Optimizing Energy Communities

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Dedicated to my biggest lifelong supporters: Clara, Pedro and Miguel. You are my safe space.

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Resumo

As comunidades energéticas emergiram como uma solução importante para a gestão energética das cidades. Comunidades energéticas podem capacitar os cidadãos para contribuir em primeira mão para projetos de energias renováveis e aumentarem a sua autossuficiência energética, reduzindo as faturas de eletricidade e a pegada de carbono. Esta tese desenvolveu um modelo e metodologia para otimizar comunidades de energias renováveis, de acordo com a legislação nacional e internacional mais atualizada. O modelo executa simulações para um investimento de 25 anos com resolução horária. A comunidade estudada vende o excedente de eletricidade a um edifício terciário adjacente e usa um novo mecanismo de partilha de energia entre pares, no qual os residentes comercializam eletricidade gratuitamente dentro da comunidade. Um modelo de autoconsumo individual foi desenvolvido para fins de comparação. Foram selecionados dez domicílios com tipos de moradores diferentes, permitindo variedade de resultados e conclusões técnicas, económicas e ambientais. Os resultados relativos a um agregado familiar selecionado mostram que a comunidade sem armazenamento de energia proporciona aos consumidores os melhores valores atuais líquidos de qualquer investimento, até 14 806 €, com receitas que podem atingir 432 € por ano com custos reduzidos de operação, manutenção e substituição. Investir no modelo de comunidade energética com baterias de iões de lítio de 40 kWh reduz as faturas anuais de eletricidade em 1 670 € e permite aos consumidores reduzir a sua dependência energética da rede em 80%, reduzindo assim as emissões de CO_2 para 20%.

Palavras-chave: comunidades energéticas, autossuficiência energética, edifício terciário, partilha de energia entre pares, análise económica , emissões de CO_2.

Abstract

Energy communities are emerging as an important solution for the way cities manage their energy. Energy communities can empower citizens to contribute first-hand to renewable energy projects and increase their energy self-sufficiency, lowering their electricity bills and carbon footprint significantly. This thesis developed a thorough and transparent model and methodology to optimise renewable energy communities, according to the most up-to-date national and international legislation. The model runs simulations for a 25-year long investment with an hourly resolution. This studied community features the sale of electricity surplus to an adjacent tertiary building and a novel peer-to-peer energy sharing mechanism in which prosumers trade electricity for free within the community. An individual self-consumption model was developed for comparison purposes. Ten households with very different types of residents were selected, allowing for variety in technical, economical and environmental results and conclusions. Results on a selected household show that the energy community without energy storage provides consumers with the best net present values of any investment, up to 14 806€, since revenues can be as high as 432€ per year with reduced operation, maintenance and replacement costs. Investing in the energy community model paired with 40 kWh lithium-ion batteries reduces yearly electricity bills by a maximum of 1 670€ and allows consumers to reduce their energy dependency on the grid by 80%, thus reducing the CO_2 emissions to 20%.

Keywords: energy communities, energy self-sufficiency, tertiary building, peer-to-peer energy sharing, economic analysis , CO_2 emissions.

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Nomenclature

Greek symbols

ε Carbon dioxide emission factor

Roman symbols and abbreviations

a Electricity surplus quota

b Electricity deficit quota

C Money outflux

CF Money influx

CG Cost of buying electricity from the grid

D Total electricity deficit of the energy community

d Number of houses with electricity deficit after the peer-to-peer process

def Electricity deficit after the peer-to-peer process

E Electricity

Em Carbon dioxide emissions

ES Electricity sold to the grid

Inv Initial equpment investment costs

NCF Net cash flows

OM Operation and maintenance costs

P Price associated to an investment scenario

PNI Price associated with a no-investment scenario

Pr Market closing prices

PS Remuneration for selling electricity

R Remuneration from selling electricity to the grid

r Discount rate

Rep Equipment replacement costs

S Total electricity surplus of the energy community

s Number of houses with electricity surplus after the peer-to-peer process

SoC State of charge

sur Electricity surplus after the peer-to-peer process

x Relative allocation of benefits

Subscripts

EC Related to the energy community

g Index of year

$Grid - EC$ Between the grid and the energy community

h Index of hour

m Index of month

max Maximum

$MIBEL - PT$ Portuguese area of the Iberic Energy Market

min Minimum

n Index of household

p Peak

$TB - EC$ Between the tertiary building and the energy community

$TB - Grid$ Between the tertiary building and the grid

Superscripts

CS Related to a case study

Df Final demand

Di Initial demand

DPV Demand after photovoltaic modules are used for self-consumption

ESS Related to the energy storage system

Grid Related to the portuguese electrical grid

NI Related to a no-investment scenario

PV Related to the photovoltaic modules

Abbreviations

A.V.	Audio-Visual
APA	Portuguese Environment
CIEG	Costs of General Economic Interest
COP	Conference of the Parties
CO_2	Carbon Dioxide
CSC	Collective Self-Consumer
DGEG	Directorate-General of Energy and Geology
DR	Demand Response
DSO	Distribution System Operator
DoD	Depth of Discharge
EBOS	Electronic Balancing of the System
EC	Energy Community
EGAC	Collective Self-Consumption Manager Entity
ERSE	Regulatory Entity for Energy Services
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FI	Fairness Index
FiT	Feed-in Tariff
GHG	Greehhouse Gas

HSS	Hydrogen Storage System
IEA	International Energy Agency
IEC	Special Consumption Tax
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISC	Individual Self-Consumer
LCOE	Levelized Cost of Energy
LEC	Local Energy Community
LPG	Load Profile Generator
MCDA	Multi-Criteria Decision Analysis
MIBEL	Iberian Energy Market
MILP	Mixed-Integer Linear Programming
MV	Medium Voltage
NAT	Network Access Tariffs
NLV	Normal Low Voltage
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
P2P	Peer-to-peer
PBP	Payback Period
PRR	Recovery and Resilience Plan
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RAC	Self-Consumption Regulation
RC	Regular Consumer
REC	Renewable Energy Community
RED	Renewable Energy Directive
RES	Renewable Energy Solutions

RMSA	National Electric System’s Supply Security Monitoring Report
RNC2050	Roadmap to Carbon Neutrality 2050
SBOS	Structural Balancing of the System
SS	Self-Sufficiency
TB	Tertiary Building
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
VAT	Value-Added Tax

Chapter 1

Introduction

1.1 Motivation and Framework

The last decades of scientific data lead to a clear conclusion— if growing CO_2 emission rates are not dealt with, the average global temperature will continue to rise, affecting biodiversity and life on the planet irreversibly. Ergo, in 1992, countries started joining an international treaty called the United Nations Framework Convention on Climate Change (UNFCCC) to establish international cooperation and reverse the damage of climate change by setting maximum temperature increase goals. In 1995, the first Conference of the Parties (COP) took place in Germany and two years later, in Japan, the Kyoto Protocol was adopted— a legally-binding commitment towards greenhouse gas (GHG) emission reduction targets [1]. In 2015, at COP 21, the Paris Agreement was adopted. It set a long-term temperature goal of 2ºC above pre-industrial levels until the end of the century [2].

The European Commission has developed the European Green Deal, with the objective to achieve carbon neutrality by 2050 [3]. To help reach this goal and to support the post-pandemic digital and green transition, the Recovery and Resilience Facility was devised, with €648 billion of investments from the €1.8 trillion NextGenerationEU Recovery Plan [4]. Portugal received €22 216 million to support the development of their Recovery and Resilience Plan (PRR) [5]. This plan aims to financially aid services ranging from the national healthcare system to electric mobility and buildings' energy efficiency [6].

The recent inclination toward decarbonization accompanied by the creation of ambitious government targets, policy support and increasing competitiveness have escalated the investment in renewable energy solutions as electricity generation alternatives to fossil fuels, seen in Figure 1.1, according to the International Energy Agency (IEA). This increased investment value has resulted in some renewable technologies already having lower levelized costs of energy than fossil fuel solutions [7]. Consequently, since 2015, the quota of Renewable Energy Solutions (RES) in the worldwide power mix has increased from 22.7% to 30.2% [8]

One of the biggest players in the energy transition is solar photovoltaic (PV) generation with a value of 5.4% of the global electricity production, meaning it is currently the 3rd highest renewable generation source, behind hydro and wind power. Having accounted for 74% of the global renewable capacity

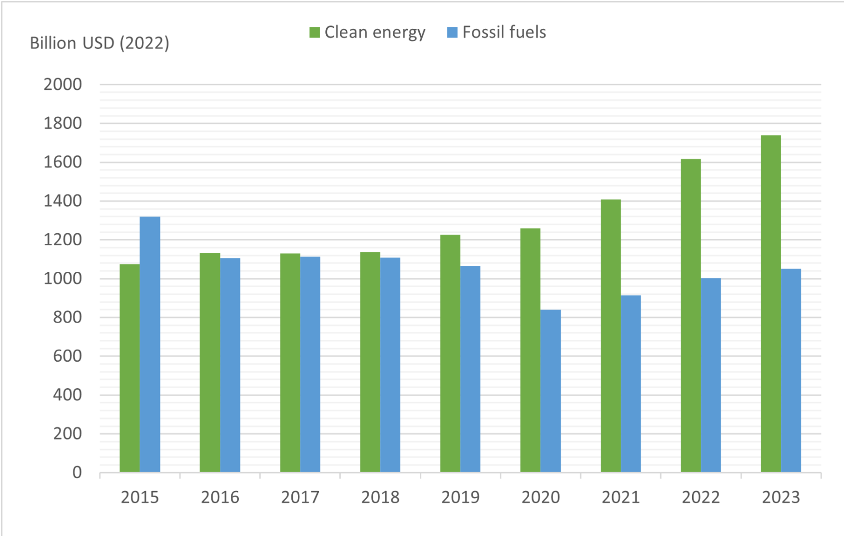


Figure 1.1: Evolution of investment in clean energy and fossil fuels since 2015, adapted from IEA [9]

additions in 2022 (350 GW added), solar PV investments comprised about 45% of the total global electricity generation investment in this year, thus keeping RES on track to surpass coal generation in 2025 as the largest electricity generation source in the world [10, 11].

In a time in which the focus is strongly on RES, consumers have started to turn into prosumers, since these have taken on an active role in the electrical energy system with relatively low capital requirements. All of these recent developments can be best explored using Energy Communities (EC), an approach that aims to meet local energy needs independently, based on trading among nearby participants, self-consumption and self-production preferably of clean energy sources at a local level, also contributing to the decarbonization and decentralization of the power generation grid.

Energy communities come as a paradigm shift in the consumer's role in the energy transition, to reorganize the production and transport of electricity and reduce the emission of pollutants. These communities are aggregations of private citizens or entities such as municipalities and enterprises that can have several benefits when compared to a centralized energy distribution model, such as: electricity bill reductions, higher self-consumption of renewable energy, lower CO_2 emission rates, better local energy management to provide services to the utility grid like peak reduction and valley filling, among many others.

The conceptualization of energy communities is diverse, with numerous terms being used to describe them, such as ”local energy communities”, ”renewable energy communities” (REC) and ”renewable energy clusters”. The difference between the used terms often lies in the adopted framework and in functioning details of the community. Bauwens et al analyzed 405 articles and 183 EC definitions and concluded there is no clear, overarching definition of this concept [12]. This research found there to be a growing emphasis on economic rather than social or political objectives, explained by the emergence of literature on peer-to-peer energy sharing methods. The recent trend on technical and economic aspects of communities is potentially diminishing their benefits in environmental, social and political fields as current literature often explores energy communities as market-value-driven instruments.

Currently, the European Union (EU) has a total of 9 252 ECs, with 4 848 of them in Germany due to the country's history of citizen-financed projects [13]. However, in 2023 Portugal only had 3 energy communities in operation despite having over 200 more awaiting licensing, as per Portuguese researcher Humberto Queiroz [14]. Portugal has Europe's second highest average PV power potential, yet bureaucratic procedures still hinder the country's advancement in the energy transition required by European legislation [15]. As geographic factors are in Portugal's favor, the correct supportive institutional setting including laws and policy-making has the potential to positively influence investors on all levels and benefit the emergence of energy communities [16].

1.2 Objectives and Contributions

This dissertation developed a novel energy community model that allows to assess the technical, economic and environmental results of investing in energy communities, by developing two self-consumption models: an individual model and a community using PV generation with and without battery storage. With the objective to decrease grid-dependency and energy disparities in the communities, residents share their energy with fellow neighbours in a novel peer-to-peer (P2P) process in which they do not ask for monetary compensation in exchange for energy. An adjacent tertiary building (TB) is considered as a buyer for electricity surplus, rivaling the utility grid's Feed-in Tariff (FiT). Using ten dissimilar families with unique consumption patterns for a complete year and with the most realistic and up-to-date electricity prices and taxes paid by consumers, while considering the evolution of production and consumption over time, a 25-year long investment will be simulated. The developed model allows to perform an assessment of: 1) the technical aspects of PV modules and of the battery energy storage solutions; 2) the economical results of the studied scenarios using metrics such as the net present value (NPV) and the internal rate of return (IRR) and 3) the environmental outcomes of each case study, by calculating the CO_2 emissions savings and the self-sufficiency (SS) of each simulated household. Other relevant metrics of energy communities such as a fairness index (FI), that evaluates the fairness of the model's developed allocation of benefits, will be discussed and compared to investing in the individual model and to not investing in any self-consumption project. Ultimately, several recommendations are suggested to potential prosumers and future policymakers.

Following the increase in global RES investment for a clean energy transition and the lower prices for investment in self-consumption technologies, this thesis sets out to answer the following research questions:

- Considering current Portuguese policies and legislation, is it economically viable and fair to invest in an energy community in Portugal, in which residents trade energy among each-other for free and can sell electricity surplus to a tertiary building?
- Is it profitable for a tertiary building to partake in an energy community as an electricity buyer?
- What role can energy communities have in the decentralization of the electrical grid and decarbonization efforts of the coming decades?

To provide an answer for the aforementioned research questions, the following objectives have been established:

- Create a model to analyse the technical, economical and environmental aspects of an energy community;
- Devise an electricity surplus selling procedure between the community and a tertiary building that allows both parties to profit from the created model;
- Develop a new benefits allocation method that distributes the gains of partaking in the developed community model fairly to all residents;
- Recommend to potential prosumers which energy community case study provides them with the best economic results and which model has the best environmental outcomes.

In a time in which there is a strong focus on lowering carbon emissions and on increasing energy efficiency, this dissertation presents valuable insights on the potential benefits of joining socially-conscious energy communities. Its contributions are listed, although not limited to the ones below:

- Developing a new energy community model that uses the yearly consumption patterns of very different families and almost 20 years of historic data for PV generation to simulate a 25 year long investment, in which energy production and consumption evolution are also considered. The variety in presented case studies with the most up-to-date Portuguese and European policies, including an extensive characterization of the electricity bills and taxes paid by each consumer provides not only prosumers, also policymakers with a detailed analysis on the most important variables of an energy community, which helps them make informed decisions;
- Proposing a novel social welfare oriented peer-to-peer energy trading mechanism which, unlike current P2P solutions, does not charge money for electricity trades among neighbouring prosumers;
- Including a tertiary building adjacent to the community acting as a buyer for surplus electricity allows to create a comprehensive community which aims for a lucrative partnership for all players, not just the community;

1.3 Thesis Structure

The present dissertation is organized in the following manner: in chapter 2, an analysis on energy communities will be conducted, followed by a revision of current European and Portuguese legislation. In chapter 3 the methodology implemented to create the self-consumption models using MATLAB software will be described. All the inputs of the developed models will be detailed in chapter 4, with which the results discussed in chapter 5 were obtained. In this chapter it is also performed an analysis on the key findings of the research. The most important conclusions of this thesis, as well as future work and recommendations will be presented in chapter 6, in which the research questions are also answered.

Chapter 2

Literature Review

2.1 Renewable Energy- Solar PV

Despite the impact of the global pandemic that started in 2020, one particular sector that thrived was renewable generation. Over the years 2010-2020, renewable power generation costs have declined significantly and lower-than-ever costs are available particularly for solar PV and wind power.

Between 2010 and 2020, the global weighted-average levelized cost of energy (LCOE), or the ratio of lifetime costs to lifetime electricity generation of residential PV systems has decreased between 49% and 82% worldwide and total installed costs have decreased between 46% and 85%. Total installed costs have continuously declined in light of more efficient manufacturing processes, reduced labour costs, increased module efficiencies and better supply chain structures. The cost related to each market still varies significantly and as markets continue to mature these differences are expected to decline [17].

Over 95% of the PV modules' market share still belongs to crystalline silicon modules. These modules' cost in Europe has dropped by 93% between 2010 and 2020. This led the way for a 16-fold capacity increase in solar PV between this period, with the global cumulative installed capacity of all solar PV increasing from 42 GW to 714 GW. The average crystalline module efficiency increased from 14.7% to 20% in this time period, driven by the market shift to more efficient monocrystalline products and passivated emitter and rear cell architectures, which are expected to reach a limit of 22% efficiency. At the module's level, power outputs have increased due to half-cut cells, multi-busbars and high-density cell packing pathways. In 2017, the typical module power output for PV modules was set at 350 W, while just 3 years later it was already 500 W [11].

2.2 Energy Communities Overview

McKenna et al gathered empirical data for 302 households with PV generation in the United Kingdom (UK). Even with significantly lower values of solar irradiation than Portugal, the average UK household used PV generation to cover 45% of their electricity consumption and achieved a 24% reduction in annual electricity consumption [18].

The potential of PV generation for self-consumption can be further explored when several residents partake in collective self-consumption. This potential was analyzed by Mena et al using 12 residential buildings in Spain with demand response (DR), the action of a consumer shifting electricity consumption to help keep the supply and demand in balance. In this study, collective self-consumption was found to be more profitable than individual self-consumption [19].

The variability of renewable energy generation makes investing in energy storage systems (ESS) a good option for reliability and filling the gaps between supply and demand. In 2017, Camilo et al also observed that self-consumption for residential consumers in Portugal can lower their electricity bills significantly enough to turn a profit. However, energy storage solutions were not economically viable due to the high investment costs [20].

Zakeri et al concluded that electricity storage, when paired with PV generation for UK residents, offers 41% to 74% annual electricity bill savings but is still not economically profitable. Thus, the authors proposed three policies to improve the economic value of energy storage investments, one of which—a dynamic pricing mechanism that rewards electricity storage at high demand hours— led to net positive results for investors [21].

It has been widely reported in current literature that battery-operated systems provide significant increases in self-sufficiency and decrease electricity costs significantly yet, their capital costs are still too high. To address this issue, several works of literature have introduced the concept of shared ESS, such as Li et al which conducted a techno-economical analysis of an optimized distributed battery sharing community of commercial buildings in Japan. This study points to a reduction in transmission losses by up to 98% when compared to a centralized ESS solution, however there are still significant economical expenditures [22].

Researchers from Cardiff University studied the possibility for residents in a neighbourhood to trade electricity among each other in a P2P mechanism and reported that regardless of having ESS or not, P2P electricity sharing reduced the electricity costs of the community by 30%. This research also found peer-to-peer trading to have a similar impact on increasing cost savings and lowering self-sufficiency as energy storage devices, at much lower capital costs, having a direct relation with the number of participants in the P2P process— the more participants, the lower the electricity costs and higher self-sufficiency [23].

Rodrigues et al have studied the optimal ESS sizing problem in a P2P energy sharing network in buildings using three different ownership structures, to find that the building-owned ESS model has the highest NPV when compared to a centralized energy sharing provider owned ESS between buildings [24]. The aforementioned literature points to how the best solution was found to be the grouping of several consumers in close proximity (generally buildings) which share an ESS, then these can interact with other communities, thus creating an energy-sharing microgrid.

As the previously analyzed literature suggests, trading energy and sharing energy resources with other nearby prosumers rather than investing in RES individually produces the highest savings, self-sufficiency and flexibility. To fully grasp the potential of these collective solutions, several studies created models of energy communities with unique frameworks using different objective functions and technologies. Their main contributions and limitations are listed, but not limited to the ones displayed in Table 2.1.

Feng et al proposed a coalitional game-based management system for profit maximization in energy communities which offers a fair payoff distribution of benefits to all participants. It was demonstrated that cooperation between participants improves their payoff and contributes to peak shaving and valley filling. Although authors have proposed a community with different configurations, all households with fixed loads have the same load profile, which fails to the represent the full potential of energy sharing communities [25].

A group of University of Bologna researchers proposed an energy community that minimizes operating costs and internal losses by modeling line resistance and voltage level using 2 feeders with 5 houses each. Producers fulfill, as much as possible, the demand of nearby consumers, to minimize losses. This work also explores the notion of information privacy, by sacrificing computational speed with a quadratic formulation and high number of sequential optimizing problems solved. Results allow to conclude that all prosumers reduce their electricity costs and have higher revenues when taking part in the EC, when comparing to trading individually with an external energy provider [26].

Jo et al explored the use of customer-owned energy storage systems from the perspective of a microgrid aggregator. The proposed model optimizes the deployment of large and small scale storage systems and a large-scale fuel fuel cell (FC) to minimize costs in a zero net energy community microgrid. The lack of consideration for efficiency values of the fuel cell lead to erroneous results, especially when these efficiency values vary between 40% to 60%, according to the United States Department of Energy [27]. In conjunction with the failure to give information about the community's participants, this study's results may be flawed and problematic to scale down [28].

Hasan Mehrjerdi proposed a zero net energy P2P home energy management system between buildings to minimize their operating costs, which included salvage costs in the end of the equipment's lifespan. The very cost-comprehensive model includes 2 buildings with solar PV generation and a third building with a hydrogen storage system (HSS), a water electrolyzer and a fuel cell. With a low efficiency of 60% and a reduced lifespan of 5 years, it is hard to see why consumers would prefer hydrogen storage over residential lithium-ion batteries. Results only display the cost of this investment, with no comparison with a "no-investment scenario" or a net present value, thus making it difficult to act as an investor [29].

Sarfarazi et al developed the most extensive and comprehensive energy community study of all analyzed literature. This work features a profit-maximizing community-owned aggregator, optimized using a novel algorithm that outperformed benchmark algorithms in both computational performance and community welfare in 4 representative case studies. The proposed EC features real household load profiles and even electric vehicle (EV) trip diaries based on surveys instead of fixed pattern consumption patterns. Authors also mathematically proved that maximizing this community's profit is equal to maximizing its community welfare, while maintaining the aggregator's fiduciary compromise to the EC [30].

A group of researchers from North China Electric Power University proposed a methodology to minimize electricity cost in a residential neighbourhood with great focus on demand response, featuring good characterization of distinct loads (interruptible, adjustable, etc). Since this model relies so heavily on DR and some loads are shifted by up to 3 hours different from their original operation time, user comfort may be a deciding factor on the adoption of these solutions [31].

Umer et al maximized social welfare in a P2P energy market, considering network constraints in a 2-stage approach that allows prosumers to interact directly, with no need for a third party. A limit on the maximum amount of electricity that can be traded in P2P is proposed, to ensure safe network voltage levels. Social welfare with P2P was found to be better (seller prosumers get more money and buyer prosumers pay less) than when using Feed-in Tariff mechanisms with the grid. The proposed model does not feature storage, hence prosumers do not have an option but to trade their energy, consequently cost-reduction results may be overestimated when scaling up to communities with storage [32].

Manso-Burgos et al have developed a very transparent model and methodology for optimizing local energy communities in Spain with and without an ESS with different capacities and ownership. Variable and static sharing coefficients are used for power sharing among consumption points since this is the most up-to-date regulation in Spain. The designed EC was not only economically but also environmentally viable especially for larger communities, with communal ESS ownership. However, since this work does not show the consumption profiles of the community's participants, results are not easily scalable to other communities [33].

In a very innovate approach, Tostado-Véliz et al have focused their research on individual prosumers that can trade electricity with nearby communities, other prosumers and the grid. By developing a day-ahead scheduling strategy for homes with smart appliances, solar PV generation, electric vehicles and energy storage, trading with other peers and ECs proved to be more profitable than with the grid, although results still point to high dependence on the grid. This research's results rely heavily on bilateral agreements between prosumers, with no regard for the legal implications of these instruments under different countries' regulatory frameworks and for the subsequent small prosumers' acceptance of said methods, which may deter them from partaking in these investments [34].

Table 2.1: Main contributions and limitations of relevant literature

Ref.	Used technology	Objective Function	Contributions	Limitations
[25]	DR[a], PV[b], ESS[c], EV[d]	Maximize profit	Coalitional households with fair benefit allocation	Equal household loads
[26]	PV, ESS	Minimize operating cost	Cooperative prosumer behaviour	Time consuming
[28]	PV, ESS, FC[e]	Minimize operating cost	Zero net energy operation	No FC efficiency
[29]	PV, FC, HSS[f]	Minimize operating cost	Off-grid operation; Cost-comprehensive	Poor financial conclusions
[30]	DR, PV, ESS, EV	Maximize profit	Proves that maximizing social welfare also maximizes profit	
[31]	DR, PV, ESS, EV	Minimize electricity cost	Comprehensive load characterization	User comfort may be a pitfall
[32]	PV	Maximize social welfare	Infrastructure-conscious approach	Storage is not considered
[33]	PV, ESS	Multi-objective	Transparent and realistic model	No savings distribution method
[34]	DR, PV, ESS, EV	Minimize electricity cost	Focus on individual prosumers	High dependence on the grid

[a]DR- Demand response
[b]PV- Photovoltaic modules
[c]ESS- Energy storage solution
[d]EV- Electric vehicle
[e]FC- Fuel cell
[f]HSS- Hydrogen storage system

2.3 European Regulatory Framework

The European Union's Clean Energy Packages are sets of directives and measures for energy efficiency and renewable energy, and also define the regulations of internal electricity markets in the European Union. The objective of these measures is to provide guidance to EU Member States on meeting the Paris Agreement's goals [35]. The applied measures aim to increase consumers' involvement and empowerment as prosumers, mobilizing private capital and increasing the stability of the grid with increased supply security thus achieving economic, environmental and societal benefits for all members.

In 2018, the EU created its Directive (EU) 2018/2001, or RED II, also known as the Renewable Energy Directive, which established sustainability goals in the EU, including a goal of 32% of RES in the EU's final gross energy consumption by 2030 [36]. From then onward, consumers legally became players in the energy market (prosumers). As such, the EU set Directive (EU) 2019/944 to establish the updated generation, transmission, distribution, storage and supply rules for internal electricity markets and better connect wholesale and retail markets and push for decentralization of the energy market [37].

The 2016 Clean Energy Package was the first to identify groups of citizens that fulfilled certain criteria as Local Energy Communities (LEC). In the 2020 version of the Clean Energy Package, renewable energy communities are defined with the goal "to provide environmental, economic or social community benefits for its shareholders of members or local areas where it operates, rather than financial profits" through the EU Directives 2018/2001 and 2019/944 [36,37].

As per European legislation, REC members have to be near the renewable energy projects the community develops and are constrained to using only RES for heating and electricity. The 2020 Clean Energy Package constitutes a framework for RECs which identifies the basic rights that these communities and their members are entitled to, such as:

- The non-discriminatory treatment of RECs as final customers, producers, suppliers, distribution system operators (DSO), or other forms of market participation;

- Fair and balanced costs applied to the RECs, ensuring a level-playing field;

- The cooperation of a DSO with RECs to facilitate energy transfers within the community.

Since the purpose of RECs is not individual generation of capital, but rather collective benefits, the monetary participation of members should not affect their weight in decision-making processes, making capital injection irrelevant to voting rights. Consequently, members cannot hold more than 40% more voting rights than others. Although participants can have shares of an EC and engage in energy sharing with other members, they might not be given the ability to exert effective control of the community. Thus, these would be considered participating members, not controlling members, so that abusive power relationships between members are avoided and the decision-making process can remain equitable.

2.4 Portuguese Legislation

Following EU Directive 2018/2001 and 2019/944, different countries within the EU have opted for unique frameworks for REC participants' rights and duties. Portugal set regulation toward carbon neutrality in 2050 with its Roadmap to Carbon Neutrality (RNC2050) [38]. Three months later, Decree-Law 162/2019 was issued to promote and facilitate the self-consumption of energy and the creation of renewable energy communities by removing economic and social barriers. This Regulation establishes the legal framework for renewable energy communities in Portugal as a collective renewable energy self-consumption project for-profit or non-profit, with the main goal to provide environmental, economic and social benefits, instead of financial gains. These communities must be based on open and voluntary participation, in which everyone has the right to join and partake in decision-making processes, from small and medium companies to private citizens. Participants must be geographically close to one-another. The exact distance is not provided in this Regulation, as each situation is to be evaluated individually by the Directorate-General for Energy and Geology (DGEG) [39].

Owing to Regulation 266/2020 of the 20th of March of 2020, the individual self-consumer has the right to trade energy surplus through an organized market or with a bilateral agreement, always using a market facilitator. This regulation also states that individual self-consumers are exempt of paying 50% of the Cost of General Economic Interest (CIEG) and collective self-consumers are exempt of paying 100% of CIEG [40]. This value is not regulated by Portugal's Regulatory Entity for Energy Services (ERSE) although it is reflected in the final value paid by consumers in their electricity bills as 29% of the electricity price in low voltage systems, making this a very significant incentive [41].

The Portuguese Regulatory Entity for Energy Services approved the Regulation for Self-Consumption, Regulamento do Auto-Consumo (RAC) of electric energy in Regulation 373/2021, which states that RECs need to appoint a Collective Self-consumption Manager Entity, Entidade Gestora do Autoconsumo Coletivo (EGAC) to connect them to the DSO and local energy markets. The EGAC is also in charge of choosing how to manage energy sharing in the REC via energy sharing coefficients and report that process to the DSO. Each REC may have their own fixed or consumption-proportional energy sharing coefficients, provided that they are agreed upon by all the stakeholders [42].

Also in 2021, the European Comission approved Portugal's Recovery and Resilience Plan. The PRR is an investment incentive plan which financially supports small-scale energy efficiency and production investments [43]. With this incentive, a solar PV investment (or any other renewable energy production source for self-consumption purposes) with or without storage has a government contribution fee of 85%, limited at 2500€ per project.

The transition toward a decentralized model must be accompanied by changes in the national electrical system. This led to the creation of the Decree-Law 15/2022, of the 14th of January of 2022 which intended to optimize electricity flows between consumers that act collectively by incentivizing the creation of new energy services and by issuing the mass installation of smart meters at the consumers' expense. This made it possible for consumers to act either individually or as a community in electricity production and markets by also creating the figure of the aggregator. Aggregators establish contracts between actors in the energy market and are responsible for eliminating barriers to participation in electricity markets. Consumers were enabled to produce electricity and choose its final destination: self-consumption; selling for profit; storage or grid flexibility services [44]. One of the new services mentioned in this Decree-Law is the process of virtually selling electricity by selling Guarantees of Origin instead of the electricity itself. These are certificates that prove electricity was generated using renewable sources and can be sold to a third party. This solution might even help some companies reach their emissions quotas, thus having lower carbon taxes, which creates several synergistic connections between RECs and adjacent buildings [45].

In 27th of July of 2023, ERSE approved Regulation 815/2023 as the new Regulation for Self-Consumption, thus revoking the previous RAC defined in Regulation 373/2021. This new Regulation incorporated and revoked the regime for renewable energy self-consumption established by Decree-Law 162/2019 and revised several regulations in the electric sector, one of which being that consumers are no longer financially responsible for acquiring, installing and operating smart meters, as had been defined in Decree-Law 15/2022. Two new collective self-consumption energy sharing modalities between prosumers are introduced, thus making them four options in total as of this Regulation's issuance: fixed, dynamic, hierarchical and consumption-proportional coefficients [46].

All the most important legislation on Renewable Energy Communities that was described in this Chapter is displayed, in order of its issuance, in Table 2.2.

Table 2.2: Most relevant Renewable Energy Community legislation for Portugal

Document	**Description**	**Issuing Entity**	**Date**
EU Directive 2018/2001 [36]	Promotes RES and self-consumption	European Parliament and the council of the EU	2018
EU Directive 2019/944 [37]	Establishes common rules for internal electricity market	European Parliament and the council of the EU	2019
RNC2050 [38]	Portugal's carbon neutrality proposal	Presidency of the Council of Ministers	
Decree-Law 162/2019 [39]	Establishes REC framework	Presidency of the Council of Ministers	2019
Regulation 266/2020 [40]	Individual self-consumer enabled to trade energy surplus; CIEG reduction	Regulatory Entity for Energy Services	2020
Regulation 373/2021 [42]	EGAC figure is created	Regulatory Entity for Energy Services	2021
PRR [43]	Financial aid for self-consumers	Presidency of the Council of Ministers	2021
Decree-Law 15/2022 [44]	Aggregator figure is created	Presidency of the Council of Ministers	2022
Regulation 815/2023 [46]	New revised RAC	Regulatory Entity for Energy Services	2023

Chapter 3

Proposed Model

This thesis intends to explore the potential benefits of taking part in a proposed renewable energy community model with 10 households that is coordinated by an aggregator. Two bottom-up optimization models were created using Matlab software using non-linear programming with an hourly resolution. This chapter contains the framework that defines the individual self-consumption and energy community case study scenarios, whose parameters are defined in chapter 4.

3.1 Individual Prosumers Model

To study the efficacy of renewable energy communities, comparison baselines must be created. It is the case of the "Individual Prosumers Model", whose power flows are demonstrated in Figure 3.1. This model features an individual self-consumption 25-year investment for 10 houses in PV modules and battery energy storage that can be easily found in the market as a self-consumption kit [47, 48]. If surplus cannot be stored, it has to be sold to the grid for a Feed-in Tariff. If electricity is required and the ESS cannot provide it, the consumer must resort to the grid as well.

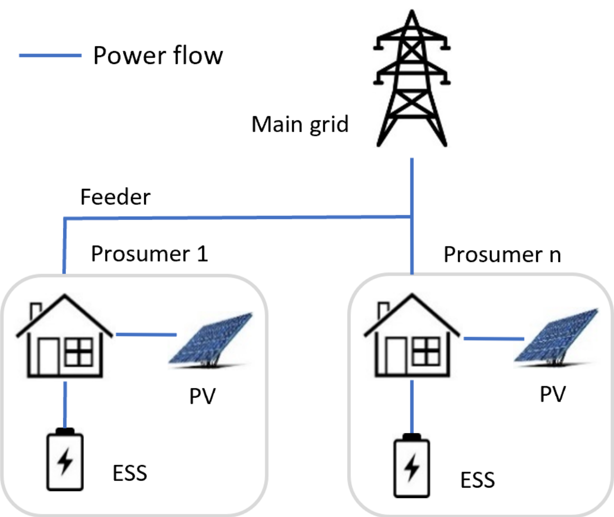


Figure 3.1: Functional structure of the individual prosumer model

3.2 Renewable Energy Community Model

The proposed community model, whose power and information flows are shown in Figure 3.2, is composed of 10 residential households, assumed to be geographically close to one-another, while being connected to the same feeder. All the households are equipped with individual PV generation to cover for their consumption in a 25 year long investment. A group of Portuguese researchers explored how the implementation of a renewable energy project in Portugal affected residents, failing to empower them in decision-making processes and centralizing benefits in big profit-driven companies, leading to resistance from the locals [49]. With the motivation to empower vulnerable citizens in the most fair approach possible, this thesis proposes that households share energy with fellow residents with no expectation of a monetary counterpart in a novel P2P process to promote social welfare and eliminate energy disparities. Any subsequent electricity surplus or demand that may exist after the P2P is handled with a community-owned ESS, to increase self-sufficiency. If the ESS cannot provide the demanded electricity to the EC, only then do residents resort to the main grid. In the case that electricity surplus cannot be stored in the ESS, the aggregator evaluates, between the grid and an adjacent tertiary building which of the two provides the most profitable offer for the surplus, then proceeds to sell it to the highest bidder. Communication channels between all agents must be bidirectional, thus enabling communication flow between all directions. With this flow of information, an aggregator can manage the real-time needs of the community.

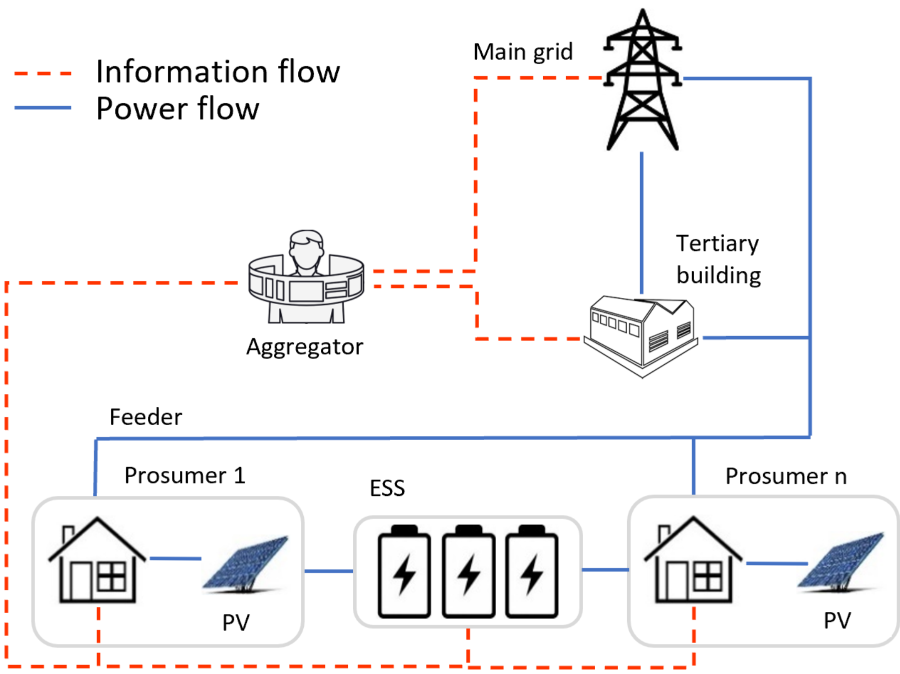


Figure 3.2: Functional structure of the proposed EC model

3.3 Optimization Methodology

The proposed models were created using MATLAB software (Matlab R2022a version). The simulations that the developed model runs to calculate the energy flows in the REC are depicted as a Flowchart in Figure 3.3. This figure represents the two created models– individual, on the left, and community on the right. The inputs required to run simulations are listed in Table 3.1 and include the load consumption profiles of each household, the characteristics of the used equipment and financial information such as the equipment's costs, the discount rate of the investment, the applied electricity tariffs and value-added tax (VAT), among others.

Individual Scenarios: after using solar PV generation for self-consumption purposes, households use privately-owned battery storage solutions to cover for their energy mismatches. After the self-consumption process, in case that electricity surplus occurs, the ESS is used to store it, as long as it does not reach its maximum State of Charge (SoC). In the case that the house's electricity surplus is higher than the ESS's available energy, the battery is charged with the highest possible electricity amount and the remainder is sold to the grid. If, however, the prosumer requires more electricity than the ESS can provide, the house is provided with the highest possible amount of electricity from the battery, until it reaches SoC_{min} and the remainder deficit is purchased from the grid. If the ESS is able to provide the REC with its electricity requirements, it is discharged. This process is repeated every hour *h* of the 219 000 hours in a 25-year long investment and for every household *n* so that techno-economical conclusions can be drawn.

EC scenarios: for every hour, the model uses the individual prosumers' PV generation to cover for their electricity needs, in the same procedure as in the individual scenarios. If these needs are not met for any user and if other users have electricity to spare, then the system advances to the P2P stage, in which energy is traded between prosumers to assure that no energy demand is unmet. Once all surplus or demand are balanced, if the community requires electricity, a community-owned battery is discharged. If the community has energy to spare, this battery is charged. Only if the battery cannot be used does the community buy electricity from the grid. If, however, the community has surplus and the ESS is fully charged, households are able to communicate their surplus to the grid and to a tertiary building which acts as an electricity buyer. The aggregator receives the price that the grid is offering to buy electricity for and the price for which the TB is buying its electricity. The aggregator then calculates the average between these prices (meaning there is a profit factor of 50%) to obtain the price for which electricity can be sold by the EC to the TB, if the TB is the highest bidder. The applied profit factor allows for profit to be made by the REC and the TB, since the EC can get a higher offer from the TB than with the FiT and the TB can buy electricity from the EC at a lower value than from the grid. This process is then repeated for every hour *h* of the 25 years.

Table 3.1: Input parameters used in the developed EC model

Input parameters	Description	Units	Ind. Scenarios	REC Scenarios
Consumption profiles	The consumption profiles of each consumer over the first year of the investment	kWh	✓	✓
PV module generation profile	The hourly generation of a PV module, according to its power, in the selected location	kWh/kW$_p$	✓	✓
Electricity purchase price from grid in NLV[a]	The electricity tariff paid by NLV consumers to the utility grid	€/kWh	✓	✓
Electricity purchase price from grid in MV[b]	The electricity tariff paid by MV consumers to the utility grid	€/kWh	✗	✓
Feed-in Tariff	The remuneration offered by the grid to consumers for selling electricity	€/kWh	✓	✓
Energy cost evolution in NLV	The yearly variation of the electricity purchase prices from the grid in NLV	%/year	✓	✓
Energy cost evolution in MV	The yearly variation of the electricity purchase prices from the grid in MV	%/year	✗	✓
Energy consumption evolution	The yearly evolution of NLV consumers' electricity consumption	%/year	✓	✓
Profit factor	The factor that determines the electricity selling price between the REC and the TB	%	✗	✓
Discount rate	The rate of return used to discount future cash flows to the present value	%	✓	✓
Equipment investment costs	Investment cost of all the selected equipment	€/kWp	✓	✓
Equipment O&M[c] costs	Operation and maintenance cost of all the selected equipment	€/kWp/year	✓	✓
Taxes and fees costs	All the taxes and fees that each consumer must pay during the investment	€	✓	✓
PV module power	The peak power of each PV module	kWp	✓	✓
PV module derate factor	The power output reduction, per year, of each PV module	%/year	✓	✓
ESS capacity	The theoretical amount of energy that can be stored in the ESS	kWh	✓	✓
ESS depth of discharge	The amount of ESS energy that can be used	%	✓	✓
ESS round-trip efficiency	Defines how much energy can actually be used with the ESS	%	✓	✓

[a]NLV- Normal low voltage (contracted power up to 41.4 kVA).
[b]MV- Medium voltage (contracted power from 200 kVA to 10 MVA).
[c]O&M- Operation and maintenance.

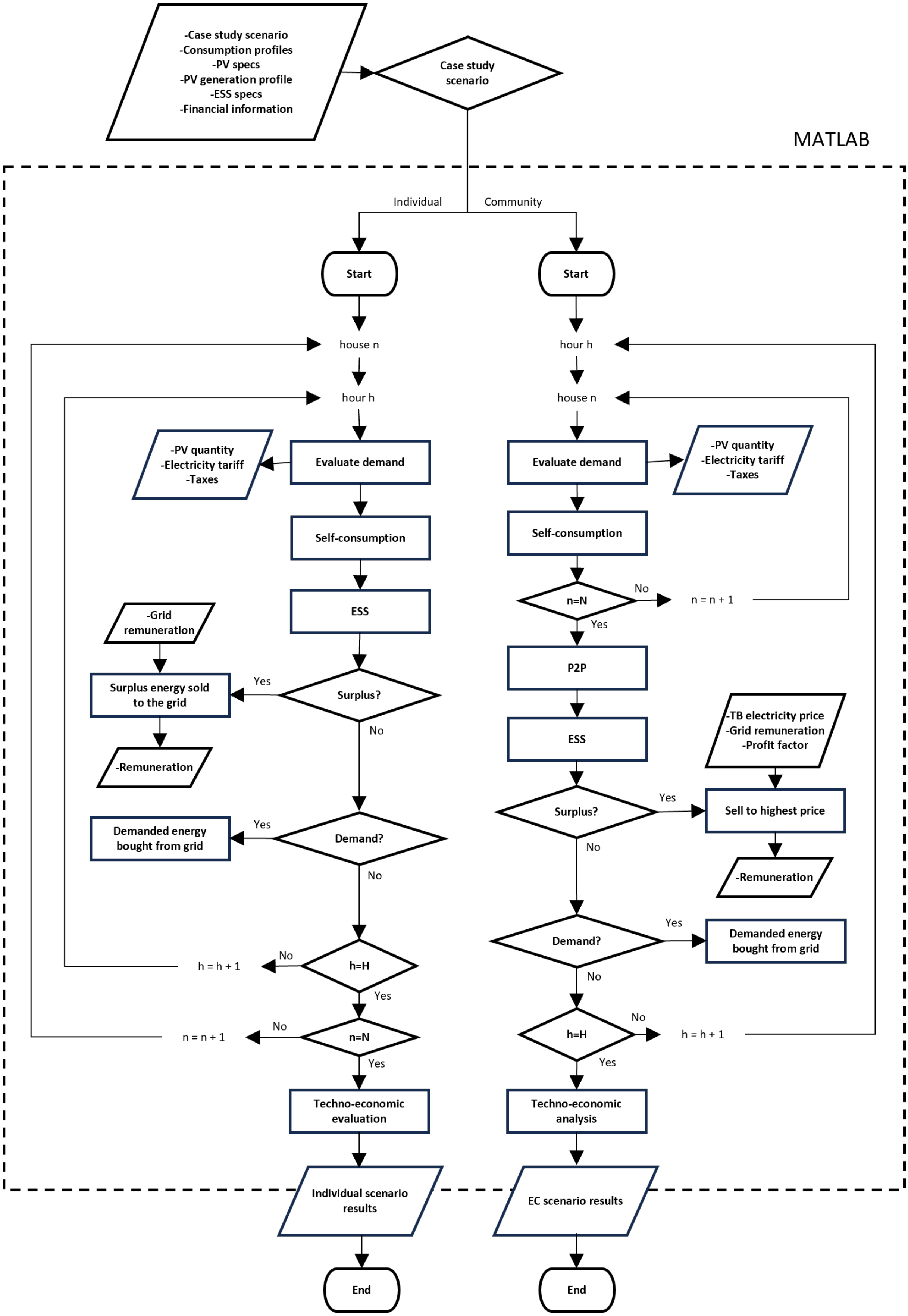


Figure 3.3: Methodology employed to optimize individual and community models

3.4 Energy Management Strategy- Mathematical Formulation

3.4.1 Self-Consumption

When the modules are producing electricity, it is used to cover for the demand that the installation may have at that moment. Normally, production and consumption profiles do not match entirely, which is exemplified in Figure 3.4, in which the green shaded area represents how much electricity needs to be purchased from the grid and the blue shaded area is how much electricity surplus results from self-consumption. This mismatch results in valleys and peaks in energy profiles.

Each of the EC's households has a PV installation that is designed according to the household's electricity demand over the first year of the investment, *i.e.* if a house consumes 8 000 kWh of electricity in a year, the chosen number of PV modules is the lowest for which the estimated production is above 8 000 kWh (considering the average irradiation data values for the REC location). As different houses have different consumption profiles, so will they have different capacities of PV installations.

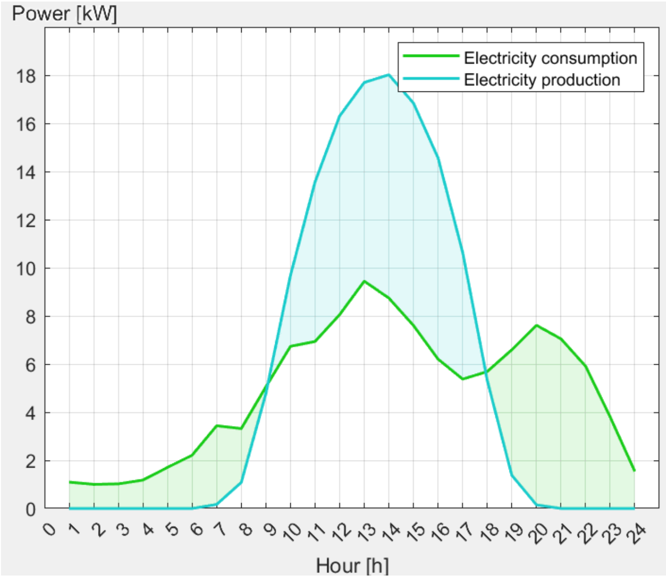


Figure 3.4: Example of the mismatch between a household's PV production and consumption

The self-consumption process is equal for individual scenarios and EC scenarios: for every house n in every hour h of every year g, an energy balance is required, that can be seen in Equation 3.1. This equation states that the electricity demand for each house n in each time step h of a certain year g of the simulations, after using PV, ($E^{DPV}_{n,g,h}$) is equal to the difference between the initial demand ($E^{Di}_{n,g,h}$) and the generation ($E^{PV}_{n,g,h}$) of each member of the REC.

$$E^{DPV}_{n,g,h} = E^{Di}_{n,g,h} - E^{PV}_{n,g,h} \tag{3.1}$$

Where:

$E^{DPV}_{n,g,h}$ = electricity demand from house n in year g and hour h, after using PV generation, in kWh

$E^{Di}_{n,g,h}$ = initial electricity demand from house n in year n and hour h, in kWh

$E^{PV}_{n,g,h}$ = electricity generation of house n in year n and hour h, in kWh.

3.4.2 P2P Energy Sharing

For every hour h of each year g, the energy status of all members n is evaluated. If there are, simultaneously, situations of surplus and demand within residents after using their PV power for self-consumption, the aggregator balances this mismatch via a social-welfare-conscious P2P mechanism: those that require the most electricity receive more than those with an inferior demand; users with the most surplus will donate more electricity than users with inferior values of surplus. Consequently, electricity disparities across the created EC will be diminished. The P2P process is governed by Equations 3.2-3.7 consecutively for every instant *h* of the investment, after using each house's generation for self-consumption.

For every instant h of a given year g, every household n has its demand and supply values evaluated to see how many households ($d_{g,h}$) had an electricity deficit after using PV generation ($E^{DPV}_{n,g,h} > 0$) and how many houses ($s_{g,h}$) had an electricity surplus ($E^{DPV}_{n,g,h} < 0$). This way, these prosumers can trade energy between them before interacting with the ESS and the grid. This will diminish electricity discrepancies throughout the community, since all consumption patterns are different from one-another. When there is an instant in which there is the possibility for P2P to occur, the aggregator starts this trading process by analyzing the total of surplus ($S_{g,h}$) and deficit ($D_{g,h}$) available in that time period, seen in Equation 3.2 and Equation 3.3, respectively.

$$\begin{aligned} S_{g,h} &= \sum_{n=1}^{s_{g,h}} E^{DPV}_{n,g,h} \\ \text{s.t.} \quad & E^{DPV}_{n,g,h} < 0 \end{aligned} \tag{3.2}$$

Where:

$S_{g,h} =$ total electricity surplus across all the houses of the EC at a given instant h of a year g, in kWh
$s_{g,h} =$ number of houses that had electricity surplus in a given instant h of year g.

$$\begin{aligned} D_{g,h} &= \sum_{n=1}^{d_{g,h}} E^{DPV}_{n,g,h} \\ \text{s.t.} \quad & E^{DPV}_{n,g,h} > 0 \end{aligned} \tag{3.3}$$

Where:

$D_{g,h} =$ total electricity deficit across all the houses of the EC at a given instant h of a year g, in kWh
$d_{g,h} =$ number of houses n that had electricity deficit in a given instant h of year g.

The created prosumer trading mechanism was designed to be as community-conscious as possible. To achieve this goal, two variables were created: $a_{n,g,h}$ and $b_{n,g,h}$. These are defined in Equation 3.4 and Equation 3.5, respectively, and reflect the percentual contribution (or quota) of each house to the total surplus and deficit, respectively, hence $0 < a_{n,g,h} \leq 1$ and $0 < b_{n,g,h} \leq 1$.

$$a_{n,g,h} = \frac{E^{DPV}_{n,g,h}}{S_{g,h}} \quad \text{s.t.} \quad E^{DPV}_{n,g,h} < 0 \tag{3.4}$$

Where:

$a_{n,g,h}$ = electricity surplus quota of a household n in a given hour h of year g

$$b_{n,g,h} = \frac{E^{DPV}_{n,g,h}}{D_{g,h}} \quad \text{s.t.} \quad E^{DPV}_{n,g,h} > 0 \tag{3.5}$$

Where:

$b_{n,g,h}$ = electricity deficit quota of a household n in a given hour h of year g

At a given hour *h* of a certain year g, if one user n has the most surplus of the EC, its $a_{n,g,h}$ will be the highest. This household will contribute with more energy than other prosumers that have less energy surplus in the process represented in Equation 3.6. This equation states that when electricity surplus exceeds deficit in the EC ($S_{g,h} > D_{g,h}$), a house n that has surplus in hour h of the year g will trade its surplus ($E^{DPV}_{n,g,h}$) proportionally to its percentual contribution to the total EC surplus (equal to the surplus quota) and end up with $sur_{n,g,h}$. The same mechanism is applied in $b_{n,g,h}$ for the deficit, thus relieving users with higher electricity needs since they receive more energy, as per Equation 3.7, according to their deficit quota. For example, if one user has 4 kWh of surplus and the total surplus of the community is 10 kWh, this user has $a_{n,g,h} = 0.4$ and $b_{n,g,h} = 0$. The prosumer trading process uses this prosumer's surplus to cover for 40% of the deficit in the EC, as per Equation 3.6.

$$sur_{n,g,h} = \mid E^{DPV}_{n,g,h} \mid - a_{n,g,h} \times D_{g,h} \quad \text{s.t.} \quad E^{DPV}_{n,g,h} < 0 \tag{3.6}$$

Where:

$sur_{n,g,h}$ = electricity surplus that house n has available in year g and hour h after the prosumer trading process, in kWh.

$$def_{n,g,h} = E^{DPV}_{n,g,h} - b_{n,g,h} \times S_{g,h} \quad \text{s.t.} \quad E^{DPV}_{n,g,h} > 0 \tag{3.7}$$

Where:

$def_{n,g,h}$ = electricity deficit that house n has available in year g and hour h after the prosumer trading process, in kWh.

A graphic representation of the effects of Equation 3.6 can be seen in Figure 3.5. This figure illustrates how the P2P mechanism starts, for a given instant in which the REC's total electricity surplus surpasses its total electricity deficit. The model calculates what is the lowest electricity demand (0.1 kWh in the presented example) and sets that value as the 1st step for electricity balancing. Each house with a deficit receives 0.1 kWh of electricity. As Figure 3.6 shows, House 1 will give 0.17 kWh of electricity, while House 2 gives the remaining 0.03 kWh. This occurs since House 1 has a higher surplus quota, defined in Equation 3.4. Consequently, as per Equation 3.6, House 1 will donate a higher percentage of electricity surplus. Once all houses have received the 0.1 kWh of electricity, the model calculates the next step for balancing, which is equal to 0.4 kWh. Although House 2 only has 0.17 kWh of electricity available to donate, House 1 has 0.83 kWh so, as in the previous step, it donates more electricity than House 2. Hence, House 1 donates 0.33 kWh of electricity and House 2 donates 0.07 kWh of its surplus. The final overview of this particular example is displayed in Figure 3.7, in which House 1 still has 0.5 kWh of electricity surplus and House 1 has 0.1 kWh of surplus, while House 3 and House 4 have had their electricity deficits covered.

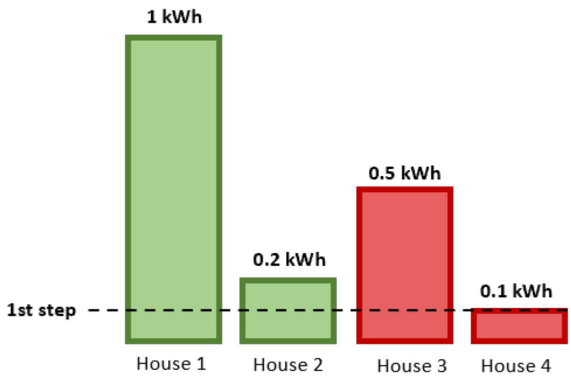


Figure 3.5: Example of the first step in the proposed P2P process, when total surplus surpasses total demand

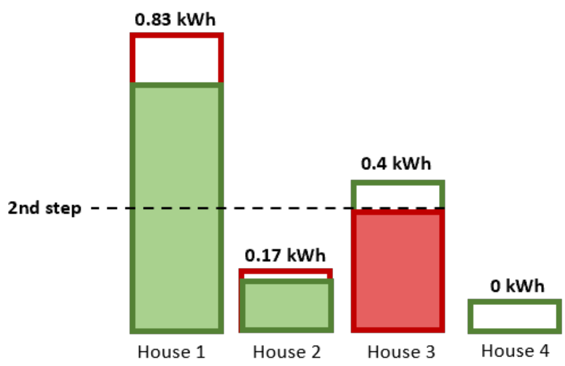


Figure 3.6: Example of the second step in the proposed P2P process, when total surplus surpasses total demand

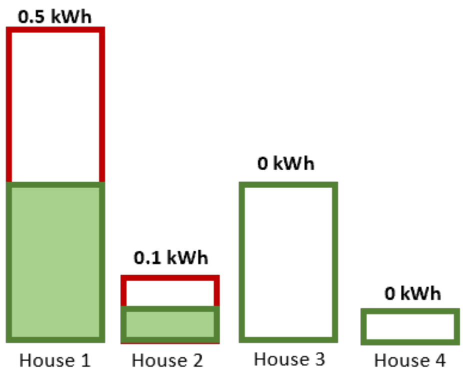


Figure 3.7: Example of the final energy overview of the proposed P2P process, when total surplus surpasses total demand

If, however, the REC's total electricity deficit surpasses its electricity surplus, Equation 3.7 is used, which is visually displayed in Figure 3.8. In this example, the 1st step of the P2P process requires each house with surplus to give 0.5 kWh of electricity to balance the energy disparity in the EC for this given instant. This would mean that 1 kWh would have to be provided to cover for the deficit with the 1st step, which is not possible since House 1 has 0.5 kWh of electricity available to donate, in contrast with House 2 which only has 0.1 kWh to donate. Hence, both houses with surplus must distribute their donations according to Equation 3.7. In this situation, in which surplus is not enough to cover the deficit, the model calculates each house's deficit quota with Equation 3.5 and uses it in Equation 3.7 to determine that House 3 will receive 0.4 kWh of electricity and House 4 will only receive 0.2 kWh. The result is shown in Figure 3.9– a decrease in the energy disparity between the houses with electricity deficit from 0.5 kWh to 0.3 kWh (a reduction of 40%).

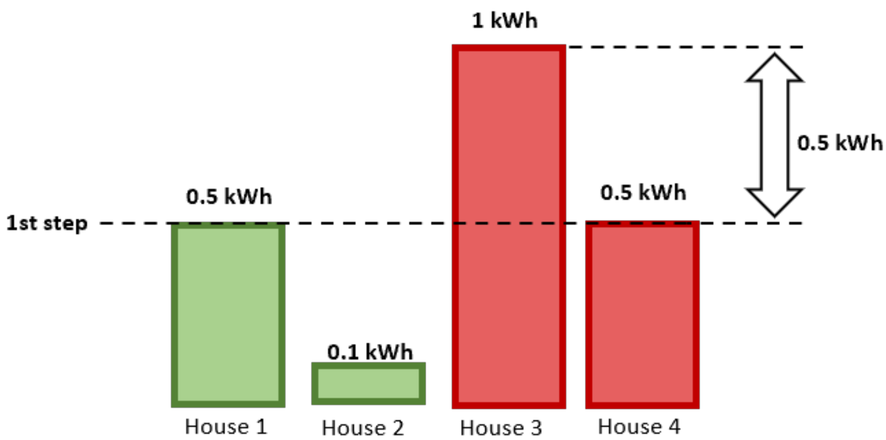


Figure 3.8: Example of the first step in the proposed P2P process, when total demand surpasses total surplus

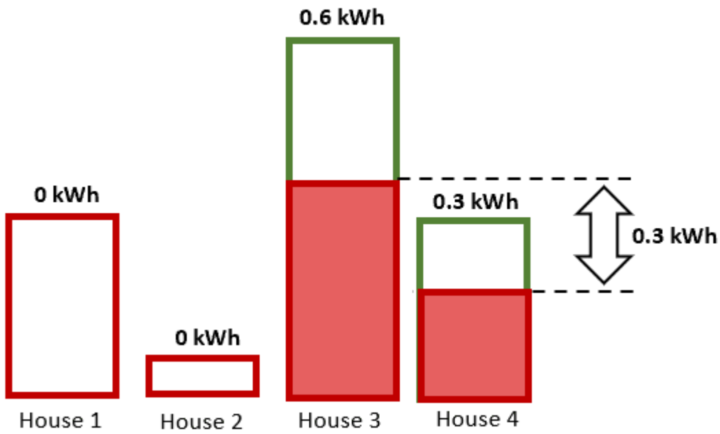


Figure 3.9: Example of the final energy overview of the proposed P2P process, when total demand surpasses total surplus

3.4.3 Battery Energy Storage System

After individual self-consumption, for individual prosumers, with the values of surplus or deficit in a certain house n for year g and hour h, the optimization model proceeds to use individual energy storage as described in Algorithm 1 pseudo-code. If a house has surplus it is sent to charge the battery, as long as its state of charge is not at its maximum value (SoC_{max}). In the case that the ESS cannot store all the surplus, all energy that cannot be stored is sold. If there is still demand, this battery can also be discharged, provided its state of charge is not at its minimum value (SoC_{min}), in which case the house must purchase the remaining electricity demand from the grid.

Algorithm 1 Battery operation algorithm for individual prosumers

Inputs: Household's electricity deficit or surplus for every instant *h* and battery specifications
Output: Battery state of charge and electricity deficit or surplus at every time instant *h*

if there is generation surplus **then**
    if $SoC < SoC_{max}$ **then**
        if charging all surplus leads to reaching $SoC = SoC_{max}$ **then**
            charge until $SoC = SoC_{max}$ and remainder is sold
        else charge ESS
        end if
    else if $SoC = SoC_{max}$ **then** sell all surplus
    end if
else if there is electricity deficit **then**
    if $SoC > SoC_{min}$ **then**
        if discharging all deficit leads to reaching $SoC = SoC_{min}$ **then**
            discharge ESS until $SoC = SoC_{min}$ and remainder is bought from the grid
        else discharge ESS
        end if
    else if $SoC = SoC_{min}$ **then** buy all electricity deficit from the grid
    end if
end if

Collective self-consumption prosumers' energy storage follows Algorithm 2 pseudo-code. The difference between these prosumers and the individual self-consumers is that, in the community model there are two situations which do not occur in the individual model: 1) if the community has a surplus value higher than the amount of energy that can be stored in the ESS, each prosumer stores an equal amount of energy in the ESS until it is fully charged and the remaining surplus is sold and 2) if the community has a higher demand value than how much energy the ESS can discharge, each prosumer receives an equal amount of energy, after which they have to resort to the grid in case of unmet demand.

Algorithm 2 Battery operation algorithm for EC households

Inputs: Electricity deficit or surplus for every instant *h* and the battery's specs
Output: Battery state of charge and electricity deficit or surplus at every time instant *h*

if there is generation surplus **then**
  if $SoC < SoC_{max}$ **then**
    if charging all surplus leads to reaching $SoC = SoC_{max}$ **then**
      charge an equal amount from all prosumers until $SoC = SoC_{max}$ and remainder is sold
    else charge ESS
    end if
  else if $SoC = SoC_{max}$ **then** sell all surplus
  end if
else if there is energy deficit **then**
  if $SoC > SoC_{min}$ **then**
    if discharging all deficit leads to reaching $SoC = SoC_{min}$ **then**
      discharge ESS equally to each prosumer until $SoC = SoC_{min}$ and remainder is bought from the grid
    else discharge ESS
    end if
  else if **then**$SoC = SoC_{min}$ buy all electricity deficit from the grid
  end if
end if

3.4.4 Tertiary Building and Main Grid

For individual and community scenarios, if the battery is at SoC_{min}, households that require energy have to purchase it from the grid.

In individual scenarios, if prosumers have surplus after using the ESS, they sell it for a FiT (Feed-in Tariff) to the main grid. For community residents, however, in case the battery is fully charged and the REC tries to charge it, the surplus energy can be sold to a nearby tertiary building or to the main grid. The REC aggregator receives the tertiary building's electricity buying price in that moment (€$_{TB-Grid}$) and for how much money the EC could sell its electricity to the main grid (€$_{Grid-EC}$). If the value that the TB is buying energy for in MV is higher than the value of selling electricity to the main grid in NLV, the aggregator evaluates how much the difference is between them to calculate an intermediate value (€$_{TB-EC}$) for which the REC can sell its electricity to the TB, a process that is represented in Figure 3.10. So as to provide a fair trade offer to the TB, the aggregator applies a 50% profit factor to the community's profit margin, which is represented in green in Figure- 3.10 and splits the difference between the prices €$_{TB-Grid}$ and €$_{Grid-EC}$, thus selling the REC's surplus electricity for final value of €$_{TB-EC}$.

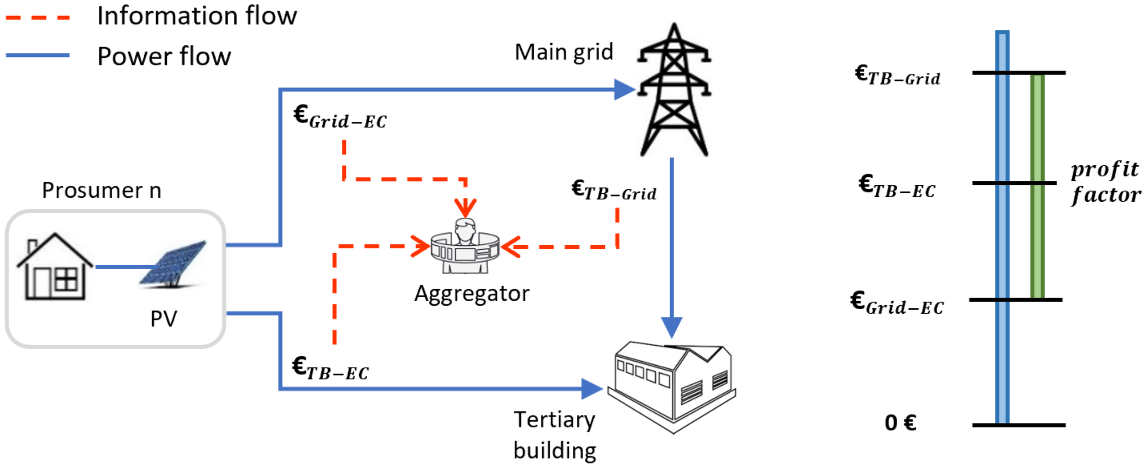


Figure 3.10: Calculation of the electricity selling price between the REC and the TB

3.5 Result Assessment Metrics

When evaluating the viability of an investment, it is not advisable to only use economic modelling methodologies, since these fail to consider the benefits and risks that a renewable energy investment might include. Hence, having multiple criteria evaluation is fundamental to assess and select an optimal investment option [50].

3.5.1 Net Present Value

The net present value is a tool for economic analysis of an investment that is based on the time value of money– the concept of a dollar today possibly being worth more than a dollar tomorrow, since it can be used to generate interest, gains or losses. The NPV determines the present value of an investment using its estimated future cash flows discounted to the present day, with a certain discount rate to account for the project's risk, among other factors.

In this type of investment, there are direct cash flows when energy is sold by the EC, however the savings provided by this investment relative to not investing are also considered as positive cash flows. The result is an NPV that reflects if the savings that investing in this EC provides, plus the profit from selling energy make it monetarily advantageous for investors to join the community. A positive NPV indicates that the investment should be accepted, given the chosen discount rate of 5%, according to the International Renewable Energy Agency (IRENA) [17].

The developed Matlab model calculates which is the net profit value for each resident, as in Equation 3.8. For each house *n* up to a total of N=10 houses, each of the investment's yearly net cash flows ($NCF_{n,g}$) are summed and discounted, for a period of g=1 to G=25 years.

$$NPV_n = \sum_{g=1}^{G=25} \frac{NCF_{n,g}}{(1+r)^g} \tag{3.8}$$

Where:
$n =$ index of each house, from n=1 to N=10
$g =$ index of the year of investment, from g=1 to G=25
$NCF_{n,g} =$ net cash flows in house n for the year g, in €
$r =$ discount rate, in %.

The net cash flows for each house in each year ($NCF_{n,g}$) are obtained by calculating the difference between the influx ($CF_{n,g}$) and outflux ($C_{n,g}$) of money in the investment, as seen in Equation 3.9.

$$NCF_{n,g} = CF_{n,g} - C_{n,g} \tag{3.9}$$

Where:
$CF_{n,g} =$ money influx of each house n in year g, in €
$C_{n,g} =$ money outflux of each house n in year g, in €.

This investment's outflux of capital ($C_{n,g}$) consists of the initial investment of each house, before the investment starts, the replacement of batteries and inverters ($Rep_{n,g}$) and the yearly operation and maintenance costs of all the equipment ($OM_{n,g}$), as per Equation 3.10.

$$C_{n,g,} = Inv_n + Rep_{n,g} + OM_{n,g} \tag{3.10}$$

Where:
$Inv_n =$ initial investment of each house n before the investment, in €
$Rep_{n,g} =$ equipment replacement costs for each house n in year g, in €
$OM_{n,g} =$ operation and maintenance costs for each house n in year g, in €.

The influx of capital is not always a direct inflow, as it consists of the savings provided by the investment when compared to not investing and also the potential profit made from selling electricity surplus. This relation is reflected in the final electricity bill of consumers, as seen in Equation 3.11. The time step chosen is $h = 1$ hour, consequently the influx ($CF_{n,g}$) is calculated for each hour of the considered 25 years, year by year so that it can be discounted using the NPV method in Equation 3.8.

$$CF_{n,g} = \sum_{h=1}^{H=8760} (PNI_{n,g,h} - P_{n,g,h}) \tag{3.11}$$

Where:
$h =$ index of each time step, from h=1 to H=8760
$PNI_{n,g,h} =$ electricity bill of not investing in the project for each house n in year g and hour h, in €
$P_{n,g,h} =$ electricity bill having invested in the project for each house n in year g and hour h, in €.

The electricity bill of not investing in these RES solutions ($PNI_{n,g,h}$) is equivalent to buying all electricity demand from the grid during every hour of the 25–year period, as per Equation 3.12. Each house has a different electricity demand ($E^{Di}_{n,g,h}$), hence they will use different tariffs when purchasing electricity from the grid and incur in different taxes, thus making the cost of buying from the grid ($CG_{n,g,h}$) dependent on the house (n) as well.

$$PNI_{n,g,h} = E^{Di}_{n,g,h} \times CG_{n,g,h} \tag{3.12}$$

Where:
$CG_{n,g,h} =$ cost of buying electricity from the grid for house n, year g and hour h, in €/kWh.

The electricity bill having invested in the project ($P_{n,g,h}$) is defined depending on whether each house has electricity surplus ($E^{Df}_{n,g,h} < 0$) or deficit ($E^{Df}_{n,g,h} > 0$) after all the energy-trading processes (self-consumption of PV generation, ESS usage and P2P in EC scenarios) are over, as Equation 3.13 dictates. As part of the generated electricity covers consumption and another part is sold, the price of investing in these projects ($P_{n,g,h}$) is lower than the price of not investing ($PNI_{n,g,h}$), thus returning positive cash flows to investors, as per Equation 3.11.

$$\begin{cases} P_{n,g,h} = E^{Df}_{n,g,h} \times PS_{n,g,h} \ , & if \ \ E^{Df}_{n,g,h} < 0 \\ P_{n,g,h} = E^{Df}_{n,g,h} \times CG_{n,g,h} \ , & if \ \ E^{Df}_{n,g,h} > 0 \end{cases} \tag{3.13}$$

Where:
$E^{Df}_{n,g,h} =$ final electricity deficit (>0) or surplus (<0) for each house n in year g and hour h, having invested in any of the proposed models, in kWh
$PS_{n,g,h} =$ remuneration received by house n for selling electricity in year g and hour h, in €/kWh.

3.5.2 Internal Rate of Return

The internal rate of return method evaluates the profitability of investments by providing the investor with the discount rate that would return a null net present value in Equation 3.14.Therefore, the IRR provides the real rate of return of the investment. An IRR higher than the discount rate informs investors that the investment is economically viable.

$$0 = NPV_n = \sum_{g=1}^{G=25} \frac{NCF_{n,g}}{(1+IRR)^g} \tag{3.14}$$

3.5.3 Payback Period

Unlike the NPV, the payback period method (PBP) does not consider the time value of money, making it a non-discount method. The PBP calculates how much time it will take for an investment to return the initial capital invested. In this work, a simple payback period is utilized, in which savings are considered to be evenly distributed along each year.

3.5.4 Self-Sufficiency

This thesis is focused not only on assessing the economic viability of investment scenarios, but also in increasing prosumers' self-sufficiency by analyzing their electricity demand before ($E^{Di}_{n,g,h}$) and after investing in the proposed models ($E^{Df}_{n,g,h}$), as per Equation 3.15. High values of $SS_{n,g,h}$ for a certain consumer n reflect lower grid dependency and a good ability to generate and consume prosumers' own electricity in a certain time frame for analysis of g years and h hours.

$$SS_{n,g,h} = 1 - \sum_{g}\sum_{h}\frac{E^{Df}_{n,g,h}}{E^{Di}_{n,g,h}} \tag{3.15}$$

Where:

$SS_{n,g,h}$ = self-sufficiency of a consumer n in a certain time frame of g years and h hours.

3.5.5 CO_2 Emissions

One of the most important aspects of the energy transition is reducing the emission levels of greenhouse gases, the most emitted of which being CO_2. This thesis explores the possibility to reduce CO_2 emissions when investing in the modeled case studies, therefore CO_2 emissions of each case study, for each consumer, are compared to a no-investment scenario, as seen in Equation 3.16, in which all electricity demandd is bought from the grid. For this, it was considered the emission factor of the Portuguese Electrical Grid (ε^{Grid}) in Equation 3.17 and Equation 3.18, in which the CO_2 emissions for a selected case study ($Em^{CS}_{n,g,h}$) and for a no-investment scenario ($Em^{NI}_{n,g,h}$) are calculated, respectively, for a selected household n in a certain analysis time frame of g years and h hours. Emission factors quantify how much CO_2 is associated with an activity, measured in weight of emitted particles per unit of said activity.

$$Em_{n,g,h} = \sum_{g}\sum_{h}\frac{Em^{CS}_{n,g,h}}{Em^{NI}_{n,g,h}} \tag{3.16}$$

Where:

$Em_{n,g,h}$ = the CO_2 emissions of a consumer n in a certain time frame of g years and h hours compared to not investing, in grams of CO_2

$Em^{CS}_{n,g,h}$ = the CO_2 emissions of a consumer n in a certain time frame of g years and h hours, for a certain case study, in grams of CO_2

$Em^{NI}_{n,g,h}$ = the CO_2 emissions of a consumer n in a certain time frame of g years and h hours, when not investing, in grams of CO_2.

$$Em_{n,g,h}^{CS} = \varepsilon^{Grid} \times E_{n,g,h}^{Df} \tag{3.17}$$

Where:

$\varepsilon^{Grid} =$ the CO_2 emission factor associated with using the Portuguese ELectrical Grid, in gCO_2/kWh

$$Em_{n,g,h}^{NI} = \varepsilon^{Grid} \times E_{n,g,h}^{Di} \tag{3.18}$$

3.5.6 Fairness Index

Even when an energy community's goal is not financial, a fair and meritocratic value sharing method is key to the community's stability [51]. The fairness index ranges from [0,1] and reflects how fair the economic benefits allocation within an energy community is. A FI close to a unity value indicates that all the members of the REC are receiving equally fair benefits. The FI of a community (FI_{EC}) can be calculated using Jain's Index adapted to the REC in Equation 3.19, where the relative allocation of benefits of all residents N in a certain time frame ($x_{n,g,h}$) is normalised [52].

$$FI_{EC} = \frac{1}{N} \times \frac{(\sum_{n=1}^{N=10} x_{n,g,h})^2}{\sum_{n=1}^{N=10} (x_{n,g,h})^2} \tag{3.19}$$

The relative allocation of benefits of each household n is defined in Equation 3.20 as the ratio between the influx of money obtained by a member ($CF_{n,g,h}$) and this member's generation quota ($E_{n,g,h}^{PV}$) within the community in the selected time frame for analysis of g years and h hours.

$$x_{n,g,h} = \frac{CF_{n,g,h}}{\sum_g \sum_h E_{n,g,h}^{PV}} \tag{3.20}$$

There are several ways to distribute benefits among communities and obtain each resident's money influx ($CF_{n,g,h}$) which, in current literature, generally consist of creating a "pool" with the community's electricity bill savings and earnings from selling electricity surplus. This pool is later distributed using pre-determined allocation methods and each resident has its final money influx value determined in this fashion. This thesis does not use these methods and proposes a different benefits allocation, which will be compared to bundling all the consumers' electricity bill savings and profits to be later distributed.

1) Proposed benefits allocation (MP): this thesis proposes that each household has its electricity managed by the aggregator using the proposed methodology in which PV generation is used for self-consumption, then all residents partake in the P2P process, after which the community-owned battery is used and any remaining surplus can be sold, any remaining demand must be purchased from the grid, as described in chapter 3.4.1. Whatever savings and profit each consumer makes after all these processes will be used to calculate the subsequent money influx obtained by a member n in a certain amount of years g and hours h, as defined in Equation 3.21. Thus, as money influxes are calculated with the difference between electricity prices having invested in the created case studies (which include selling energy surplus, as per Equation 3.13) and not having invested at all (as seen in Equation 3.12),

prosumers give to and receive energy from other residents, without ever aggregating it all to be later redistributed.

$$CF_{n,g,h} = \sum_{g} \sum_{h} PNI_{n,g,h} - P_{n,g,h} \tag{3.21}$$

2) Equal quota allocation (EQ): distributes the total savings and profits of all residents N in a certain amount of years g and hours h ($(CF_{EC})_{g,h}$) equally among all members of the community, which all receive the same benefit ($CF_{n,g,h}$), as seen in Equation 3.22.

$$CF_{n,g,h} = \frac{(CF_{EC})_{g,h}}{N} \tag{3.22}$$

The total REC money influx ($(CF_{EC})_{g,h}$) is not related to a single household n, but rather to the total money influx of all residents N in a certain amount of years g and hours h. Hence, it is obtained using Equation 3.23, by summing the individual money influxes of all prosumers in the selected time frame for analysis.

$$(CF_{EC})_{g,h} = \sum_{n=1}^{N=10} \sum_{g} \sum_{h} CF_{n,g,h} \tag{3.23}$$

3) Consumption-based allocation (CB): allocates $(CF_{EC})_{g,h}$ according to the consumption quota of each household in a certain amount of years g and hours h, i.e. the ratio between the consumption of said household and total consumption of the community in this period, as seen in Equation 3.24. This method only rewards one side– high consumptions– and does not compensate households with high electricity generation.

$$CF_{n,g,h} = \frac{\sum_{g} \sum_{h} E^{Df}_{n,g,h}}{\sum_{n=1}^{N=10} \sum_{g} \sum_{h} E^{Df}_{n,g,h}} \times (CF_{EC})_{g,h} \tag{3.24}$$

4) Bâra and Oprea have proposed an allocation method (BP) that distributes the REC's total money influx based on each consumer's contribution to the total electricity surplus and deficit of the community, $a_{n,g,h}$ and $b_{n,g,h}$, respectively, as previously defined in Equation 3.4 and Equation 3.5. The method proposed by these authors, defined in Equation 3.25, incentivises users which have high surplus quotas and low demand quotas. Thus, houses with high electricity generation and low consumption are the ones that receive the highest benefits and households with lower generation and high consumption receive the lowest shares of benefits [53].

$$CF_{n,g,h} = \begin{cases} (1 - b_{n,g,h}) \times \frac{(CF_{EC})_{g,h}}{N}, \ if \ E^{Df}_{n,g,h} > 0 \\ (1 + a_{n,g,h}) \times \frac{(CF_{EC})_{g,h}}{N}, \ if \ E^{Df}_{n,g,h} < 0 \end{cases} \tag{3.25}$$

Chapter 4

Simulation Conditions

4.1 Households Characterization

Portugal's capital city, Lisbon, was selected as the proposed community's location. With an annual average sunshine of 2799 hours and one of Europe's highest annual average solar irradiation values, this city is a great location for investment in PV power generation [54].

To create a community means that a certain number of households must be selected and residents must be allocated to live in the houses. Hence, it was chosen to have 10 households with very different types of residents in them. These range from families with children and a senior at home, to a single person living alone, as described in Table 4.1. The type of household is extremely pertinent information, since it affects not only the consumption profile, but also the taxes in residents' electricity bills and their savings when investing.

Table 4.1: Characterization of each house's residents

House	Residents description
House 1	Working couple, 2 children, 2 seniors
House 2	Couple, one at work, one working at home, 3 children
House 3	Single woman, without work, 2 children
House 4	Family, without work, 2 children
House 5	Family, without work, 3 children
House 6	Family, parents without work, 2 children
House 7	Couple, 30 - 64 years old, both at work, with homehelp
House 8	Single woman, without work, 30 - 64 years old
House 9	Couple, both shift workers, 30 - 64 years old
House 10	Couple over 65 years old

The six created case study scenarios displayed in Table 4.2 have the purpose of showing the social, economic and environmental effects of partaking in the proposed REC for an investment period of 25 years, comparing to investing in an individual self-consumption model for the same amount of time.

Table 4.2: Created case study scenarios and their main characteristics

Case study scenario	PV generation	ESS ownership	ESS capacity [kWh]	Energy selling options	P2P
I1	Consumption-fitted	Individual	0	Grid	✗
I2	Consumption-fitted	Individual	2	Grid	✗
I3	Consumption-fitted	Individual	4	Grid	✗
EC1	Consumption-fitted	Community	0	Grid and Tertiary Building	✓
EC2	Consumption-fitted	Community	20	Grid and Tertiary Building	✓
EC3	Consumption-fitted	Community	40	Grid and Tertiary Building	✓

Individual scenarios: scenario I1 consists of all consumers investing solely in a PV system according to their yearly electricity consumption, as per Chapter 3.4.1. Each consumer has different consumption patterns, therefore they will have different numbers of PV modules. In Scenarios I2 and I3, all consumers have a PV installation, as described previously, and individual battery energy storage devices of 2 or 4 kWh, respectively.

EC scenarios: scenario EC1 consists of all consumers having the previously described PV installation, but also taking part in the proposed community described in Chapter 3.2, with P2P energy sharing and the possibility to sell electricity surplus to a tertiary building. Scenarios EC2 and EC3 have all the consumers partaking in the REC, with the PV generation as described in all other scenarios, and community-owned lithium-ion battery storage devices of 20 or 40 kWh, respectively.

4.2 Equipment Overview

In order to run energy management simulations, all the used devices' most important parameters must be defined. The selected parameters for each device are shown in Table 4.3, with the reference from which each parameter is based upon.

Silicon-based photovoltaic solar energy installations have dominated the renewable energy industry for several years and are expected to continue to grow for years to come, remaining as an essential renewable solution [55]. Consequently, this thesis assumes that all used PV modules are 460 Wp crystalline silicon. These modules have a 0.5% derate factor which means that, for every year, the modules have a power output decrease of 0.5% [56]. Each module has a 25-year operation period [56].

Based on lithium-ion batteries' longer lifetime and higher energy efficiency over lead-acid batteries, lithium-ion batteries were chosen as the ESS technology for this thesis [57]. A battery's round-trip efficiency is its ratio of useful energy output to useful energy input. As per the U.S. National Renewable Energy Laboratory (NREL), although literature for this value ranges 77-98%, the representative round-trip efficiency is 86%, which is the value chosen for this thesis [58]. In a study conducted in 2023, Orth et al observed that although several manufacturers claim to have ESS with a Depth of Discharge (DoD) of 100%, empirical results point to a more realistic observed DoD of 95%, consequently this thesis uses a conservative DoD of 90% with the state of charge assumed to be between $SoC_{min} = 5\%$ of and $SoC_{max} = 95\%$ of the total storage capacity [59]. The selected lithium-ion batteries are considered to have a lifetime of 12.5 years, consequently over the 25-year investment period there is the need to replace the ESS once [60].

Photovoltaic modules and batteries require inverters to convert direct current (from the solar PV) into an alternating current that can be used by the household appliances. Inverters, like the ESS, are assumed to have a lifetime of 12.5 years and need to be replaced once during the total investment period [61]. The selected inverter is considered to be hybrid, meaning it is capable of operating with both the PV modules and the ESS.

According to NREL, the biggest costs related to residential PV, with or without energy storage, are soft costs such as inspection, permitting, overhead and profit, as per Figure 4.1. Electrical and structural balancing of the systems (EBOS and SBOS) contribute significantly to the final cost of these investments. The EBOS comprise the electric components of an installation, such as the wiring, fuses, circuit breakers, among others. In a similar fashion, the SBOS refer to all the structural components needed to hold one of these systems in place, such as the foundations of the solar modules. The final cost in 2023 associated with residential PV modules, excluding inverters, is 1 981 €$/kW_p$, or 2 154 €$/kW_p$ with inverters as these cost 173 €$/kW_p$. The cost of adding a lithium-ion battery storage system is currently 1 422 €$/kW_p$ which, when summing with the PV modules and inverters amounts to a total of 3 576€$/kW_p$. PV modules' operation and maintenance costs (O&M) are 28 €$/kW_p$ and energy storage's O&M costs are set at 32 €$/kW_p$ [58].

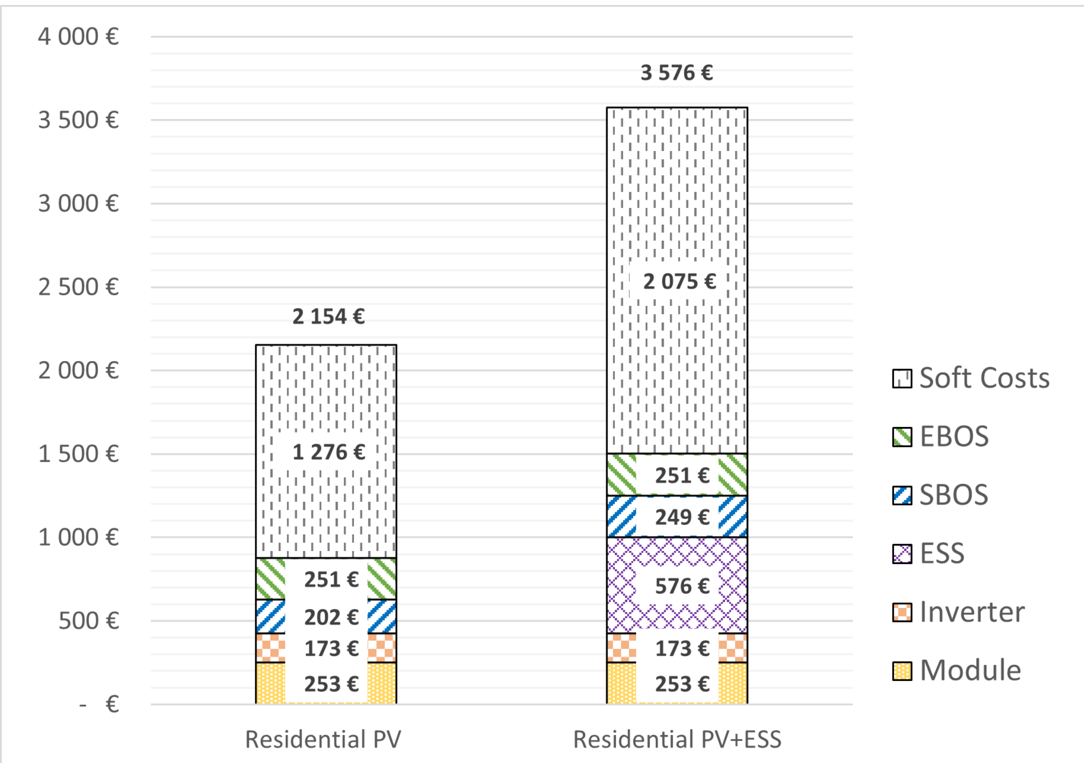


Figure 4.1: Cost benchmark of Residential PV and Residential PV with Energy Storage, in €$/kW_p$, adapted from NREL [58]

To analyze CO_2 emissions, the emission factor of the Portuguese grid was gathered. According to the Portuguese Environment Agency, Agência Portuguesa do Ambiente (APA), using 1 kWh from the Portuguese grid is equivalent to emitting 162 grams of CO_2 [62].

Table 4.3: Main characteristics of each of selected equipment

		Reference
	PV Modules	
Power per module	460 Wp	Assumed
Technology	Crystalline silicon	[55]
Cost	1 981 €$/kW_p$	[58]
O&M Cost	28 €$/kW_p$	[58]
Derate factor	0.5%/year	[56]
Lifetime	25 years	[56]
	Battery Energy Storage System	
Technology	Lithium-ion	[57]
Cost	1 422 €$/kW_p$	[58]
O&M Cost	32 €$/kW_p$	[58]
Depth of discharge	90%	[59]
Round-Trip efficiency	86%	[63]
Lifetime	12.5 years	[57]
	Inverter	
Cost	173 €$/kW_p$	[58]
Lifetime	12.5 years	[33]
	Portuguese Electrical Grid	
Emission factor	162 gCO_2/kWh	[62]

4.3 Electricity Consumption

The consumption profiles for one year of the households referred in Table 4.1 were gathered from the Load Profile Generator (LPG) tool [64]. LPG is a modelling tool that performs the full behaviour simulation of people in a household and uses that to generate energy consumption load curves. The consumption files gathered from LPG are related to the first year of consumption.

Each of the selected residents has their average daily electricity consumption profile displayed in Figure 4.2, where it is possible to see that house 1 has the highest daily electricity consumption profile and house 8 has the lowest consumption profile.

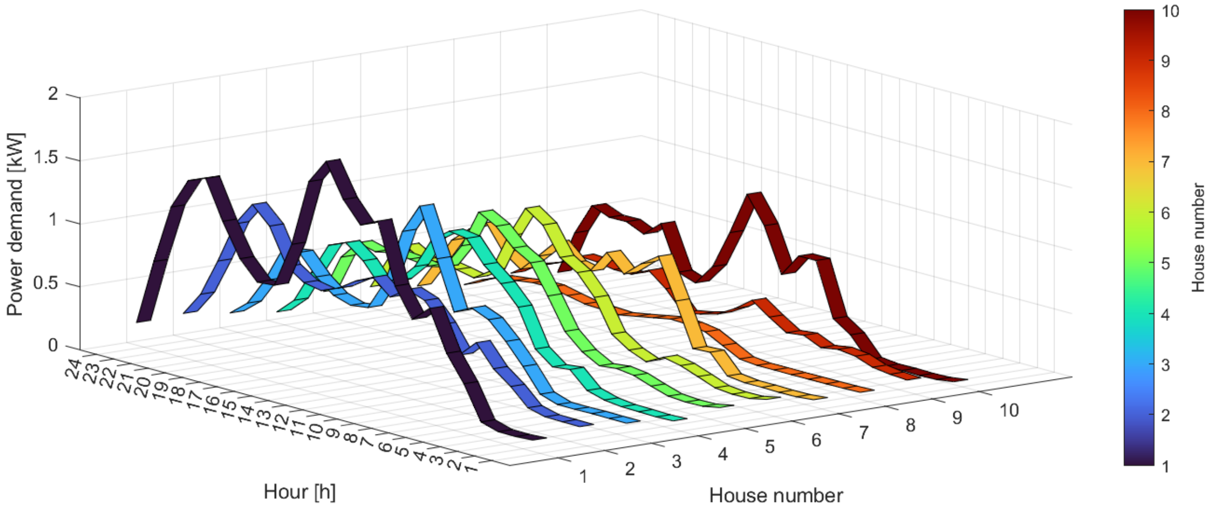


Figure 4.2: Average daily electricity consumption profile of the community's residents

4.4 Electricity Generation

The Photovoltaic Geographical Information System (PVGIS) is an online tool that provides information on solar radiation and PV systems for a given location. This thesis used PVGIS to obtain a time series of hourly values of power generation of a 460 W_p crystalline silicon panel from 2005 to 2020 in Lisbon. The values were obtained for the following conditions: fixed panel mounting, with an optimized slope and azimuth and a reference 14% system loss factor that accounts for losses in cables and power inverters, for dirt and other factors [65]. The 16 years of data collected from the PVGIS software were averaged to make a yearly profile of power generation of the selected 460 W_p PV module in Lisbon.

Using the electricity consumption per household and generation per module in the first year, the number of PV modules per household was calculated, as explained in Section 3.4.1. The total consumption over the first year of the investment and the subsequent number of PV modules per house are displayed in Table 4.4.

Table 4.4: Number of photovoltaic modules according to each household's first year demand

	House 1	House 2	House 3	House 4	House 5	House 6	House 7	House 8	House 9	House 10
Demand [kWh]	8 180	5 540	4 650	4 460	4 500	4 030	4 030	1 460	2 370	3 700
PV modules	9	6	5	5	5	5	5	2	3	4

4.5 Household Consumers - Electricity Tariff Structure

The 10 selected households are all connected to the utility grid using Normal Low Voltage, according to their consumptions, with a contracted power under 41.4 kVA. In the Tariff Structure of the Electric Sector, ERSE differentiates final NLV customers in two counting cycles: daily and weekly. Clients who opt for the daily cycle have the same pricing schedule for all days of the year. Those who chose a weekly cycle have their pricing vary between week days, saturdays and sundays [66]. The hourly periods (peak, intermediate, off-peak and super off-peak), are differentiated via users' counting cycle and voltage level. The hourly period corresponds to the way electricity consumption is priced in the 24 hours of each and 7 days of each week. In Portugal, a NLV consumer can chose between tariff structures: daily, with one single period pricing during the day; bi-hourly, with 2 periods are differently priced during the day and tri-hourly, in which 3 periods are differently priced during the day (with super off-peak pricing equal to off-peak). For the purpose of this thesis, a tri-hourly weekly counting cycle was selected.

The Tariff Structure of the Electric Sector also specifies how electricity prices vary throughout each day of the year, seen in Table 4.5 for the chosen weekly cycle for domestic consumers. The tariff structure format varies with daylight savings which, in 2024, started at the 31th of March, during spring and ended in the 27th of October, mid autumn. Consequently, the summer-winter shift is reflected in this thesis' pricing schedules. Spring is composed of 27 days of winter tariff and the remaining of summer tariff. Autumn has 60 days of summer tariff and the remaining of winter tariff. As such, only the winter and summer seasons have a fixed tariff structure.

Table 4.5: Weekly cycle for NLV consumers in mainland Portugal in 2023, adapted from ERSE [66]

Legal winter time period		**Legal summer time period**	
From monday to friday		**From monday to friday**	
Peak:	09.30/12.00 h	Peak:	09.15/12.15 h
	18.30/21.00 h		
Intermediate:	07.00/09.30 h	Intermediate:	07.00/09.15 h
	12.00/18.30 h		12.15/24.00 h
	21.00/24.00 h		
Off-peak:	00.00/02.00 h	Off-peak:	00.00/02.00 h
	06.00/07.00 h		06.00/07.00 h
Super off-peak:	02.00/06.00 h	Super off-peak:	02.00/06.00 h
Saturday		**Saturday**	
Intermediate:	09.30/13.00 h	Intermediate:	09.00/14.00 h
	18.30/22.00 h		20.00/22.00 h
Off-peak:	00.00/02.00 h	Off-peak:	00.00/02.00 h
	06.00/09.30 h		06.00/09.00 h
	13.00/18.30 h		14.00/20.00 h
	22.00/24.00 h		22.00/24.00 h
Super off-peak:	02.00/06.00 h	Super off-peak:	02.00/06.00 h
Sunday		**Sunday**	
Off-peak:	00.00/02.00 h	Off-peak:	00.00/02.00 h
	06.00/24.00 h		06.00/24.00 h
Super off-peak:	02.00/06.00 h	Super off-peak:	02.00/06.00 h

4.6 Household Consumers - Electricity Price

The final electricity bill paid by a consumer is composed of three main categories: 1) network access tariffs (NAT), which are approved by ERSE, 2) energy and commercialization, defined by each energy supplier (or by ERSE in the regulated market) and 3) taxes and fees, approved by the Portuguese government.

4.6.1 1) Network Access Tariffs

Approved by ERSE, network access tariffs refer to an electricity component that includes the global use of the electric system and the transport and distribution network. It is a fixed term that depends on consumers' contracted power. As defined in 2024, 43% of NAT cost is related to CIEG [67]. As seen in chapter 2, individual self-consumers are exempt of paying 50% of CIEG and collective self-consumers do not pay CIEG. Consequently, individual self-consumers are exempt of paying 21.5% NAT and collective self-consumers are exempt of paying 43% NAT. The resulting NAT paid by each type of consumer in this thesis, including regular consumers (RC), is displayed in Table 4.6.

Table 4.6: Prices of the Network Access Tariffs applied to NLV consumers

	NAT[a]- RC[b]	NAT- ISC[c]	NAT- CSC[d]
Peak [€/kWh]	0.0472	0.0311	0.0151
Intermediate [€/kWh]	0.0195	0.0169	0.0144
Off-peak [€/kWh]	0.0062	0.0052	0.0042
Super off-peak [€/kWh]	0.0062	0.0052	0.0042

[a]NAT- Network access tariff.
[b]RC- Regular consumer.
[c]ISC- Individual self-consumer
[d]CSC- Collective self-consumer

4.6.2 2) Energy and Commercialization

EDP Comercial is one of Portugal's biggest energy suppliers in the liberalized market. Using EDP's online energy tariff tool, Table 4.7 was composed with the tri-hourly tariffs using a weekly cycle for all the contracted power values in this thesis [68]. Beside the different consumption-based tariffs, consumers must also pay a fixed daily cost based on their contracted power– the higher the contracted power, the higher fixed daily cost is paid by that consumer.

Depending on the type of consumption a household takes part in, CIEG reductions may apply to their energy cost per energy unit, meaning the electricity costs displayed in Table 4.7 only apply to a regular consumers, not to ISC or CSC. The final electricity prices per kWh can be seen in Table 4.8, in which individual self-consumers and collective self-consumers feature reduced prices, when compared to regular consumers.

Table 4.7: Pricing of a tri-hourly weekly cycle for regular NLV consumers, adapted from EDP [68]

	3.45 kVA	4.6 kVA	5.75 kVA	6.9 kVA	10.35 kVA
Fixed price [€/day]	0.2187	0.2623	0.2623	0.3501	0.4776
Peak [€/kWh]	0.3040	0.3040	0.3040	0.3060	0.3060
Intermediate [€/kWh]	0.1819	0.1819	0.1819	0.1831	0.1831
Off-peak [€/kWh]	0.1491	0.1491	0.1491	0.1501	0.1501
Super off-peak [€/kWh]	0.1491	0.1491	0.1491	0.1501	0.1501

Table 4.8: Pricing of a tri-hourly weekly cycle for each NLV consumer type, adapted from EDP [68]

		3.45—5.75 kVA			6.9—10.35 kVA		
		RC	ISC	CSC	RC	ISC	CSC
Energy price [€/kWh]	Peak	0.3040	0.2879	0.2719	0.3060	0.2899	0.2739
	Intermediate	0.1819	0.1793	0.1768	0.1831	0.1805	0.178
	Off-peak	0.1491	0.1481	0.1471	0.1501	0.1491	0.1481
	Super off-peak	0.1491	0.1481	0.1471	0.1501	0.1491	0.1481

4.6.3 3) Taxes and Fees

Adding to the NAT, energy and commercialization costs, Portuguese consumers need to pay 3 more components in their electricity tariff: audiovisual contribution (A.V. Contribution), a fee equal to €2.85 per month destined to finance public radio and television services; DGEG fee, equal to €0.07 per month for using and exploring electric installations and the special consumption tax, Imposto Especial de Consumo (IEC) which is charged at €0.001 per kWh of consumed electricity.

All the mentioned costs in chapter 4.6 are subject to taxation from the Portuguese government, through the value-added tax. Portuguese residents with a contracted power equal to, or higher than 10.35 kVA pay 23% of VAT over their electricity consumption. In 2022, the Portuguese government reduced the VAT rate for electricity consumers with a contracted power less than or equal to 6.9 kVA, from 23% to 13% [69]. In Portugal's "Famílias Primeiro" plan, electricity's VAT value was decided to be lowered to 6% in certain situations: households with 4 or less residents with a contracted power equal to or less than 6.9 kVA pay 6% of VAT for electricity purposes in their first 100 kWh consumed each month, with the remaining consumption being taxed at 23%; families of 5 or more people, for whom the limit of the 6% VAT is increased to 150 kWh. The purpose of this measure is to incentivize households to lower their consumption, so that energy can be taxed at lower costs [70, 71]. All the consumption-based VAT values paid by the households in the proposed model are listed in Table 4.9, where it is also possible to see the maximum hourly consumption value per house and the subsequent contracted power chosen for that house.

Table 4.9: Contracted power and VAT per house

	Max. Cons. [kWh]	Contracted Power [kVA]	VAT (Cons. <100kWh)	VAT (Cons. <150kWh)	VAT (Cons. >150kWh)
House 1	7.42	10.35	23%	23%	23%
House 2	6.52	6.90	6%	6%	23%
House 3	5.08	5.75	6%	23%	23%
House 4	5.15	5.75	6%	23%	23%
House 5	5.35	5.75	6%	6%	23%
House 6	5.99	6.90	6%	23%	23%
House 7	4.27	4.60	6%	23%	23%
House 8	2.16	3.45	6%	23%	23%
House 9	3.73	4.60	6%	23%	23%
House 10	5.31	5.75	6%	23%	23%

All the components of Portuguese NLV consumers' electricity bills and their respective VAT are displayed in Table 4.10, according to the contracted power of each household and to the latest regulations.

Table 4.10: Components of the electricity bill and their corresponding VAT in NLV

		VAT	
		1.15 kVA - 6.9 kVA	6.9 kVA - 10.35 kVA
Contracted Power	NAT fixed term	23%	23%
	Remaining fixed term	23%	23%
Energy Consumption	≤ 100 kWh[a]	6%	23%
	≤ 150 kWh[b]	6%	23%
	> 100 kWh[a]	23%	23%
	> 150 kWh[b]	23%	23%
A.V. Contribution		6%	6%
DGEG Fee		23%	23%
IEC		23%	23%

[a]For a household with 4 or less residents
[b]For a household with 5 or more residents

4.7 P2P and Surplus Selling Taxation

Portuguese law requires citizens to create receipts anytime a service is performed or goods are sold continuously to a private citizen or a company, which can be taxed. This also means that, in order to perform P2P energy sharing, the REC residents would have to have open activity in the Portuguese Finances. However, according to Article 53 of the Portuguese VAT code, if a citizen earns under €14 500 from their business activity, they are exempt of paying taxes on their earnings [72]. Due to the low transactional volume of electricity in this model, it is a safe assumption in this thesis that EC citizens are able to sell energy legally to the grid or the tertiary building, free of tax. This thesis has a heavy focus on social welfare, consequently it is assumed that residents trade their electricity surplus for free with fellow EC residents. Hence, neither the P2P nor the surplus selling processes are taxed.

4.8 Tertiary Building

The TB is represented by an isolated university campus building of Instituto Superior Técnico, in Lisbon, with the assumption that it is located near the households. By analyzing the TB electricity consumption values for 2019, the highest hourly value of consumption was 347.746 kWh, hence it fits the medium voltage level defined by ERSE, which ranges from 200 kVA to 10 MVA of contracted power [73]. The weekly cycle pricing schedule for MV consumers in Portugal is displayed in Table 4.11, for the legal winter and summer time periods.

Table 4.11: Weekly cycle for MV consumers in mainland Portugal, adapted from ERSE [66]

Legal winter time period		**Legal summer time period**	
From monday to friday		**From monday to friday**	
Peak:	17.00/22.00 h	Peak:	14.00/17.00 h
Intermediate:	00.00/00.30 h	Intermediate:	00.00/00.30 h
	07.30/17.00 h		07.30/14.00 h
	22.00/24.00 h		17.00/24.00 h
Off-peak:	00.30/02.00 h	Off-peak:	00.30/02.00 h
	06.00/07.30 h		06.00/07.30 h
Super off-peak:	02.00/06.00 h	Super off-peak:	02.00/06.00 h
Saturday		**Saturday**	
Intermediate:	10.30/12.30 h	Intermediate:	10.00/13.30 h
	17.30/22.30 h		19.30/23.00 h
Off-peak:	00.00/03.00 h	Off-peak:	00.00/03.30 h
	07.00/10.30 h		07.30/10.00 h
	12.30/17.30 h		13.30/19.30 h
	22.30/24.00 h		23.00/24.00 h
Super off-peak:	03.00/07.00 h	Super off-peak:	03.30/07.30 h
Sunday		**Sunday**	
Off-peak:	00.00/04.00 h	Off-peak:	00.00/04.00 h
	08.00/24.00 h		08.00/24.00 h
Super off-peak:	04.00/08.00 h	Super off-peak:	04.00/08.00 h

Regulation for the electric sector divides the tariffs paid by MV users according to trimesters: the first from January 1st to march 31st; the second from April 1st to June 30th; the third from July 1st to September 30th and the fourth from October 1st to December 31st [74].

Moreover, the Tariff Structure of the Electric Sector, ERSE defines the several components of the MV tariff divided per period as follows [66]:

- Contracted power price (€/kW.day) is a fixed price paid per day per kW of consumed electricity. For this thesis a contracted power value of 600 kW was selected, a very conservative value since it is almost double the highest hourly consumption value of the considered tertiary building, equal to 349.75 kW;

- Contracted power price in peak hours (€/kW.day) is a fixed price like the contracted power price, however it only applies to the peak hours of each day;

- Active energy price (€/kWh) is related directly to the consumption of electricity, as the price paid per consumed kW of energy;

- Reactive energy price (€/kvarh) is considered to be equal to zero, assuming that Instituto Superior Técnico compensates its reactive power.

The resulting electricity pricing for the TB in the proposed REC is displayed in Table 4.12, depending on the time day, on the period of the year and on each component of electricity. To each component an additional VAT of 23% is also paid to the Portuguese government.

Table 4.12: Pricing of the TB electricity tariff in MV, adapted from SUELETRICIDADE [75]

Electricity prices in MV		**Prices**
Contracted power		**[€/day]**
		0.1109
Contracted power in peak hours		**[€/kW.day]**
		0.2258
Active energy		**[€/kWh]**
Periods I, IV	Peak hours	0.1394
	Intermediate hours	0.1308
	Off-peak hours	0.1112
	Super off-peak hours	0.0991
Periods II, III	Peak hours	0.1292
	Intermediate hours	0.1250
	Off-peak hours	0.1085
	Super off-peak hours	0.1044
Reactive energy		**[€/kvarh]**
	Inductive	0.0015
	Capacitive	0.0011

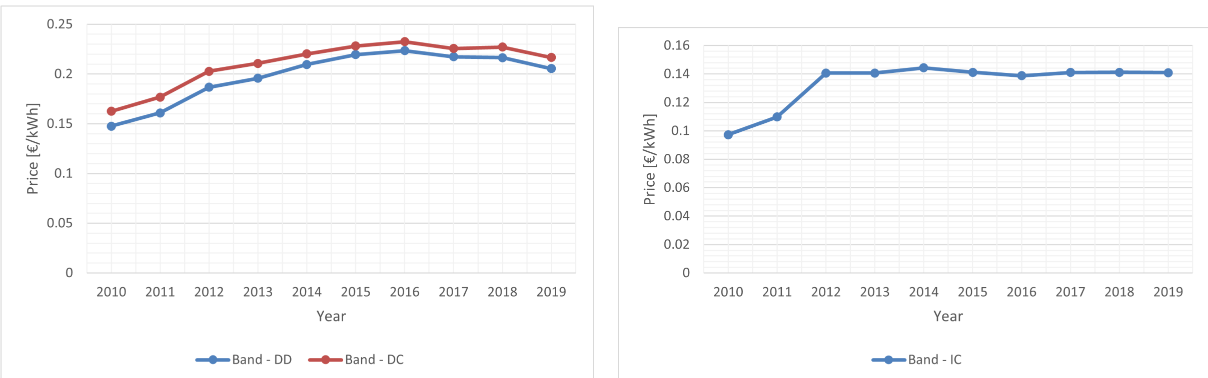
4.9 Parameter Evolution

4.9.1 Electricity Consumption

It is not expected that household-related consumption patterns will remain constant for the next decades. Portugal's National Electric System's Supply Security Monitoring Report (RMSA) allows to evaluate the supply security of the Portuguese electric system's needs. This report takes into account national and international energy policy guidelines and the importance of EV and plug-in hybrid vehicles to make considerations on the Portuguese electric system's outlook for the 2023-2040 period. The previous considerations result in 5 scenarios of demand evolution that were analyzed in the RMSA and the conclusion is that there is an increase in electricity consumption in all scenarios, with the average increase values for the 2023-2040 period ranging from +1.6% in the Ambition Superior Scenario to +0.6% in the Conservative Inferior Scenario. The Ambition Central Scenario's demand result of +1.4% was used in this thesis as the yearly electricity consumption increase factor for all NLV consumers since the evolution of electrification and EV and plug-in hybrid electric vehicles utilization as well as new working-from-home solutions will impact greatly the consumption profiles of the next decades [76]. The evolution of the tertiary building's consumption is not relevant since this thesis' focus is on residential consumption patterns, therefore no considerations on this parameter were made for the TB.

4.9.2 Electricity Price

The domestic and the industrial sectors' electricity price variations were analyzed for the time interval of 2010-2019, considered to be representative of a normal market behaviour period. Each consumer is characterized by DGEG with a consumption band for each year, depending on their consumption total. All the analyzed households have annual consumptions that put them in either consumption band DC or DD. The considered tertiary building has an annual consumption of little over 1 000 MWh (1 038 MWh), which means it belongs to the consumption band IC [77]. Hence, the electricity price evolution for each of these bands, according to DGEG, is represented in figure 4.3 [78].



(a) Weighted average electricity prices including all taxes for the DC and DD bands (€/kWh)

(b) Weighted average electricity prices including all taxes for the IC band (€/kWh)

Figure 4.3: Evolution of energy prices for the considered consumption bands in Portugal from 2010 to 2019, adapted from DGEG [78]

By analyzing figure 4.3 one can verify that electricity prices for consumption bands DC and DD experienced the same trend: an accentuated increase from 2010 to 2016, followed by a slower yearly decrease from 2016 to 2019. It is notable that despite the intense increase of the electricity price for the IC consumption band in 2010 to 2012, from 2012 onward electricity prices have remained almost constant. This means that no regular trend can be observed, therefore this thesis considers that electricity prices remain constant in the simulated 25 years.

4.10 Remuneration from the Grid

Portuguese self-consumers can opt for two models of remuneration when selling electricity to the grid: fixed remuneration that varies between 0.04 €and 0.06 €per provided kWh of electricity, or a varying remuneration value that depends on the Iberian Energy Market (MIBEL), which was chosen for this thesis [79].

Portuguese Decree-Law 15/2022 defines the acquisition of electricity by the last resort trader to producers with a connecting power of up to 1 MW, using Equation 4.1. As per equation 4.1, the remuneration for electricity supplied to the grid ($R_{n,g,m}$) by these producers in a certain month depends on the multiplication between the amount of electricity to be sold ($ES_{n,g,m}$) and the average market closing prices of the Portuguese area of the MIBEL adjusted to the production profile of each producer n in month m ($Pr_{MIBEL-PT,n,g,m}$). After the multiplication, it is subtracted the network access tariffs ($NAT_{n,g,m}$) and the final remuneration for electricity supplied to the grid is obtained [44, 80].

$$R_{n,g,m} = ES_{n,g,m} \times Pr_{MIBEL-PT,n,g,m} - NAT_{n,g,m} \tag{4.1}$$

Where:

$R_{n,g,m}$ = remuneration obtained by selling electricity for house n in a given month m and year g, in €
$ES_{n,g,m}$ = electricity sold to the grid by a given house n in month m and year g, in kWh
$Pr_{MIBEL-PT,n,g,m}$ = the average market closing prices of the Portuguese area in the MIBEL adjusted to house n in a given month m of year g, in €/kWh
$NAT_{n,g,m}$ = network access tariff costs associated with selling energy to the grid from house n, in month m of year g, in kWh .

The average market closing prices of the MIBEL ($Pr_{MIBEL-PT,n,g,m}$) adjusted to each producer's production profile are calculated as per Equation 4.2, in which the electricity sold to the grid ($ES_{n,g,m,h}$) for every hour of each month is multiplied by the closing price of the Portuguese area of the MIBEL in that same hour ($Pr_{MIBEL-PT,g,m,h}$). The sum of the previous multiplication for a complete month is then divided by the total electricity sold in that period ($E_{n,g,m}$) [81].

$$Pr_{MIBEL-PT,n,g,m} = \frac{\sum_h^H (ES_{n,g,m,h} \times Pr_{MIBEL-PT,g,m,h})}{ES_{n,g,m}} \tag{4.2}$$

Where:

$ES_{n,g,m,h}$ = electricity sold to the grid by a given house n in hour h in month m and year g, in kWh

$Pr_{MIBEL-PT,g,m,h}$ = the average market closing prices of the Portuguese area in the MIBEL in a given hour h of month m and year g, in €/kWh .

Selling electricity to the grid implies that producers must pay network access tariffs over the surplus energy that is sold. The network access tariffs payed by prosumers (as seen in chapter 4.6) depend on the the household and on the type of investment (whether it is a regular consumer, an individual self-consumer, or a collective self-consumer), and can be calculated with Equation 4.3, in which the total NAT cost ($NAT_{n,g,m}$), per month m in year g, for a consumer n depends on how much electricity was sold during each hour, as network access tariffs vary from peak to intermediate and off-peak hours.

$$NAT_{n,g,m} = \sum_{h}^{H}(ES_{n,g,m,h} \times NAT_{n,g,m,h}) \tag{4.3}$$

Where:

$NAT_{n,g,m,h}$ = network access tariff of house n, in hour h of month m in year g, in €/kWh.

The average monthly price of electricity purchased by Portugal in the MIBEL is displayed in yellow in Figure 4.4. In this Figure, the MIBEL electricity price adjusted according to the production profile of house 1 can be seen in green. It is from this value that the monthly network access tariff costs are deducted and the monthly remuneration for which these prosumers can sell each kWh of electricity surplus for in each month, is seen in blue.

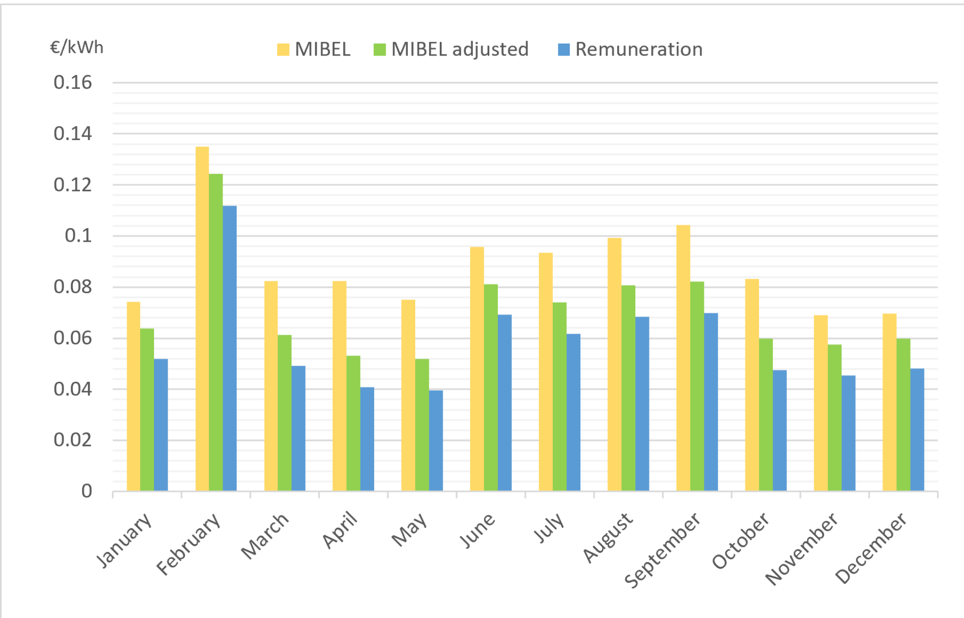


Figure 4.4: Electricity injection remuneration, according to the MIBEL, adjusted to house 1

4.11 Average Electricity Price Analysis

The average daily electricity prices for one year of investment, displayed in Figure 4.5, allow to conclude that regular NLV consumers pay more per kWh of grid-purchased energy than self-consumers, within which collective self consumers (case study scenarios EC1, EC2 and EC3) pay less per kWh of electricity than individual self-consumers (case study scenarios I1, I2 and I3). This cost-reduction mechanism provided by the Portuguese government, adding with the previously analysed grid electricity procurement reductions provided by the proposed community model, have significant effects on the final electricity bill paid by consumers and, consequently, on the value of joining an energy community. It is also visible in this figure that the electricity price paid by the tertiary building in medium voltage (represented in blue) is lower than the electricity price paid by any of the represented consumers, however it is always higher than the average remuneration provided by the grid for electricity injection (seen in light green). This means that the collective self-consumption scenarios always find it more profitable to sell electricity for an intermediate value (represented in black) to the TB than to sell electricity to the grid.

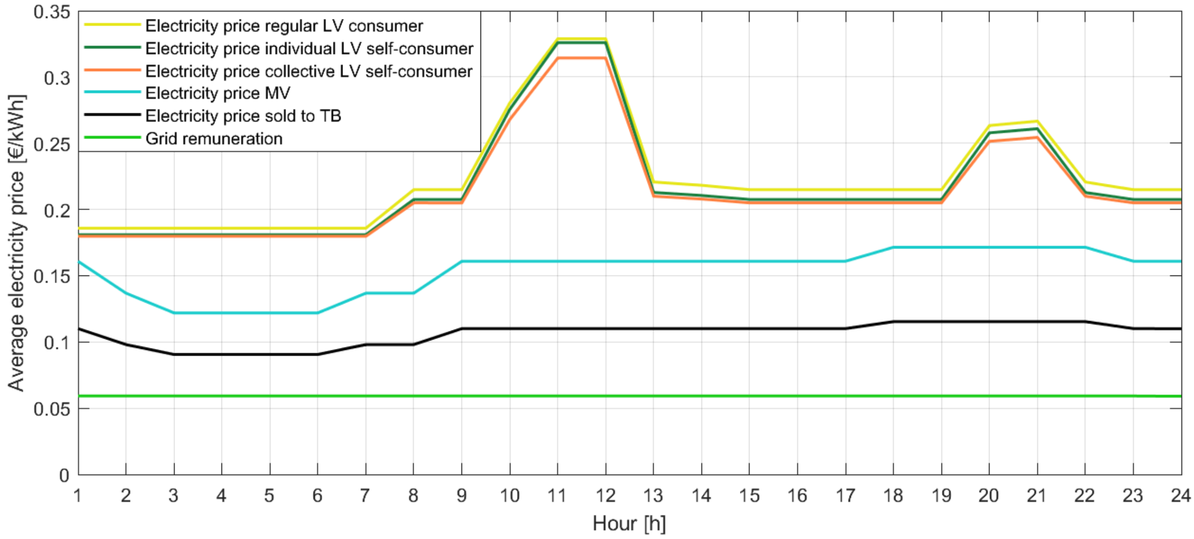


Figure 4.5: Electricity prices for house 1 and the tertiary building on a week-day

Chapter 5

Results and Discussion

The objective of this chapter is to analyse the efficacy of the proposed collective self-consumption model by comparing several collective and individual self-consumption case studies with each other and with a no-investment scenario. Results are presented and discussed for techno-economic and environmental metrics in detail for a selected household and in a less extensive fashion for the whole community. All presented results in this chapter refer to the first year of the investment, unless otherwise stipulated.

5.1 House 1 Analysis

5.1.1 Energy Flows— Representative Days

This section presents the economic and environmental results for house 1, as it is the household with the highest number of residents and with the highest electricity consumption values. As described in chapter 3, individual scenarios can only trade energy with individually-owned ESS and with the grid. Community case study scenarios, on the other hand, can trade energy with a community-owned ESS, with the grid, with other residents and with a tertiary building. All possible energy trades the household can make are represented for both individual and community case study scenarios in Figure 5.1. The definitions for these energy trades are as follows:

- Grid in: electricity received into the house from the grid.
- Grid out: electricity sold from house to the grid.
- P2P in: electricity received into the house via peer-to-peer trades.
- P2P out: electricity sent from the house via peer-to-peer trades.
- TB out: electricity sold from the house to the tertiary building.
- ESS in: electricity discharged from the battery and sent to the house.
- ESS out: electricity sent from the house to charge the battery.

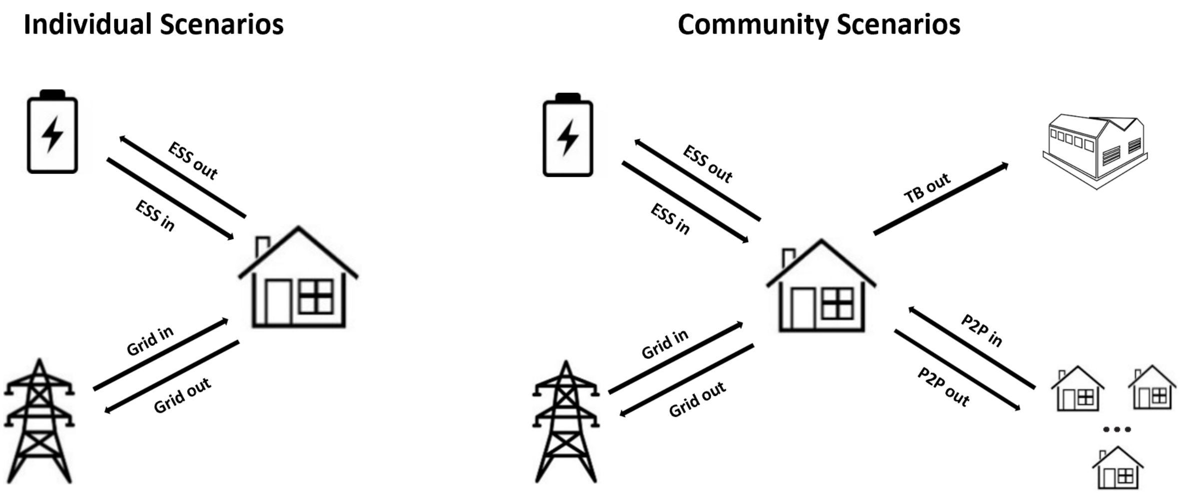


Figure 5.1: Representation of the energy trades in the created case studies

To observe the energy transactions that house 1 has using different case studies, a 24 hour period was selected. However, during the year, PV generation varies immensely: it is higher during the Northern Hemisphere's summer and lower in this Hemisphere's winter season. Consequently, two distinct representative days were selected to observe the energy transactions that house 1 has in 24 hours with different case studies: a day in the winter season (22nd of December, the winter solstice when astronomical winter begins) and another day in the summer season (21st of June, the summer solstice when the astronomical summer begins). The only variable in this comparison between case studies is the PV modules' generation, since the consumption is equal so as to provide a better comparison between case studies.

It was chosen to represent only the cases with no storage (I1 and EC1) and with the highest value of battery capacity (I3 and EC3) for this analysis, since case studies I2 and EC2 were created merely to show the variation of results when using different capacities of energy storage.

In Figure 5.2, one can observe the power transactions of the selected household for a representative winter day using individual case study I1 and the same scenario, using summer generation values in Figure 5.3. Since individual scenario 1 only provides consumers with PV generation (in blue) and the ability to inject their generation surplus into the grid (in yellow), it is notable that, although PV generation lowers the energy purchased from the grid (in orange), consumption values (in purple) still create a heavy dependency on the grid, especially in the winter day represented in Figure 5.2. In the winter day, PV modules only start producing electricity from 9 in the morning until 18 in the evening, with the highest value of production equal to 3 kWh, compared to the summer day which has PV production from 6 in the morning to 21 in the night, with a highest production of about 4 kWh. This means that the summer day has less grid dependency and more electricity can be sold for a profit than in the selected winter day, for the same consumption value.

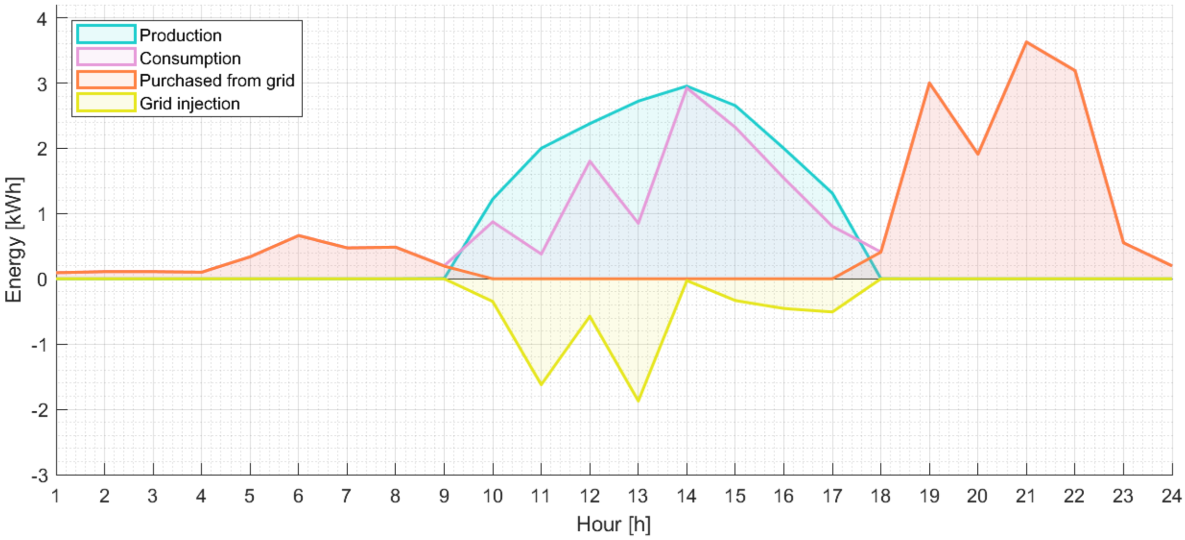


Figure 5.2: Power flows of house 1 during a representative winter day, using scenario I1

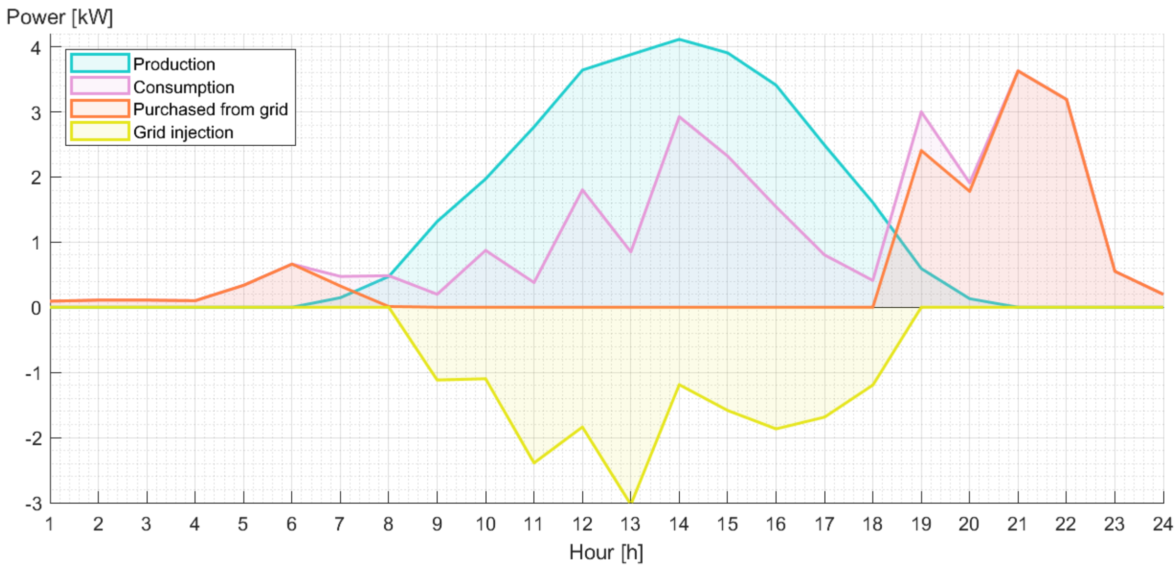


Figure 5.3: Power flows of house 1 during a representative summer day, using scenario I1

In Figure 5.4 the representative winter day is displayed using individual self-consumption scenario I3, in which prosumers have individual 4 kWh batteries that can store generated energy for later use (whose flows are seen in green). During the hours when PV generation is highest, the batteries are charged (shown as a negative value, as electricity leaves the house) and when the sun is setting, as demand increases, the battery is used to cover for some of the demand (shown as a positive value, as electricity is going to the house). The effect of using battery storage is even more noticeable in the summer day shown in Figure 5.5, which features further decreased values of power purchased from the grid.

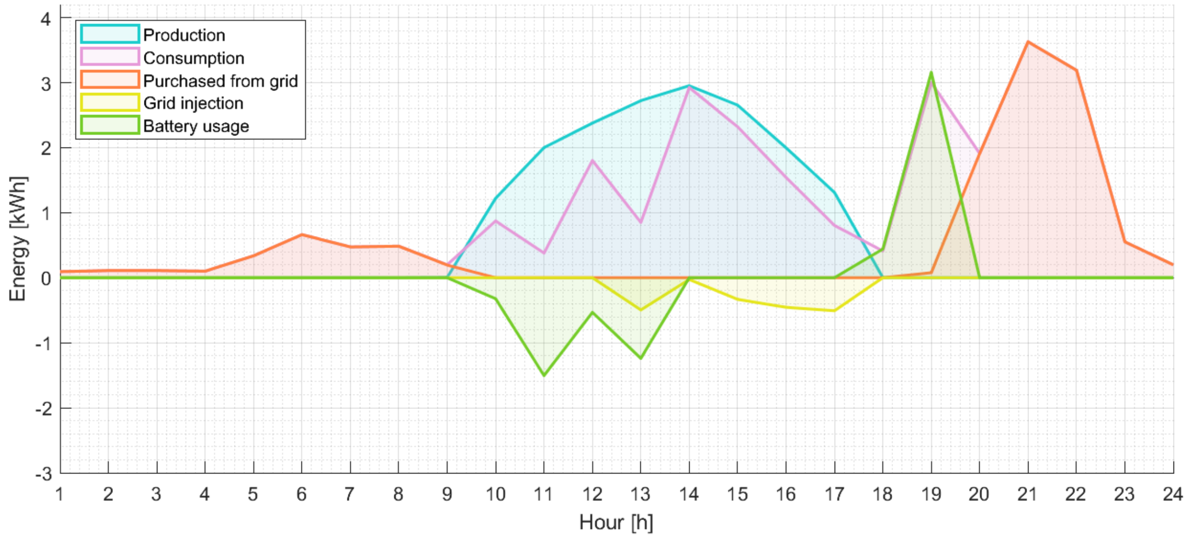


Figure 5.4: Power flows of house 1 during a representative winter day, using scenario I3

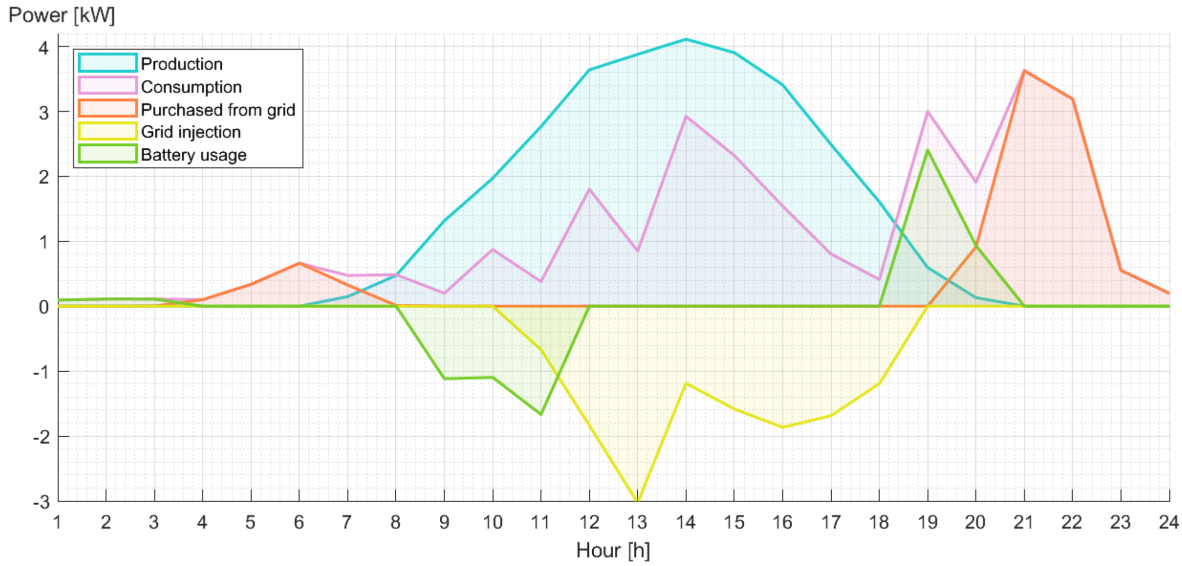


Figure 5.5: Power flows of house 1 during a representative summer day, using scenario I3

The proposed collective self-consumption model EC1 introduces P2P energy trading (in black) and the possibility to sell energy to a TB, meaning electricity surplus is not necessarily sold to the grid. In the consumption scenario shown in Figure 5.6 and Figure 5.7 for the winter and the summer day, respectively, giving electricity to fellow residents (represented as negative P2P energy values, as electricity leaves the house) lowers the amount of energy that is sold for profit. However, the house also receives electricity from fellow residents (represented as positive P2P energy values, as electricity enters the house), which lowers the final amount that needs to be purchased from the grid.

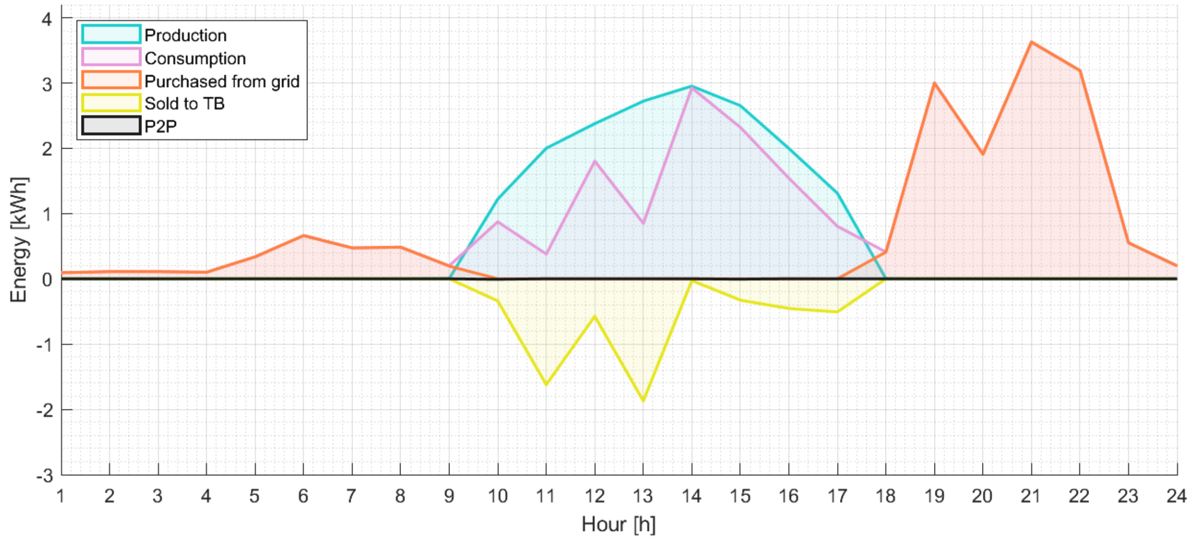


Figure 5.6: Power flows of house 1 during a representative winter day, using scenario EC1

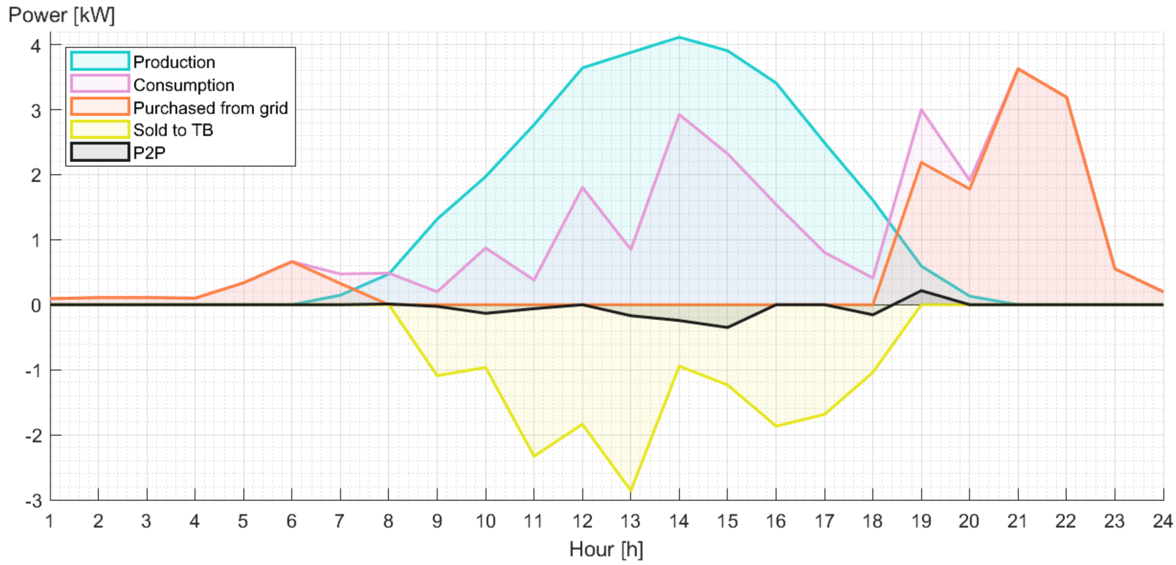


Figure 5.7: Power flows of house 1 during a representative summer day, using scenario EC1

The combination of P2P energy trading and community-owned battery usage (represented in green) in the developed collective-consumption scenario EC3 diminishes the energy dependency on the utility grid, even in the winter day represented in Figure 5.8, with far more significant effects in the selected summer day, shown in Figure 5.9, where it is visible that house 1 only needs to request power from the grid after 22 at night as the community-owned energy storage covers the highest demand period. In this day there is also a very significant value of electricity that is sold for profit.

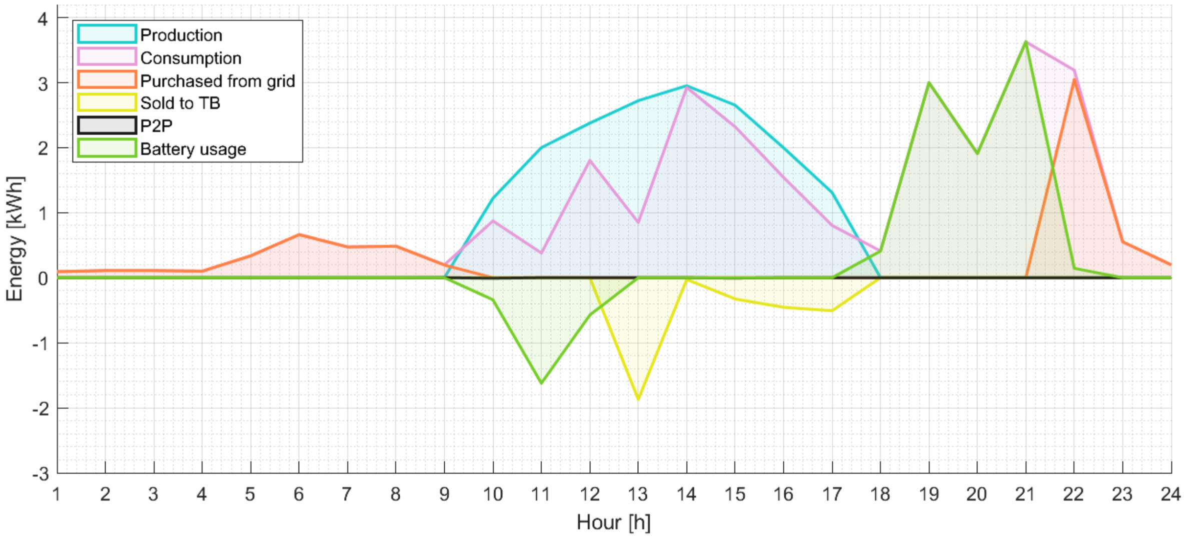


Figure 5.8: Power flows of house 1 during a representative winter day, using scenario EC3

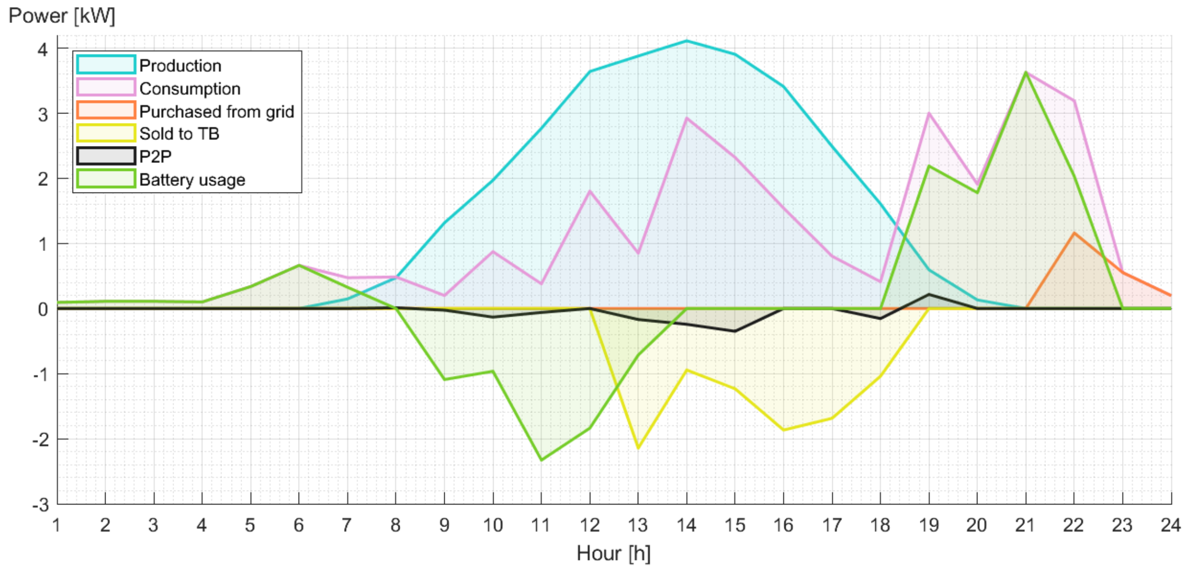


Figure 5.9: Power flows of house 1 during a representative summer day, using scenario EC3

5.1.2 Electricity Balance

The results for the final electricity balance are displayed in Figure 5.10 and their numeric values are seen in Table A.1 in Annex B.

Not investing in any self-consumption solutions means that these house's residents need to purchase all of their demand from the grid, a total of 8 161 kWh. Individual investment case study scenario I1 introduces the usage of PV energy generation, which reduces the total amount of purchased electricity from the grid to under 4 000 kWh, a reduction of 51%. Investment scenario I1 also allows prosumers to sell their surplus to the grid. Over the first year, this household's residents are able to sell 4 557 kWh of electricity, while being remunerated for this service, according to the methodology explained in section 4.10. If self-consumption prosumers are interested in purchasing energy storage solutions, scenarios I2 and I3 feature 2 kWh and 4 kWh lithium-ion batteries. These solutions, as seen in Figure 5.10, allow to further decrease the energy dependency on the grid, seeing that in scenario I3 investors only need to purchase 2 927 kWh of electricity from the grid, about 36% of their total electricity demand over the first year. By storing a total of 1 452 kWh of their energy for later use (bearing in mind that not all of this electricity can be used, since the ESS does not have an efficiency of 100%, as per section 4.2), scenario I3 residents not only lower their grid consumption, but also their surplus amount, a value that decreases to 3 075 kWh.

The proposed energy community model allows prosumers to trade energy with fellow residents and introduces a tertiary building as a possible buyer for surplus energy. Joining the proposed community without any energy storage solution results in a grid dependency inferior to that of an individual self-consumer with a 2 kWh ESS in scenario I2, as per Figure 5.10 and Table A.1. The analysis of Figure 5.10 also allows to verify that, for these consumers, the TB proved to be a more profitable option than the main grid when selling electricity since all 3 905 kWh of surplus was sold to the TB and no electricity was sold to the grid. An inferior value of electricity is sold in scenario EC1 when compared to scenario I1, which is the value of electricity that this household donated to fellow residents in the P2P electricity trading process, a total of 652 kWh. However, this does not necessarily mean that this scenario presents lower revenues for investors, as the TB provides a higher buying price for electricity than the grid does. Grid-consumption values using EC1 are lower than when investing in I2 and I1, since this house receives 408 kWh of electricity from the P2P process. Collective self-consumption scenarios EC2 and EC3 feature the usage of 20 kWh or 40 kWh of community-owned energy storage, respectively. For these consumers, 20 kWh of energy storage in EC2 results in a grid dependency 68% lower than not having invested at all, a value that is even higher than when using a 4 kWh individual battery in scenario I3. As for the individual scenarios, using battery storage lowers dependency on the grid by sacrificing the value of electricity that can be sold. Similarly, in EC1, house 1 prosumers sell 3 905 kWh of their electricity, however in EC3 they only sell 1 983 kWh of electricity, since the remaining energy is used to charge the ESS, about 2 000 kWh. Having battery operation means that these residents can also rely on it to cover for their electricity demand. This particular household, in scenario EC3, charged the ESS with 1 923 kWh of electricity and discharged it for 1 961 kWh of their own consumption during high consumption and high-cost hours, meaning the final grid demand of 1 624 kWh (80% lower than in a no-investment scenario) has been shifted to non-peak hours in a considerable amount. This household donated 244 kWh more of electricity to other households than these have donated back. However, this house also used the battery to get more electricity than it charged the ESS with, therefore balancing this prosumers' contribution in the electricity outlook of the community.

The visual and numeric electricity balance of all other households can be seen in Appendix A.

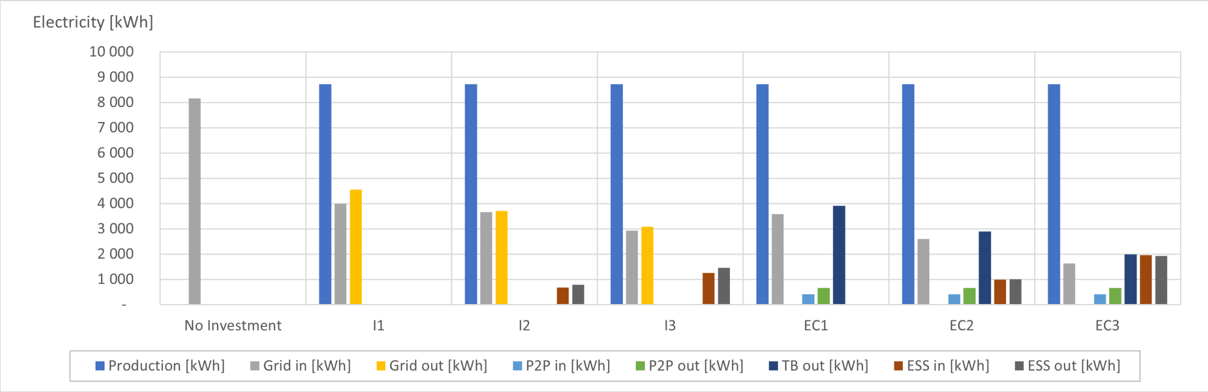


Figure 5.10: Representation of the electricity balance for house 1

5.1.3 Economic Analysis

The economic results for house 1 prosumers with the 6 created case study scenarios are displayed in Table 5.1, in which the cells highlighted in yellow represent the worst value of its column and the cells highlighted in green represent the best value of its column. As in the energy balance analysis conducted in section 5.1.1, this section will not focus on case studies I2 or EC2 since, as made visible in Table 5.1, these case study scenarios are never the best or worst of any evaluation metrics.

The created individual and collective self-consumption case study scenarios were developed in such a way that investors can quickly compare case study I1 to EC1, I2 to EC2 and I3 to EC3, as they require equal initial capital expenditures. Investing in scenarios with no energy storage both cost consumers a total of 6 419 €, which comprises the cost of PV modules and inverters. These solutions are the cheapest to maintain and operate, with yearly O&M costs of 116 €. If, however, consumers opt to have battery storage, the investment rises to 9 264 €in scenarios I2 and EC2 or to 12 109 €for I3 and EC3. Purchasing batteries not only requires almost 100% more initial investment, it also increases a consumer's yearly expenses to 180 €(EC2) or 244 €(EC3).

When analysing the revenues generated, not having energy storage provides house 1 prosumers with the highest results, the best of which are attained using EC1, in which 432 €are obtained via energy surplus selling (entirely to the TB). This value is higher than case study I1, in which only 272 €are obtained from selling energy to the grid, even though scenario EC1 sells 652 kWh less of electricity than I1, as this value is donated to other residents in the P2P process, as seen in section 5.1.1. The lowest revenues are obtained when consumers opt to have energy storage, the worst of which is obtained using I3, with 184 €generated from selling surplus for a FiT to the grid.

Individual self-consumption case study I1 features the lowest cost savings of all created scenarios, as it only comprises PV electricity generation, with no energy storage, or any other solutions to manage electricity, with a still significant reduction of 1165 €in the final electricity bill, when compared to not having invested at all. Using battery storage in scenario I3 increases the electricity bill cost savings in 218 €, however the best results are achieved when using community scenario EC3, in which house 1 consumers can reduce the electricity bill in the first year by 1670 €, 287 €more than in scenario I3, as even though in EC3 they charge the ESS with almost 500 kWh more than in I1, these consumers discharge the ESS with more energy than I3 and receive a further 408 kWh from other residents, thus allowing for such high cost reductions.

Table 5.1: Economic indicators, house 1

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	6 419	116	272	1 165
I2	9 264	180	222	1 219
I3	12 109	244	184	1 383
EC1	6 419	116	432	1 264
EC2	9 264	180	321	1 460
EC3	12 109	244	219	1 670

As per Table 5.2, the lowest overall NPV is obtained for individual self-consumers with 4 kWh batteries in I3, with a net present value of 2 614 €. Individual self-consumers that are looking for the best NPV should only purchase PV modules, using I1, which has a NPV of 10 769 €. For collective self-consumption scenarios, higher values of revenues and cost savings (when compared to individual self-consumers) result in attractive NPV values, the lowest of which is 7 379 €for EC3 and the highest NPV of all analysed scenarios is 14 806 €when using EC1, since revenues are the highest and even though EC2 and EC3 have higher cost savings, their high equipment procurement costs still hinder battery-operated case studies from having a better NPV in this investment.

Scenarios with ESS boast higher values of cost savings, although the high costs and low energy-selling revenues these solutions attain reflect heavily on the NPV and IRR, which are higher without energy storage. The best IRR is attained in EC3, with a value of 24.2% and using I3 provides the worst IRR of 7.3%, which is the closest to the investment's discount rate of 5% (at which the NPV is null).

The lowest amount of time it takes for prosumers to get their investment back is little over 4 years, when they invest in EC1. The investment that requires prosumers to wait the most in order for the initial capital expenditures to be fully recovered is I3, taking almost 9 and a half years. In a similar fashion to the NPV analysis, the higher investment, operation and maintenance costs that battery operation requires deeply compromise how fast investors can recover their money.

Table 5.2: Economic indexes, house 1

	NPV [€]	PBP [years]	IRR [%]
I1	10 769	5.1	19.4
I2	5 956	7.6	11.3
I3	2 614	9.4	7.3
EC1	14 806	4.1	24.2
EC2	11 018	5.8	16
EC3	7 379	7.3	11.2

5.1.4 Environmental Analysis

The last evaluation metric is environmental, as displayed in Table 5.3, as it compares each scenario's self sufficiency and CO_2 emissions to a no-investment scenario. The least self-sufficient solution is I1, in which there is a reduction of electricity demand from the grid of 51% and using the highest value of individual self-consumption battery capacity can increase the SS to 64%. Comparing EC1 and I1, EC1 has a SS value of 56%, meaning that the proposed P2P mechanism increases the self-sufficiency of this household in 5%. If, however, prosumers want to achieve the highest self-sufficiency possible, scenario EC3 provides them with an 80% reduction in electricity demand from the grid.

The CO_2 emission reduction of each scenario is complementary to the self-sufficiency: if a household can rely more on its own power generation rather than on the utility grid, it has a high SS result and lower CO_2 emissions. Scenario I1 has a reduction of 51% in grid dependency, therefore CO_2 emissions decrease by 49%. Using battery storage in I3 achieves a 64% reduction in CO_2 emissions. Collective self-consumers with no energy storage in EC1 have slightly higher grid-dependency than I3 and therefore higher CO_2 emissions. However, case study EC3 only uses the grid to purchase 20% of its total demand, had it not invested. This results in CO_2 emissions reductions of 80%, compared to a no-investment scenario.

Table 5.3: Environmental outcomes, house 1

	Self-sufficiency [%]	CO2 Emissions [%]
I1	51	49
I2	55	45
I3	64	36
EC1	56	44
EC2	68	32
EC3	80	20

The economic and environmental results for all the houses of the energy community can be seen in Appendix B.

5.2 Community Analysis

5.2.1 P2P Energy Trading

One key advantage of partaking in the proposed energy community model is that energy is traded within residents for free. As a consequence of the sequence of the energy balancing mechanisms in this methodology, best seen in the flowchart represented in Figure 3.3, the results of traded energy in the P2P process are equal for all community scenarios (EC1, EC2 and EC3)— it is not relevant if the community has a battery for P2P, since it occurs before the battery is considered thus, adding energy storage in EC2 and EC3 only affects how much energy is required from the grid, or sold, not how much energy is traded within the communities.

The results of the peer-to-peer trading are displayed in Figure 5.11, in which it is possible to see that most residents have differences between how much electricity they donate (P2P out) and how much electricity they receive (P2P in). House 2, for example, donates 86% more electricity than it receives and house 10 receives 76% more electricity than it donates. These differences are created by the disparities in household consumption profiles, which are tackled in the designed P2P process in which households with the most demand receive more energy surplus and the houses with the highest values of surplus donate the most electricity.

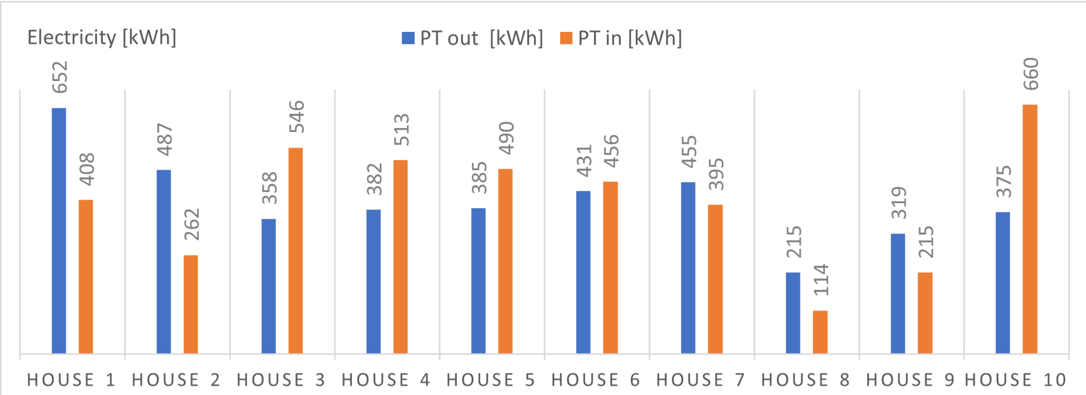


Figure 5.11: Electricity balance of the P2P process for all households

5.2.2 Battery Operation

The electricity that is used from each house to charge each case study's battery is displayed in Figure 5.12. In the collective self-consumption scenarios, most households are not able to store as much energy as in the self-consumption scenarios, meaning either these residents donated significant values of electricity in the P2P process, or the battery was already full.

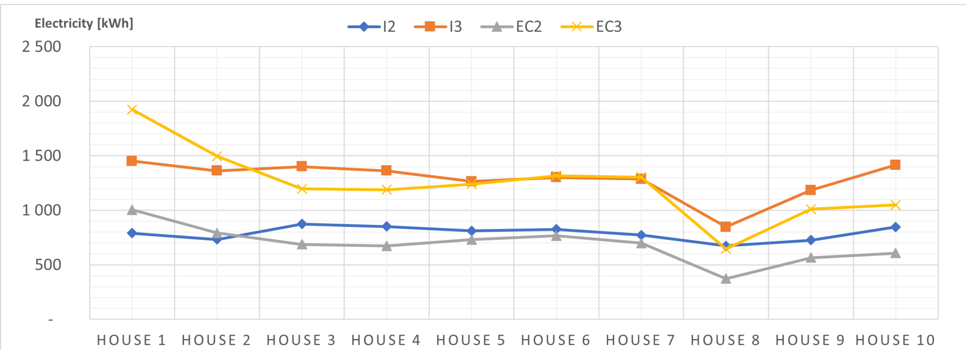


Figure 5.12: Electricity used to charge each scenario's battery, from each house

In Figure 5.13, in which the electricity that is discharged from the batteries to meet each house's demand for all case studies is shown. The same trend of Figure 5.12 is observed: most households receive more energy from the individual self-consumption scenarios than from the collective self-consumption scenarios. Once more, the P2P process in EC scenarios manages electricity before the ESS is considered, hence the higher ESS-usage values for individual prosumers.

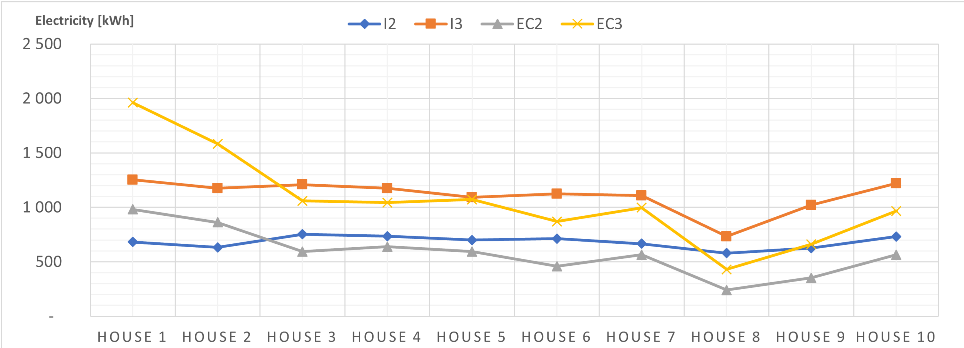


Figure 5.13: Electricity discharged from the batteries and sent to each house, for each scenario

To evaluate the efficacy of the proposed energy storage systems, their status of operation are also analysed in this section. Batteries can either be empty, meaning they are at $SoC_{min} = 5\%$ of their total capacity and the battery cannot be further discharged; they can be full, meaning their state of charge is at $SoC_{max} = 95\%$ and they cannot be further charged, according to the selected DoD of 90%, and finally batteries' SoC can be between SoC_{min} and SoC_{max}, meaning they are capable of both charging or discharging at that instant.

The percentage of time that each self-consumer's batteries are at each SoC (maximum, minimum, or in-between) of case study I2 is presented in Figure 5.14, where it is possible to see that most residents have their 2 kWh batteries empty for over 50% of the time. These batteries are full around 15% to 20% of the time for most households. The high percentage of time in which batteries are empty is a reflection of high demand compared to the ESS capacity when PV generation is over, or much lower, in the evening. Only for house 8, the one with the lowest electricity demand, does the battery have significantly better results, being empty only around 30% of the time and full for about 15% of the year, which means that a 2 kWh battery capacity is only a good fit for this low consumption household. Prosumers with the highest electricity demands are the ones that have the battery at SoC_{min} or SoC_{max} the most, with some consumers having the battery empty for 60% of the time and full for about 20% of the time, meaning this capacity is not a good fit for them.

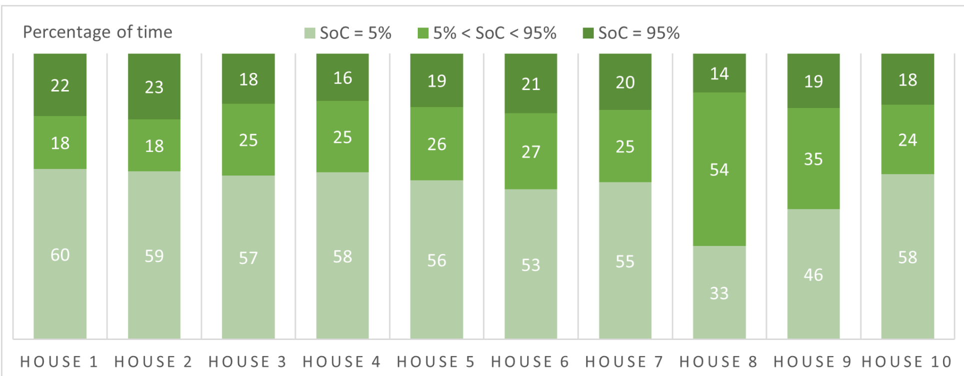


Figure 5.14: Percentage of time in which each house's battery was at each state of charge in I2

The percentage of time that each scenario I3 self-consumer's 4 kWh batteries are at each SoC is presented in Figure 5.15. This scenario features households' batteries empty for a significant amount of time, between 40% and 50% for most consumers. The percentage of time that the batteries are full is reduced, when compared to I2, as they are mostly full between 10% an 15% of the time. This means that, for a battery capacity increase of 100% from the capacity in case study I2, there is an improvement in how the batteries aid the houses in lowering their dependency on the grid for their electricity consumption purposes, especially in house 8 and house 9, for which the 4 kWh battery is a very good fit, with an operation status between the minimum and maximum state of charge of around 70% for house 8 and 60% for house 9. Houses with high consumption have a lower dependency on the grid, however these still require a substantial amount of energy to meet their consumption demands.

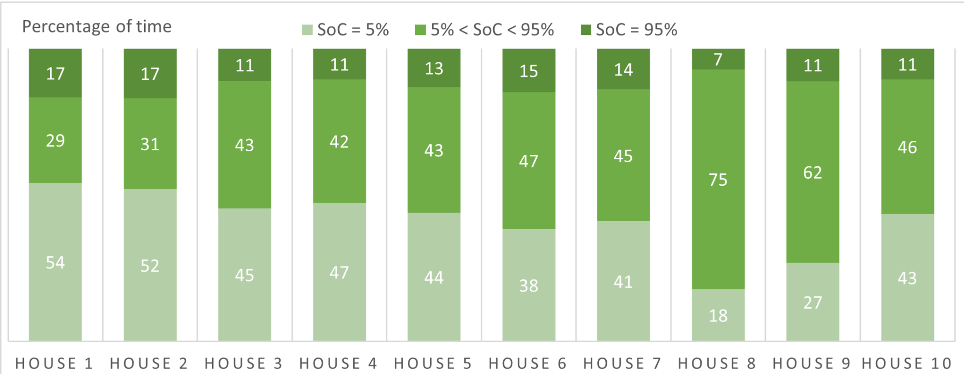


Figure 5.15: Percentage of time in which each house's battery was at each state of charge in I3

The results for the percentage of time that EC2 and EC3 batteries were at each SoC can be viewed in Figure 5.16. As for the individual batteries in scenario I2, the battery in EC2 is empty for almost 60% of the time and full for around 17% of this year, meaning this ESS is not a great fit for the total EC consumption. The 40 kWh community-owned battery in EC3 results in an empty SoC under 50% of the time and a full SoC less than 10% of the year. Although the higher capacity battery in EC3 fairs better than the 20 kWh one in EC2, it is empty for a large percentage of time, since some of the consumers have very high consumption values when there is no PV generation, either in the start or at the end of the day.

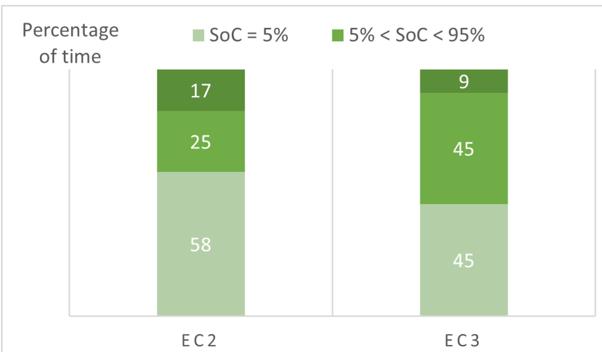


Figure 5.16: Percentage of time in which the batteries were at each state of charge in EC2 and EC3

5.2.3 Self-Sufficiency

The grid demand results for each house are displayed in Figure 5.17, in which it is possible to see that the created REC model EC3 decreases electricity demand to a great extent more than any other investment scenario for all households except house 8 and 9, which have the lowest considered consumption profiles (whose lowest electricity demand are achieved in with I3).

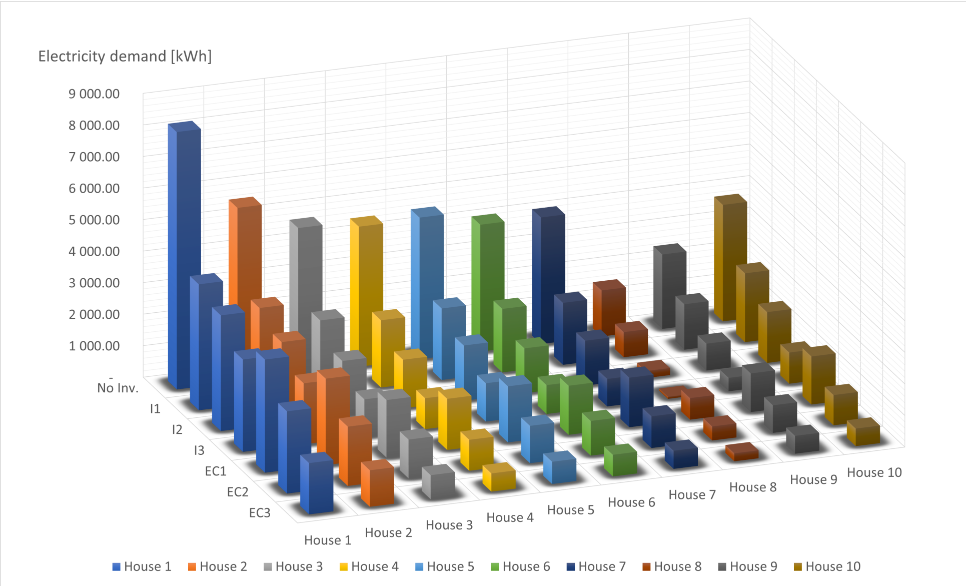


Figure 5.17: Grid demand values for all houses, per case study

The self-sufficiency of each household is obtained comparing the grid demand values to a no-investment scenario. The SS results in each scenario are visible in Figure 5.18, which has a direct correlation with Figure 5.17: low values in grid demand are associated with high values of SS. In a general way, all households achieve the highest self-sufficiency values when partaking in a case study EC3 and all houses attain the lowest SS when investing in scenario I1. This is result of I1 not using any energy management solution, only PV generation, and EC3 using P2P sharing and battery storage to improve how the same total PV generation is managed.

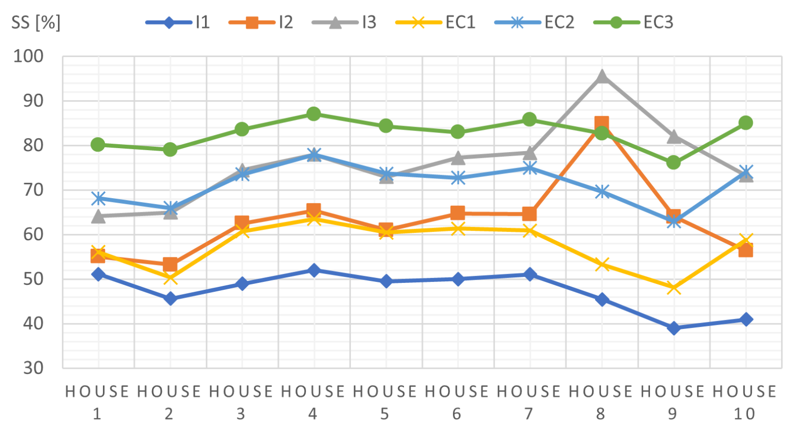


Figure 5.18: Self-sufficiency of each household, for each case study scenario

5.2.4 CO_2 Emissions

The total amount of CO_2 emitted by each house, per case study, is displayed in Figure 5.19, from which it is possible to conclude that the solution that reduces the community's carbon footprint the most is EC3, since it features a 40 kWh lithium-ion battery and the P2P mechanism, which make it possible to manage locally the PV generation and reduce the usage of the grid the most.

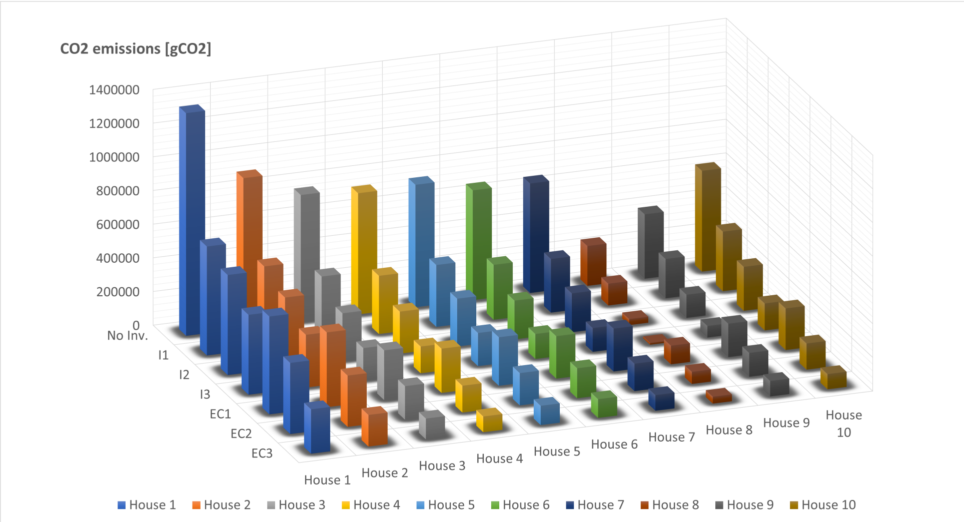


Figure 5.19: CO_2 emissions of each house, for each case study scenario

The higher the self-sufficiency of a household in a certain case study, the less CO_2 emissions it is likely to have. This inverse relation is seen in Figure 5.20, in which the results for the CO_2 emissions are graphically displayed. There are two case studies which result in the most appreciative carbon emission reductions for all houses: I3 and EC3, the case studies with the highest value of battery storage capacities. The best overall scenario is the proposed community, using a 40 kWh battery (EC3), which decreases CO_2 emissions from 76% to 87%, depending on the household.

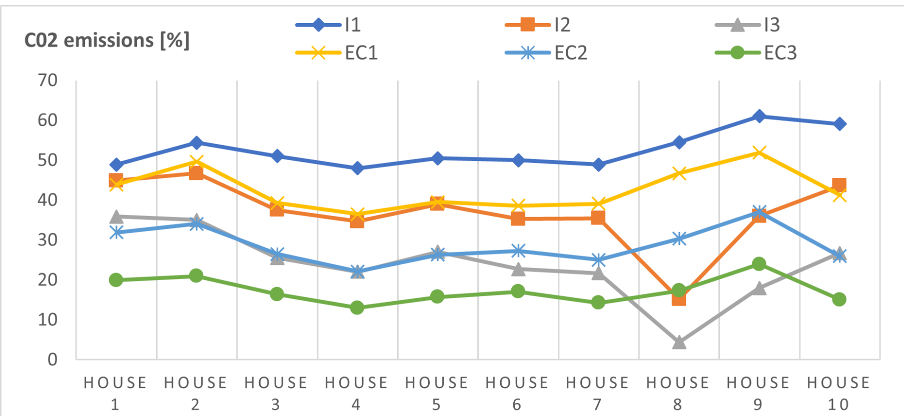


Figure 5.20: CO_2 emissions of each household compared to not investing, for each case study scenario

5.2.5 Sold Energy Surplus

Individual self-consumers can only sell their electricity surplus to the grid for a FiT remuneration. The values of electricity sold to the grid by prosumers in individual self-consumption scenarios and the income received by each house, for all 10 considered houses, are presented in Table 5.4. The scenario in which the most electricity is sold to the grid is I1, since this case study only features the usage of PV generation for self-consumption, which means that surplus energy cannot be stored or otherwise managed, it must be sold to the grid. By adding battery storage in scenarios I2 and I3, the energy that is stored for later usage cannot be sold, therefore when using the individual 4 kWh batteries in I3, all consumers face an income decrease, although consumers with lesser generation are the ones with the biggest variation— about 32% less income is generated for house 1 in scenario I3, comparing to I1, however house 8 receives 68% less income in I3, compared to not using energy storage in I1.

Table 5.4: Electricity sold to the grid for individual consumers and subsequent income

	Energy sold to grid [kWh]			Income [€]		
House	**I1**	**I2**	**I3**	**I1**	**I2**	**I3**
House 1	4 557	3 698	3 075	272	222	184
House 2	3 302	2 548	1 920	195	152	115
House 3	2 578	1 688	1 165	153	102	72
House 4	2 539	1 670	1 163	153	101	71
House 5	2 625	1 797	1 346	160	112	84
House 6	2 835	1 992	1 519	172	122	94
House 7	2 797	2 006	1 496	169	121	91
House 8	1 275	595	422	76	35	24
House 9	1 989	1 250	795	118	74	46
House 10	2 367	1 503	939	140	89	55
Total	26 863	18 748	13 840	1 608	1 129	836

Collective self-consumers never sell electricity to the grid, since the TB is always a more profitable option than selling energy to the grid for a FiT. The total values of electricity sold to the TB, for community scenarios, are displayed in Table 5.5. By comparing Table 5.5 to Table 5.4 it is possible to conclude that community consumers have less electricity to sell, due to the P2P balancing process. In a similar fashion to the individual self-consumers, the community residents also see their incomes reduced when using battery storage, however the discrepancy between the income reduction of houses with the higher generation profiles and the ones with the lowest generation is lower— house 1 receives 49% less income in EC3 than in EC1, nevertheless house 8 has a decrease in income from electricity surplus selling of 61% as a consequence of the P2P mechanism, that redistributes electricity within the community and balances energy mismatches as much as possible.

Even though the collective EC scenarios sell less electricity than the individual self-consumers (since they donate energy to fellow prosumers), EC residents still make more revenue than individual scenarios, since the average remuneration for the REC electricity given by the TB is 0.11 €/kWh and the average FiT for which individual self-consumers sell their electricity is 0.06 €/kWh.

Table 5.5: Electricity sold to the TB for EC scenarios and subsequent income

	Energy sold to the TB [kWh]			Income [€]		
House	**EC1**	**EC2**	**EC3**	**EC1**	**EC2**	**EC3**
House 1	3 905	2 901	1 983	432	321	219
House 2	2 815	2 024	1 320	310	223	146
House 3	2 220	1 533	1 024	245	170	114
House 4	2 157	1 484	968	239	165	108
House 5	2 239	1 508	999	249	168	112
House 6	2 404	1 638	1 087	267	182	121
House 7	2 343	1 645	1 038	260	183	116
House 8	1 060	688	413	117	76	46
House 9	1 670	1 105	660	184	122	73
House 10	1 991	1 384	942	220	153	105
Total	22 805	15 910	10 435	2 523	1 765	1 159

After analysing the profit that the community makes by selling electricity to the tertiary building, which is visible in Table 5.5, it is important to see how this entity fairs in this business and if the proposed community model is profitable for both sides. For this, it was calculated how much the tertiary building would have to pay for the energy provided to it by the community, had it bought it from the grid in medium voltage. Subtracting from it the price paid by the TB for the community's energy, the electricity bill savings of the TB were attained. In Table 5.6, the results for the electricity bill savings provided by each house to the TB are presented. For both sides, it is more profitable if the community does not have energy storage, since the electricity surplus is reduced. Thus, the TB saves more money with EC1, a total of 1 150€, than with any battery-operated solution, as the TB savings for EC2 are reduced to 802€ and to 527€ with EC3.

Table 5.6: Electricity bill savings the TB achieves with EC scenarios

	Tertiary Building savings [€]		
House	**EC1**	**EC2**	**EC3**
House 1	198	147	101
House 2	143	103	67
House 3	113	78	52
House 4	109	74	49
House 5	112	75	50
House 6	120	82	54
House 7	117	82	52
House 8	54	35	21
House 9	85	56	34
House 10	101	70	48
Total	1152	802	527

Both the community residents and the adjacent tertiary building can profit from any of the proposed collective self-consumption models. The households have notable profit outcomes in this business proposal, while the TB has moderate savings slightly under half of the community's profits. These results prove that the selected profit factor of 50% in section 3.4.4 can provide desirable profit margins for all players in this investment.

5.2.6 Fairness Index Evaluation

In this section, an analysis on how fair the proposed collective self-consumption models are is conducted. For this, the distribution of benefits in the proposed model (MP) will be compared to 3 gains distribution methods: distributing gains equally to all residents of the community (EQ), distributing gains according to the consumption of each resident (CB) and distributing the total EC gains according to each consumer's contribution to the total electricity surplus and deficit of the community (BP).

The FI results of each created case study with the 4 different benefit distributions are presented in Figure 5.21, in which it is possible to see that the most fair distribution method is this thesis' proposed collective self-consumption model (MP), with FI values between 0.995 for EC1 and 0.99 for EC3. The consumption-based (CB) benefit allocation method is the second most fair, with FI values between 0.988 for EC1 and 0.967 for EC3. The BP method is the least fair of all considered options, with an equal distribution of benefits (EQ) being slightly more fair than it for all case study scenarios.

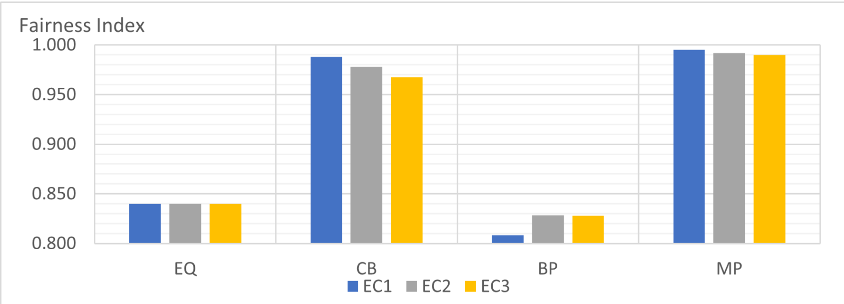


Figure 5.21: Fairness index of several EC benefits distribution methods

Although there is a slight connection between houses with high consumption and houses with high relative allocation of benefits, seen in Figure 5.22, the relative allocation of benefits per house is similar for most households in EC1. As energy storage capacity increases, the proposed model in this thesis decreases in fairness of benefit distribution, since the individual relative allocation of benefits of each prosumer in EC2 and EC3 changes and prosumers with the higher consumption and generation profiles benefit gradually more than consumers with lower consumption and generation profiles, meaning their contribution is limited in communities with higher capacities of battery energy storage.

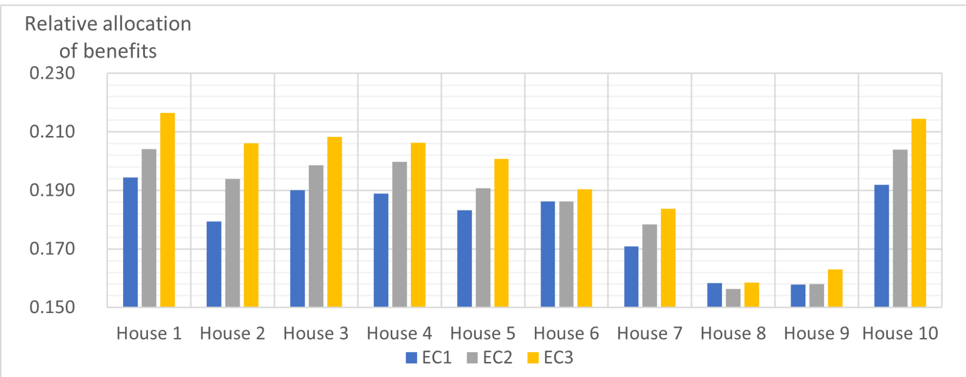


Figure 5.22: Relative allocation of benefits of the EC model

Chapter 6

Conclusions

The present thesis created a model for energy communities that aimed to optimise the energy trading between members using PV modules for self-consumption, with or without battery storage solutions. The developed model fosters social welfare by trading energy among residents without monetary compensation. The created community is composed of 10 households and an adjacent tertiary building, which buys electricity surplus from the residents. Having taken into account yearly consumption profiles for the selected households, with the most accurate electricity prices and taxes and the evolution of consumption and PV generation, this model allowed to perform the simulation of a 25-year investment. The simulations allowed to evaluate the technical, economic and environmental aspects of energy communities using relevant result assessment metrics compared to an individual self-consumption model and to a no-investment scenario, and to verify the equity of the community model's benefits allocation for each member using a fairness index.

The created individual and collective self-consumption models allowed to perform an analysis on the most important aspects of an energy community: the evaluation of daily power flows of a household, from which it is possible to graphically interpret how energy is managed in the devised model; the electricity balance for a house using collective self-consumption was compared to investing individually and to not investing, thus allowing for an extensive and detailed analysis of the house's energy balance for that time period; the state of charge of the used battery storage systems were analysed, so as to examine if they were a good fit for the residents; and all the relevant economic results for individual and collective self-consumers were detailed and compared, providing information on the yearly electricity bill cost savings and revenues a household can obtain and on the net present value and investment rate of return of the 25-years of investment, among others.

The best economic and environmental results are always attained by energy communities, rather than individual self-consumers. The total discounted capital expenditures (including equipment replacement and O&M costs over 25 years) required to have the highest capacity batteries in EC3 (19 188€) are more than double those of an investment without storage in EC1 (8 548€), with yearly operation and maintenance costs also increasing by 110%. Therefore, although EC3 has the most pronounced yearly electricity bill cost savings of 1 670€, they are not enough to achieve net present values as high as in scenario EC1, equal to 14 806€, with a considerable internal rate of return of 24.2%.

In all case study scenarios the residents make significantly more income from selling their surplus energy to the TB at an average price of 0.11€/kWh (which results from a compromise between the price at which the TB buys electricity from the grid and the FiT offered by the grid for the community's surplus energy), rather than to the grid whose average monthly FiT is equal to 0.06€/kWh. The tertiary building achieves the lowest yearly electricity bill cost savings of 527€ with the community that uses the highest battery capacity (EC3), as more energy is stored and less of it is sold to the TB. Therefore, the community without battery storage (EC1) provides the TB with the best cost savings, reducing this building's electricity bill costs 219% more than EC3. In all scenarios the developed model was found to be profitable for all players.

The P2P mechanism and the 40 kWh community-owned battery in EC3 allow prosumers to be the least dependent on the grid, with self-sufficiency results of 80%, thus also achieving the lowest CO_2 emissions, with a reduction to 20%.

The novel distribution of benefits of the developed model was compared to 3 other allocation methods using a fairness index. With FI values higher than all other methods and almost equal to 1, in the analysed case studies, the model is proven to be fairly distributing the generated benefits of partaking in an REC, even though the FI decreases for increased battery capacities.

Taking into consideration all the analysed results from the energy community model, the main conclusions on this dissertation's research questions are:

- Considering current Portuguese policies and legislation, is it economically viable and fair to invest in an energy community in Portugal, in which residents trade energy among each-other for free and can sell electricity surplus to a tertiary building?

  Not only is it economically viable to invest in an energy community in Portugal, in which residents trade energy among each-other for free and can sell electricity surplus to a tertiary building, it is also more profitable than investing in individual self-consumption solutions or not investing at all. Furthermore, it is possible to partake in an energy community in a fair way, even when residents have contrasting capital investments and consumption patterns;

- Is it profitable for a tertiary building to partake in an energy community as an electricity buyer?

  The created model proved to produce significant electricity bill cost savings for the tertiary building that buys electricity surplus from the community, thus evidencing substantial profitability for this building when partaking in the investment with the community;

- What role can energy communities have in the decentralization of the electrical grid and decarbonization efforts of the coming decades?

  The local management of energy resources and usage of battery storage solutions of the energy community demonstrated pronounced self-sufficiency results and a subsequent CO_2 emission reduction capacity higher than any other investment options. Therefore, allowing to conclude that energy communities can be of vital importance in the clean energy transition, towards an evermore decentralized and decarbonized energy service framework.

Taking into account the results obtained for the proposed energy community model, the following recommendations are made to potential prosumers:

- Prosumers that want to invest in the self-consumption project that gives them the best economic outcomes should choose to partake in an energy community with PV generation, P2P energy sharing (even though energy may be donated for free) and no battery operation, that sells electricity surplus to a tertiary building (EC1). This scenario achieves net present values as high as 14 806€, with internal rate of returns of up to 24.2%, since investment and operation costs are low and cost savings and revenues are high;

- For prosumers that want to be as self-sufficient as possible and reduce their carbon footprint, it is advisable to invest in the energy community with PV generation, P2P energy sharing (which was demonstrated to be a substantial factor in increasing local energy usage), with the highest battery capacity (EC3). Investing in this community leads to more energy being locally stored, thus reducing grid demand to 20% and increasing CO_2 emission reductions to 80%, while providing residents with an internal rate of return of 11.2% and a net present value of 7 379€.

The present dissertation developed an energy community model that is based on current legislation, in Portugal. Furthermore, the following recommendations are made regarding future public policy implementation:

- The FiT is not competitive and the utility grid could benefit from buying private citizens' electricity surplus to aid in peak hours' load management. Thus, it is recommended that the grid puts into practice a dynamic FiT that benefits prosumers for selling electricity in peak hours, instead of the current two options which, at best, vary on a monthly basis;

- Different demographic groups have divergent motivations, priorities and attitudes towards investing in renewable energy projects. Surveys can be conducted in Portugal to a wide-array of citizens, so that these are taken into account by policymakers when designing outreach efforts, since although older citizens may prioritise electricity cost savings, younger adults may respond positively to the long-term financial and environmental benefits of energy community adoption. All groups should identify with the possibility to use these communities as a basis for inter-generational collaboration that fosters inclusiveness and mentorship.

- Perhaps the most important recommendation is that the Portuguese government takes a proactive approach and removes bureaucratic barriers to the creation of energy communities, such as the granting of licenses to legally operate RECs, given by DGEG in a process that takes one year or more. Consequently, not only the process of creating RECs would be faster, this would also allow for future legislation to be based upon a bigger and more realistic sample, eventually creating a positive feedback cycle of empirical-data-driven future policies.

As energy community projects increase in number and variety, future studies akin to this dissertation could include the forecast of each resident's consumption, including the usage of electric vehicles, to enable the demand side management of the households, in which the aggregator asks members to shift their consumption to different hours, according to the objective of the model. This solution would require a model with higher computational complexity that uses solutions such as Mixed-Integer Linear Programming (MILP). By conducting surveys on different demographic groups of Portuguese citizens, a Multi-Criteria Decision Analysis (MCDA) could be conducted, in which different types of investors are modelled, with unique priorities and beliefs, so that conclusions and recommendations on energy communities can be tailored specifically to the Portuguese people. An analysis on future policies alike the recommended dynamic FiT could be implemented to guide policymakers towards integrating innovative solutions in future legislation that empower the citizens to provide services to the utility grid, without jeopardizing their own interests.

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Appendix A

Electricity Balance Results per House

In this annex it is shown the results for the electricity balance of the households, which refer to the first year of the investment.

Table A.1: Numeric display of the electricity balance for house 1

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	8 161	-	-	-	-	-	-
I1	8 725.44	3 992	4 557	-	-	-	-	-
I2	8 725.44	3 667	3 698	-	-	-	682	791
I3	8 725.44	2 927	3 075	-	-	-	1 252	1 452
EC1	8 725.44	3 584	-	408	652	3 905	-	-
EC2	8 725.44	2 604	-	408	652	2 901	981	1 005
EC3	8 725.44	1 624	-	408	652	1 983	1 961	1 923

Table A.2: Numeric display of the electricity balance for house 2

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	5 516						
I1	5 817	3 001	3 302	-	-	-	-	-
I2	5 817	2 579	2 548	-	-	-	633	733
I3	5 817	1 933	1 920	-	-	-	1 175	1 363
EC1	5 817	2 739	-	262	487	2 815	-	-
EC2	5 817	1 879	-	262	487	2 024	862	791
EC3	5 817	1 156	-	262	487	1 320	1 584	1 496

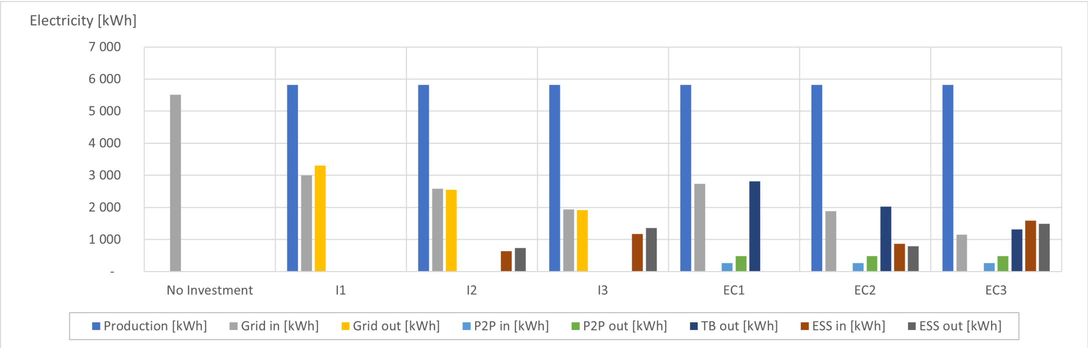

Figure A.1: Representation of the electricity balance for house 2

Table A.3: Numeric display of the electricity balance for house 3

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	4 637						
I1	4 847	2 368	2 578	-	-	-	-	-
I2	4 847	1 740	1 688	-	-	-	753	874
I3	4 847	1 184	1 165	-	-	-	1 209	1 401
EC1	4 847	1 821	-	546	358	2 220	-	-
EC2	4 847	1 229	-	546	358	1 533	593	688
EC3	4 847	761	-	546	358	1 024	1 061	1 197

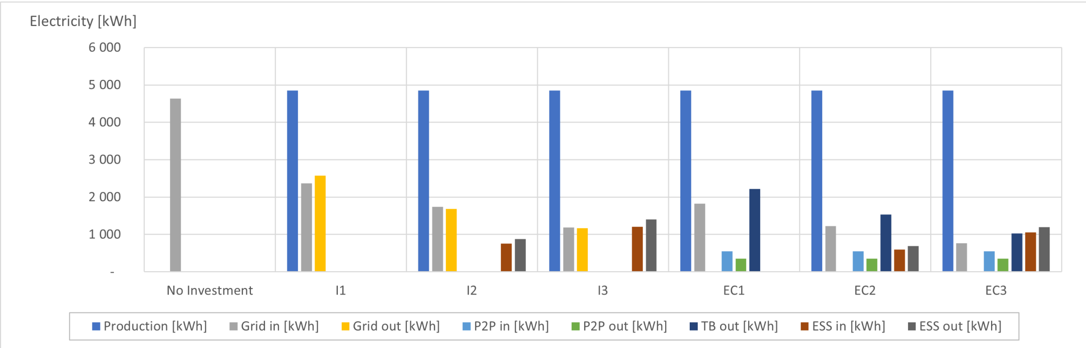

Figure A.2: Representation of the electricity balance for house 3

Table A.4: Numeric display of the electricity balance for house 4

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	4 441						
I1	4 847	2 133	2 539	-	-	-	-	-
I2	4 847	1 540	1 670	-	-	-	734	852
I3	4 847	980	1 163	-	-	-	1 176	1 363
EC1	4 847	1 620	-	513	382	2 157	-	-
EC2	4 847	982	-	513	382	1 484	639	674
EC3	4 847	576	-	513	382	968	1 044	1 189

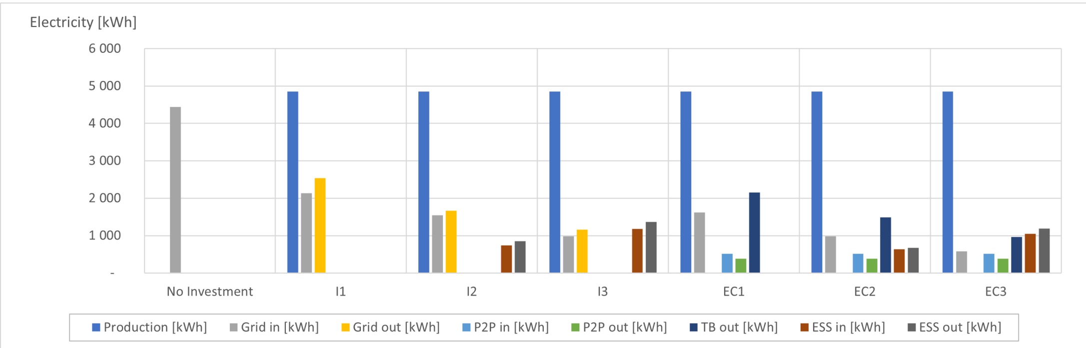

Figure A.3: Representation of the electricity balance for house 4

Table A.5: Numeric display of the electricity balance for house 5

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	4 489						
I1	4 847	2 266	2 625	-	-	-	-	-
I2	4 847	1 751	1 797	-	-	-	699	811
I3	4 847	1 214	1 346	-	-	-	1 091	1 265
EC1	4 847	1 776	-	490	385	2 239	-	-
EC2	4 847	1 183	-	490	385	1 508	594	732
EC3	4 847	705	-	490	385	999	1 072	1 241

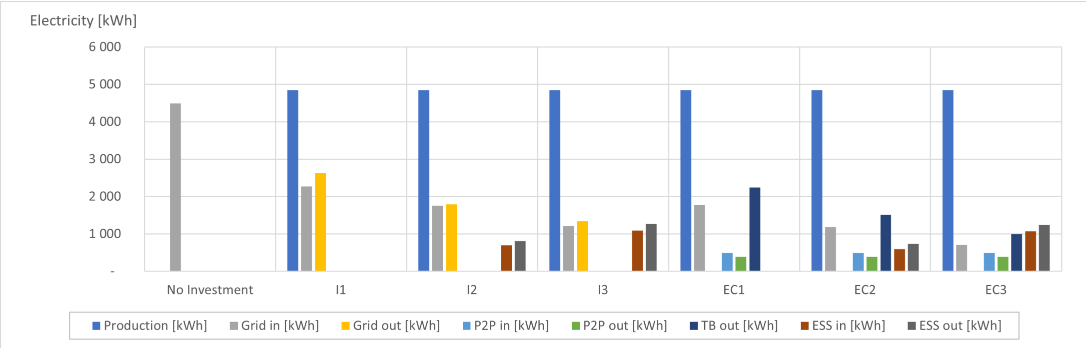

Figure A.4: Representation of the electricity balance for house 5

Table A.6: Numeric display of the electricity balance for house 6

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	4 024						
I1	4 847	2 012	2 835	-	-	-	-	-
I2	4 847	1 420	1 992	-	-	-	712	826
I3	4 847	916	1 519	-	-	-	1 123	1 302
EC1	4 847	1 555	-	456	431	2 404	-	-
EC2	4 847	1 098	-	456	431	1 638	458	767
EC3	4 847	686	-	456	431	1 087	870	1 318

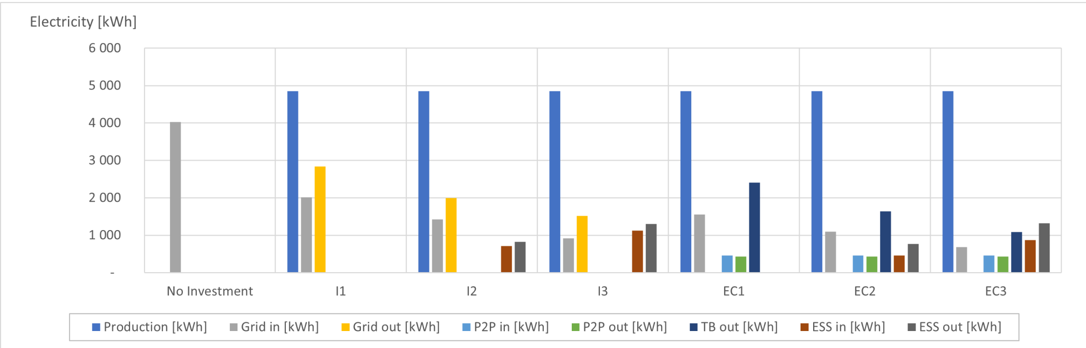

Figure A.5: Representation of the electricity balance for house 6

Table A.7: Numeric display of the electricity balance for house 7

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	4 014						
I1	4 847	1 964	2 797	-	-	-	-	-
I2	4 847	1 423	2 006	-	-	-	666	773
I3	4 847	870	1 496	-	-	-	1 108	1 286
EC1	4 847	1 570	-	395	455	2 343	-	-
EC2	4 847	1 004	-	395	455	1 645	566	698
EC3	4 847	573	-	395	455	1 038	997	1 305

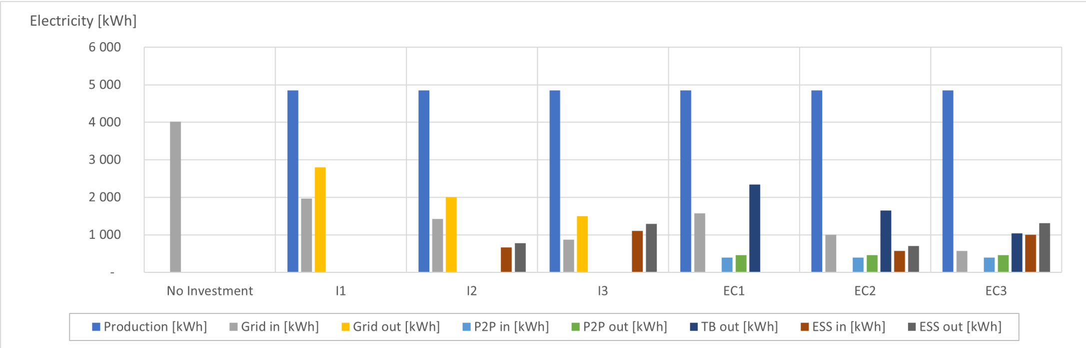

Figure A.6: Representation of the electricity balance for house 7

Table A.8: Numeric display of the electricity balance for house 8

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	1 460						
I1	1 939	796	1 275	-	-	-	-	-
I2	1 939	221	595	-	-	-	580	673
I3	1 939	65	422	-	-	-	733	848
EC1	1 939	682	-	114	215	1 060	-	-
EC2	1 939	443	-	114	215	688	240	373
EC3	1 939	252	-	114	215	413	430	647

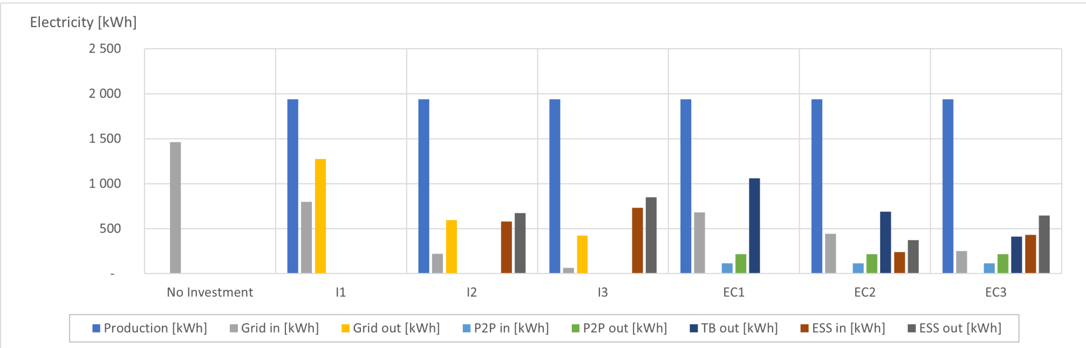

Figure A.7: Representation of the electricity balance for house 8

Table A.9: Numeric display of the electricity balance for house 9

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	2 361						
I1	2 908	1 441	1 989	-	-	-	-	-
I2	2 908	850	1 250	-	-	-	626	726
I3	2 908	424	795	-	-	-	1 022	1 185
EC1	2 908	1 226	-	215	319	1 670	-	-
EC2	2 908	875	-	215	319	1 105	352	566
EC3	2 908	565	-	215	319	660	661	1 010

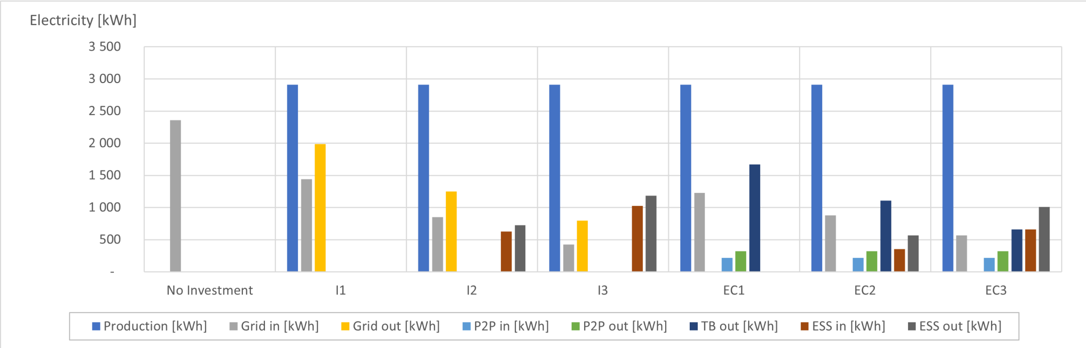

Figure A.8: Representation of the electricity balance for house 9

Table A.10: Numeric display of the electricity balance for house 10

	Production [kWh]	Grid in [kWh]	Grid out [kWh]	P2P in [kWh]	P2P out [kWh]	TB out [kWh]	ESS in [kWh]	ESS out [kWh]
No Investment	-	3 694						
I1	3 878	2 183	2 367	-	-	-	-	-
I2	3 878	1 610	1 503	-	-	-	731	848
I3	3 878	988	939	-	-	-	1 220	1 415
EC1	3 878	1 523	-	660	375	1 991	-	-
EC2	3 878	959	-	660	375	1 384	565	608
EC3	3 878	556	-	660	375	942	967	1 049

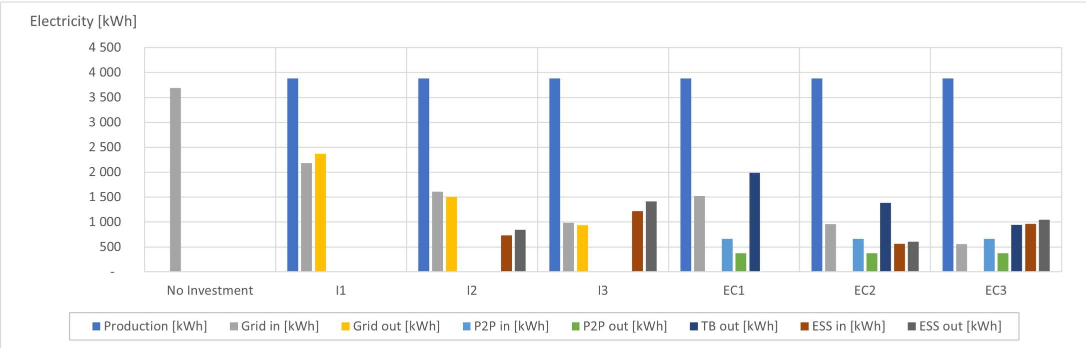

Figure A.9: Representation of the electricity balance for house 10

Appendix B

Economic and Environmental Results per House

In this annex it is shown the Tables for the economic and Environmental indexes for houses 2 to 10.

Table B.1: Economic indicators, house 2

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	5 946	77	195	679
I2	8 791	141	152	752
I3	11 637	205	115	889
EC1	5 946	77	310	733
EC2	8 791	141	223	904
EC3	11 637	205	146	1 052

Table B.2: Economic indexes, house 2

	NPV [€]	PBP [years]	IRR [%]
I1	6 752	4.6	21.5
I2	2 206	8.7	8.7
I3	-1 459	11.9	3.1
EC1	9 264	3.7	27.3
EC2	5 404	6.4	13.5
EC3	1 312	9.2	6.6

Table B.3: Environmental outcomes, house 2

	Self-sufficiency [%]	CO2 Emissions [%]
I1	46	54
I2	53	47
I3	65	35
EC1	50	50
EC2	66	34
EC3	79	21

Table B.4: Economic indicators, house 3

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	4 955	64	153	563
I2	7 800	128	102	692
I3	10 646	192	72	808
EC1	4 955	64	245	676
EC2	7 800	128	170	793
EC3	10 646	192	114	896

Table B.5: Economic indexes, house 3

	NPV [€]	PBP [years]	IRR [%]
I1	5 812	4	24.9
I2	1 590	8.4	8.3
I3	-1 967	21.6	2.0
EC1	9 087	2.9	13.8
EC2	4 709	6.3	5.5
EC3	351	9.8	24.9

Table B.6: Environmental outcomes, house 3

	Self-sufficiency [%]	CO2 Emissions [%]
I1	49	51
I2	62	38
I3	74	26
EC1	61	39
EC2	73	27
EC3	84	16

Table B.7: Economic indicators, house 4

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	4 955	64	153	574
I2	7 800	128	101	689
I3	10 646	192	71	804
EC1	4 955	64	239	677
EC2	7 800	128	165	803
EC3	10 646	192	108	892

Table B.8: Economic indexes, house 4

	NPV [€]	PBP [years]	IRR [%]
I1	5 897	4	25.3
I2	1 683	8.4	8.5
I3	-2 001	21.7	1.9
EC1	9 141	2.9	34.7
EC2	4 908	6.3	14.0
EC3	361	9.9	5.5

Table B.9: Environmental outcomes, house 4

	Self-sufficiency [%]	CO2 Emissions [%]
I1	52	48
I2	65	35
I3	78	22
EC1	64	36
EC2	78	22
EC3	87	13

Table B.10: Economic indicators, house 5

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	4 955	64	160	543
I2	7 800	128	112	633
I3	10 646	192	84	746
EC1	4 955	64	249	639
EC2	7 800	128	168	757
EC3	10 646	192	112	862

Table B.11: Economic indexes, house 5

	NPV [€]	PBP [years]	IRR [%]
I1	5 625	4.1	24.3
I2	1 194	9	7.5
I3	-2 550	23.2	1.1
EC1	8 663	3	33.5
EC2	4 296	6.6	13.1
EC3	-124	10.2	4.8

Table B.12: Environmental outcomes, house 5

	Self-sufficiency [%]	CO2 Emissions [%]
I1	50	50
I2	61	39
I3	73	27
EC1	60	40
EC2	74	36
EC3	84	16

Table B.13: Economic indicators, house 6

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	4 955	64	172	548
I2	7 800	128	122	658
I3	10 646	192	94	754
EC1	4 955	64	267	636
EC2	7 800	128	182	720
EC3	10 646	192	121	801

Table B.14: Economic indexes, house 6

	NPV [€]	PBP [years]	IRR [%]
I1	5 711	4.1	24.5
I2	1 485	8.6	8.1
I3	-2 317	22.5	1.5
EC1	8 690	3	33.6
EC2	3 913	6.8	12.4
EC3	-817	11	3.8

Table B.15: Environmental outcomes, house 6

	Self-sufficiency [%]	CO2 Emissions [%]
I1	50	50
I2	65	35
I3	77	23
EC1	61	39
EC2	73	27
EC3	83	17

Table B.16: Economic indicators, house 7

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	4 955	64	169	499
I2	7 800	128	121	605
I3	10 646	192	91	721
EC1	4 955	64	260	568
EC2	7 800	128	183	681
EC3	10 646	192	116	775

Table B.17: Economic indexes, house 7

	NPV [€]	PBP [years]	IRR [%]
I1	5 316	4.4	22.8
I2	883	9.3	6.9
I3	-2 765	23.8	0.7
EC1	7 793	3.3	31.1
EC2	3 314	7.1	11.4
EC3	-1 230	11.4	3.2

Table B.18: Environmental outcomes, house 7

	Self-sufficiency [%]	CO2 Emissions [%]
I1	51	49
I2	65	35
I3	78	22
EC1	61	39
EC2	75	25
EC3	86	14

Table B.19: Economic indicators, house 8

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	1 982	26	76	174
I2	4 827	90	35	274
I3	7 673	154	24	302
EC1	1 982	26	117	190
EC2	4 827	90	76	227
EC3	7 673	154	46	262

Table B.20: Economic indexes, house 8

	NPV [€]	PBP [years]	IRR [%]
I1	2 147	2.2	48.6
I2	-950	11.4	0
I3	-5 649	-	0
EC1	3 061	1.6	67.1
EC2	-988	11.4	-0.9
EC3	-5 856	-	-14.8

Table B.21: Environmental outcomes, house 8

	Self-sufficiency [%]	CO2 Emissions [%]
I1	45	55
I2	85	15
I3	96	4
EC1	53	47
EC2	70	30
EC3	83	17

Table B.22: Economic indicators, house 9

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	2 973	39	118	244
I2	5 818	103	74	354
I3	8 664	167	46	438
EC1	2 973	39	184	275
EC2	5 818	103	122	338
EC3	8 664	167	73	401

Table B.23: Economic indexes, house 9

	NPV [€]	PBP [years]	IRR [%]
I1	3 162	2.2	47.9
I2	-723	11.2	2.2
I3	-4 789	-	0
EC1	4 697	1.5	69
EC2	-41	9.4	4.8
EC3	-4 842	-	-7.3

Table B.24: Environmental outcomes, house 9

	Self-sufficiency [%]	CO2 Emissions [%]
I1	39	61
I2	64	36
I3	82	18
EC1	48	52
EC2	63	37
EC3	76	24

Table B.25: Economic indicators, house 10

	Initial Inv. [€]	OM cost [€]	Revenues [€]	Cost Savings [€]
I1	3 964	52	140	396
I2	6 809	116	89	502
I3	9 655	180	55	637
EC1	3 964	52	220	525
EC2	6 809	116	153	638
EC3	9 655	180	105	727

Table B.26: Economic indexes, house 10

	NPV [€]	PBP [years]	IRR [%]
I1	4 439	3.3	30.4
I2	-54	9.9	4.8
I3	-3 375	-	-1.4
EC1	8 066	2.1	48.6
EC2	3 756	6.2	13.8
EC3	-728	10.5	3.8

Table B.27: Environmental outcomes, house 10

	Self-sufficiency [%]	CO2 Emissions [%]
I1	41	59
I2	56	44
I3	73	27
EC1	59	41
EC2	74	26
EC3	85	15