0,7045 | 0,0195 | 0,1695 | 0,1065 |
| **April** | 0,7145 | 0,0156 | 0,1915 | 0,0784 |
| **May** | 0,7901 | 0,0096 | 0,1418 | 0,0585 |
| **June** | 0,7976 | 0,0084 | 0,0924 | 0,1017 |
| **July** | 0,8894 | 0,0123 | 0,0518 | 0,0466 |
| **August** | 0,8696 | 0,0209 | 0,0609 | 0,0486 |
| **Spetember** | 0,6695 | 0,0137 | 0,2164 | 0,1004 |
| **October** | 0,5597 | 0,0208 | 0,2075 | 0,2119 |
| **November** | 0,5681 | 0,0501 | 0,2156 | 0,1662 |
| **December** | 0,5317 | 0,0685 | 0,2360 | 0,1638 |

Table D.3: Repartition coefficients optimized to minimize total cost

| Month | Consumer C1 | Consumer C2 | Consumer C3 | Consumer C4 |
|---|---|---|---|---|
| **January** | 0,6556 | 0,0000 | 0,1905 | 0,1539 |
| **February** | 0,5251 | 0,0000 | 0,2529 | 0,2219 |
| **March** | 0,5031 | 0,0000 | 0,2662 | 0,2306 |
| **April** | 0,5764 | 0,0000 | 0,3095 | 0,1141 |
| **May** | 0,6081 | 0,0000 | 0,2668 | 0,1251 |
| **June** | 0,5355 | 0,0000 | 0,2471 | 0,2174 |
| **July** | 0,5916 | 0,0000 | 0,2028 | 0,2056 |
| **August** | 0,5200 | 0,0442 | 0,2317 | 0,2041 |
| **Spetember** | 0,4797 | 0,0000 | 0,3097 | 0,2106 |
| **October** | 0,4381 | 0,0000 | 0,2819 | 0,2801 |
| **November** | 0,5624 | 0,0000 | 0,2376 | 0,2000 |
| **December** | 0,5925 | 0,0000 | 0,2571 | 0,1504 |

# Appendix E

# Repartition coefficients where the data is aggregated by months and hourly periods

Table E.1: Repartition coefficients for the different repartition algorithms

| **Type of Coefficients** | **Consumer C1** | **Consumer C2** | **Consumer C3** | **Consumer C4** |
|---|---|---|---|---|
| **Equatitive** | 0,2500 | 0,2500 | 0,2500 | 0,2500 |
| **Proportional to Energy Production in Sunny Hours** | 0,4491 | 0,1016 | 0,2386 | 0,2108 |
| **Optimized to Minimize Total Cost** | 0,3900 | 0,1068 | 0,2541 | 0,2490 |

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