

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO



Local Electricity Market Simulator for Energy Communities

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Resumo

As Comunidades de Energias Renováveis são uma excelente medida para a sustentabilidade do planeta. Permitem uma melhor gestão dos recursos energéticos, trazendo benefícios para todos os *prosumers* pertencentes à comunidade.

Com um mercado local de energia dentro de uma comunidade de energia renovável, é possível vender ou comprar energia entre os membros participantes, sendo cada membro responsável pela apresentação de uma proposta.

Ao longo deste documento foi elaborado um estudo do comportamento de diferentes tipos de mecanismos de cálculo do preço num Mercado Energético Local dentro de uma Comunidade de Energia Renovável, acrescentando quatro novos mecanismos aos já existentes.

Palavras-chave: Comunidades de Energia Renovável, Mercado Energético Local, *Prosumer*, Mecanismos de Cálculo do Preço, Preço Interno.

Abstract

Renewable Energy Communities are an excellent measure for the sustainability of the planet. They allow for better management of energy resources, bringing benefits to all prosumers belonging to the community.

With a local energy market within a renewable energy community, it is possible to sell or buy energy between participating members, with each member being responsible for submitting a bid.

This thesis will study the behaviour of different pricing mechanisms in a Local Energy Market inside a Renewable Energy Community, adding four new mechanisms to the existing ones.

Keywords: Renewable Energy Communities, Local Energy Market, Prosumer, Pricing Mechanisms, Internal Price.

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O meu muito sincero Obrigado.

João Pinho

*“As nossas capas, rotas, velhinhas
Todas de negro, tremem no ar
São andorinhas, são andorinhas
Que se preparam p’ra migrar”*

As Nossas Capas, Grupo de Fados da Faculdade de Engenharia da Universidade do Porto

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Abbreviations and Symbols

AC	Allocation Coefficient
BTM	Behind The Meter
CSC	Collective Self-Consumption
DER	Distributed Energy Resources
DGEG	Directorate-General for Energy and Geology
DSO	Distribution System Operator
ESS	Energy Storage Systems
ISC	Individual Self-Consumption
ISP	Interval Settlement Period
IU	Installation of Use
LEM	Local Energy Market
MMR	Mid Market Rate
REC	Renewable Energy Community
RES	Renewable Energy Sources
EGAC	Self-Consumption Management Entity
SCPU	Self-Consumption Production Unit
SDR	Supply and Demand Ratio
SDRC	Supply and Demand Ratio Compensated
SDRC-Half	Supply and Demand Ratio Compensated-Half

Chapter 1

Introduction

In this chapter, the most general aspects of the thesis will be presented, including the motivation for the development of the study, Portuguese and European Legislation for Renewable Energy Communities and Self-Consumption Production Units, which are subject to change, the dissertation's objectives, and the document's structure.

1.1 Context and Motivation

In 2019, renewable energy contributed 26.4%, [1], to the total energy produced, with energy obtained from fossil fuels equal to 61.3% and nuclear power with 10.4%. It should be noted that these energy sources from the combustion of fossil fuels release large amounts of CO_2 at the end of the year.

Given this data, reducing CO_2 emissions and making our planet as sustainable as possible becomes necessary. The installation of distributed generation units in a Renewable Energy Community (REC) makes it possible to reduce dependence on power stations that produce energy from fossil fuels, making it possible to realise the goal of reducing the CO_2 emissions, [2].

The Self-Consumption Production Units (SCPU) are installed for individual and collective self-consumption in REC. In general, self-consumption can be defined as an electricity production model, which can be renewable or non-renewable, in which the energy produced is used by the prosumer himself, and surplus energy may be produced.

Self-consumption systems with injection into the grid are considered in the REC and produce energy according to the consumption needs of the installation and the possibility of storing energy in the system itself. If the system does not have a storage unit, all the surplus must be injected into the grid.

Two possibilities arise. One where storing the surplus in a battery is possible, where an optimization process can manage the battery usage. The other possibility is for the prosumer to actively enter the local market by presenting their surplus as a selling proposition or selling to the retailer or an aggregator if they have a licence.

The advantages of Self-Consumption can be summarised as energy efficiency, climate protection, and the possibility for prosumers to participate in energy transactions. Self-consumption also provides prosumers with the ability to control their electricity bills better. On a more global level, introducing Self-Consumption may facilitate the planning and operation of distribution networks and lead to the development of storage equipment, intelligent appliances, and more flexible contracts for prosumers.

1.2 Legislation and Regulation

This section will address the essential Portuguese decrees regulating REC and SCUP. Decree-Law No. 15/2022, [3], addresses, among other, the legislation for producing electricity by production units based on renewable energy intended for Self-Consumption at the Installation of Use (IU). These are referred to as Self-Consumption Production Units.

According to the decree above, self-consumption is the electricity consumption from one or more SCUP by one or more prosumers. The final consumer is considered a REC prosumer and can store. Self-consumption can be of two types, individual or collective, regardless of voltage level.

In Individual Self-Consumption (ISC), the energy is consumed by the IU where the SCUP is installed, and the owner, if he has surplus production, may store or sell the surplus energy. The legal framework allows ending consumers to keep or trade renewable electricity. However, these activities cannot be the primary commercial focus in non-domestic settings.

Collective Self-Consumption (CSC) refers to the consumption made in two or more use installations. Within a collective self-consumption regime, participating prosumers must follow internal regulations. The main points of this internal regulation focus on the access requirements for new prosumers, the exit of existing prosumers, the mode of sharing the energy produced for self-consumption, the destination of the self-consumption surplus, payment of tariffs when applicable, and the commercial relationship policy to be adopted.

An essential aspect of a SCUP is the concept of proximity. The concept of proximity includes the UPAC and the IUs connected by direct line or internal network or when they operate through the RESP at different voltage levels. Based on Decree-Law No. 15/2022, SCUP and user facilities must be connected by the internal network, this network being a private service network, installed within a geographical limit or through the Public Service Electricity Grid (PSEG), with the use of the latter mentioned implying the accounting of network access tariffs and applicable taxes and fees. Proximity does not apply to private networks.

Self-consumption activities require the prior control procedures set out in Article 11 of the Decree-Law No. 15/2022 and depend on the installed power of the SCUP. A title is issued by the Directorate-General for Energy and Geology (DGEG), a Portuguese public body responsible for inspecting electrical installations. This title depends on whether the self-consumption is individual or collective; if it is individual, the title is attributed to the prosumer. If it is collective, it is attributed to a Self-Consumption Management Entity (EGAC).

SCME is responsible for the practice of acts of operational management of the current activity, including the control of the internal network when it exists; for the articulation with the DGEG electronic management platform; for the connection with the RESP and the articulation with the respective operators, namely in what concerns production sharing and allocation coefficients; for the commercial relationship to be adopted for the surplus; for other functions that are assigned to it by the self-consumers that are part of this CSC.

The Decree-Law No. 15/2022 incorporates the concept of Renewable Energy Communities in alignment with the European Directive (EU) 2018/2001, [4]. This legal framework enables self-consumers of renewable energy to actively participate in producing, consuming, storing, sharing, and engaging in the energy market without financial burdens. The REC is defined as a legally established entity operating on an open and voluntary basis, comprising members, partners, or shareholders that can be natural or legal entities, both public and private. Notably, these entities, including small and medium-sized enterprises or local authorities, must be near renewable energy projects or associated activities.

The REC operates autonomously and responsibility for its operation lies with the participating prosumers. This distinguishes it from the CSC model, in which management responsibilities are assigned to the group of self-consumers, governed by internal regulations. In REC, a collective entity comprising community members and additional participants without ownership in the energy production units assumes management. Nonetheless, both models facilitate peer-to-peer energy trading.

1.3 Objectives

The objective of this thesis is to simulate, study and analyze the behaviour of LEM based on the participating prosumers and their resources, which can be photovoltaic panels and batteries, more formally known as Energy Storage Systems (ESS). By using different mechanisms to calculate the market price, it is possible to obtain different LEM behaviours, making it possible to increase or decrease energy exchanges between prosumers and how these exchanges influence the REC.

The simulation software developed aims to optimize the resources of prosumers connected to the REC in two phases, using an optimization function used in previous work. The same software calculates the market price, and the amount of energy traded that results from prosumers' bids, also taking into account the management of flexible resources and their impact on the price. It assumes a post-delivery market design and analyses the behaviour of this market considering different scenarios of participants and resources, [5], [6], [7], [8].

The software was developed in Python, starting from battery management optimization software and local prices computation routines previously developed and provided by INESC TEC.

1.4 Structure

This Dissertation document includes a literature review in **Chapter 2**, where previous studies and theoretical concepts such as renewable energy communities, local energy markets, optimization algorithms and pricing mechanisms are addressed.

Chapter 3 describes the structure of the renewable energy community considered, the optimization algorithm considered, the pricing mechanisms used and which will be analysed and, finally, the programme structure used to simulate the REC operation and the LEM internal price calculation

Chapter 4 explains the scenarios created to simulate the REC operation and contains the analysis of the results from the simulations.

Lastly, in **Chapter 5** contains the conclusions drawn from the work.

Chapter 2

Literature Review

2.1 Introduction

This chapter will review the literature on REC and LEM. The main topics are the functioning of a REC, market pricing mechanisms, and types of local energy markets. Since the main focus of this dissertation is to simulate LEM, previously used simulators will also be covered.

These themes are relevant to the dissertation since they are directly related to the work developed and are the basis of it.

2.2 Renewable Energy Communities

In [4], a Renewable Energy Community is defined as a collective entity established, whether for profit or not, based on open and voluntary membership by its members, partners or shareholders, who can be natural or legal persons, of public or private nature, including, namely, small and medium-sized enterprises or local authorities, which is autonomous from its members or partners, but effectively controlled by them.

In [7], the final consumer is considered essential to achieve the national energy and climate plans targets (NECPs), [9]. Thus, final consumers are now considered self-generators of renewable energy or prosumers. Prosumers can participate in CSC and REC where LEM mechanisms are in place that facilitate the sale of surplus energy produced.

REC are an association of prosumers and consumers that can produce, consume, store, sell and share renewable energy. These communities are a way to promote the distribution of renewable energy sources (RES) and local energy trading and enable prosumers to play an active role in LEM, [10].

Since prosumers can sell their energy surplus to other REC prosumers, they will obtain an economic benefit compared to feed-in tariff revenues or direct trading in wholesale electricity markets (not applied to small consumers). These prosumers sell the energy in the LEM, which is considered a structure to organise the energy exchanges, peer-to-peer or bilateral contracts, inside the REC, [6], [7].

LEM enhance the grid's reliability and resilience by generating energy close to where it is consumed. This proximity reduces energy losses and strengthens the overall stability of the grid, resulting in more efficient energy distribution, [11].

Prosumers can accomplish self-consumption inside the REC in two ways: behind the meter or with external generation facilities owned by themselves or other REC members. Behind the meter, readings consider the energy generated, subtracting it from the consumption, and the retailer only charges for the actual supply, considering this adjustment. For the energy share internally, the REC manager sends the Allocation Coefficient (AC) to the Distribution System Operator (DSO) or the entity responsible for the metering, [5].

2.2.1 Examples of REC

The first REC in Portugal appeared in 2021 in Miranda do Douro through an investment by Santa Casa da Misericórdia. The photovoltaic generation feeds the buildings of the Santa Casa facilities, and in case of excess, the extra energy is given to the fire brigade and the municipality, [12].

Another example of a REC in Portugal is in Lanheses Business Park in Viana do Castelo. This is a REC in a business context and involves companies such as Steep Plastique, Recial, Equinovento, Eurostyle Systems Portugal and BorgWarner. In this case, the companies produce energy through photovoltaic and wind power to reduce costs associated with energy expenses [13].

Another example of a REC in Portugal is in Lanheses Business Park in Viana do Castelo. This is a REC in a business context and involves companies such as Steep Plastique, Recial, Equinovento, Eurostyle Systems Portugal and BorgWarner. In this case, the companies produce energy through photovoltaic and wind power to reduce costs associated with energy expenses, [13].

In Europe, the ElektrizitätsWerke Schönau is a REC founded by a group of anti-nuclear activists in 1994 in Schönau, Germany. Today, it has more than 185000 users and owns wind and solar parks and gas and electricity grids. Some objectives of this REC are to contribute to increasing public knowledge about the environmental and health risks associated with nuclear energy production, reduce the community's energy consumption, and persuade the local utility company to exclude nuclear energy from its energy sources, [14].

2.3 Local Energy Markets

As mentioned, prosumers can sell their extra energy in a LEM to other consumers at competitive prices, depending on the total cost, which includes energy and grid tariffs. This means a prosumer can take two active positions, selling energy to and buying energy from other prosumers in the REC.

Combining all these factors leads to an economic benefit to the community compared to the more traditional method, where the consumer buys energy from the retailer. Thus, a LEM can be considered a market structure to organise energy exchanges in a REC.

Reference [11] outlines some possible disadvantages of LEM. Firstly, the current grid access tariffs encourage investment in Distributed Energy Resources (DER) without considering the electricity system's sustainability. Significant additions of Renewable Energy Sources (RES) can cause vulnerabilities in the grid, such as voltage changes or lower power quality, which can increase the complexity of distributed grid operation. Secondly, it raises the question of to what extent private DER is more profitable than an on-grid generation, which allows economies of scale and larger facilities efficiencies.

According to [15], there are three types of marketplaces: Peer-to-Peer (P2P), Community or Collective Self-Consumption (CSC) and Transactive Energy (TE), and the authors have reviewed these market types based on 139 articles that are referenced in [15]. These marketplaces are explained next.

2.3.1 Types of Local Energy Markets

2.3.1.1 Peer-to-Peer

The Peer-to-Peer (P2P) market type offers a promising solution for the future of electric power systems. P2P is characterised by its flexible energy sharing, allowing users to negotiate energy exchanges with each other freely, [11]. P2P aims to create a decentralised and democratised electricity market, enabling individuals to generate energy from RES and sell the surplus energy to others. Numerous pilot projects have already implemented this market concept, where consumers, organised as energy communities, directly generate, use, store, and exchange energy without intermediaries.

The communication between peers in P2P can be classified into two schemes: centralised and decentralised. In the centralised scheme, information flows from each peer to a centralised platform. In contrast, the decentralised scheme involves bilateral communication using a P2P network like blockchain. Reference [16] provides a detailed description of both systems.

Various market designs should be considered to adapt a Local Energy Market (LEM) to different geographical locations, regulations, and resources. In [17], a post-delivery LEM is proposed, where peers engage in bilateral energy trading after the delivery period. This model aims to create an energy trading compliant with the current regulatory framework.

The potential economic benefits provided by P2P marketplaces are crucial for the widespread adoption of this concept. In [11], the economic viability of P2P transactions among regular low-voltage customers in Portugal is examined. The research determines that the financial success of these transactions relies on several factors, including regulations (such as discounts on network use tariffs, consumer/producer rights and responsibilities, organisational models, and the role of energy suppliers), the physical configuration of the distribution network, and the resources involved (including the capacity of distributed generation and consumption patterns).

2.3.1.2 Community Self-Consumption

REC prosumers participating in the CSC market design involves trading their energy surplus within a specific community arrangement, [18]. This idea originated from the regulatory framework discussed in Section 2.3, which emphasises the empowerment of energy prosumers. While participants in P2P markets can directly trade energy among themselves or through centralised intermediaries, CSC participants are situated within a community and thus operate more collaboratively.

The governance process within a community plays an essential role in the CSC approach. In [19], a market structure based on the community is introduced, wherein members are overseen by a third party responsible for interfacing with the LEM and system operator and ensuring compliance with collective agreements. A centralised governance model can optimize a predefined global objective since a single entity possesses complete knowledge of the community's data. Conversely, a decentralised scheme can safeguard members' privacy and foster trust in the market's operations. Both can be compatible depending on the implementation.

2.3.1.3 Transactive Energy

Transactive Energy markets aim to establish an energy trading ecosystem based on information and communication technology, fostering a dynamic balance of supply and demand within an electricity infrastructure. While P2P and CSC markets primarily focus on modelling small-scale LEM, TE markets can encompass various scales. For instance, reference [20] addresses bidding strategies within a microgrid.

Like P2P and CSC markets, effective supervisory control is crucial in TE markets to ensure continuous and efficient operation of the transactive energy system. In this case, participants exchange data either with a central controller or a network of controllers.

2.4 Optimization, Collective Benefits Sharing and Pricing Mechanism

Energy resources can be managed through a Two-Stage Optimization algorithm to ensure that a prosumer experiences a favourable cost-benefit balance in their energy consumption while supporting the REC in which they participate without any negative impact on their position. A prosumer can also sell energy within the REC, which involves an energy exchange between the REC prosumers. As the REC involves a LEM, the LEM must employ a pricing mechanism to determine the market price for a specific interval settlement period (ISP).

This section covers the topics of optimization, energy sharing and market price calculation mechanisms.

2.4.1 Optimization

In [5], it is possible to verify an optimization algorithm with two stages that allow reaching a collective optimization of a REC, and in [6], the two-stage optimization algorithm was used in some case examples. The first stage aims to achieve individual optimization per prosumer that minimises individual energy costs. In the second stage, the collective cost minimization objective is subjected to a constraint to ensure that no prosumer incurs an energy cost higher than its individual optimal cost. To this end, it is necessary to establish a transaction price that can be used to calculate the individual cost in the second phase, thus compensating for the internal energy allocations. The next chapter will refer to the equations considered for the two-stage optimization.

2.4.2 Energy Sharing

According to the REC definition and considering the purpose of these communities, prosumers will share energy among themselves through the network. Every prosumer has a retailer from which they can buy and sell energy. Energy exchanges are accounted for by quantity and price, as stated in [5].

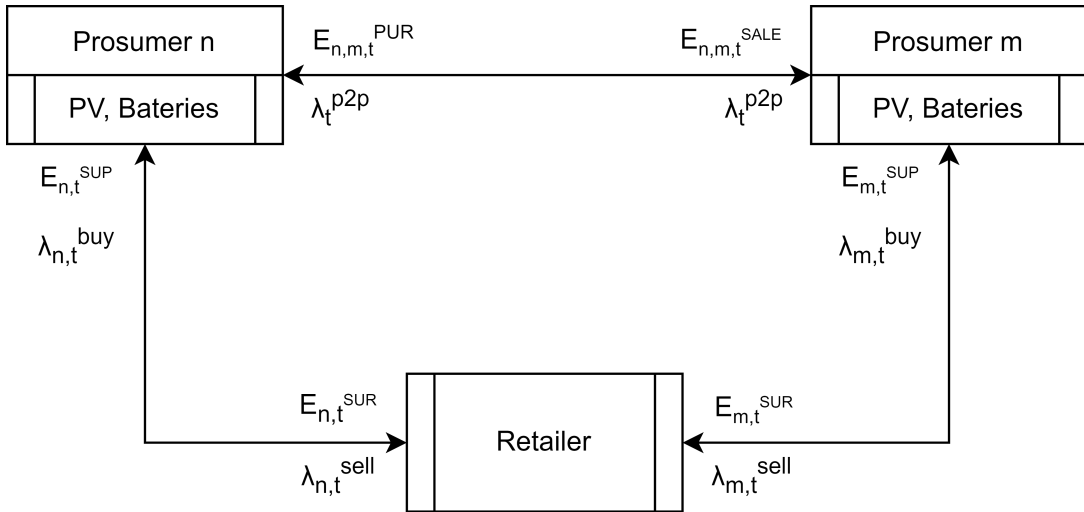


Figure 2.1: Exchanges inside a REC.

In Figure 2.1, it is possible to verify that two prosumers, n and m , exchange energy among themselves and individually with the retailer. In this case, Prosumer n sells its surplus $E_{n,m,t}^{SALE}$ (or stores) to Prosumer m , or, if it needs to buy, it buys $E_{n,m,t}^{PUR}$ from m at the internal price, λ_t^{p2p} . Similarly, it sells $E_{n,t}^{SUR}$ for $\lambda_{n,t}^{sell}$ to its retailer or buys $E_{n,t}^{SUP}$ energy for $\lambda_{n,t}^{buy}$. Prices and quantity traded will be influenced by two-stage optimization to minimise individual and collective costs of REC.

2.4.3 Pricing Mechanism

A local market of a REC needs to define an internal price, λ_t^{p2p} , to have energy exchanges between prosumers. The internal price of the LEM can be calculated through the mechanisms analysed in [7].

- **Pool**

According to the proposal in [7], the pool's combined selling and buying curves can be constructed based on the energy supplied by the members of the REC and their opportunity costs with their respective retailers. Each ISP within the REC will submit a selling bid when injecting energy, consisting of the injected energy amount and the buying price from their retailer. Similarly, a buying bid is submitted when consuming energy, including the consumed energy amount and the selling price from the retailer. It's important to note that a prosumer will only have a buying or a selling bid for each ISP. The equilibrium of the pool is determined by intersecting the aggregated selling and buying bids, which establishes the market price.

Figure 2.2 from [7] shows an example of a pricing mechanism pool where the curves cross and set the transfer price. When there is no crossing, it checks if the last bid aggregated and the internal price is the price associated with that bid, either sell or buy.

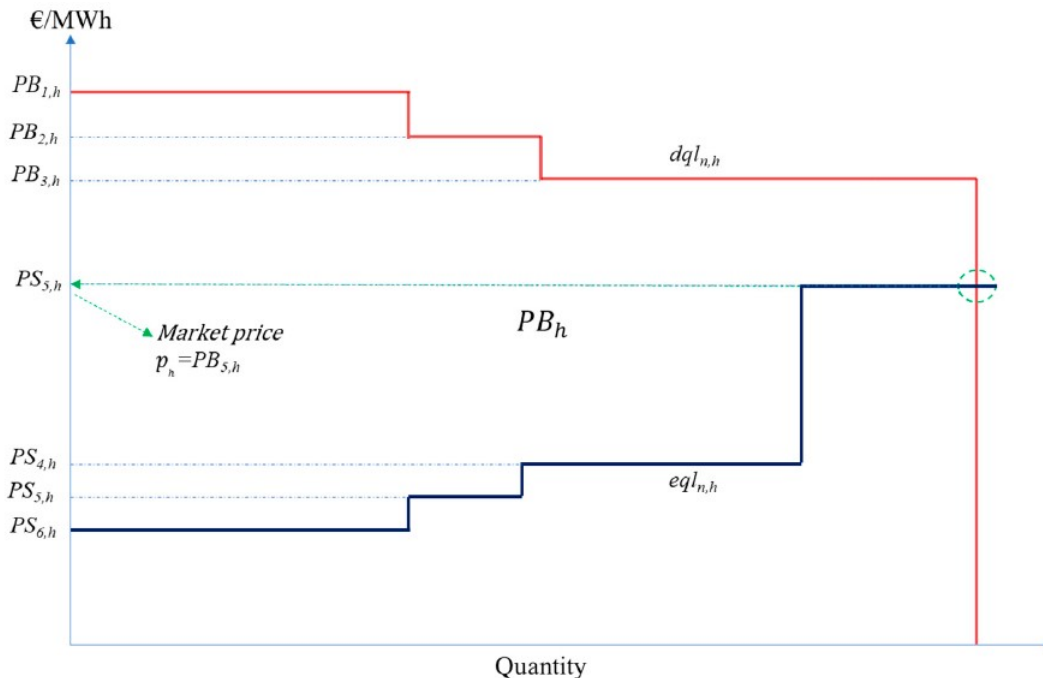


Figure 2.2: Example of a Pool mechanism price calculation

- **Mid Market Rate (MMR)**

This mechanism computes an internal transaction price as the intermediate value between

the highest value of the last sale offer and the lowest value of the last purchase offer:

$$p_h = \frac{\lambda_t^{buy} + \lambda_t^{sell}}{2} \quad (2.1)$$

where:

$$\lambda_t^{sell} = \max_n(\lambda_{n,t}^{sell}), \lambda_t^{buy} = \min_n(\lambda_{n,t}^{buy}) \quad (2.2)$$

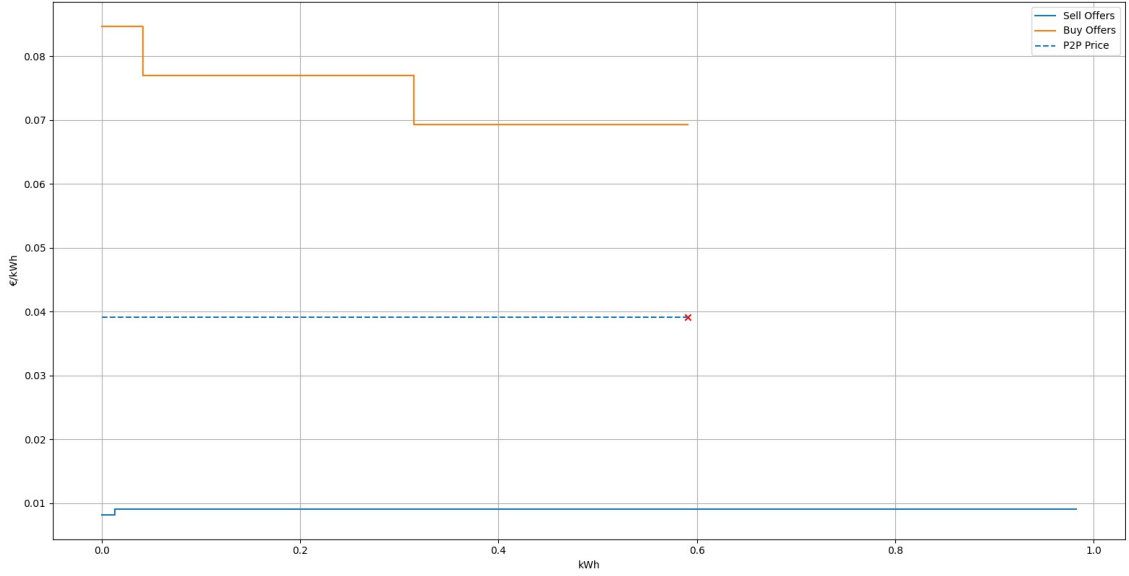


Figure 2.3: Example of an MMR mechanism price calculation

Figure 2.3 shows an example of the lines of the buying and selling bids and the price and energy of the last bid. This pricing mechanism was also mentioned in [21], [22], [23].

- **Supply and Demand Ratio**

The SDR pricing mechanism is determined by calculating the sdr_h , which represents the proportion of energy produced by prosumers with surplus energy, compared to the energy required by those who need supply:

$$sdr_h = \frac{eq_h}{dq_h} \quad (2.3)$$

In equation 2.3, eq_h refers to the total net local energy injection of all REC, and dq_h is the total net local energy consumption measured at the REC.

The sdr_h variable can have several values, with its value representing what happens inside the REC. If $sdr_h > 1$, the REC has local generation greater than consumption, and the price p_h is the same as the selling price λ_t^{sell} to the retailer.

$$p_h = \lambda_t^{sell} \quad (2.4)$$

If $0 > sdr_h > 1$, there was local energy generation, but the consumption was greater. Then:

$$p_h = \frac{\lambda_t^{buy} \times (\lambda_t^{sell} + \lambda)}{(\lambda_t^{buy} - \lambda_t^{sell}) \times sdr_h + \lambda_t^{sell}} \quad (2.5)$$

In equation 2.5, λ represents the compensation factor, which is restricted to the range of $0 < \lambda < (\lambda_t^{buy} - \lambda_t^{sell})$ to continue incentivising internal trades when the REC has grid surplus.

If $sdr_h = 0$, the REC has no surplus, and the energy is bought from the retailer, with $p_h = \lambda_t^{buy}$. When $sdr_h = 1$, the local generation and demand within the REC are balanced, resulting in no energy exchange with the grid. Consequently, the internal energy price reaches its minimum value.

In [24], was introduced a compensation factor which ensures that the advantage of consuming energy during periods of surplus local generation is distributed among the prosumers who contribute to this surplus. With the incorporation of this compensation, the internal energy price and the average buying price are transformed. SDRC-Half is identical to SDRC, but the compensation factor is halved.

If $0 < sdr_h < 1$, then:

$$p_h = \frac{\lambda_t^{buy} \times (\lambda_t^{sell} + \lambda)}{(\lambda_t^{buy} - \lambda_t^{sell} - \lambda) \times sdr_h + \lambda_t^{sell} + \lambda} \quad (2.6)$$

And, if $sdr_h > 1$, then:

$$p_h = \lambda_t^{sell} + \frac{\lambda}{sdr_h} \quad (2.7)$$

Figure 2.4 from [25] shows the relation between the internal prices and SDR, where the Prosumers sell and buy prices reduce with the increasing of SDR on the interval of [0, 1]. The SDR and SDRC pricing mechanisms were mentioned in [21], [22], [25], [24].

Several papers compare these pricing mechanisms, and these are some conclusions about them:

- The Pool mechanism seems the most economically efficient since it is based on the optimal market equilibrium, where prices reflect the real opportunity costs of REC for each ISP. Its calculation is simple and in line with economic theory, making it easy to explain and justify to potential REC members. However, this mechanism may exhibit more significant price fluctuations as prices vary between retailers' buying and selling prices.
- MMR slightly underperforms SDR when retailers' price signals fluctuate daily. This mechanism can be easily explained as sharing the benefits derived from the difference between bid and ask prices equally. However, they do not consider the actual contribution of local load balances to price formation, which reduces incentives for load management and flexibility.

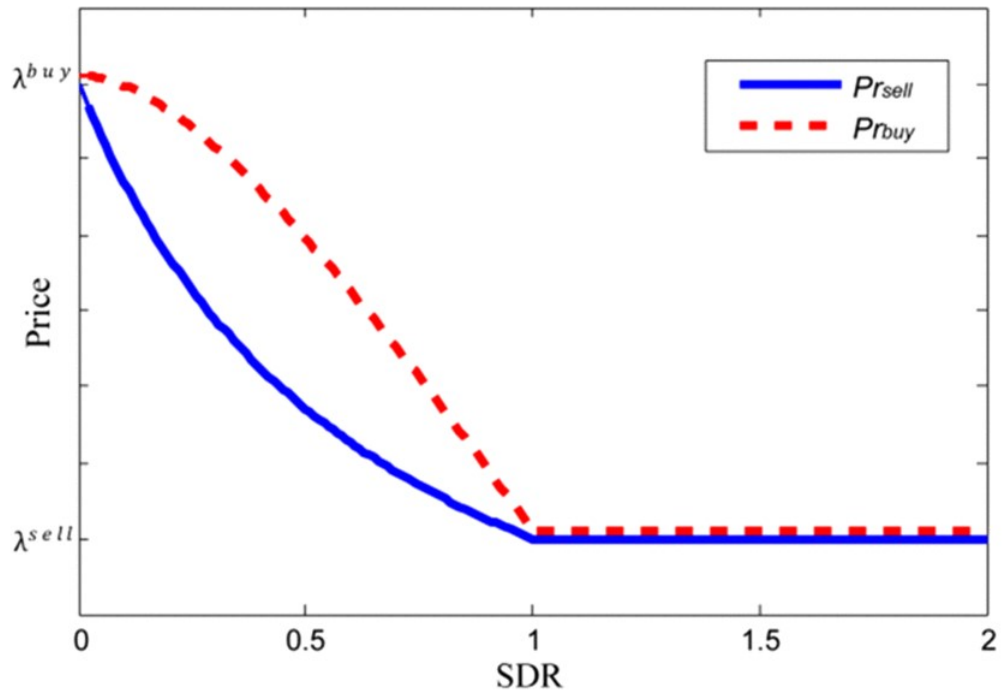


Figure 2.4: Relation between the internal prices and SDR

- SDR perform well as it provides a dynamic internal price that adjusts according to the energy availability in the community. Consequently, they provide strong incentives for demand response and generate more efficient economic signals. These methods aim to mimic market behaviour by establishing a relationship between price, participants' opportunity costs and available supply and demand.

Chapter 3

Problem and Methodology

This chapter will address the problem and the methodology used to develop the thesis. The first part proposes an example of REC structure to apply the methodology implemented. Next, the optimization algorithm applied in the methodology will be analysed, including the objective function and its constraints. The work carried out considered some improvements in the pricing mechanisms described, which will be explained in this chapter and tested in the following. Finally, the Python algorithm developed in partnership with INESC TEC will be described in detail using flowcharts.

3.1 REC Structure

A REC with five prosumers with different consumption, generation and battery parameters were considered. It is assumed that all prosumers belonging to the REC can have consumption, generation and batteries, all behind the meter (BTM), allowing each prosumer to make their buy and sell bids.

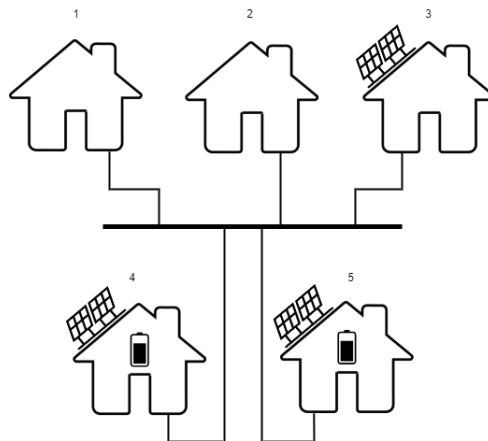


Figure 3.1: REC structure representation diagram

The prosumers will follow the sharing model similar to the previous chapter, buying and selling energy to other LEM prosumers and retailers. Prosumer n sells its surplus to Prosumer m , $E_{n,m,t}^{SALE}$, for λ_t^{p2p} , the internal price, or sells the surplus $E_{n,t}^{SUR}$ to the retailer for $\lambda_{n,t}^{sell}$. The same Prosumer n can buy $E_{n,m,t}^{PUR}$ from another Prosumer m for the internal price or buy $E_{n,t}^{SUP}$ from the retailer for $\lambda_{n,t}^{buy}$. A REC prosumer can only submit one buy or sell bid for each ISP.

3.2 Two-Stage Optimization

This section will address two-stage optimization, with the first stage on individual optimization and the second stage on collective optimization, without prejudicing individual optimization.

3.2.1 Stage One

This stage is about individual optimization, where the main objective is to reduce individual energy costs. Table 3.1 characterises each equation used, and Table 3.2 identifies the variables used in Stage One of the optimization.

Equation 3.1 refers to the arbitrage objective function of Stage One of the optimization, where the costs of each individual prosumer are to be minimized as much as possible. The sum of the costs of this stage equals the cost of the REC in the period indicated.

The equations from 3.2 to 3.11 are subject to equations that are meant to be the constraints in this optimization algorithm. Equations 3.12 and 3.13 define self-consumed energy for the purposes of applying the tariff for access to the networks for self-consumption.

Table 3.1: Optimization - Stage One equation functions

Equation function	
3.1	Arbitrage objective function
3.2	Equilibrium constraint
3.3	Net consumption constraint
3.4	Impede simultaneous buy and sell from retailer
3.5	BESS energy content update constraint
3.6	BESS SoC limits constraints
3.7	BESS power limit constraints
3.8	Positive net consumption constraint (for determining self-consumption)
3.9	Self-consumption definition constraint (when bottom-limited by positive net consumption)
3.10	Self-consumption definition constraint (when bottom-limited by external generation)
3.11	Positive variables' constraints
3.12	
3.13	

Table 3.2: Nomenclature for the Stage One of the Optimization

Indices and sets		
$t \in T$	Set of time intervals/slots over the operation period.	-
$n \in N$	Set of prosumers with associated meter.	-
$k \in K$	Generation facilities with meter.	-
Parameters		
Δt	Optimization step.	h
$\hat{\lambda}_{n,t}^{buy}$	Supply energy tariff of n at t .	€/kWh
$\hat{\lambda}_{n,t}^{sell}$	Feed-in energy tariff of n at t .	€/kWh
$\hat{E}_{n,t}^C$	Prosumer's n load profile at t .	kWh
$\hat{E}_{n,t}^G$	Prosumer's n behind-the-meter generation at t .	kWh
$\hat{E}_n^{B,N}$	Nominal capacity of the battery of n .	kWh
$\hat{SOC}_n^{B,min}$	Minimum state of charge of the battery of n .	%
$\hat{SOC}_n^{B,max}$	Maximum state of charge of the battery of n .	%
$\hat{P}_n^{B,max}$	Maximum input and output power of the battery of n .	kW
$\hat{\eta}_n^{B,C}$	Charging efficiency of the battery of n .	%
$\hat{\eta}_n^{B,D}$	Discharging efficiency of the battery of n .	%
$\hat{\beta}_{k,n}$	Peer n ownership on k generation.	%
$\hat{E}_{k,t}^G$	External generation of facility k , at t .	kWh
$\hat{\lambda}_t^{grid}$	Global access tariff for self-consumption, at t .	€/kWh
\hat{M}	A very big number (e.g., 1E6).	kWh
Variables		
$E_{n,t}^B$	Energy stored by the battery of n , at t .	kWh
$SOC_{n,t}^B$	SOC of the battery of n , at t .	%
$E_{n,t}^{B,C}$	Energy charged by the battery of n , at t .	kWh
$E_{n,t}^{B,D}$	Energy discharged by the battery of n , at t .	kWh
$E_{n,t}^{SUP}$	Energy supplied to n from its retailer, at t .	kWh
$E_{n,t}^{SUR}$	Energy surplus sold by n to its retailer, at t .	kWh
$\delta_{n,t}^{SUP}$	Auxiliary binary variable to impede n from simultaneously buying and selling to the retailer at t .	-
$E_{n,t}^{CMET}$	Net consumption at meter n , at t .	kWh
$E_{n,t}^{SLC}$	Energy self-consumed by n , at t (in theory, g.t.e. that value).	kWh
$E_{n,t}^{CMET,+}$	Consumption at meter n , at t (in theory, g.t.e. that value).	kWh
$\delta_{n,t}^{SLC}$	Auxiliary binary variable for signalling that n is self-consuming at t .	-

$$\min \sum_{t \in T} (E_{n,t}^{SUP} \times \hat{\lambda}_{n,t}^{buy} - E_{n,t}^{SUR} \times \hat{\lambda}_{n,t}^{sell} + E_{n,t}^{SLC} \times \hat{\lambda}_t^{grid}) \quad (3.1)$$

$$E_{n,t}^{SUP} + \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G = E_{n,t}^{CMET} + E_{n,t}^{SUR}, \quad \forall t \in T, n \in N, k \in K \quad (3.2)$$

$$E_{n,t}^{CMET} = \hat{E}_{n,t}^C + E_{n,t}^{B,C} - \hat{E}_{n,t}^G - E_{n,t}^{B,D}, \quad \forall t \in T, n \in N \quad (3.3)$$

$$E_{n,t}^{SUP} \leq \hat{M} \times (\delta_{n,t}^{SUP}), E_{n,t}^{SUR} \leq \hat{M} \times (1 - \delta_{n,t}^{SUP}), \quad \forall t \in T, n \in N \quad (3.4)$$

$$E_t^B = E_{t-1}^B + (E_{n,t}^{B,C} \times \hat{\eta}_n^{B,C} - \frac{E_{n,t}^{B,D}}{\hat{\eta}_n^{B,D}}), \quad \forall t \in T, n \in N \quad (3.5)$$

$$S\hat{O}C_n^{B,min} \leq SOC_{n,t}^B = \frac{E_{n,t}^B}{\hat{E}_n^{B,N}} \times 100\% \leq S\hat{O}C_n^{B,max}, \quad \forall t \in T, n \in N \quad (3.6)$$

$$\frac{E_{n,t}^{B,C}}{\Delta t}, \frac{E_{n,t}^{B,D}}{\Delta t} \leq \hat{p}_n^{B,max}, \quad \forall t \in T, n \in N \quad (3.7)$$

$$E_{n,t}^{CMET,+} \geq E_{n,t}^{CMET}, \quad \forall t \in T, n \in N \quad (3.8)$$

$$E_{n,t}^{SLC} \geq E_{n,t}^{CMET,+} - \hat{M} \times (1 - \delta_{n,t}^{SLC}), \quad \forall t \in T, n \in N \quad (3.9)$$

$$E_{n,t}^{SLC} \geq \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G - \hat{M} \times (\delta_{n,t}^{SLC}), \quad \forall t \in T, n \in N, k \in K \quad (3.10)$$

$$E_{n,t}^{B,C}, E_{n,t}^{B,D}, E_{n,t}^B, SOC_{n,t}^B, E_{n,t}^{SUP}, E_{n,t}^{SUR}, E_{n,t}^{CMET,+}, E_{n,t}^{SLC} \geq 0, \quad \forall t \in T, n \in N \quad (3.11)$$

$$E_{n,t}^{CMET,+} = \max(E_{n,t}^{CMET}, 0) \quad (3.12)$$

$$E_{n,t}^{SLC} = \min(\max(E_{n,t}^{CMET}, 0), \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G) \quad (3.13)$$

3.2.2 Stage Two

In Stage Two of the optimization, the main objective is to reduce the operation costs for the REC. In this stage, the results of Stage One are used to ensure that the total individual costs after Stage Two are equal or lower compared to the previous stage.

Table 3.3 shows all the equations used in Stage Two, and Table 3.4 shows the variables used, some of which were used in Stage One.

Equation 3.14 refers to the arbitrage objective function of Stage Two of the optimization, where the operation costs of the REC should be minimised as much as possible by making the individual prosumer costs equal to or lower than those of the previous stage.

The equations from 3.15 to 3.29 are the constraints in this stage of the optimization algorithm.

Table 3.3: optimization Stage Two equation functions

Equation function	
3.14	Arbitrage objective function
3.15	Transaction sold position equals mirrored bought position constraint
3.16	Equilibrium constraint
3.17	Impede simultaneous buy and sell from retailer
3.18	Net consumption constraint
3.19	BESS energy content update constraint
3.20	BESS SoC limits constraints
3.21	BESS power limit constraints
3.22	Equal to or better than O.F. value from stage 1 constraint
3.23	Positive net consumption constraint (for determining self-consumption)
3.24	Positive allocated energy constraint (for determining self-consumption)
3.25	Self-consumption definition constraint (when bottom-limited by positive net consumption)
3.26	Self-consumption definition constraint (when bottom-limited by positive allocated energy)
3.27	Constraint for imposing positive allocation coefficients (<i>maximum</i> = $-E_{n,t}^{CMET}$)
3.28	Constraint for imposing positive allocation coefficients (<i>minimum</i> = 0)
3.29	Positive variables' constraints
3.30	
3.31	
3.32	

$$\min \sum_{t \in T} \left(\sum_{n \in N} (E_{n,t}^{SUP} \times \hat{\lambda}_{n,t}^{buy} - E_{n,t}^{SUR} \times \hat{\lambda}_{n,t}^{sell} + E_{n,t}^{SLC} \times \hat{\lambda}_t^{grid}) \right) \quad (3.14)$$

$$E_{n,m,t}^{PUR} = E_{m,n,t}^{SALE}, \quad \forall t \in T, n, m \in N, n \neq m \quad (3.15)$$

$$E_{n,t}^{SUP} + \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G + \sum_m (E_{n,m,t}^{PUR} - E_{n,m,t}^{SALE}) = E_{n,t}^{CMET} + E_{n,t}^{SUR}, \quad \forall t \in T, n, m \in N, n \neq m, k \in K \quad (3.16)$$

$$E_{n,t}^{CMET} = \hat{E}_{n,t}^C + E_{n,t}^{B,C} - \hat{E}_{n,t}^G - E_{n,t}^{B,D}, \quad \forall t \in T, n \in N \quad (3.17)$$

$$E_{n,t}^{SUP} \leq \hat{M} \times (\delta_{n,t}^{SUP}), \quad E_{n,t}^{SUR} \leq \hat{M} \times (1 - \delta_{n,t}^{SUP}), \quad \forall t \in T, n \in N \quad (3.18)$$

$$E_t^B = E_{t-1}^B + (E_{n,t}^{B,C} \times \hat{\eta}_n^{B,C} - \frac{E_{n,t}^{B,D}}{\hat{\eta}_n^{B,D}}), \quad \forall t \in T, n \in N \quad (3.19)$$

$$S\hat{O}C_n^{B,min} \leq SOC_{n,t}^B = \frac{E_{n,t}^B}{\hat{E}_n^{B,N}} \times 100\% \leq S\hat{O}C_n^{B,max}, \quad \forall t \in T, n \in N \quad (3.20)$$

Table 3.4: Nomenclature for the Stage Two of the Optimization

Indices and sets		
$t \in T$	Set of time intervals/slots over the operation period.	-
$n \in N$	Set of prosumers.	-
$k \in K$	Generation facilities with meter.	-
Parameters		
Δt	Optimization step.	h
$\hat{\lambda}_{n,t}^{buy}$	Supply energy tariff of n at t .	€/kWh
$\hat{\lambda}_{n,t}^{sell}$	Feed-in energy tariff of n at t .	€/kWh
$\hat{E}_{n,t}^C$	Prosumer's n load profile at t .	kWh
$\hat{E}_{n,t}^G$	Prosumer's n behind-the-meter generation at t .	kWh
$\hat{E}_n^{B,N}$	Nominal capacity of the battery of n .	kWh
$S\hat{O}C_n^{B,min}$	Minimum state of charge of the battery of n .	%
$S\hat{O}C_n^{B,max}$	Maximum state of charge of the battery of n .	%
$\hat{P}_n^{B,max}$	Maximum input and output power of the battery of n .	kW
$\hat{\eta}_n^{B,C}$	Charging efficiency of the battery of n .	%
$\hat{\eta}_n^{B,D}$	Discharging efficiency of the battery of n .	%
\hat{C}_n^{ind}	Energy bill of n from Stage One.	€
$\hat{\beta}_{k,n}$	Peer n ownership on k generation.	%
$\hat{E}_{k,t}^G$	External generation of facility k , at t .	kWh
$\hat{\lambda}_t^{grid}$	Global access tariff for self-consumption, at t .	€/kWh
$\hat{\lambda}_t^{p2p}$	(Fictitious) local energy price, at t .	€/kWh
\hat{M}	A very big number (e.g., 1E6).	kWh
Variables		
$E_{n,t}^B$	Energy stored by the battery of n , at t .	kWh
$SOC_{n,t}^B$	SOC of the battery of n , at t .	%
$E_{n,t}^{B,C}$	Energy charged by the battery of n , at t .	kWh
$E_{n,t}^{B,D}$	Energy discharged by the battery of n , at t .	kWh
$E_{n,t}^{SUP}$	Energy supplied to n from its retailer, at t .	kWh
$E_{n,m,t}^{PUR}$	Energy bought locally by n to m , at t .	kWh
$E_{n,t}^{SUR}$	Energy surplus sold by n to its retailer, at t .	kWh
$E_{n,m,t}^{SALE}$	Energy sold locally by n to m , at t .	kWh
$\delta_{n,t}^{SUP}$	Auxiliary binary variable to impede n from simultaneously buying and selling to the retailer at t .	-
$E_{n,t}^{SLC}$	Energy self-consumed by n , at t (in theory, g.t.e. that value).	kWh
$E_{n,t}^{CMET,+}$	Consumption at meter n , at t (in theory, g.t.e. that value).	kWh
$E_{n,t}^{ALC+}$	Consumed energy bought locally by n (in theory, g.t.e. that value).	kWh
$\delta_{n,t}^{SLC}$	Auxiliary binary variable for defining self-consumed energy by n .	-
$\delta_{n,t}^{COEFF}$	Auxiliary binary variable for imposing positive allocation coefficients.	-

$$\frac{E_{n,t}^{B,C}}{\Delta t}, \frac{E_{n,t}^{B,D}}{\Delta t} \leq \hat{P}_n^{B,max}, \quad \forall t \in T, n \in N \quad (3.21)$$

$$\sum_t (E_{n,t}^{SUP} \times \hat{\lambda}_{n,t}^{buy} - E_{n,t}^{SUR} \times \hat{\lambda}_{n,t}^{sell} + E_{n,t}^{SLC} \times \hat{\lambda}_t^{grid} + \sum_m (E_{n,m,t}^{PUR} - E_{n,m,t}^{SALE}) \times \hat{\lambda}_t^{p2p}) \leq \hat{C}_n^{ind}, \quad \forall t \in T, n, m \in N, n \neq m \quad (3.22)$$

$$E_{n,t}^{CMET,+} \geq E_{n,t}^{CMET}, \quad \forall t \in T, n \in N \quad (3.23)$$

$$E_{n,t}^{ALC+} \geq \sum_m (E_{n,m,t}^{PUR} - E_{n,m,t}^{SALE}) + \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G, \quad \forall t \in T, n, m \in N, n \neq m, k \in K \quad (3.24)$$

$$E_{n,t}^{SLC} \geq E_{n,t}^{CMET,+} - \hat{M} \times (1 - \delta_{n,t}^{SLC}), \quad \forall t \in T, n \in N \quad (3.25)$$

$$E_{n,t}^{SLC} \geq E_{n,t}^{ALC+} - \hat{M} \times \delta_{n,t}^{SLC}, \quad \forall t \in T, n, m \in N, n \neq m \quad (3.26)$$

$$\sum_m (E_{n,m,t}^{SALE} - E_{n,m,t}^{PUR}) - \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G \leq -E_{n,t}^{CMET} + \hat{M} \times \delta_{n,t}^{COEFF}, \quad \forall t \in T, n, m \in N, n \neq m, k \in K \quad (3.27)$$

$$\sum_m (E_{n,m,t}^{SALE} - E_{n,m,t}^{PUR}) - \sum_k \hat{\beta}_{k,n} \times \hat{E}_{k,t}^G \leq \hat{M} \times (1 - \delta_{n,t}^{COEFF}), \quad \forall t \in T, n, m \in N, n \neq m, k \in K \quad (3.28)$$

$$E_{n,t}^{B,C}, E_{n,t}^{B,D}, E_{n,t}^B, SOC_{n,t}^B, E_{n,t}^{SUP}, E_{n,t}^{SUR}, E_{n,t}^{CMET,+}, E_{n,t}^{SLC}, E_{n,m,t}^{PUR}, E_{n,m,t}^{SALE}, E_{n,t}^{ALC+} \geq 0, \quad \forall t \in T, n, m \in N \quad (3.29)$$

$$E_{n,t}^{CMET,+} = \max(E_{n,t}^{CMET}, 0) \quad (3.30)$$

$$E_{n,m,t}^{ALC+} = \max\left(\sum_m (E_{n,m,t}^{PUR} - E_{n,m,t}^{SALE}) + \sum_k \hat{\beta}_{k,n} \times E_{k,t}^G, 0\right) \quad (3.31)$$

$$E_{n,t}^{SLC} = \min\left(\max(E_{n,t}^{CMET}, 0), \max\left(\sum_m (E_{n,m,t}^{PUR} - E_{n,m,t}^{SALE}) + \sum_k \hat{\beta}_{k,n} \times E_{k,t}^G, 0\right)\right) \quad (3.32)$$

The optimization algorithm considered in the work developed was also considered in the documents referenced with [5] and [7].

3.3 Pricing Mechanisms

This section will describe the pricing mechanisms used and how they work. As mentioned at the beginning of the chapter, some pricing mechanisms have already been described in the previous chapter: Pool, MMR, SDR, SDRC and SDRC-Half.

The pricing mechanisms MMR, SDR, SDRC and SDRC-Half have been renamed, and from now on, any reference to these pricing mechanisms in this document will be with Total Mid Market Rate (TMMR), Total Supply and Demand Ratio (TSDR), Total Supply and Demand Ratio Compensated (TSDRC) and Total Supply and Demand Ratio Compensated Half (TSDRC-Half). These pricing mechanisms, when used, consider all bids and offers in the market, even if they are not used.

The new pricing mechanisms considered are adaptations of the existing ones already mentioned and calculate the price similarly. The difference lies in using the opportunity costs corresponding to the real behaviour of each REC prosumer for each ISP: if the REC prosumer is consuming, only its buying price from its retailer is considered; if it is generating, only its selling price to its retailer is considered. The names given for this adaptation of the pricing mechanisms described previously are Partial Mid Market Rate (PMMR), Partial Supply and Demand Ratio (PSDR), Partial Supply and Demand Ratio Compensated (PSDRC), and Partial Supply and Demand Ratio Compensated Half (PSDRC-Half).

The LEM must initially ascertain the buying and selling bids to calculate the internal price. The bids are organised based on monetary value. Selling bids are arranged in ascending order of merit and descending order of the energy to be sold. On the other hand, buying bids are organised in descending order of price and descending order of energy quantity.

If there are only purchase bids, the LEM price is defined as the highest price of the purchase bids, and if there are only sale bids, the market price is defined as the lowest price of the sale bids. The market price is zero if no bids exist for purchase and sale. The pricing mechanism kicks in if there are both buying and selling bids. We will then analyse how pricing mechanisms act in the face of bids and offers.

3.3.1 Total and Partial Mid Market Rate

Moving to Total and Partial MMR, the difference is between the buying and selling bids used for the price calculation. Total MMR will use all bids for the price calculation, and Partial MMR only considers the last bids that have enough energy for the demand. Then, the MMR method calculation is applied.

Figure 3.2 shows the difference between the bids considered for TMMR and PMMR. TMMR considers all bids, while PMMR only considers the offers that can satisfy the demand.

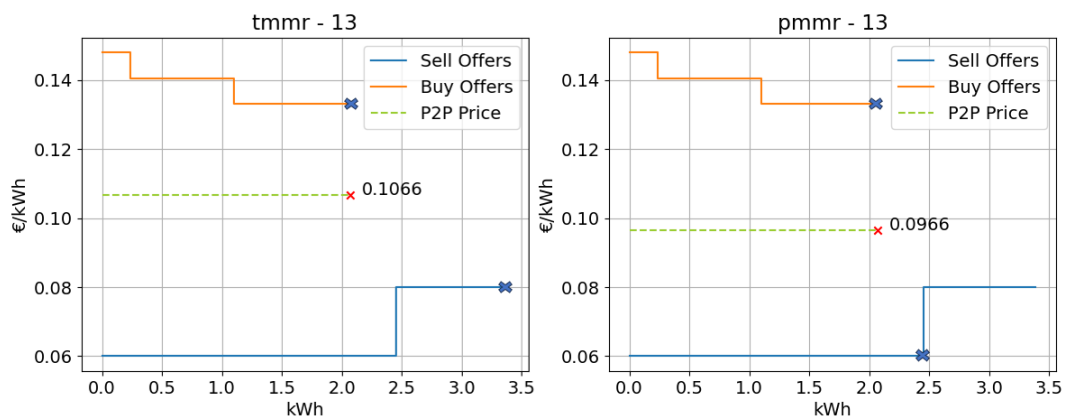


Figure 3.2: Examples of the computed TMMR and PMMR pricing mechanisms

3.3.2 Total and Partial Supply and Demand Ratio

Supply and Demand Ratio equations are in the previous chapter; the only difference is the bids considered. Figure 3.3 shows the offers considered, and then the program applies the equations to return the LEM internal price with SDR.

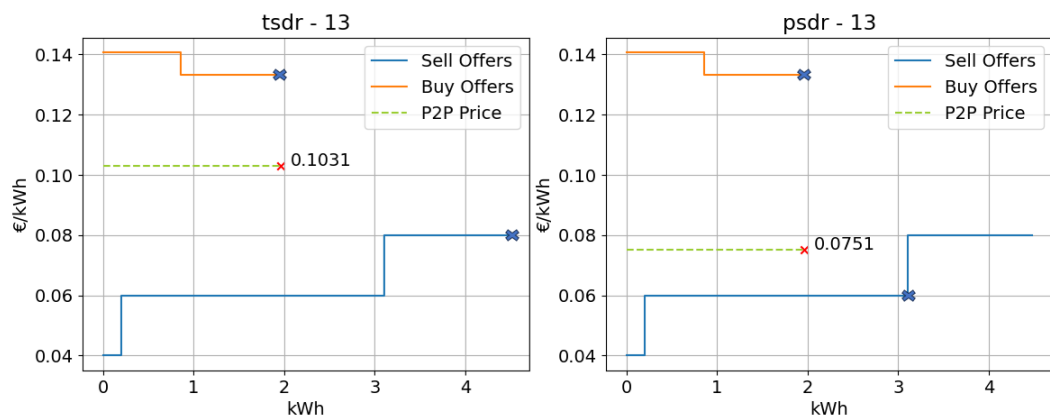


Figure 3.3: Examples of the computed TSDR and PSDR pricing mechanisms

3.3.3 Total and Partial Supply and Demand Ratio Compensated

As well as TSDR and PSDR, the TSDRC and PSDRC will do the same, but the compensation factor is applied. Figure 3.4 shows that TSDRC and PSDRC return different LEM internal prices.

3.3.4 Total and Partial Supply and Demand Ratio Compensated-Half

Compared to TSDRC and PSDRC, TSDRC-Half and PSDRC-Half reduce the compensation factor by 50%. The bids are all considered for the TSDRC-Half, and for PSDRC-Half, only the used offers were considered. Figure 3.5 proves the difference between these two pricing mechanisms.

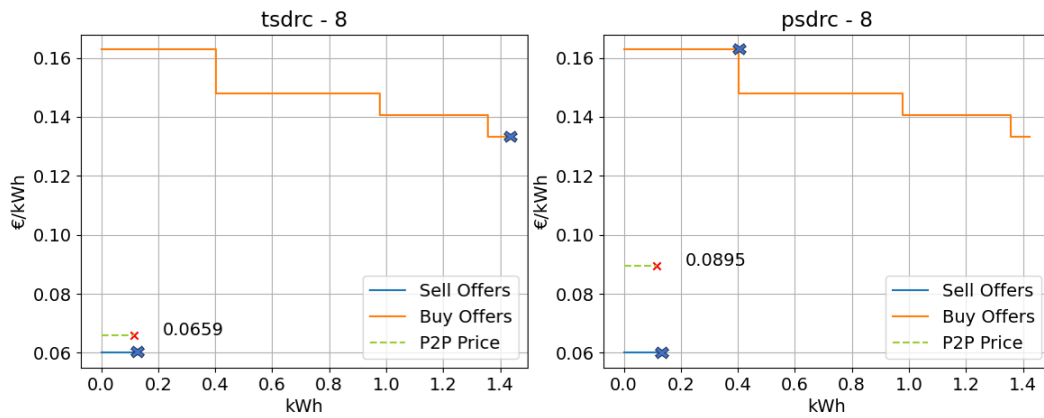


Figure 3.4: Examples of the computed TSDRC and PSDRC pricing mechanisms

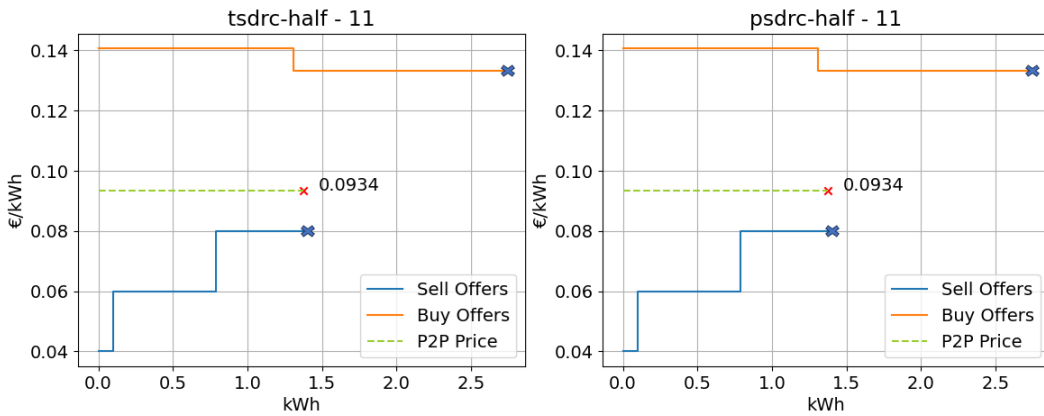


Figure 3.5: Examples of the computed TSDRC-Half and PSDRC-Half pricing mechanisms

Implementing these adaptations to existing pricing mechanisms is intended to try a new approach to prosumers' selling and buying bids in a LEM. Consider a scenario with more selling bids than buying bids, where there is a difference between the prices of the buy bids and where the total quantity of sell bids is higher. It will be noted that when considering all sell bids for calculating the LEM internal price, prices will tend to be higher depending on the mechanism. This is because the quantity of energy sought for purchase is lower, so the sales offers considered will be those with the lowest price.

Conversely, in a scenario with more buy bids than sell bids, the buy bids considered will be the ones with the highest price, and, as such, the LEM internal price will tend to be higher.

3.4 Algorithm Structure

This section presents how the Python Program was developed for INESC TEC. The main program and LEM internal price based on the pricing mechanisms will be explained using charts.

PyCharm 2022.3.2, [26], was used to develop the work, and the Python version was 3.10.9, [27]. For the optimization process, the PuLP library, [28], was used to construct the two-stage

MILP. The open-source CBC solver, [29], was initially chosen for the optimization process but was later traded for Gurobi, version 10.0.1, [30], to reduce the total simulation time.

3.4.1 Main

The main part of the program contains the price calculation and the optimization algorithm. Figure 3.6 shows the programme's steps to arrive at the results. It is based on an iterative process between calculating the market price and the optimization algorithm. The market price calculation provides a list of prices for 24 hours, and the optimization provides the elements listed in block 6 of Figure 3.6. The condition for stopping the cycle is described in block 7, and when the condition is met, the programme returns the results.



Figure 3.6: Main part of the program

3.4.2 LEM internal price calculation

The other important part to explain is how the pricing mechanisms were implemented in the program to calculate the LEM internal prices. Nine different pricing mechanisms were considered, but eight of them are similar. As mentioned in the previous section, the difference is in the prosumers' bids for the calculation. Figure 3.7 explains how the program implemented all theory to calculate the LEM internal price.

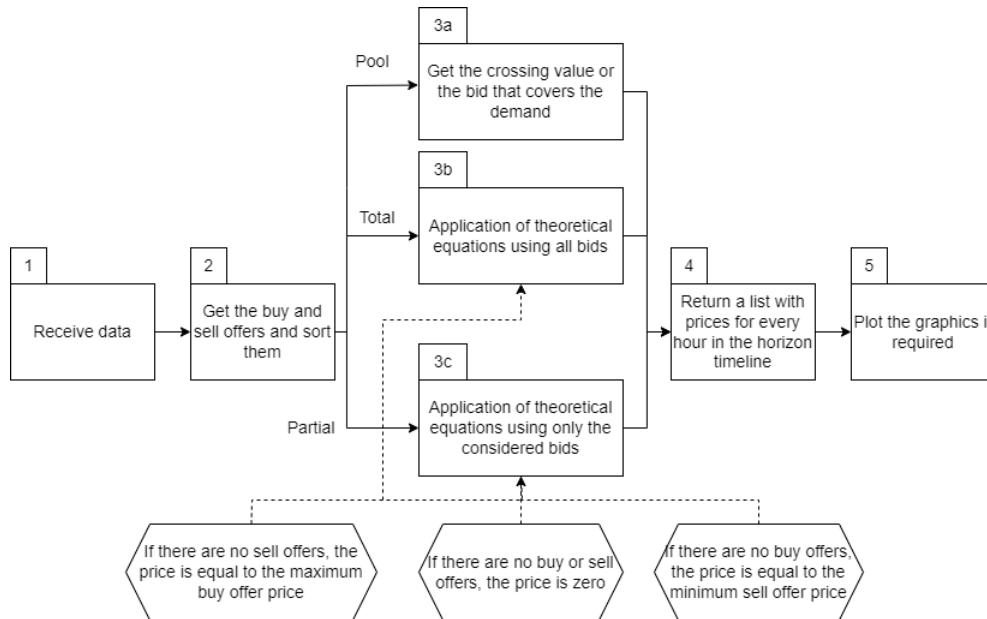


Figure 3.7: Flowchart explaining the implementation of the pricing mechanisms in the program

Chapter 4

Scenarios, Simulations And Results

This chapter will discuss the different scenarios used to study LEM in the REC and the data used in the scenarios. The expected results and results obtained in the simulations will also be discussed.

4.1 Data and Scenarios

The data needed to set up the scenarios are the following:

Table 4.1: Inputs for each scenario

Inputs	Function	Data references
Consumption	Consumption of a Prosumer	[31], [32], [33]
Generation	Generation of a Prosumer	[34], [35]
Market price	Prosumer purchase offer	[36]
Feed-in tariff	Prosumer sale offer	-
Battery capacity	Prosumer battery capacity	[37]
Battery power	Prosumer battery power	[37]

The consumption data is from 2013 for five houses in England, [31]. These data have been normalized to vary in a range of [0, 1]. They are multiplied by the usual contracted power in Portugal (3.45kVA or 6.90 kVA, depending on the scenario) to simulate typical Portuguese Consumption, [32], [33].

The generation data was also normalized to vary in a range of [0, 1] and multiplied by a solar inverter's maximum output power. The data are from INESC TEC's PV production 2016, [34]. In this case, the inverters considered were the Huawei SUN2000-3KTL-L1 and the Huawei SUN2000-5KTL-L1, [35], with the maximum power varying between 3.0kW and 5.0kW, depending on the scenario.

The market price data are from [36] and represent the hourly price of 2022 in €/MWh and converted to €/kWh. Feed-in tariffs were obtained by manipulating market price data to achieve variability for the selling bids.

All data is hourly and has been dated as being for the year 2022.

The battery data, nominal capacity and maximum output power, are based on the datasheet referenced in [37], related to batteries produced by Growatt. Other important battery data to consider include charging and discharging efficiency, maximum and minimum state of charge and the initial energy. These values are percentages, and 90% was assumed for the charging and discharging efficiency. For the minimum and maximum state of charge, 0% and 100% were assumed, respectively, and 50% for the initial state of charge.

Other data are essential to consider, such as the duration of the intervals to be analysed, which in this case is one hour. The day chosen for the analysis was the 1st of May. This day was fully analysed, with a step of one hour.

4.2 Scenarios

Four different types of scenarios were used. Scenario 1 is the base scenario that will be used as a term of comparison for the other scenarios. All other scenarios are adaptations of this scenario, where the initial data are modified based on scenario 1, the base scenario.

Table 4.2 is about what changes in every scenario and shows the parameters changed in every scenario and its units.

Table 4.2: Comparison between Scenarios and Parameters

	Scenario 1 (Base)						Scenario 2 (+ Generation)							
	Load	Generation	Market Price	Feedin	Bat_cap	Bat_max	Load	Generation	Market Price	Feedin	Bat_cap	Bat_max	Load	kVA
Prosumer 1	3,45	0,00	0,90	0,90	0,00	0,00	3,45	0,00	0,90	0,90	0,00	0,00	Gen	kW
Prosumer 2	3,45	0,00	0,95	0,95	0,00	0,00	3,45	0,00	0,95	0,95	0,00	0,00	Market	Coefficients
Prosumer 3	3,45	3,00	1,00	1,00	0,00	0,00	3,45	5,00	1,00	1,00	0,00	0,00	Feedin	Coefficients
Prosumer 4	3,45	3,00	1,05	1,05	5,00	2,50	3,45	5,00	1,05	1,05	5,00	2,50	Bat_cap	kWh
Prosumer 5	3,45	3,00	1,10	1,10	10,00	5,00	3,45	5,00	1,10	1,10	10,00	5,00	Bat_max	kWp
	Scenario 3 (+ Batteries)						Scenario 4 (+ Load)							
	Load	Generation	Market Price	Feedin	Bat_cap	Bat_max	Load	Generation	Market Price	Feedin	Bat_cap	Bat_max	Load	kVA
Prosumer 1	3,45	0,00	0,90	0,90	0,00	0,00	6,90	0,00	0,90	0,90	0,00	0,00	Gen	kW
Prosumer 2	3,45	0,00	0,95	0,95	0,00	0,00	3,45	0,00	0,95	0,95	0,00	0,00	Market	Coefficients
Prosumer 3	3,45	3,00	1,00	1,00	0,00	0,00	6,90	3,00	1,00	1,00	0,00	0,00	Feedin	Coefficients
Prosumer 4	3,45	3,00	1,05	1,05	15,00	7,50	3,45	3,00	1,05	1,05	5,00	2,50	Bat_cap	kWh
Prosumer 5	3,45	3,00	1,10	1,10	20,00	10,00	6,90	3,00	1,10	1,10	10,00	5,00	Bat_max	kWp

The parameters "Market Price" and "Feedin" correspond to each prosumer's buy and sell offers. These parameters are coefficients for each prosumer multiplied by the data from [36] to obtain different buying and selling bids in €/kWh for each prosumer.

The main objective of analysing additional scenarios is to understand how the small changes will influence the LEM internal price and, consequently, the REC operation costs.

To study the REC operation, it is necessary to analyse:

- The initial consumption for every prosumer (first iteration and last iteration after optimization);
- LEM internal price and retailer prices;
- The batteries SOC;
- Prosumers' transactions with the retailer and other prosumers.

The LEM internal price is calculated using the different pricing mechanisms mentioned in Chapter 3.

4.3 Results and Discussion

4.3.1 Scenario 1, Base scenario

Scenario 1 is the base scenario considering the lowest usually contracted power in Portugal (3,45kVA) and a power of 3,0 kWp for each prosumer with solar generation. The coefficients "Market Price" and "Feedin" for the buying and selling bids go from 0,90 to 1,10, so prosumers have different buy and sell bids. Prosumer 1 has the lowest "Market Price" and "Feedin" coefficients for buying and selling bids, and Prosumer 5 has the highest. Finally, Prosumers 4 and 5 have a battery each. Prosumer 4 battery has a 5kWh capacity and a maximum power of 2,5 kWp, and Prosumer 5 battery has a 10kWh capacity and a maximum power of 5 kWp.

This scenario is expected to have a low operation cost for the REC, many trades between the prosumers and low dependency on the retailer in the hours with more production. Prosumers may buy energy in the LEM or from their retailer in hours without generation, depending on the internal LEM price. When considered individually, Prosumers 1 and 2 are likely to experience low costs, while Prosumers 3, 4, and 5 are expected to have profits within this context.

Figure 4.1 shows the prosumers' initial liquid consumption in the program's first iteration and their value for the buying and selling bids. Each prosumer presents the buying and selling bids for every algorithm iteration. When the bar columns are above zero, a prosumer has a negative liquid consumption, which means that this prosumer consumed energy from the REC grid. The prosumer injects energy into the REC grid if it is below zero.

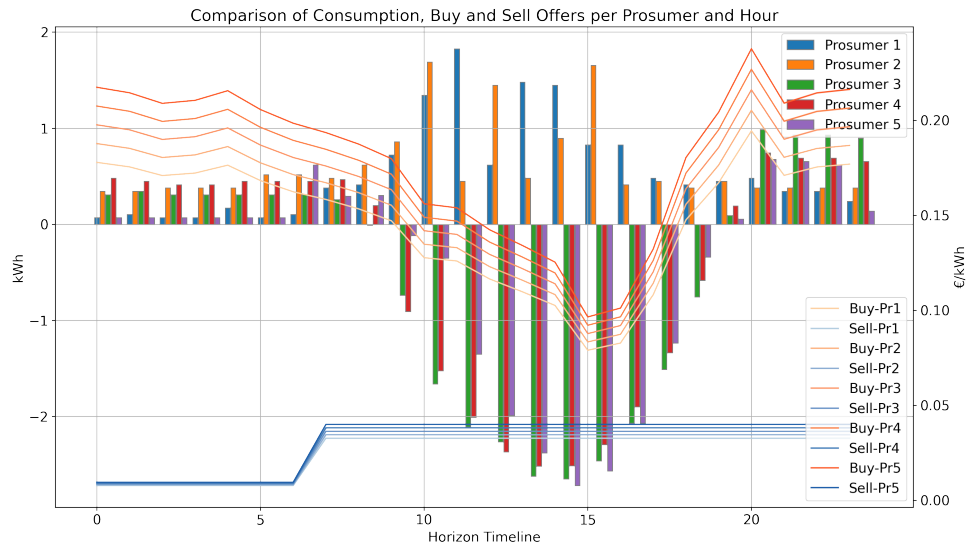


Figure 4.1: Scenario 1 initial liquid consumption and buying and selling bids

In this figure, it is possible to see that Prosumers 3, 4 and 5 have a surplus in hours 9-18. It is possible to see that the prosumers buying bids (orange) in those hours are lower and higher in the hours without production. Selling bids are lower than the buying bids and are almost constant.

In the last iteration of the program, where the REC has achieved the ideal REC operation cost or the maximum number of iterations, after Stage One of the optimization, it is possible to see that the prosumers have different liquid consumption because the batteries are dispatched to reduce individual costs. The liquid consumption can be calculated by considering the consumption and the battery charge and subtracting the generation and the battery discharge for each hour. Figure 4.2 shows that Stage One of the optimization changes the liquid consumption for the prosumers.

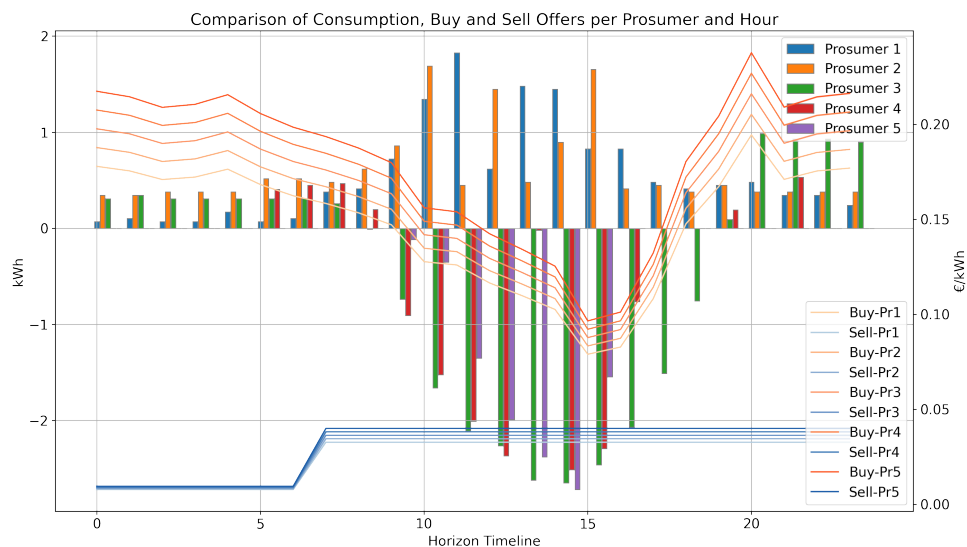


Figure 4.2: Scenario 1 liquid consumption and buying and selling bids after Stage One of the optimization

As can be seen, Prosumers 4 and 5 do not have consumption in the first hours, which means they used their batteries to reduce their individual cost, as is supposed to happen in Stage One of the optimization. The liquid consumption after Stage One is equal for every pricing mechanism since it only considers the prosumers' initial consumption.

After Stage Two of the optimization, it is possible to observe new liquid consumption compared to Stage One. The new liquid consumption from Stage Two is calculated to benefit the REC without prejudicing the individual consumption of prosumers. The LEM internal prices are calculated with different pricing mechanisms, so the results after Stage Two differ.

4.3.1.1 Pool

Figure 4.3 represents the liquid consumption after Stage Two of the optimization. Prosumer 1 is represented with blue, Prosumer 2 with orange, 3 with green, 4 with red and 5 with purple.

Figure 4.4 is the evolution of the battery SOC and charge and discharge of every prosumer. Only Prosumers 4 and 5 have batteries; Prosumer 5 is the prosumer represented with purple, and Prosumer 4 is the prosumer with red.

Figure 4.5 has five rows and four columns. The rows represent the prosumers; the columns are the Energy bought in LEM, the Energy sold in LEM, Energy bought from the retailer, and Energy sold to the retailer, from left to right. The bar charts representing the LEM exchanges do not break down the energy exchanges made from prosumer to prosumer, but rather the total exchanges of each prosumer in a given hour.

Figure 4.6 shows the horizon timeline's LEM internal price per iteration in the horizon timeline. Green is the last iteration LEM internal price.

With these figures, it is possible to study how REC work with a Pool pricing mechanism in this scenario.

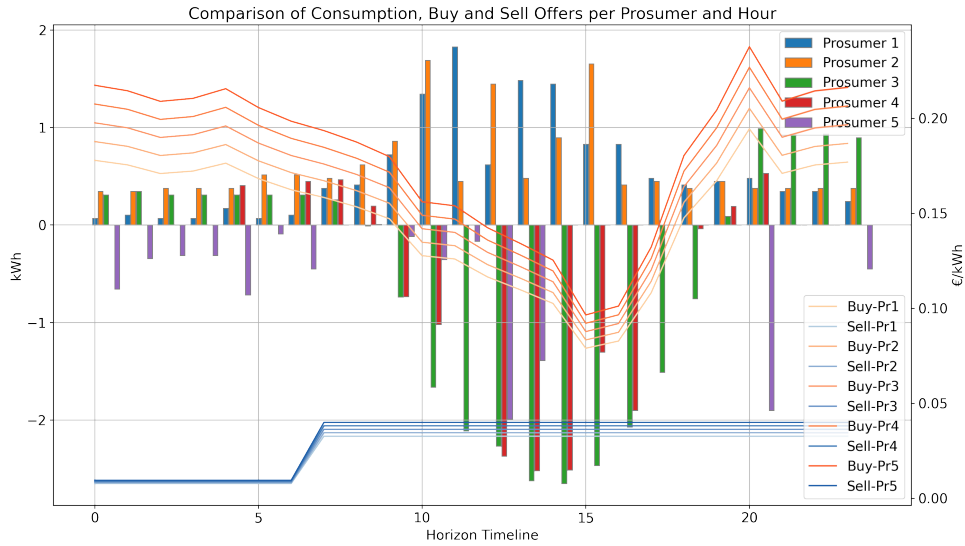


Figure 4.3: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with Pool

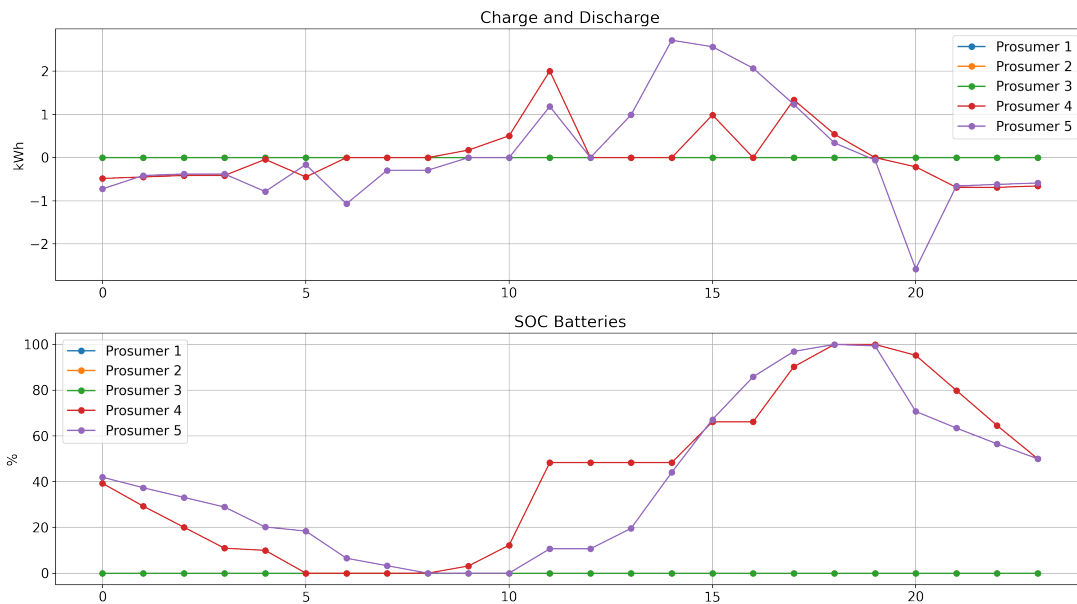


Figure 4.4: Batteries SOC, Charge and Discharge in Scenario 1 with Pool

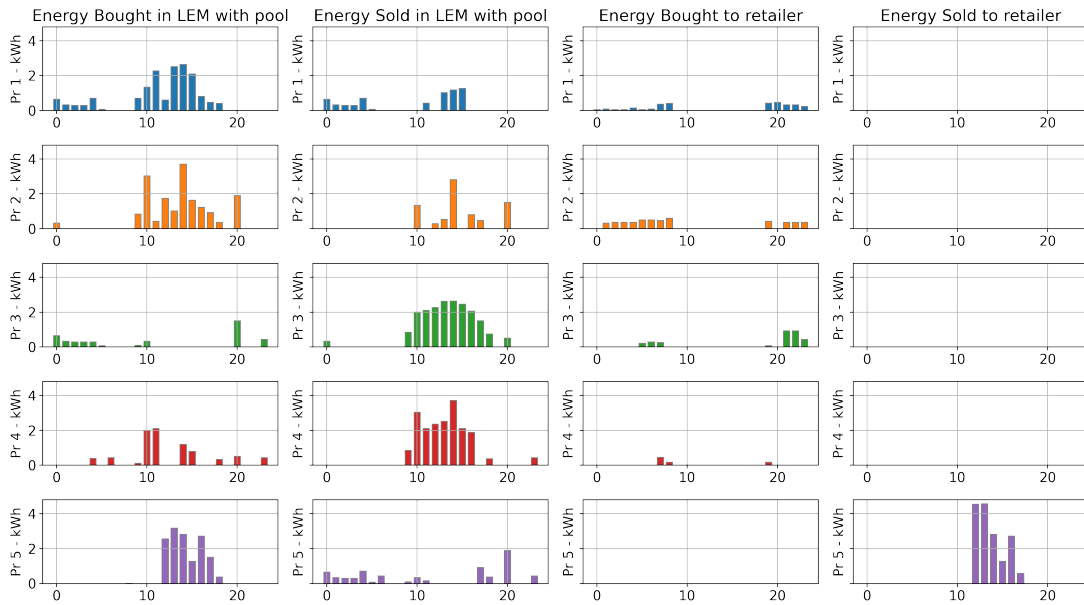


Figure 4.5: Prosumers' Energy trades in Scenario 1 with Pool



Figure 4.6: LEM internal price evolution in Scenario 1 with Pool

In the first seven hours, 0-8, Prosumer 5 uses his battery to consume and sell energy in LEM. Prosumer 4 discharges his battery to nullify consumption, but when he does not use the battery, he buys energy in LEM. Prosumer 1 buys the energy from Prosumer 5, then sells it to Prosumer 3. The reason is that Prosumer 1 got the LEM bid accepted, but he buys energy from the retailer at a lower price than Prosumer 3. Prosumer 2 only gets from Prosumer 5 in the first hour because he sells more energy, then he needs to turn to the retailer.

Hours 9-18, since there is more generation than consumption, the LEM internal price will be defined as the last sell offer that can cover the demand from the buy offers. Prosumer 3 and 4 sell all their energy in the LEM because they have the lowest feed-in tariff. Prosumer 5 sells surplus energy to the retailer instead of in the LEM because he has the higher feed-in tariff. Prosumers 3 and 4 have covered the demand from Prosumers 1 and 2, which only consume energy. It is important to notice that Prosumer 4 and 5 also charge their batteries to reach full charge.

In hour 19, all prosumers consume except Prosumer 5, and all prosumers buy their energy from their retailer. Hour 20, Prosumer 5 uses his battery to null his consumption and sell energy in LEM to Prosumer 2, which consumes and then resells the energy to 3. Prosumer 3 does the same but sells to Prosumer 4. Prosumer 1 did not take part in these trades because he had a lower price to buy from the retailer than in the LEM. Hour 23 is similar to hour 20, but Prosumers 1, 2 and 3 buy energy from the retailer because the retailer has a lower price than LEM. Only Prosumer 4 buy energy from 5. In hour 22, Prosumers 4 and 5 use their battery to null consumption. Prosumers 1, 2 and 3 buy energy from the retailer.

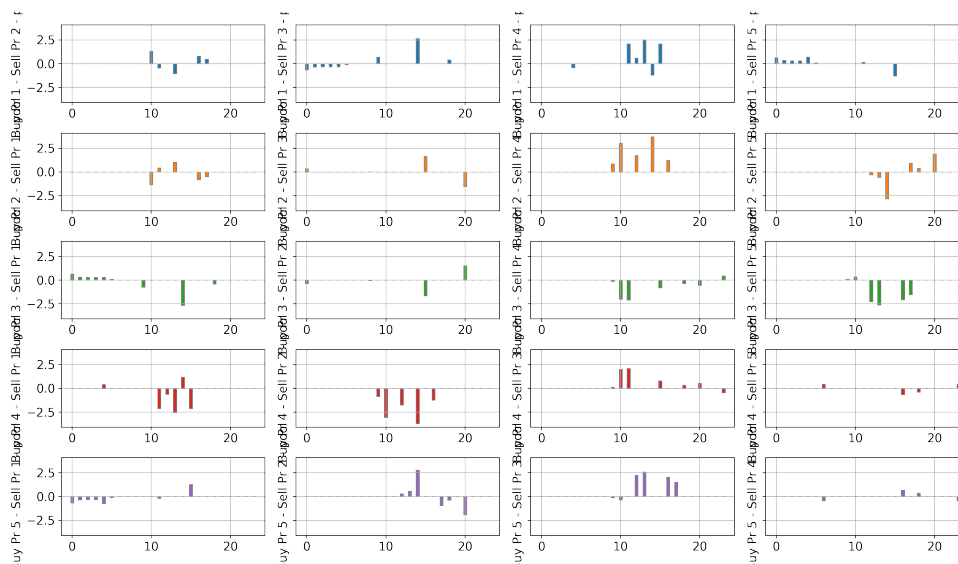


Figure 4.7: Prosumers' trades inside REC in Scenario 1 with Pool

Figure 4.7 represents the energy trades between prosumers. Every row is the prosumer who buys energy, and the columns are the prosumer who sells the energy. If the bar is above the x-axis, the prosumer bought energy; if it is below the x-axis, it means the prosumer sold. This figure is important to ensure that a prosumer buys energy from one or more prosumers but can only sell it to others in one hour. Hour 11 is the perfect example of this occurrence. Prosumer 3 sells energy to Prosumer 4. Prosumer 1 buys energy from Prosumers 4 and 5 and sells the energy to Prosumer 2, which only consumes it. Prosumer 5 sells the remaining energy to the retailer because it has the highest selling price.

To conclude this mechanism for calculating the market price, there is only a dependency on the retailer when there is no power and not enough energy is sold from the battery in the first few

hours. local market prices are high but then tend to fall as production increases. At peak times, the energy is sold to the retailer by the prosumer, who has the highest selling price to the retailer. In the final hours, prosumers without batteries are dependent on the retailer.

4.3.1.2 TMMR

With TMMR, there are some differences when compared to the Pool in this scenario. Figures 4.8 to 4.11 represent the REC operation.

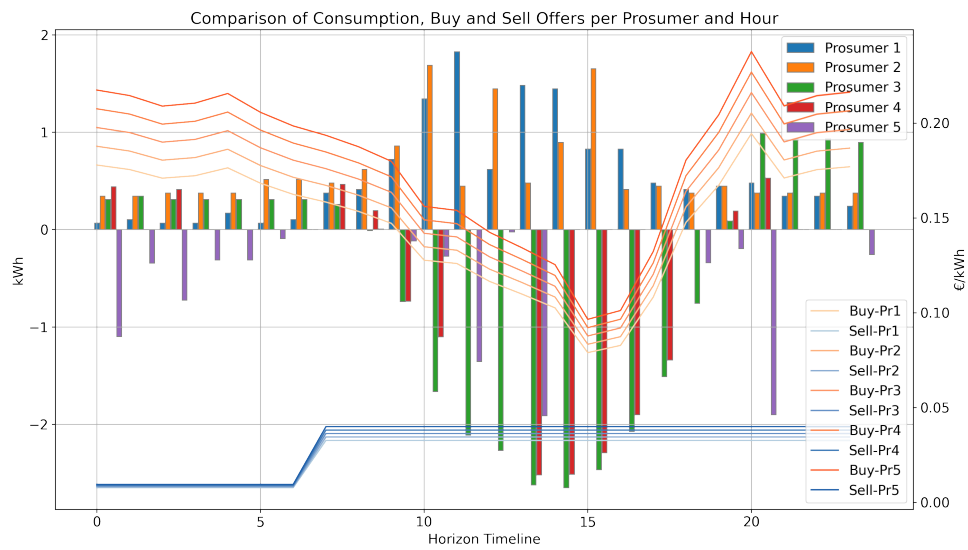


Figure 4.8: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with TMMR

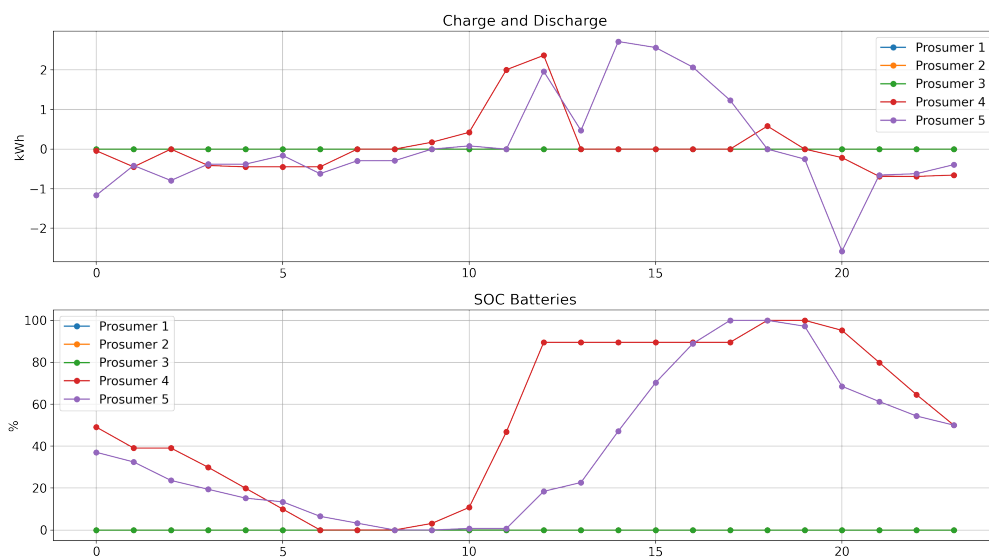


Figure 4.9: Batteries SOC, Charge and Discharge in Scenario 1 with TMMR

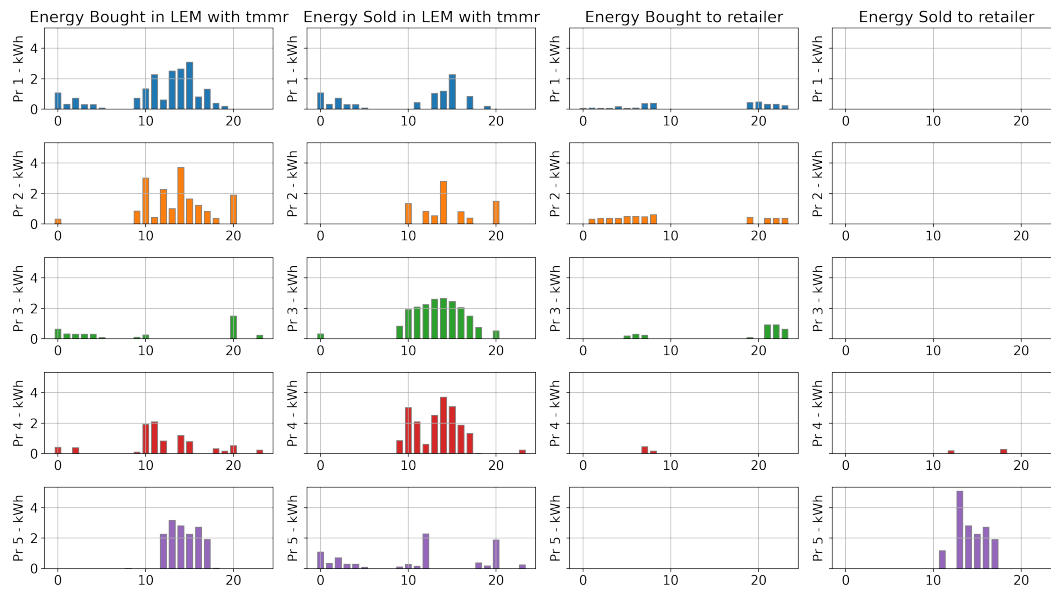


Figure 4.10: Prosumers' Energy trades in Scenario 1 with TMMR

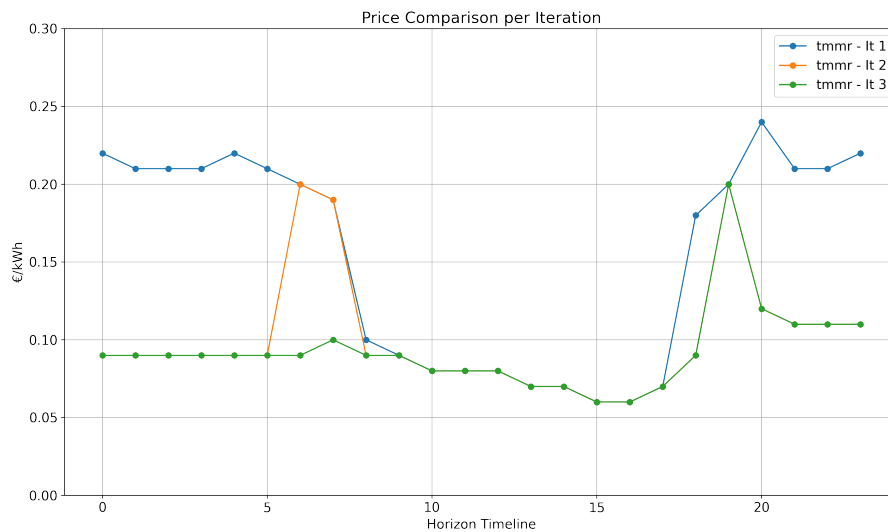


Figure 4.11: LEM internal price evolution in Scenario 1 with TMMR

The major difference between Pool and TMMR is the LEM internal price. Also, Prosumer 4 sells energy to the retailer.

The first nine hours, 0-8, equal the Pool case. In hours 5, and 8, Prosumers 1 and 2 buy energy from the retailer since they have the two lowest bids, and there is no production inside the REC, but only Prosumer 1 sells energy in REC. In hours 6 and 19, Prosumers 1 and 2 buy energy from the retailer, but Prosumer 2 buys some energy from Prosumer 1 in LEM and sells energy in LEM because his sell bids were accepted.

In hours 12 and 18, Prosumer 4 sells energy to the retailer. Prosumer 4 in these hours has liquid consumption equal to zero, which means the energy he produces uses totally. Since the REC has more production than consumption, Prosumer 4 buys energy from Prosumer 1 and sells it to the retailer. In hour 9, Prosumer 4 did not sell all his energy, so he sold the rest to the retailer.

All the other hours have similar occurrences compared to Pool.

4.3.1.3 PMMR

PMMR is expected to have results similar to TMMR, but when the consumption is higher, the LEM internal price with PMMR will be higher, and when there is more production, the LEM internal price is expected to be lower. Figures 4.12 to 4.15 show the results for the PMMR in Scenario 1.

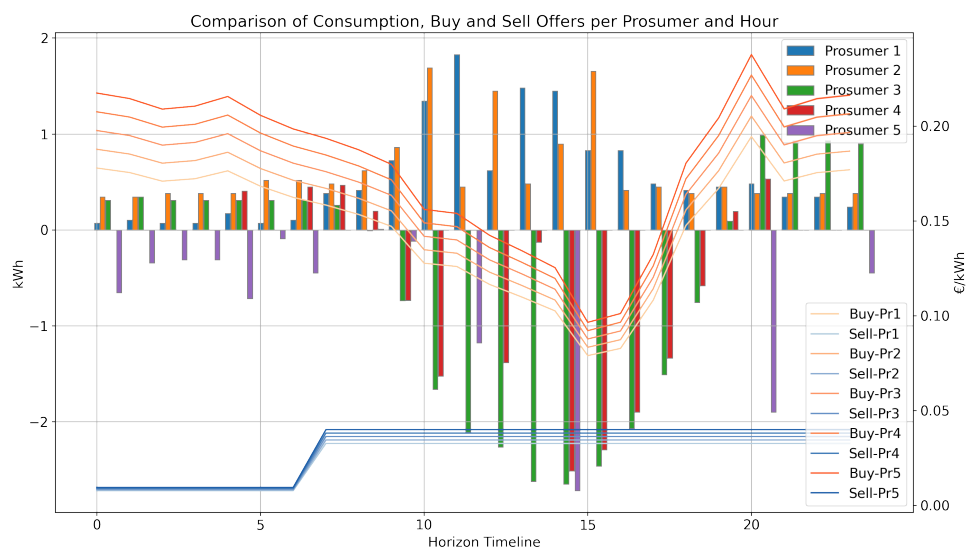


Figure 4.12: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with PMMR

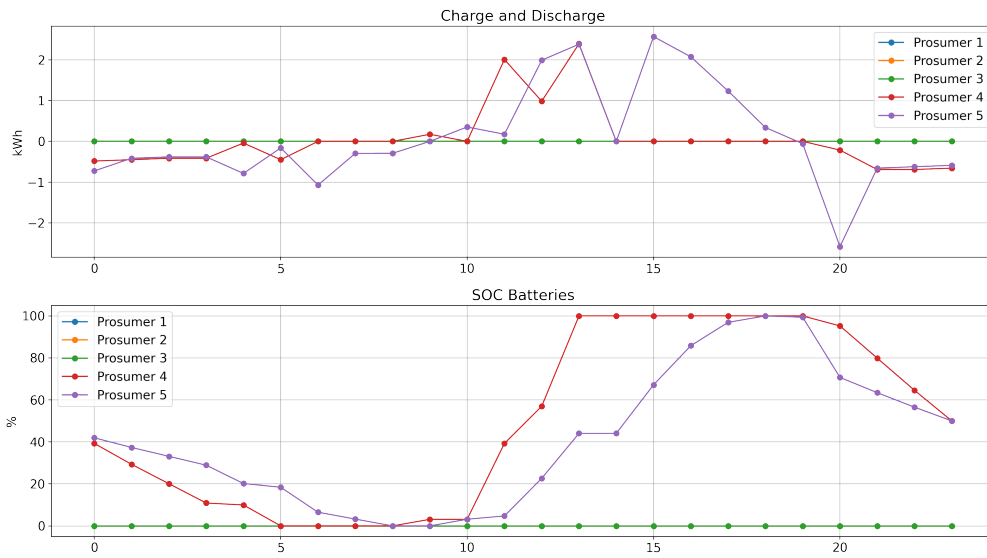


Figure 4.13: Batteries SOC, Charge and Discharge in Scenario 1 with PMMR

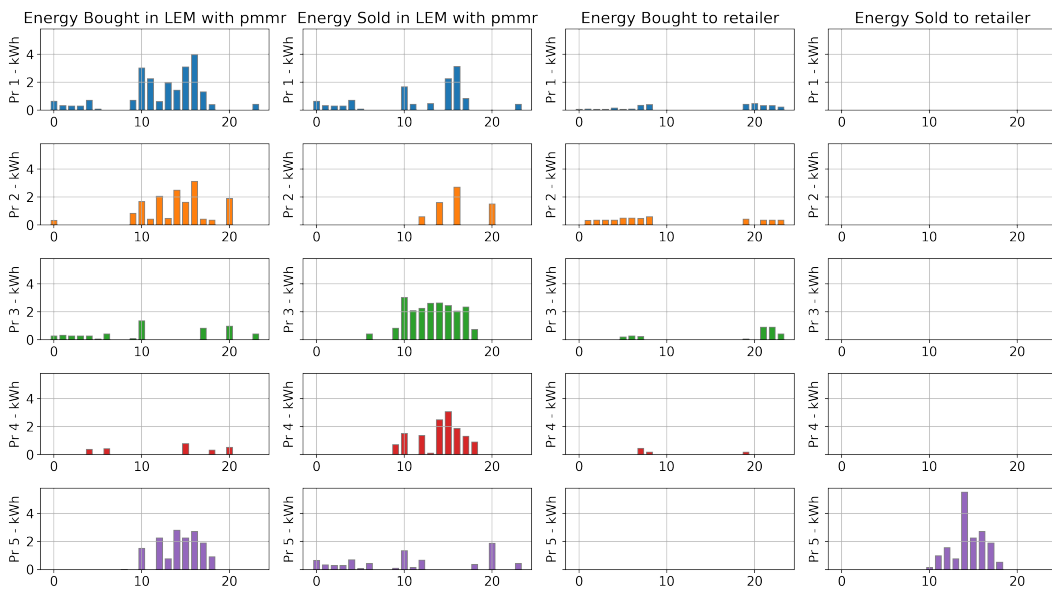


Figure 4.14: Prosumers' Energy trades in Scenario 1 with PMMR

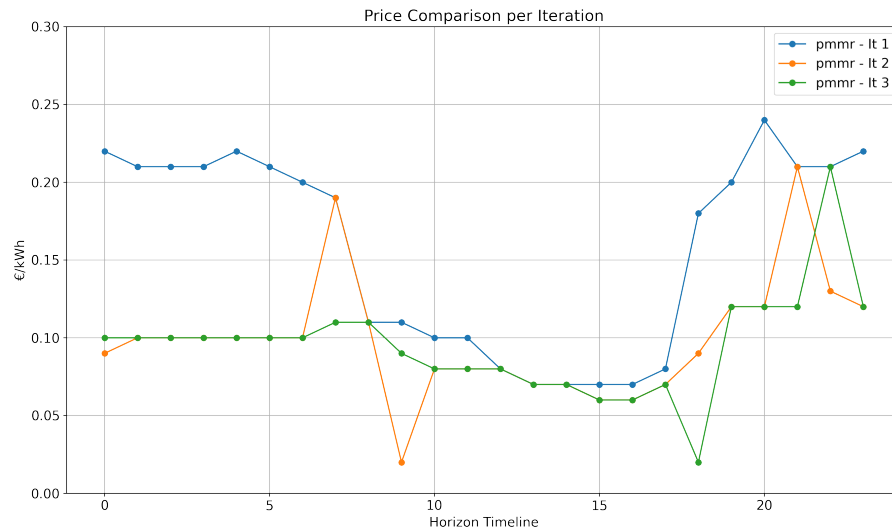


Figure 4.15: LEM internal price evolution in Scenario 1 with PMMR

In this case, the trades between the prosumers are very similar compared to the TMMR. Prosumer 5 sells energy from his battery discharge to Prosumer 1 in the first hours since Prosumer 1 has the first and only offer to be accepted in LEM for these hours. Prosumer 1 sells the energy to Prosumer 3 and gets energy from the retailer because he buys energy from the retailer for a lower price compared to Prosumer 3. Hours 7-8, every Prosumer has to get his energy from the retailer, except for Prosumer 5, who can use his battery.

Hours with more production, Prosumers 4 and 5 charge their battery. Prosumers 3 and 4 sell their energy in LEM, and Prosumers 1 and 2 buy it. Prosumer 5 sells all the REC surplus to the retailer because he has the highest sell price.

Prosumer 4 and 5 discharge their batteries in the final hours to nullify their consumption. Prosumer 5 can generate a surplus to sell in LEM using the battery. Looking for hours 20 and 23, where Prosumer 5 sells his surplus generated from the battery. In hour 20, Prosumer 2 buys the energy from 5 and consumes and sells the energy to Prosumers 3 and 4. Prosumer 1 buys energy from the retailer because he has the lowest price to get energy from the prosumer, and Prosumer 5 does not generate enough surplus for every prosumer. Hour 23, Prosumer 1 buys energy from Prosumer 5 and from the retailer. Consumes the energy from the retailer and sells the energy from Prosumer 5 to Prosumer 3. Once more, the reason for that is the retailer's buying price.

4.3.1.4 TSDR

TSDR considers all bids and does not have a compensation factor. With low demand and high generation, a low internal price is expected to be achieved; with low production and high demand, a high internal price is expected. Figures 4.16 to 4.19 reveal the TSDR influence in the REC operation.

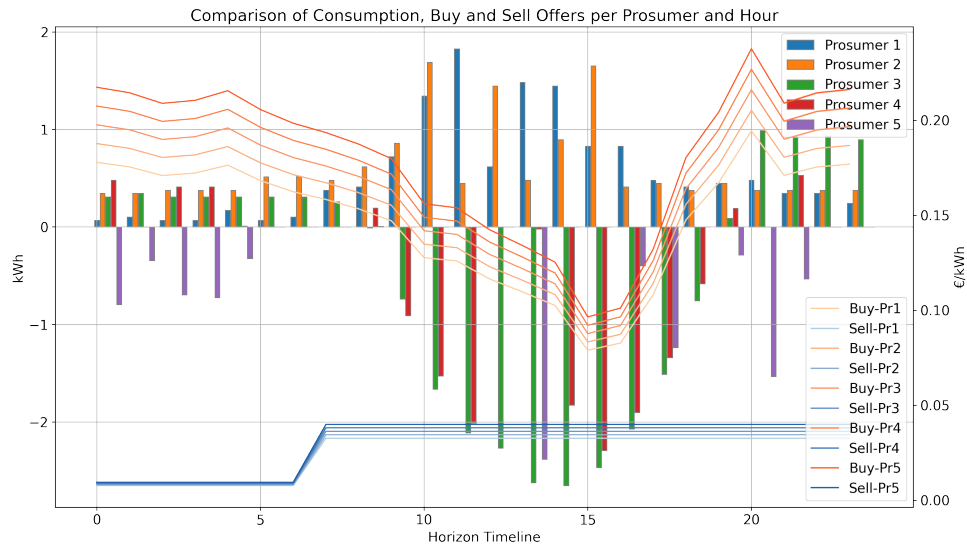


Figure 4.16: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with TSDR

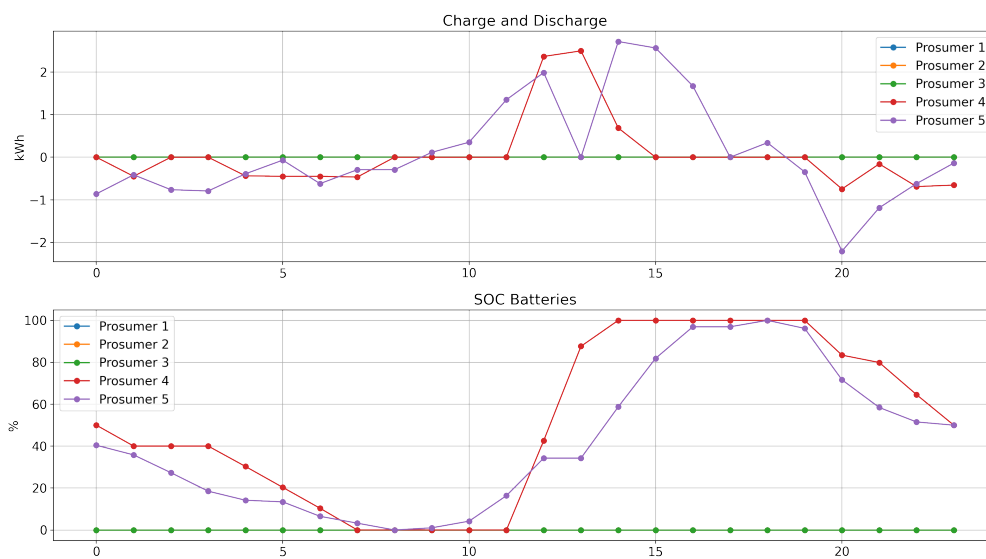


Figure 4.17: Batteries SOC, Charge and Discharge in Scenario 1 with TSDR

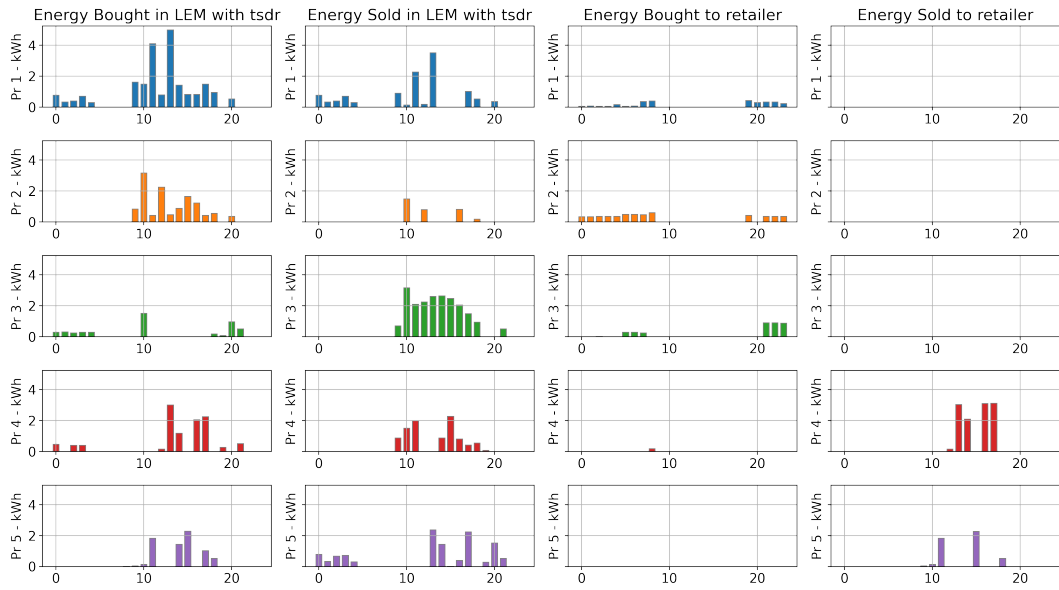


Figure 4.18: Prosumers' Energy trades in Scenario 1 with TSDR

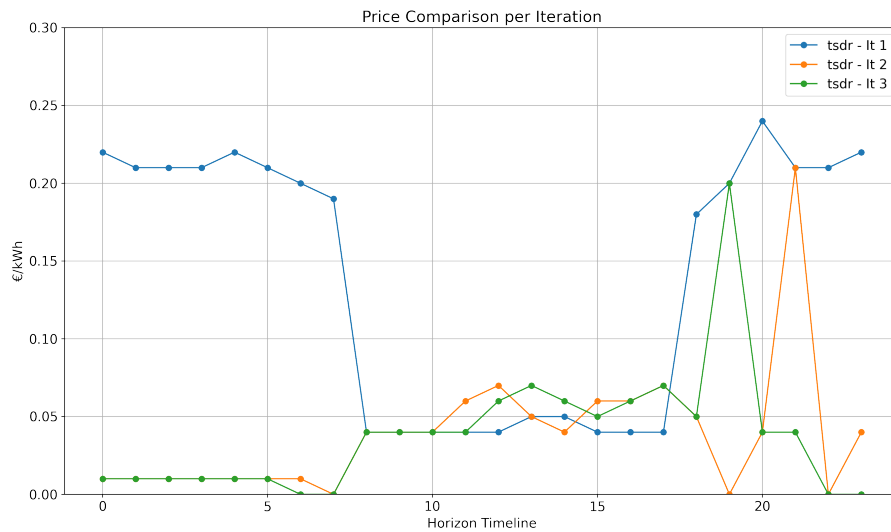


Figure 4.19: LEM internal price evolution in Scenario 1 with TSDR

Analysing Figure 4.16, it is possible to see that in the first five hours, Prosumer 5 creates a surplus to sell in LEM for the internal price, which is very low. Prosumer 1 buys the energy and sells it to Prosumer 3, which has a higher buying price from the retailer, and Prosumer 1 and 2 buy the energy for a lower price. Prosumers 4 and 5 use their battery to nullify their consumption in hours 0-7. For hours 7-9, Prosumers 1, 2, 3 and 4 need energy from the retailer, while Prosumer 5 has energy from the battery.

Prosumer 3 sells all his energy in LEM in the hours with more production. The optimization selects the Prosumer that buys the energy from Prosumer 3; the prosumer consumes and sells to the next one. In the end, Prosumer 4 or Prosumer 5 sell the energy remaining energy to the retailer at a high value.

In the final hours, Prosumer 4 uses the battery to nullify his consumption, and Prosumer 5 does the same, but hours 20 and 21 create a surplus with the discharging to sell the energy in LEM. Hour 20, Prosumer 5 sells energy to Prosumer 1 and 3 for the internal price. Prosumer 2 gets the energy from Prosumer 1, and Prosumer 1 is the only member that buys energy from the retailer in that hour due to the lower buying price to the retailer.

4.3.1.5 PSDR

The PSDR only considers accepted offers and does not have a compensation factor, so that the internal market price may vary compared to the TSDR. If the value of the last accepted bid is lower during production hours, the internal price is expected to be lower. The internal price will be higher if the value of the last accepted purchase offer is lower during non-production hours. Figures 4.16 to 4.19 reveal the TSDR influence in the REC operation.

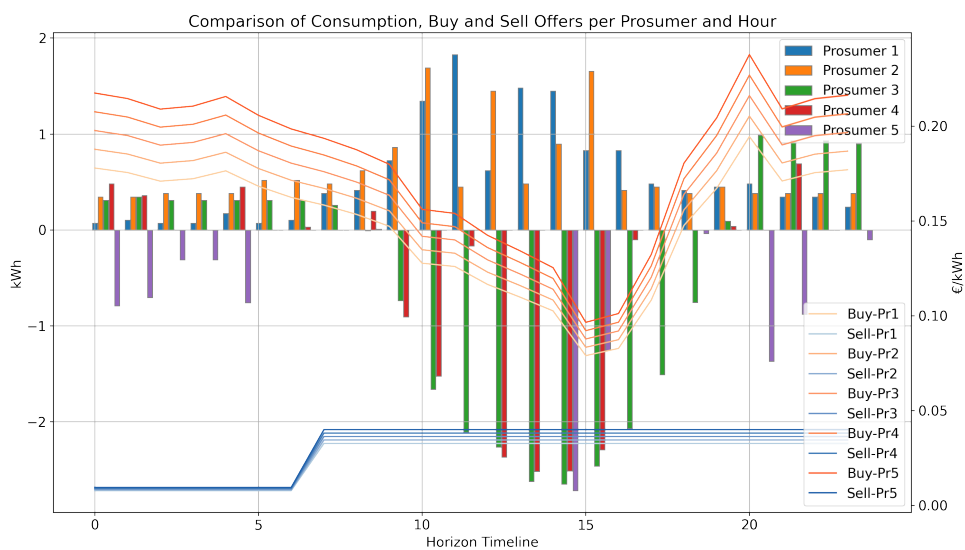


Figure 4.20: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with PSDR

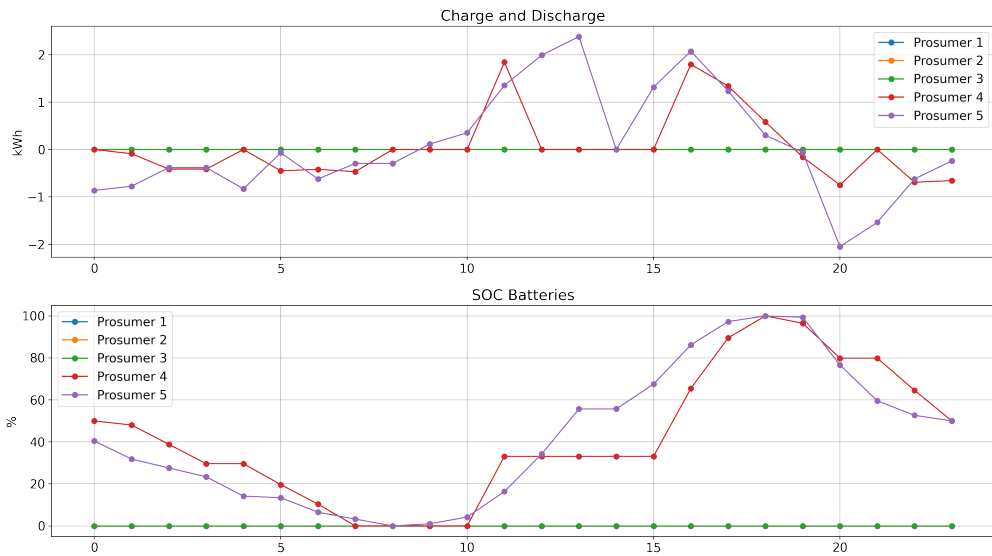


Figure 4.21: Batteries SOC, Charge and Discharge in Scenario 1 with PSDR

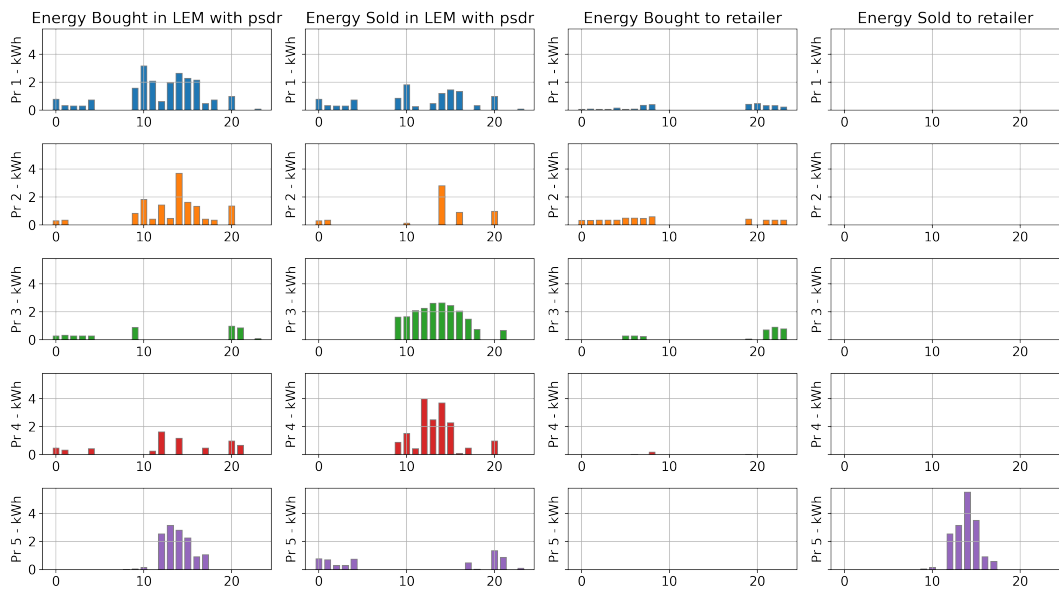


Figure 4.22: Prosumers' Energy trades in Scenario 1 with PSDR



Figure 4.23: LEM internal price evolution in Scenario 1 with PSDR

In this pricing mechanism, the REC operation is very similar to the REC operation analysed with the TSDR pricing mechanism in this scenario. The major difference is that Prosumer 5 is the only Prosumer that sells energy to the retailer. This results in a lower REC operation cost.

4.3.1.6 TSDRC

The difference between TSDRC and TSDR is the compensation factor. In the TSDRC pricing mechanism, with the compensation factor, if the difference between the prosumer's bids is higher, the price will be higher. According to [6], more trades between prosumers and generation are expected.

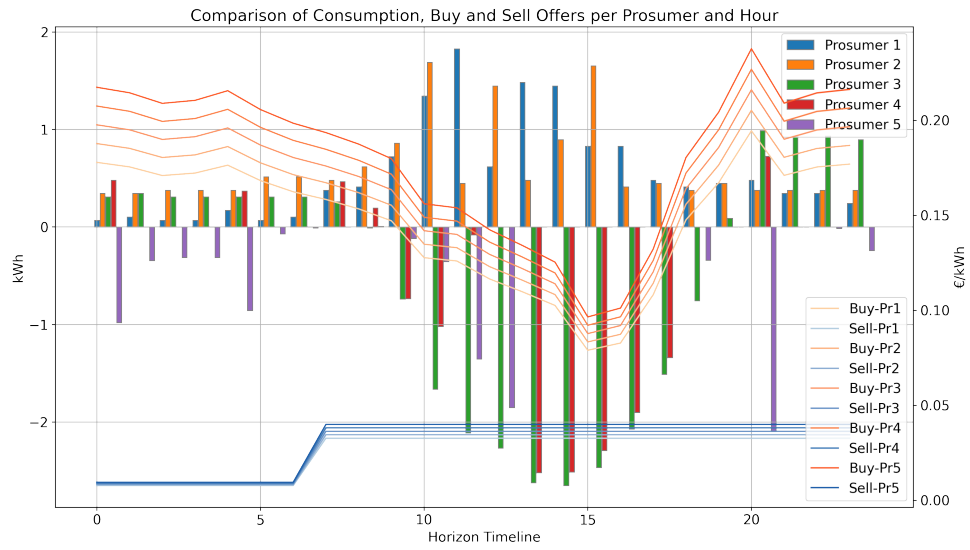


Figure 4.24: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with TSDRC

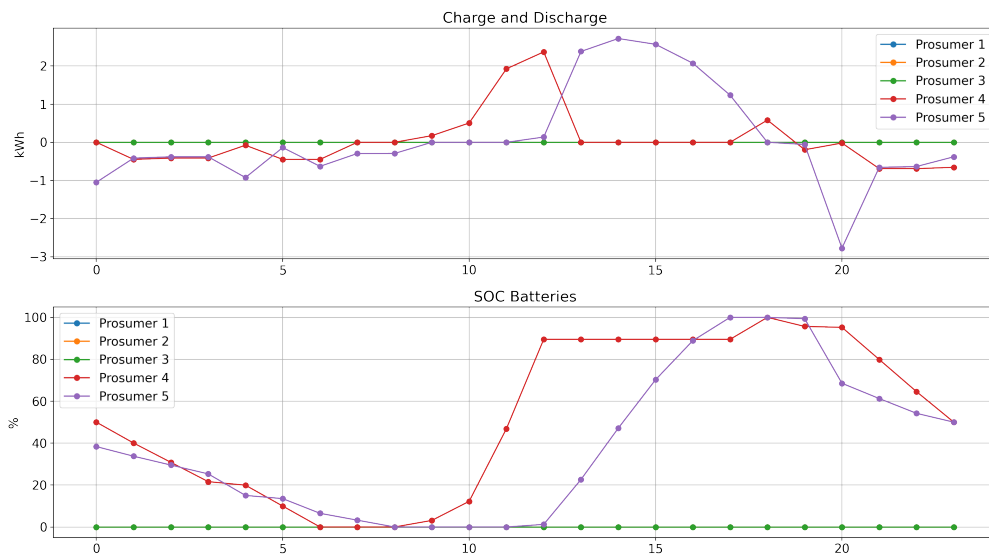


Figure 4.25: Batteries SOC, Charge and Discharge in Scenario 1 with TSDRC

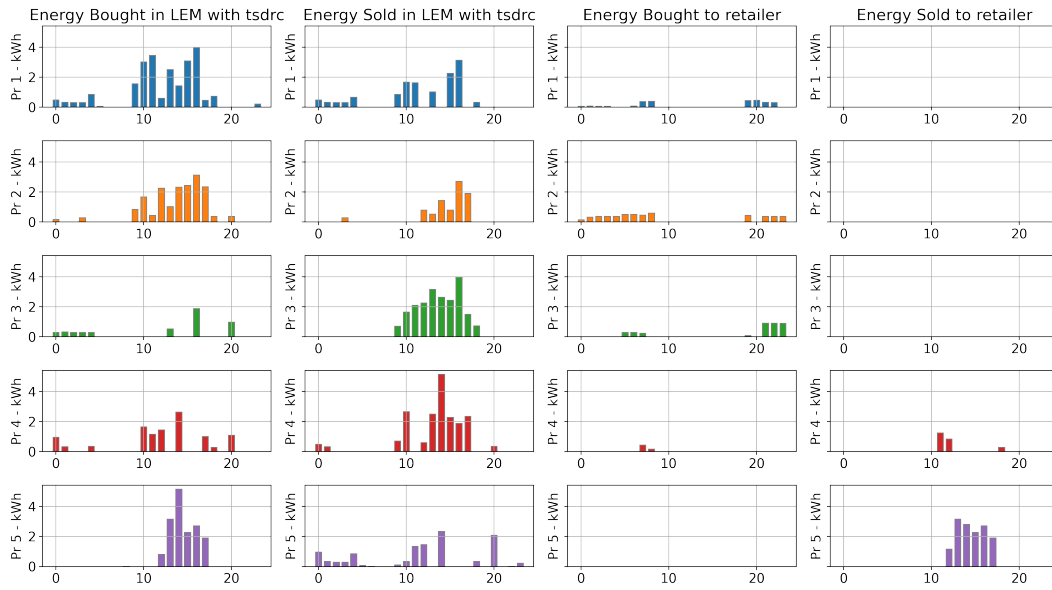


Figure 4.26: Prosumers' Energy trades in Scenario 1 with TSDRC

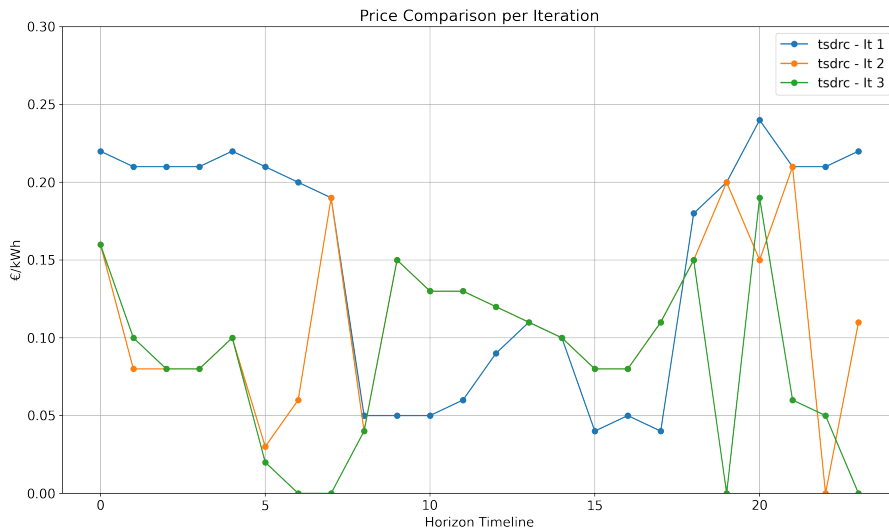


Figure 4.27: LEM internal price evolution in Scenario 1 with TSDRC

Prosumers buy energy from REC if the internal price is lower than the retailer's. Prosumer 5 sells the energy from the battery discharging in LEM for the first five hours, while Prosumer 4 only nullifies his consumption. Prosumer 4 has a low nominal capacity and low maximum power battery. Prosumer 3 is the predominant seller in the LEM in the production hours since he does not have a battery to charge and has the lowest selling bid in LEM. In the final hours, Prosumer 5 manages his battery to sell his energy for hours 20 and four 23 and reduce consumption for the other hours. Prosumer 4 only nullifies his consumption once more.

4.3.1.7 PSDRC

PSDRC has the same compensation factor as TSDRC but considers only the accepted bids for the LEM internal price calculation. Figures 4.28 to 4.31 represent the REC operation for Scenario 1 with PSDRC.

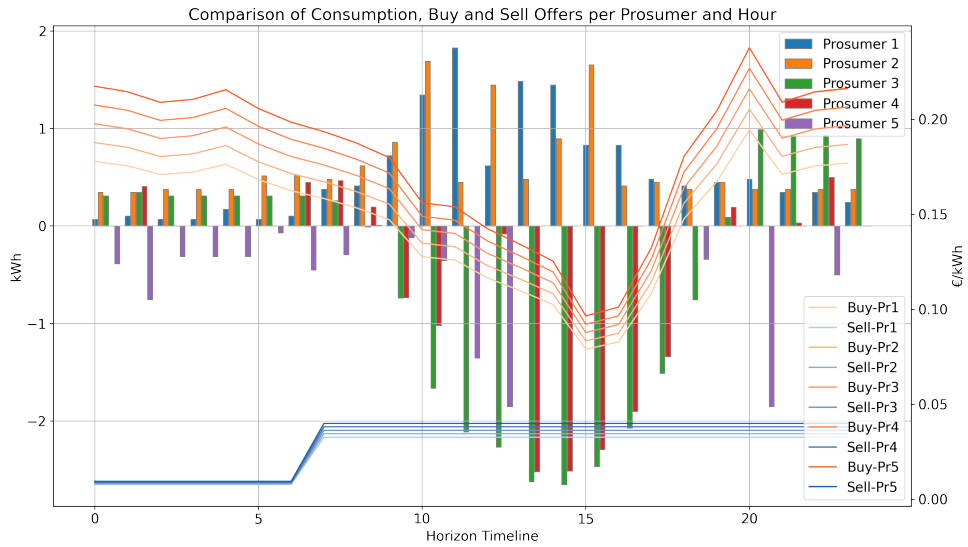


Figure 4.28: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with PSDRC

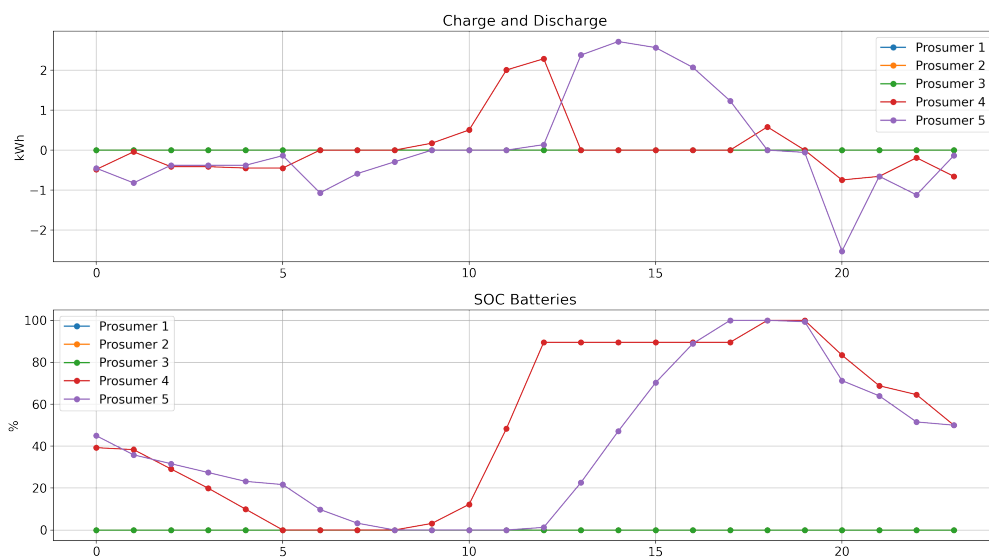


Figure 4.29: Batteries SOC, Charge and Discharge in Scenario 1 with PSDRC

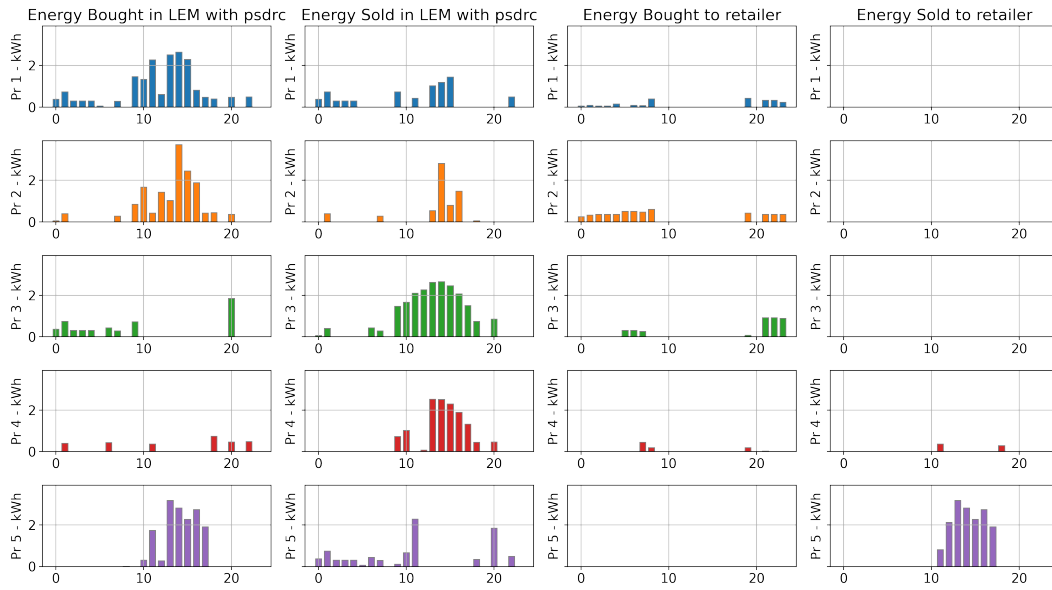


Figure 4.30: Prosumers' Energy trades in Scenario 1 with PSDRC

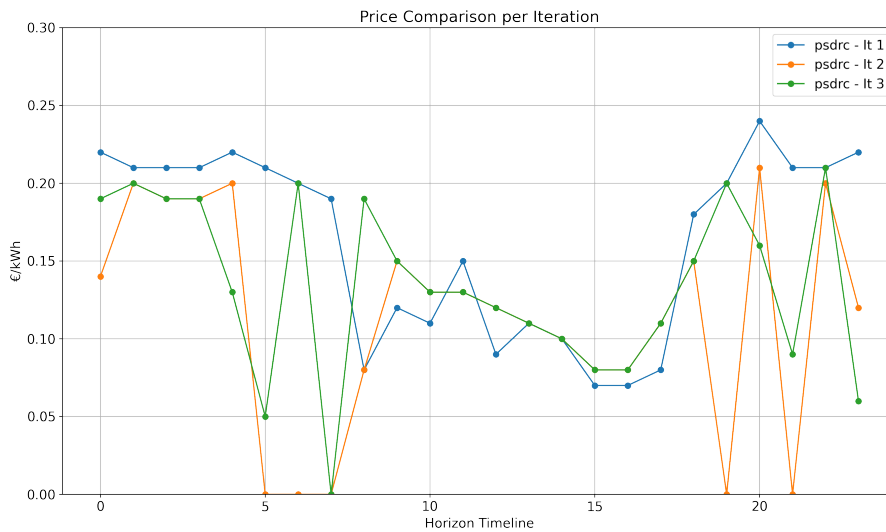


Figure 4.31: LEM internal price evolution in Scenario 1 with PSDRC

Analysing the PSDRC influence on the REC operation, it is possible to check that Prosumer 5 sells the initial energy in hours 0-7, and Prosumer 4 sells in hours 0, 6 and 7 in LEM. Prosumer 1 buys energy from Prosumer 5 in hours 0-5 and then sells the energy to Prosumer 3. In hours 6 and 7, Prosumer 5 sells the energy directly to Prosumer 3. In these hours, Prosumer 1 buys energy for a lower price in the retailer than in the LEM. Prosumer 4 sold energy in LEM in the first hours, which resulted in a dependency on the retailer in hours 7 and 8.

In the hours with more production, Prosumer 3 and Prosumer 4 always sell the bigger amount of energy in LEM. Prosumer 5 sells the overall REC surplus to the retailer for the highest value.

In the last few hours, there is still a big dependency on the retailer. Still, when Prosumer 5 sells energy in LEM with battery discharge, the optimization algorithm distributes energy for all prosumers without batteries to reduce the overall REC operation cost. Hour 20 is when all the prosumers have a higher retailer price, and Prosumer 5 disposes of energy for every member, except for 4 that have their resources. In this hour, Prosumer 5 sell bid is caught by Prosumer 3, which has the highest buy bid, and then Prosumer 3 consumes and sells to Prosumers 1 and 2.

4.3.1.8 TSDRC-Half

Compared to the TSDRC, the TSDRC-Half has half the value of the compensation factor. Considers all buying and selling offers. Figures 4.32 to 4.35 show how this pricing mechanism influenced the REC operation.

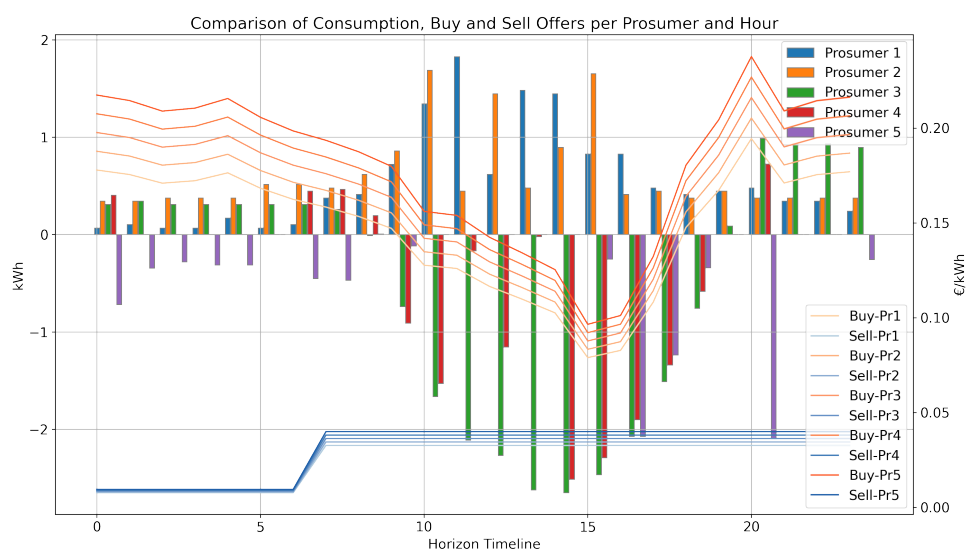


Figure 4.32: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with TSDRC-Half

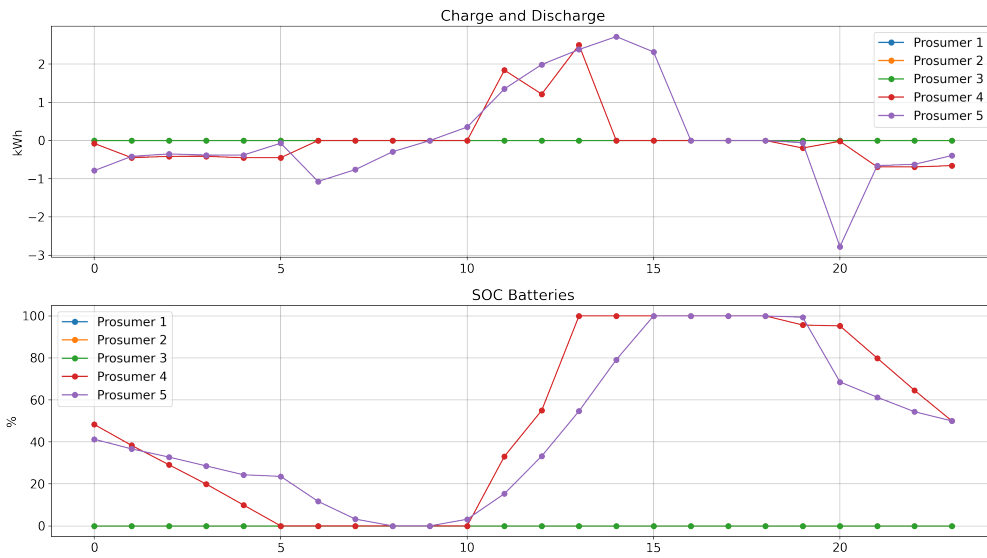


Figure 4.33: Batteries SOC, Charge and Discharge in Scenario 1 with TSDRC-Half



Figure 4.34: Prosumers' Energy trades in Scenario 1 with TSDRC-Half

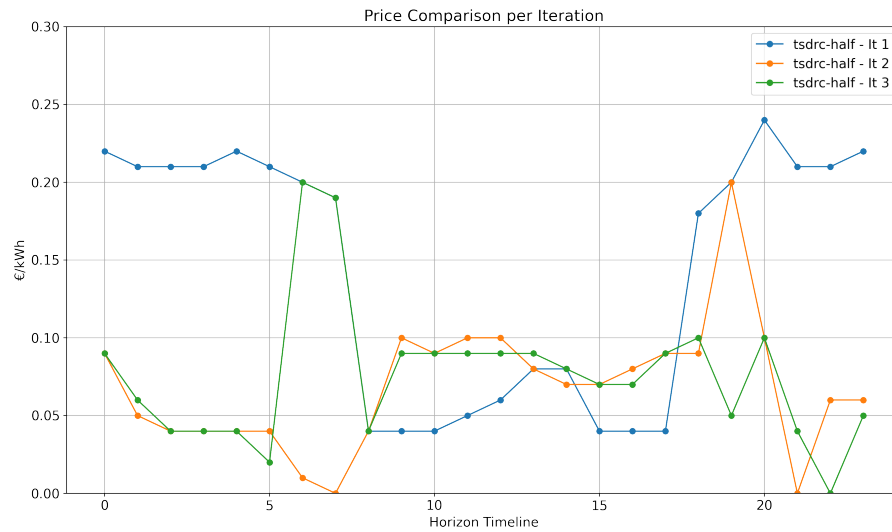


Figure 4.35: LEM internal price evolution in Scenario 1 with TSDRC-Half

For the first hours, Prosumers 4 and 5 discharge their battery gradually, Prosumer 5 to sell energy in LEM and Prosumer 4 to nullify consumption, resulting in zero liquid consumption. The market price for these hours is lower than TSDRC in the first hours. Prosumer 2 only gets energy from the retailer in hours 0-8 since Prosumer 5 does not sell the energy necessary to cover all demand.

Prosumer 3 and 4 sell their energy in the REC in the hours with more production. They have the lowest selling bids, making their offers accepted in the LEM. Prosumer 5 sells the overall REC surplus to the retailer, but Prosumer 4 also does so in hours 9, 10, 13, 17 and 18. Prosumers 4 and 5 have their batteries fully charged since hours 15 and 13, respectively, and they have to sell the overall REC surplus to the retailer since they have the higher sell price.

In the last few hours, once more, Prosumer 5 sells the energy from the battery in hour 20 because it is the hour that Prosumers have the higher retailer price. Note that Prosumer 1 needs to buy energy from the retailer because Prosumer can not sell enough energy to cover all the demand needed. Prosumer 1 has the lowest buy price to the retailer. The same occurs in hour 23, although the price for hour 20 is higher, resulting in more trades in hour 20.

4.3.1.9 PSDRC-Half

Lastly, the PSDRC-Half is equal to the TSDRC-Half but only considers the accepted bids in the LEM. The compensation factor is half the compensation factor considered in PSDRC. Figures 4.36 to 4.39 show how the REC performed with this pricing mechanism in Scenario 1.

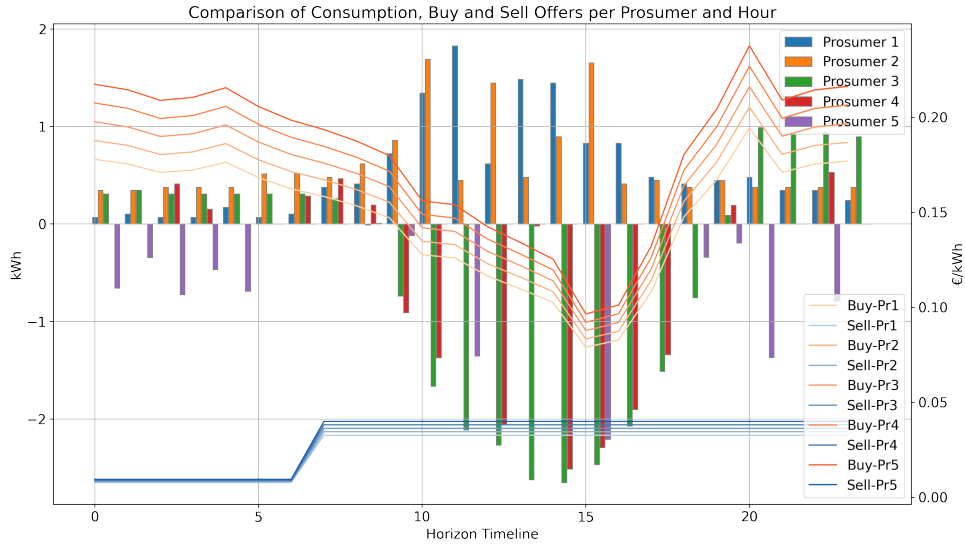


Figure 4.36: Prosumers' Liquid Consumption after Stage Two in Scenario 1 with PSDRC-Half

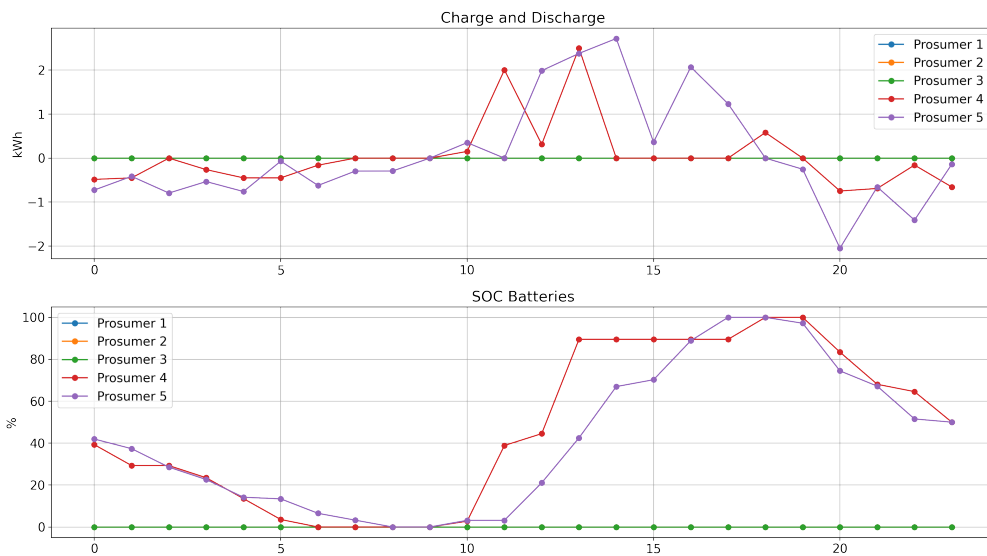


Figure 4.37: Batteries SOC, Charge and Discharge in Scenario 1 with PSDRC-Half

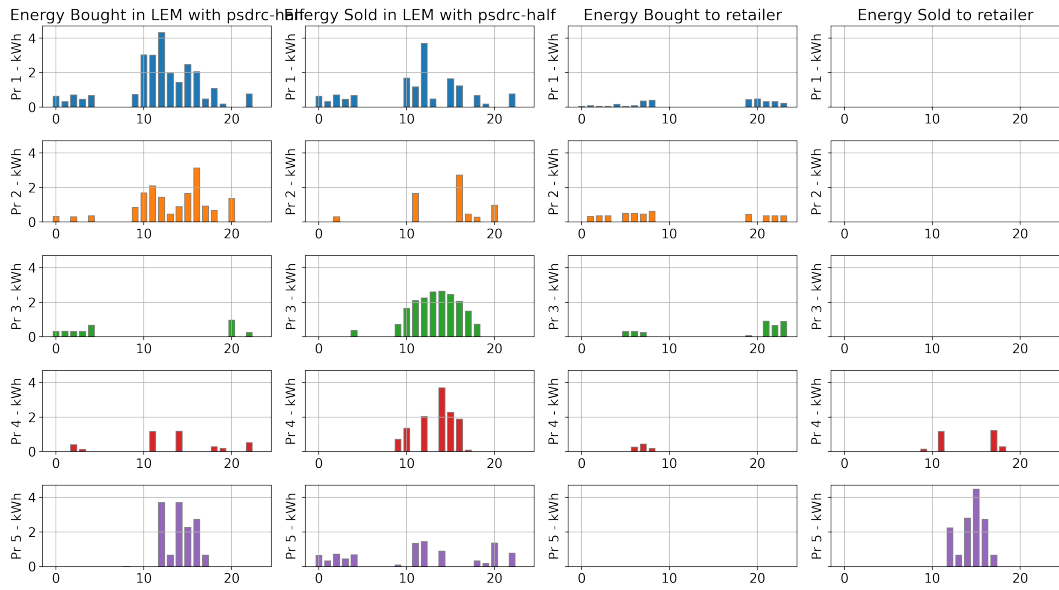


Figure 4.38: Prosumers' Energy trades in Scenario 1 with PSDRC-Half

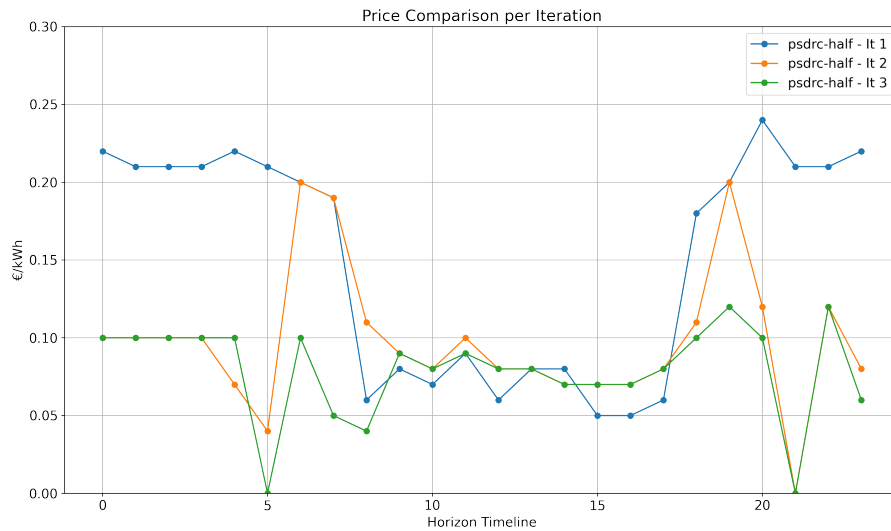


Figure 4.39: LEM internal price evolution in Scenario 1 with PSDRC-Half

This pricing mechanism has the first hours trading like the other, where Prosumer 5 sells the energy from his battery discharging to Prosumer 1. Prosumer has the first bids to be accepted, consumes, and then sells to the other prosumers, in case Prosumer 2 and 3 need the energy for their consumption. Prosumer 4 uses his battery to nullify the consumption and has zero liquid consumption. However, in hours 2 and 3, Prosumer 4 creates a surplus to sell energy in LEM. Since Prosumer 4 sold energy from his battery, in hours 6, 7 and 8, Prosumer 4 buys energy from the retailer.

In the generation hours, Prosumer 3 and 4 sell their energy in LEM. Prosumer 4 does not show sales offers in the LEM because it charges its battery. Prosumers 4 and 5 sell the overall REC surplus to the retailer because they have the highest selling price to the retailer. When Prosumer 5 sells energy in the LEM, it will not make sales to the retailer, and it is at these times Prosumer 4 sells the energy to the retailer, with the second highest selling price outside the LEM.

In the final hours, Prosumer 5 sells the energy in hour 20, and in this case, sells the energy in hour 22. Hour 20, the Prosumer 5 battery discharge sale occurs again due to high retailer prices. In hour 22, Prosumer 5 discharges his battery again and sells energy in LEM.

4.3.1.10 Pricing Mechanisms Results Comparisons

Some details need to be explored to finish the Scenario 1 study. With Table 4.3 and Figures 4.40, 4.41 and 4.42, it is possible to comprehend the influence of the pricing mechanisms in REC operation total cost, the individual costs for every prosumer, and the LEM internal price evolution.

Table 4.3 shows the cost of operating the REC with different market price calculation mechanisms for Scenario 1.

Figure 4.40 shows the individual cost of each prosumer throughout the REC's operation by price calculation mechanism.

Finally, Figures 4.41 and 4.42 show the variation in market prices over 24 hours. Figure 4.41 compares Total and Partial pricing mechanisms, including a pool and a comparison of all pricing mechanisms. Figure 4.42 extends the comparison of all pricing mechanisms included in the previous figure.

Table 4.3: REC operation cost per pricing mechanism in Scenario 1

Pricing mechanism	Cost (€)
Pool	1.7276
TMMR	1.7289
PMMR	1.7276
TSDR	1.7519
PSDR	1.7305
TSDRC	1.7408
PSDRC	1.7399
TSDRC-Half	1.7377
PSDRC-Half	1.7346
Stage One	3.9005

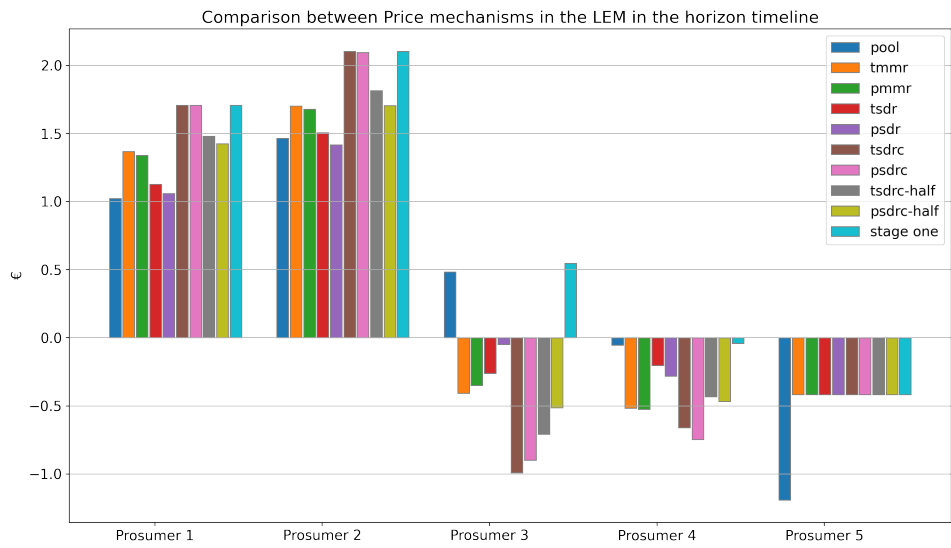


Figure 4.40: Prosumers individual operation cost per pricing mechanism in Scenario 1



Figure 4.41: LEM internal prices per pricing mechanism, Total and Partial comparison in Scenario 1

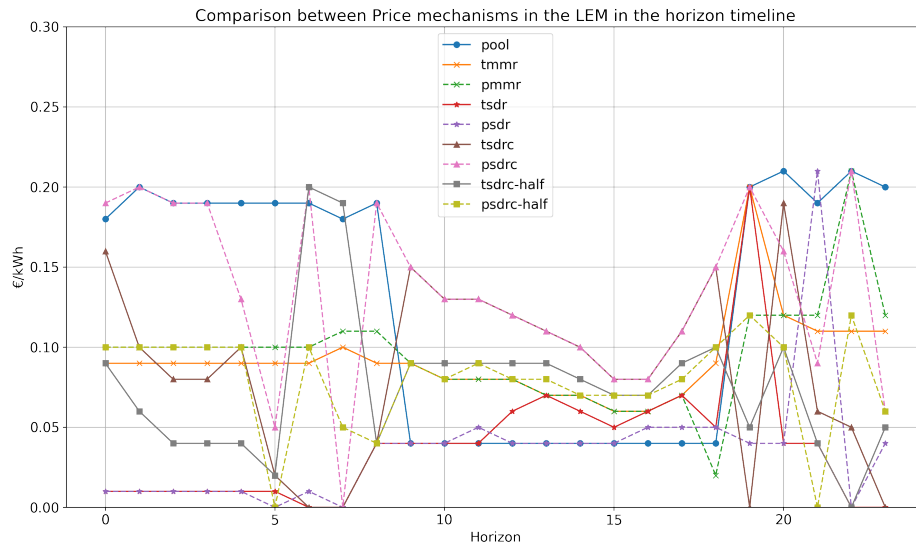


Figure 4.42: LEM internal prices per pricing mechanism in Scenario 1

Starting by analysing Table 4.3, Pool and PMMR influence the REC to have the lowest operation cost. The REC operation cost is lower when LEM assumes a Partial pricing mechanism. The REC operation cost with only Stage One of the optimization is much higher.

Analysing Figure 4.40, Prosumers 1 and 2 have a higher cost than Prosumers 3, 4 and 5. These two prosumers have a lower cost when a Partial mechanism pricing is considered in the LEM. The Pool provides these two prosumers with lower costs for each. However, Pool provides Prosumer 3 with a high cost compared to the other pricing mechanisms since, with the other pricing mechanisms, the cost is negative (profit). Prosumer 3 has a lower profit if a Partial pricing mechanism is considered over a Total because he sells more energy in the Total pricing mechanism. Prosumers 4 and 5 have negative costs for all pricing mechanisms. Prosumer 4 has more profit if a Partial pricing mechanism is selected over a Total because this Prosumer sells more energy with a Partial, unlike Prosumer 3. Prosumer 5 has a constant operation cost, except for the Pool. In Pool, Prosumer 5 has more profit over all the other pricing mechanisms because he sells the energy in LEM for a higher price. Prosumers 3, 4 and 5 are one generation old, but only the last two have batteries.

Figure 4.41 compares the LEM internal prices evolution in the horizon timeline between the Pool and between the Partials and the Totals. The Pool is high for hours with no generation but is low for hours with high generation. As mentioned before, it is expected that Partials have a lower price when there is more generation but a higher price when there is more consumption, depending on the considered bids. The comparison between TMMR and PMMR shows in the first hours that TMMR has a lower price, but in the high generation period, both have the same price. The reason is that the MMR equation considers the same offers; in this case, Prosumer 3 selling and Prosumer 1 and 2 buying bids.

Comparing TSDR and PSDR, PSDR has a lower price in the higher generation period, and the price is similar for the other periods. Hour 19 for TSDR has a high internal price because there is low energy to sell; only prosumer 5 sells energy, and the same happens in hour 21 for the PSDR pricing mechanism. For TSDRC and PSDRC, the price is equal in the production period but is higher for PSDRC in the no-generation periods. The higher LEM internal price in these periods is due to the higher λ_t^{buy} in the PSDRC mechanism compared to the TSDRC mechanism. Finally, TSDRC-Half and PSDRC-Half find themselves in a similar situation to TSDRC and PSDRC during the first few hours. In hours 5-7, the TSDRC-Half has a high internal price because Prosumer 5 has a surplus to sell, and the price rises. Hours with lower internal prices' values for the PSDRC-Half when compared to the TSDRC-Half happen because λ_t^{sell} is lower.

According to [6], hours 0-8 and 17-23, the LEM internal price is supposed to vary depending on the Prosumers batteries' charge and discharge profiles. Figure 4.42 proves this happens and shows the price stabilisation between hours 9-17.

During the work developed for INESC TEC, every pricing mechanism was analysed in all scenarios. As it is extensive work and every scenario has a very similar REC operation for every pricing mechanism, only the first scenario pricing mechanisms will be analysed in detail in the document. If some result is very different, the pricing mechanism influence in the scenario will be explained.

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4.3.2 Scenario 2, More Generation

In this scenario, all the parameters are equal to Scenario 1, with the exception of the generation. The generation was increased from 3,0 kWp to 4.5 kWp. With this change, the REC operation cost is expected to be lower, with the possibility of profit. Individually, it is expected that the prosumers with generation will have profit and prosumers without generation will not. In terms of pricing mechanisms, as soon as there is a surplus, the Partial pricing mechanisms are expected to be lower when compared to the Total.

Table 4.4: REC operation cost per pricing mechanism in Scenario 2

Pricing mechanism	Cost (€)
Pool	-0.2253
TMMR	-0.1875
PMMR	-0.1856
TSDR	-0.1422
PSDR	-0.1846
TSDRC	-0.1668
PSDRC	-0.1719
TSDRC-Half	-0.1625
PSDRC-Half	-0.17
Stage One	2.1391

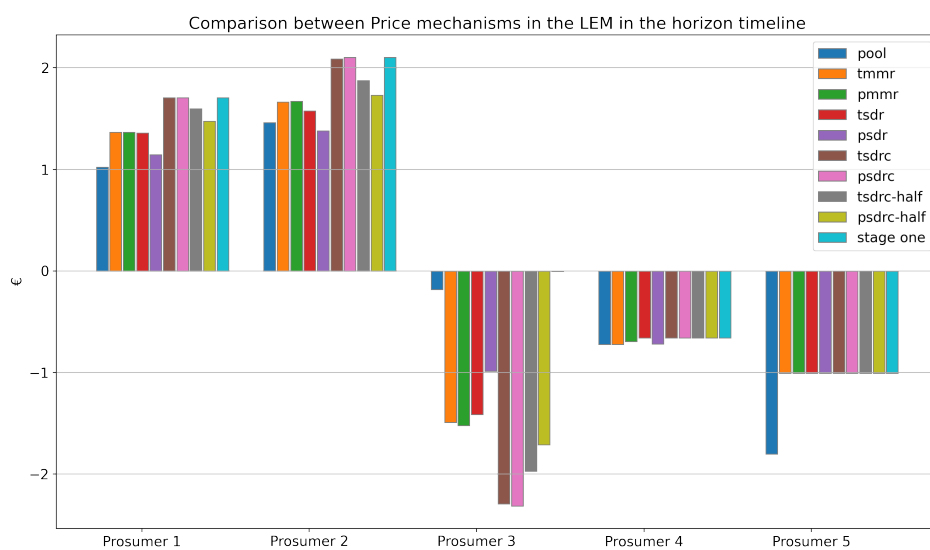


Figure 4.43: Prosumers individual operation cost per pricing mechanism in Scenario 2

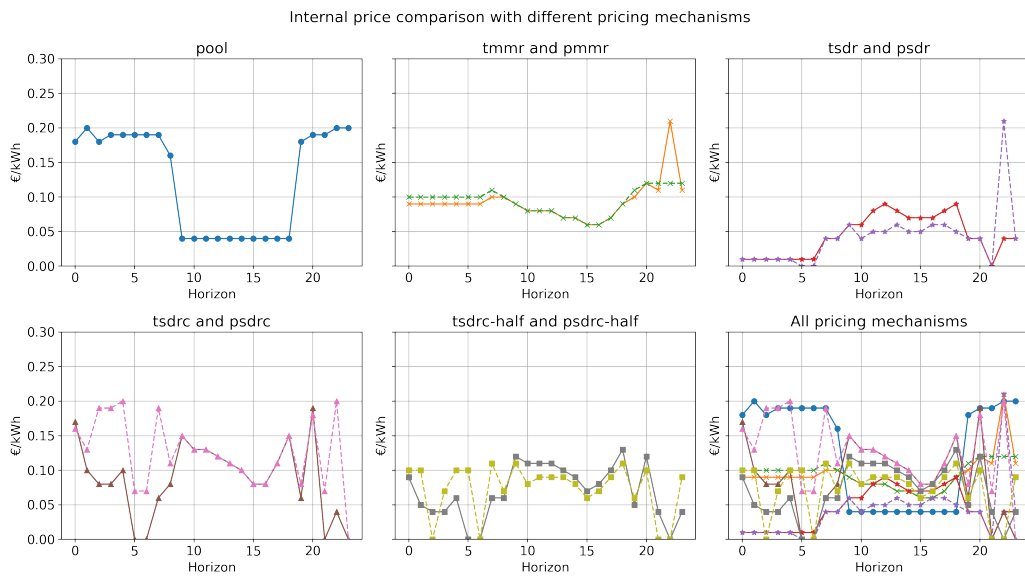


Figure 4.44: LEM internal prices per pricing mechanism, Total and Partial comparison in Scenario 2

In this scenario, all the pricing mechanisms provided a profit to the REC. However, checking different profits in Table 4.4 is possible. The pool has the highest profit, and TSDR has the lowest. Energy transactions during production hours have a greater quantity, which results in a greater monetary value associated with the transactions.

The difference between the obtained profits can be explained based on the trades with the retailer in the hours 9-18. In Pool, only Prosumer 5 sells energy to the retailer. With TMMR, PMMR and PSDR, only Prosumers 4 and 5 sell energy to the retailer, and for the rest of the pricing mechanisms, Prosumers 3, 4 and 5 sell the energy to the retailer. However, TSDR has the lowest profit because Prosumer 3, which has the lowest sell price to the retailer, sells more energy than the other pricing mechanisms. The less energy Prosumer 4 sells to the retailer, the higher the profit for the REC operation.

Figure 4.43 shows that Prosumer 1 has a lower individual cost than Prosumer 2 because he has more trades in LEM. Prosumer 1 has many trades in the high-generation zone because he usually buys energy from Prosumer 3, consumes and then resells the energy. Prosumer 3, except for Pool, has the highest profits. Prosumer 3 sells the energy at a low price in the Pool mechanism, and the consequence is a low profit with this mechanism. Prosumers 4 and 5 have an overall stable profit for every mechanism, except for Prosumer 5 in Pool, which has already been explained.

Comparing the LEM internal prices with Figure 4.44, the Pool is almost equal to the Scenario 1 Pool. Between 9-18 hours, the price is the same, and in some of the other hours, the internal price changes because the liquid consumption changes from Scenario 1 to Scenario 2 after Stage Two of the optimization.

There is no difference between TMMR and PMMR in the hours with more production because the offers considered for the equation are the same. However, in periods with no generation, the

price is lower for TMMR, as expected. Considering TSDR and PSDR, the value for the LEM internal price is lower for PSDR in the production hours. PSDR only considers the Prosumer 3 sell offer, which means a lower λ_t^{sell} , that results in a lower LEM internal price for the hours with more generation and surplus. TSDRC and PSDRC are very similar to Scenario 1 TSDRC and PSDRC; the only difference is in the zones with no generation that depends on the optimization. TSDRC-Half and PSDRC-Half follow the same pattern as TSDRC and PSDRC in the hours with no production. In the production hours, comparing TSDRC-Half and PSDRC-Half in both Scenarios 1 and 2, since there is more energy injection into the REC grid, it is possible to see a greater difference in the performance of the Partial mechanisms.

4.3.3 Scenario 3, More Batteries Capacity and Maximum Output Power

Scenario 3 keeps the parameters from Scenario 1, but the batteries have a higher nominal capacity and maximum power. Scenario 1 used a 5 kWh, 2,5 kWp for Prosumer 4 and a 10 kWh, 5 kWp for Prosumer 5. In this scenario, it was considered a 15 kWh, 7,5 kWp battery for Prosumer 4 and a 20 kWh, 10 kWp battery for Prosumer 5.

With these changes, the REC operation cost must be lower than Scenario 1. The prosumers will not depend on the retailer in the hours without production since prosumers with batteries will cover the demand. In the hours when the generation is higher, prosumers with batteries probably will not sell their energy to charge the batteries since it takes more energy to charge them.

Table 4.5: REC operation cost per pricing mechanism in Scenario 3

Pricing mechanism	Cost (€)
Pool	0.1571
TMMR	0.1571
PMMR	0.1571
TSDR	0.1571
PSDR	0.1571
TSDRC	0.1571
PSDRC	0.2738
TSDRC-Half	0.1571
PSDRC-Half	0.1571
Stage One	3.5755

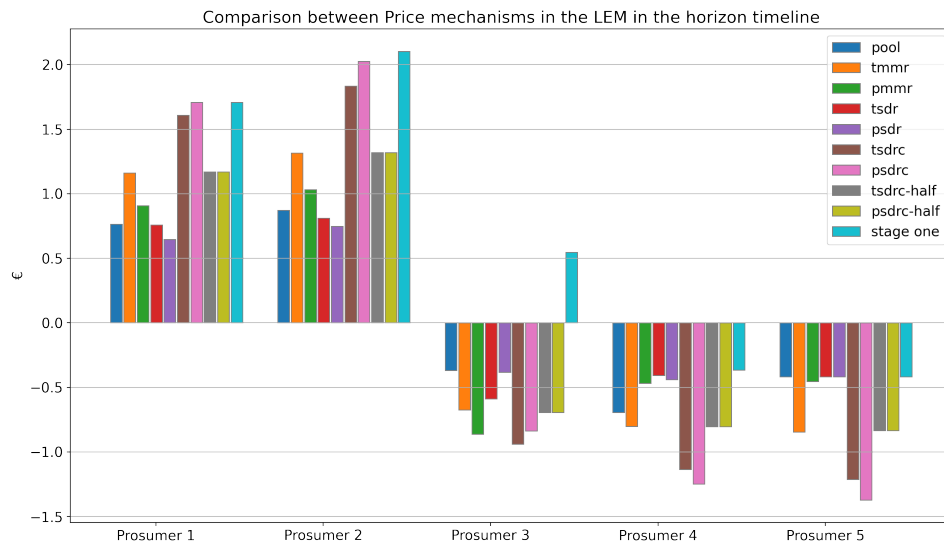


Figure 4.45: Prosumers individual operation cost per pricing mechanism in Scenario 3



Figure 4.46: LEM internal prices per pricing mechanism, Total and Partial comparison in Scenario 3

Analysing Table 4.5, the first fact that can be seen is that the REC’s operating costs have become quite stable. Also, it is possible to note that only PSDRC has a higher value for the REC operation cost than all the other pricing mechanisms. This happened because Prosumer 1 bought from the retailer at hours 9, 15 and 22, and this was the only retailer purchase for all the pricing mechanisms in this scenario. There was not enough energy to sell to Prosumer 1, and since he had the lowest buying price, he had to get the energy from the retailer.

In Figure 4.45, the prosumer's individual costs are represented, and Prosumers 4 and 5 have very similar individual costs. The energy they store in their batteries is enough to change the LEM internal price in the no-generation hours and fortifies the energy trading in those hours. Prosumer 3 sells energy in the production zone and makes an individual profit. For Prosumers 1 and 2, if their individual cost is lower for one pricing mechanism, they traded more energy in LEM.

Figure 4.46 shows the new LEM internal prices with the pricing mechanisms. Since more energy can be used from Prosumers 4 and 5 batteries in the no-production hours, the internal prices will be lower than the other scenarios. In this case, the PMMR provides a lower internal price for some hours than TMMR. The PSDRC has a higher value in the no-generation hours due to the λ_r^{buy} being lower, which results in a higher price. TSDRC-Half and PSDRC-Half are equal for every hour.

4.3.4 Scenario 4, More Consumption

In this scenario, prosumers 1, 3 and 5 experience an increase in load. The power contracted to the retailer was increased from 3,45 kVA to 6,90 kVA, while maintaining the consumption profile, resulting in a proportional increase in load. The other parameters are all equal to the Scenario 1. In this scenario, a high REC operation cost and more energy trades between prosumers and retailers in the hours with no generation are expected. The LEM internal price will be lower in the hours with more generation. As soon as there is more consumption, fewer hours will be with a low internal price for the LEM.

Table 4.6: REC operation cost per pricing mechanism in Scenario 4

Pricing mechanism	Cost (€)
Pool	5.803
TMMR	5.8016
PMMR	5.8015
TSDR	5.8066
PSDR	5.8066
TSDRC	5.8184
PSDRC	5.8195
TSDRC-Half	5.8031
PSDRC-Half	5.8013
Stage One	7.7453



Figure 4.47: Prosumers individual operation cost per pricing mechanism in Scenario 4



Figure 4.48: LEM internal prices per pricing mechanism, Total and Partial comparison in Scenario 4

By analysing Table 4.6 and Figure 4.48, it is possible to understand why TSDRC and PSDRC have a higher REC operation cost. Prosumers 3 and 4 sell energy in the production hours, and the price is higher for TSDRC and PSDRC. Figure 4.47 represents the individual costs, and it is possible to check that Prosumer 3 and 4 have a lower operation cost due to the sales in the LEM for a higher internal price.

The individual costs show quite well the costs associated with this scenario considering the increase in consumption for Prosumers 1, 3 and 5. Prosumer 3 trades in the production zone are similar to those in Scenario 1. Still, since Prosumer 3 has a higher consumption in the other hours, he needs to get energy from the retailer because the Prosumer 5 battery is more limited in its consumption, resulting in a higher cost for Prosumer 3 in an overall study for all pricing mechanisms. Prosumer 4 reduced his profit compared to Scenario 1 since there are fewer energy trades in the REC.

The Pool's internal price is low in the hours 11-17 instead of 9-18 because the amount of energy injected into the REC's network was lower due to increased net consumption. In hours 9, 10 and 18, the consumption exceeded the generation. The Partial mechanisms have calculated a higher LEM internal price in the no-production hours as expected, except for TSDR and PSDR, which are exactly the same. TSDR and PSDR considered the same offers for every hour to calculate the LEM internal price.

4.3.5 Scenario Comparisons

Overall, the Scenarios represent different parameters of the generation, load and batteries' nominal capacity and maximum power. Figure 4.49 represents the differences between the Scenarios with the different pricing mechanisms.

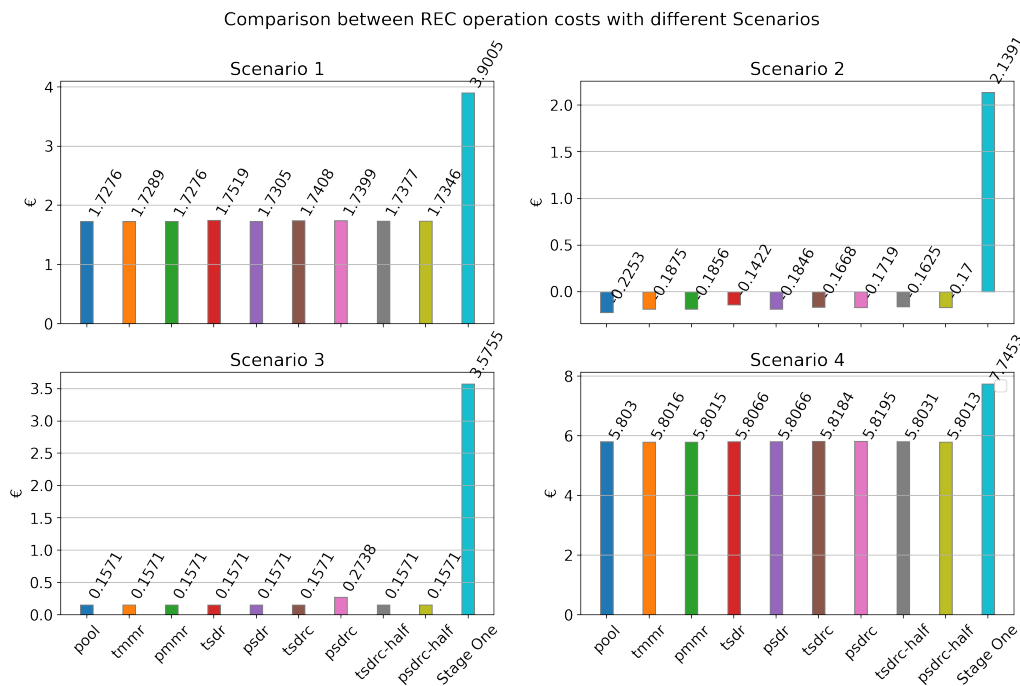


Figure 4.49: REC operation costs comparison between scenarios

According to [6], the scenarios were expected to have higher prices in the SDRC and SDRC-Half pricing mechanisms for every Scenario, which is explained by the higher dependency on the retailer, which has been partially confirmed. The REC structure and resources influenced pricing

mechanisms, the optimization algorithm, and, consequently, the REC operation, which resulted in a difference in the expected results. There is a considerable difference in REC operation cost in Scenario 2 with Pool and TSDR and Scenario 3 with the PSDRC compared to other pricing mechanisms in the same scenario.

Scenario 2 with TSDR has a lower profit because Prosumers 3, 4 and 5 sell energy to the retailer, and with Pool, since only Prosumer 5 sells energy to the Prosumer at a higher value, there is more profit for the REC.

PSDRC in Scenario 3 has a high dependency on the grid, which results in a higher operation cost. Only with this pricing mechanism did Prosumer 1 buy energy from the retailer. With the other pricing mechanisms, Prosumer 1 could satisfy his demand with energy from the REC. This occurrence reduced the LEM trades between the REC members and resulted in a higher operation cost for the community in the PSDRC pricing mechanism.

This means that the REC operation cost depends on many parameters, but the parameter influencing the most is the number of exchanges with the retailer. When buying energy from the retailer, the cost can increase significantly, and when selling, the more prosumers and the amount of energy exchanged with the retailer, the lower the cost.

All the data used to develop this study is stored in a Google Drive Folder in my Universidade do Porto personal Google account, [A](#).

Chapter 5

Conclusions and Future Work

5.1 Conclusions

The work compares how different resources and pricing mechanisms, individually or collectively, influence operation costs. The scenarios targeted changing the parameters of prosumer resources and their consumption. With the pricing mechanisms and the optimization algorithm, it was possible to develop a new study that analysed the new pricing mechanisms and how the resources and all the pricing mechanisms influenced the REC operation. The new approach to pricing mechanisms aimed to create a new approach for LEM to achieve an internal market price that would stimulate trades in the REC and less dependence on the retailer.

The first conclusion is that the pricing mechanisms are influenced by the optimization Algorithm, which decides how prosumers use their resources when they must turn to the retailer and the trades done inside the REC.

With this study, it was possible to check that prosumer A can buy energy from B and C, consume part of that energy and then sell the remaining energy to prosumers D and E, for example. Despite only having a buying or selling bid, a prosumer can elaborate trades for one hour with more than one but can only elaborate a buying or selling operation to the same prosumer.

Increasing the generation will result in a big surplus in production hours. Still, if a prosumer does not have a good battery, many surpluses will be sold to the retailer, probably at a low price.

Changing the battery parameters to higher is a great way to stabilize a REC operation cost and reduce the dependency on the retailer. Reduced retailer dependency generally means a lower cost to a prosumer or community.

In general, the Partial mechanisms can help in the REC operation costs despite the difference being lower than one cent per day.

Pool, TMMR, PMMR, TSDR, and PSDR tend to have a lower individual cost for the prosumers, but the TSDRC and PSDRC tend to benefit the prosumers with generation and penalise the consumers. However, to recapitulate what has been said above, the pricing mechanisms influence the individual costs, and REC operation costs depend on the results from the optimization Algorithm, which controls all the REC operations.

5.2 Future Work

After concluding this Dissertation, PMMR, PSDR, PSDRC and PSDRC-Half must be explored more.

These pricing mechanisms must be tested in more scenarios where the buy and sell bids have higher or lower values and different REC structures, considering a different number of prosumers and resources.

A new approach can be tested by implementing the Total and Partial pricing mechanisms, where a hybrid system calculates the LEM internal price with both Total and Partial pricing mechanisms and assumes the lower internal price calculated with these mechanisms. For example, an SDR pricing mechanism is assumed, and the LEM calculates the internal price with both TSDR and PSDR. If the price calculated was lower with the TSDR, the LEM assumes this price. If the lower price calculated was with the PSDR, the LEM assumes this price for that hour. This new approach could be called Hybrid Mid Market Rate, Supply and Demand Ratio, Supply and Demand Ratio Compensated or Supply and Demand Ratio Compensated-Half.

Appendix A

Results Data

All the results from the work developed are stored in this Google Drive Folder:
[Click here to access.](#)

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