NOVA SCHOOL OF SCIENCE & TECHNOLOGY
DEPARTMENT OF
ELECTRICAL AND COMPUTER ENGINEERING

EXPLORING ENERGY FLEXIBILITY IN RENEWABLE ENERGY COMMUNITIES

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Master in Renewable Energy Engineering

DOCTORATE IN ELECTRICAL AND COMPUTER ENGINEERING
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To Caroline.

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“All we have to decide is what to do with the time that is given to us.” (Gandalf the Grey).

Abstract

To avoid the worst effects of climate change, there must be a paradigm shift in the way energy is converted, transported, distributed, and consumed. More specifically, there should be a change from the current state, where supply always follows demand, to a new state, where demand is also adjusted instantly to the supply level. In this context, energy flexibility represents an important tool to adapt consumption to the different generation conditions, assuming particular interest in the integration of distributed energy generation systems, based on renewable sources, in an energy transition towards sustainability. In addition, energy flexibility will be fundamental in solving the challenges imposed by the increasing electrification of society's processes (e.g., introduction of electric vehicles), which highlights the additional burden imposed on energy systems, and the joint effort of society to mitigate changes with the limitation of greenhouse gas emissions.

In this context, the contribution of this Doctoral thesis is threefold: firstly, based on a literature review on demand energy flexibility, a novel characterization of the energy flexibility potential of event-based devices is proposed, considering the Portuguese legislation on the operation of renewable energy communities. The second contribution of this study is to propose a new framework to support the management of renewable energy communities, namely the energy sharing process. Lastly, the energy flexibility potential of selected event-based devices is explored in a case study to increase the benefits of energy consumers and prosumers and to assess the impact of energy flexibility on energy sharing strategies in renewable energy communities.

Keywords: Renewable Energy Community, Energy flexibility, Demand response

Resumo

Para evitar os piores efeitos das alterações climáticas, deve haver uma mudança de paradigma na forma como a energia é convertida, transportada, distribuída e consumida. Mais especificamente, deve haver uma mudança do estado atual, onde a oferta de energia segue sempre a procura, para um novo estado, onde a procura também se ajusta instantaneamente ao nível da oferta. Neste contexto, a flexibilidade energética representa uma ferramenta importante para adaptar o consumo às diferentes condições de geração de energia, assumindo particular interesse na integração de sistemas de geração de energia distribuída, baseados em fontes renováveis, numa transição energética para a uso mais sustentável de energia. Além disso, a flexibilidade energética será fundamental na resolução dos desafios impostos pela crescente eletrificação dos processos da sociedade (por exemplo, a introdução de veículos elétricos), o que impõe um fardo adicional às redes de energia, e o esforço conjunto da sociedade para limitar as emissões de gases com efeito de estufa.

Neste contexto, são três as contribuições desta tese de doutoramento: em primeiro lugar, com base numa revisão da literatura sobre a flexibilidade energética ao lado da procura, propõe-se uma nova caracterização do potencial de flexibilidade energética de dispositivos elétricos baseados em eventos, considerando a legislação portuguesa sobre o funcionamento de dispositivos de armazenamento. A segunda contribuição deste estudo é propor novas estruturas para a gestão de comunidades de energia renovável, nomeadamente o processo de partilha de energia. Por fim, o potencial de flexibilidade energética de dispositivos selecionados com base em eventos, modelados como dispositivos de armazenamento virtual, será aplicado num contexto de comunidade de energia renovável para aumentar os benefícios desta associação de consumidores e prosumidores de energia, e para avaliar o impacto da flexibilidade energética em estratégias de partilha de energia nas referidas comunidades.

Palavas chave: Comunidade de Energia Renovável, Flexibilidade Energética, Resposta da procura

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Acronyms

AC	Alternate Current
APS	Announced Planned Scenario
BESS	Battery Energy Storage System
Bld	Building
CEC	Citizen Energy Community
CHP	Combined heat and power
CI	Consumption Installation
CO_2	Carbon Dioxide
CSME	Collective Self-consumption Management Entity
DC	Direct Current
DCD	Deterministic chemical device
DL	Decree-law
DMD	Deterministic mechanical device
DR	Demand response
DSC	Dynamic Sharing Coefficient
DSM	Demand Side Management
DSO	Distribution System Operator (find first instance)
DTD	Deterministic thermal device
EBC	Energy in Buildings and Communities
EBD	Event-Based Device
EC	European Commission
EMS	Energy Management System
EU	European Union

EV	Electric vehicle
EWH	Electric water heater
FEC	Fixed and Equal Coefficient
FPC	Fixed and Proportional Coefficient
GHG	Greenhouse gas
H	Hypothesis
HEMS	Home Energy Management System
HVAC	Heating, Ventilation and Air Conditioning
ICT	Information and Communication Technology
IEA	International Energy Agency
LEC	Local Energy Community
LV	Low voltage
MV	Medium voltage
NDCD	Non-deterministic chemical device
NOCT	Nominal Operating Cell Temperature
NPV	Net present value
NZE	Net Zero Emissions
P2P	Peer-to-peer
PEV	Plug-in electric vehicle
PI	Production Installation
PV	(solar) Photovoltaics
REC	Renewable Energy Community
RES	Renewable Energy Sources
ROI	Return on Investment
RQ	Research Question
SCPU	Self-Consumption production Unit
SI	Storage Installation
SME	Small and medium enterprise
SoC	State-of-charge
STC	Standard Test Conditions
STEPS	Stated Policies Scenario
V2B	Vehicle-to-Building
V2G	Vehicle-to-Grid

V2N	Vehicle-to-Neighbour
VSI	Virtual Storage Installation

UNITS & SYMBOLS

Units:

EJ	Exajoule
GW	Gigawatt
km	Kilometre
kVA	Kilovolt-Ampère
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt-peak
m^2	Square meter
MW	Megawatt
MWh	Megawatt-hour
MWp	Megawatt-peak
ºC	Degree Celsius
TWh	Terawatt-hour
W	Watt

Symbols:

Am	Useful area of a solar PV module
bd	Instantaneous building demand in REC operation
bp	Instantaneous building production available for sharing
Ch	Charging of the Virtual Storage Installation
com	Index to reference a REC as a whole
c_{ebd}	Counter of the Event-base Device operation cycle
C_{imp}	Cost of electricity import

$C_{T,ebd}$	Total number of time instants for a complete Event-base Device operation cycle
d	Instantaneous total demand of a building
Dc	Discharging of the Virtual Storage Installation
DSC	The variable "Dynamic Sharing Coefficient"
ep	Instantaneous exported power
ESC	Export sharing coefficient
$e_{c,V.St}$	Energy consumed (or not consumed) used to calculate the state-of-charge of the Virtual Storage Installation
E_{exp}	Electricity exported to the grid
E_{imp}	Electricity import
E_{sc}	Electricity self-consumed
E_{sh}	Electricity shared for REC members
$E_{T,V.St}$	Energy needed for a complete operation cycle of an Event-Based Device
G_t	Total irradiance incident in a PV module
j	Index to reference a given REC member
m	Instantaneous power surplus after self-consumption
N	Number of modules of a given solar PV system
n	Number of timesteps
N_BLD	Total REC members
nbd	Instantaneous building demand after sharing process
nd	Instantaneous building demand after self-consumption
$p_{d,ebd}$	Power demand of an Event-base Device
$p_{d,unc}$	Total demand of uncontrollable loads
p_g	Instantaneous power output of a given solar PV system
$p_{n,unc}$	Net demand of uncontrollable loads
s	Power to share
SC	A considered energy sharing coefficient
$SOC_{V.St}$	Virtual Storage Installation's state-of-charge in a given timestep
t	A given time instant
$T_{a,NOCT}$	Ambient temperature at Nominal Operating Cell Temperature
T_a	Ambient temperature
$T_{c,NOCT}$	Solar cell's temperature at Nominal Operating Cell Temperature

$T_{c,STC}$	Solar cell's temperature at Standard Test Conditions
$t_{e,start}$	Time instant of the earliest start of an Event-base Device
$t_{l,end}$	Time instant of the late end of an Event-base Device
$T_{present}$	A tariff structure that considers the time intervals in which the EBD is available to operate
$T_{present}(max)$	The maximum value of $T_{present}$
$T_{present}(min)$	The minimum value of $T_{present}$

δ	Solar declination
Δt	Time interval between two sequential time instants
ρ	Minimum percentage of and Event-base Device demand the solar PV system must fulfil
φ	Decrease of the PV power output to the temperature
ϕ	Latitude of a given place on Earth
ω	Hour angle
η_{pe}	Conversion efficiency of the power equipments of a solar PV system
η_{sc}	Efficiency of the solar conversion to electricity over time
η_{STC}	Efficiency of the solar conversion at Standard Test Conditions
θ_z	Solar zenith angle
τ_b	Dimensionless atmospheric transmittance

1

INTRODUCTION

1.1 Motivation

According to the "World Energy Outlook 2023", developed and published by the International Energy Agency (IEA), global energy demand experienced a 1.3% increase in 2022, influenced by the growing global economy and population expansion. Within this context, the demand for electricity stands out as a keystone in the functioning of modern economies, accounting for approximately 20% of total final energy consumption. The overall global energy consumption, measured at 442 EJ (122,700 TWh), is distributed among various sectors, with industry responsible for 167 EJ (46,388 TWh), followed by buildings (133 EJ or 36,945 TWh), transport (116 EJ or 32,220 TWh), and other end-uses (27 EJ or 7,500 TWh) (International Energy Agency, 2023).

Regarding electricity, low-emission generation sources, notably nuclear (contributing 9%) and renewables (constituting 30%), have gained prominence as the world struggle with the imperative of sustainable energy solutions. Forecasts predict a substantial increase in global electricity demand due to population and income growth, alongside the electrification of various end-uses. The IEA designed three expected scenarios for the future in its analysis (International Energy Agency, 2023): the "Stated Policies Scenario" (STEPS), which is *"based on the latest policy settings, including energy, climate and related industrial policies"*; the "Announced Planned Scenario" (APS), considering that all "*national energy targets made by governments are met in full and on time*"; and the "Net Zero Emissions" (NZE) Scenario, in which global average temperature in increased by 1.5ºC to 2050. In this context, electricity demand is predicted to increase by over 80% in STEPS, 120% in APS and 150% in NZE.

Renewable energy sources (RES) have made notable pace, contributing with 30% of the global electricity mix in 2022. The projections suggest a substantial rise to nearly 50% by 2030, considering STEPS scenario. In the context of solar energy, global solar photovoltaics (PV) capacity additions, encompassing both rooftop solar and utility-scale projects, reached a record high of 1,145 GW in 2022. This achievement marks a significant milestone, being twice the level observed in 2019 and more than seven times higher than the level a decade earlier. The dominance of China in this industry is unquestionable, contributing to 45% of all capacity additions in 2022. However, the increased share of electricity generated from renewable sources cannot pace the total electricity needs, as can be seen in Figure 1.1.

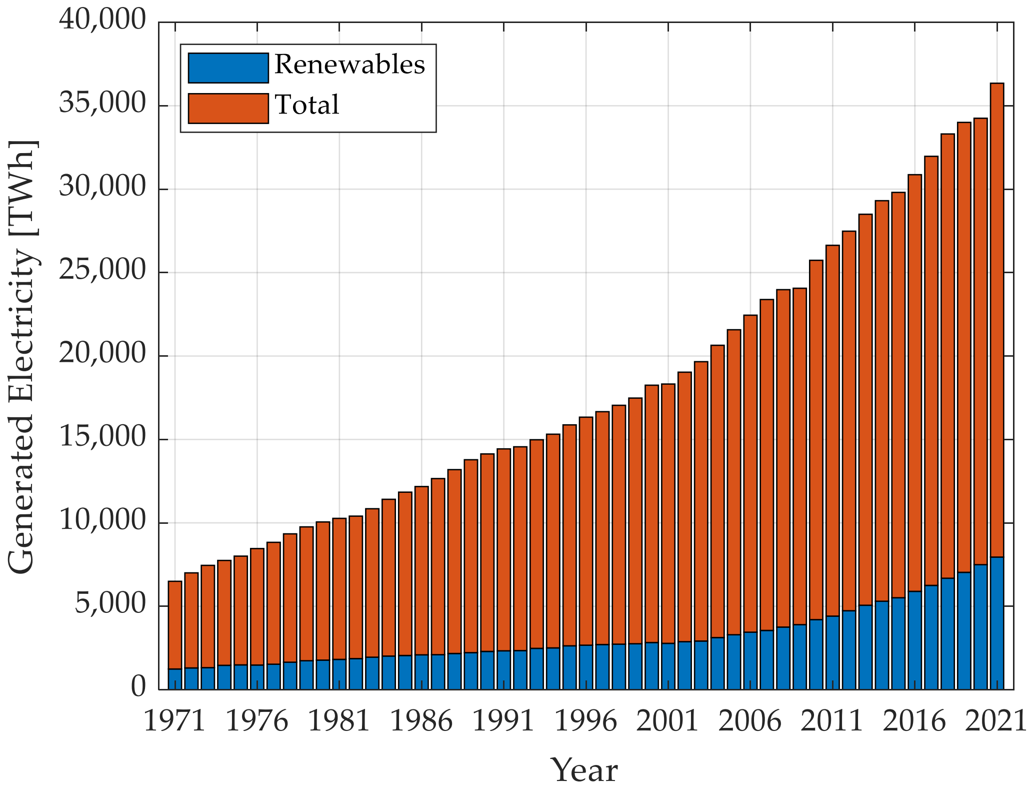

Figure 1.1 - Evolution of global electricity generation, total and from renewable sources

Unlocking and sustaining higher levels of electricity generation using renewable sources necessitates concerted efforts to overcome critical barriers. Addressing the challenges originated by the time variability of RES generation pattern requires a multifaceted approach, focusing on permitting and licensing procedures to streamline the approval of new projects. Simultaneously, grid development and connections need to be expanded and optimized to accommodate the growing capacity of RES. Furthermore, enhancing power system flexibility is paramount to integrating the increasing shares of renewable-generated electricity. This includes adopting advanced technologies and methodologies that enable the grid to respond dynamically to fluctuations in electricity generation and demand (International Energy Agency, 2023). However, the higher RES integration can introduce a series of problems in their management process (Janda, Málek and Rečka, 2017; Schmietendorf, Peinke and Kamps, 2017; Al-Shetwi *et al.*, 2020; Alam *et al.*, 2020; Basit *et al.*, 2020; Sinsel, Riemke and Hoffmann, 2020). The main issue is the energy dispatch process, which is compromised by RES time variance. There is a natural imbalance between the energy supply and demand when using RES on a generation energy system. Therefore, the energy systems operators must insert management tools to maximize RES usage. Regarding electricity consumption, the automotive sector is undergoing a paradigm shift with the rapid adoption of electric vehicles (EVs). The share of EVs in global car sales has more than tripled in the last two years, reaching an impressive 14%. Projections indicate further growth, with record-breaking sales expected in 2023, particularly in the United States (International Energy Agency, 2023). China, emerging as the global leader in the EV market, currently hosts more than half of all electric cars on the road. This shift towards electric mobility has profound implications for the energy landscape, necessitating strategic planning and infrastructure development. The evolution of the EV stock is showed in Figure 1.2 (International Energy Agency, 2023).

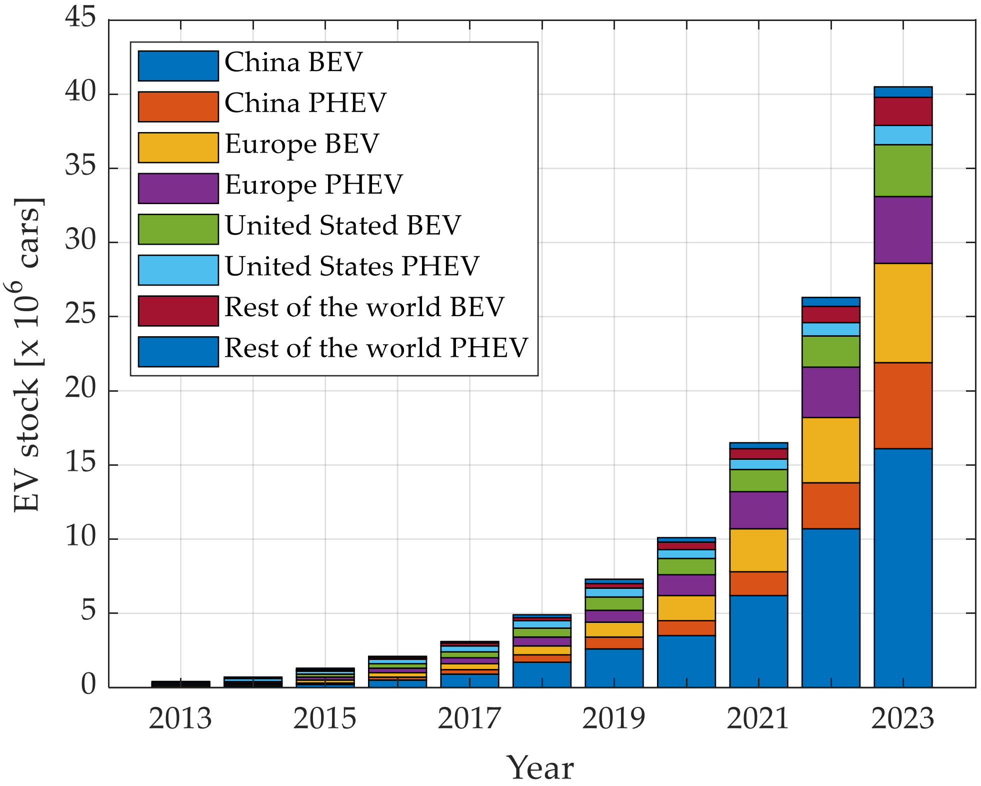

Figure 1.2 - Evolution of global EV stock

Generally, since electricity demand is time-variant, with the increase of electricity usage load peaks not predicted by the systems operators may occur. These load peaks have the potential to decrease the lifespan of the network equipment, for instance, cables and transformers (Lopes *et al.*, 2018; Queiroz, Amaral Lopes and Martins, 2020). In this context, measures that use the available system energy flexibility can mitigate these problems, by flattening the load curve at specific times during an operating cycle, usually a day.

The increasing adoption of electric vehicles, electric heat pumps, and Heating, Ventilation and Air Conditioning (HVAC) units introduces variability into the demand for electricity. Simultaneously, it presents opportunities for demand response (DR), which can be briefly defined as a change in electricity consumption pattern, from a usual behaviour, in response to external input, such as an electricity price modification (Du, 2017). It can potentially allow consumers to adjust their electricity consumption in response to grid conditions. DR plays an important role, since it uses the available flexibility of the electrical equipment usage to achieve certain objectives (e.g., peak load reduction). Its assessment and study are part of a series of techniques that can harvest the energy flexibility potential of an energy system, and address the problem derived of the RES time variance in this given energy system. The energy flexibility concept is not yet fully formalized among researchers. However, there are common characteristics of the different definitions, in which a common one can be the ability of an energy system to manage its local supply and demand, based on parameters regarding meteorological conditions, end-users, and system operators' needs (Jensen *et al.*, 2017; Junker *et al.*, 2018). However, realizing the full potential of demand response requires a supportive regulatory environment. This requires establishing adequate price signals, deploying digital tools, and implementing smart controls that enable communication and coordination between consumers and the grid (International Energy Agency, 2023). In the future, power system flexibility needs are set to increase sharply, driven by the rising share of variable solar PV and the overall growth in electricity demand. In response to these changes, ensuring electricity security in future power systems calls for innovative tools and approaches. Power generators must be more agile, capable of adjusting their output rapidly to match fluctuations in renewable energy generation. Consumers, equipped with advanced technologies, must become more connected and responsive, actively participating in demand-side management. Grid infrastructure needs to be strengthened and digitalized to facilitate more dynamic flows of electricity and information, ensuring the stability and reliability of the overall power system (International Energy Agency, 2023). Furthermore, the role of batteries becomes increasingly critical in providing the necessary short-term flexibility for the power system. Beyond 2030, batteries and demand response are expected to play a pivotal role in balancing electricity supply and demand. DR is anticipated to gain prominence as the contribution from traditional thermal power plants diminishes. The expanding use of electric heat pumps, air conditioners, and electric vehicles introduces variability into electricity demand, but it also creates opportunities for DR strategies. Realizing these opportunities hinges on creating a regulatory environment that supports and incentivizes responsive consumer behaviour.

The global emissions of Carbon Dioxide (CO_2) from the power sector accounts for almost 40% of all energy-related CO_2 emissions, highlighting the urgent need for comprehensive solutions. To mitigate the negative impacts of the increase of CO_2 and other greenhouse gases (GHG) emissions, several agreements have been signed by world leaders, such as the Kyoto Protocol (United Nations, 1998) and, more recently, the Paris Agreement (United Nations Framework Convention on Climate Change, 2015). These agreements state that the signatory countries must increase the efforts to mitigate the effects of GHG emissions on the climate change process. Regarding electricity, to reduce GHG emissions, several actions must take place, both on the generation and demand sides. On the process of electricity generation, the higher integration of RES can decrease the GHG emissions related with this process since, by default, these processes generate energy with an average low GHG emission rating. On the demand side, some important factors are part of the solution for the GHG emissions reduction. One of them refers to a more efficient final energy consumption, to decrease energy demand (Subramanyam *et al.*, 2017; Subramanyam, Ahiduzzaman and Kumar, 2017) and, consequentially, the energy generation from big fossil fuel plants. RES are also used as a tool to decrease the building's energy bills, fulfilling part of their energy needs locally (Queiroz, Amaral Lopes and Martins, 2020). Other important factor that can contribute is the increasing of local RES usage. These sources can fulfil part of the buildings' energy needs, therefore decreasing the need of energy from the network, by a technique commonly named as self-consumption. The self-consumption can be made on an individual (Salpakari and Lund, 2016; Koskela, Rautiainen and Järventausta, 2019; Taddeo *et al.*, 2020) or collective level (Lopes *et al.*, 2016; Lopes, 2017; Eseye *et al.*, 2019; El Geneidy and Howard, 2020; Martirano *et al.*, 2021). Regarding self-consumption, the European Commission (EC) have interest in its increasing, which is enforced by the publication of the Directive (EU) 2018/2001 (European Parliament and Council of The European Union, 2018). This Directive aims to promote the RES usage to achieve the European goals regarding its energy policy, such as its promotion in heating and cooling installations for a competitive and efficient distribution at district level, and the RES uptake to achieve a higher degree of energy autonomy for European outermost region, often characterised by their isolation, limited supply, and dependence on fossil fuels. The Directive also addresses the binding target to reduce the GHG emission to a level 40% below it was in 1990 – 4.19 billion tons of GHG emitted (Our World in Data, 2019), until 2030. The promotion of RES usage also targets the goals of energy supply security, sustainability, and affordance.

Regarding RES usage, the collective self-consumption of locally generated electricity is a process which can increase the percentage of such electricity consumption, coping different consumption and generation patterns of each participant by sharing eventual surplus in a building among ones with consumption needs. To ensure that a given cluster of buildings which practices collective self-consumption can have benefits from such practices, the recent published European legal framework contains the definition of Renewable Energy Community (REC) (European Parliament and Council of The European Union, 2018). One of the characteristics of this legal entity is the legal permission of energy sharing of the surplus of locally generated electricity among members and the participation on energy markets, purchasing and selling energy as may the REC manager may see fit for the members' purposes. Portugal, as one of the European Union's Member State, transpose the Directive (EU) 2018/2001 by publishing the Decree-law 15/2022 (Presidência do Conselho de Ministros, 2022), which establishes the statute for RECs. Also in the Portuguese context, Regulation no. 373/2021, published by the Portuguese Regulating Entity for Energy Services (Entidade Reguladora dos Serviços Energéticos, 2023a), defines the functioning of RECs in Portugal. The recent advancements on the installed power of distribution energy units, according Figure 1.3 (E-REDES Distribuição de Eletricidade, 2024) presents a strong motive for a wider implementation of RECs in this country.

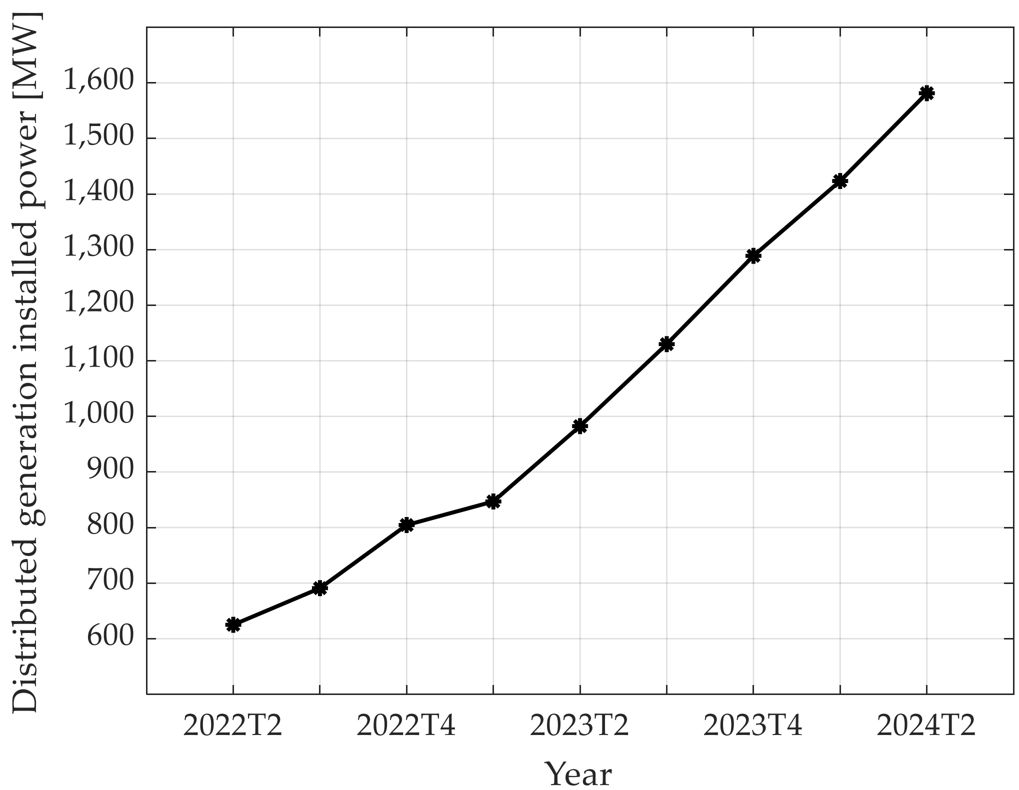

Figure 1.3 - Distributed generation installed power in Portugal

1.2 Research Questions

The building stock for residential, commercial, and public services is responsible for approximately 30% of the global final energy consumption and approximately half of the total electricity demand (International Energy Agency, 2023). Therefore, energy flexibility measures can have a significant impact on the electricity consumption pattern of the considered systems. Moreover, the possible proposed goals for the use of energy flexibility can also have a pronounced impact on several system indicators, such as economic, energy quality on a distribution level or the end-users' comfort level. On an aggregated level, these indicators can be evidence for the achievement of governmental goals regarding climate change mitigation included in laws and regulations. Also, the possibility of aggregating the energy flexibility potential of a cluster of buildings can collectively improve its benefits for building users and the environment due to the possibility for increasing locally generated electricity by matching the consumption with the generation profiles, among other management strategies. On a European level, the Directives 2018/2001 (European Parliament and Council of The European Union, 2018) and 2019/944 (European Parliament and Council of The European Union, 2019) stipulates a series of measures to achieve these objectives. One of them is the assembling of a REC, which can produce, consume, share, and export energy locally generated from renewable sources. The association of energy flexibility potential of the loads of REC members can have the ability to improve the share of energy that are locally used, similarly with the benefits of aggregated energy flexibility, which can be enhanced due to the possibility of energy sharing among REC members, stated by the European directives, and transposed by the Portuguese legal framework by the concept of the sharing coefficients.

Regarding energy consumption, according to the literature review, energy flexibility studies are focused on defining different energy demand management strategies, whether at the building-level, by managing the energy consumption of its devices, or at the grid-level by, for example, managing load peak or valley filling. To assess the ability of a building to provide energy flexibility to the system in which it is inserted, there is a necessity to analyse how its loads use energy to fulfil its requirements. For this purpose, it is common to develop models that describe the building loads behaviour, namely the devices used by the end-users of the building. As aforementioned, the most common objectives of these measures are economical, regarding the reduction of energy bills, and the assessment of demand response potentials.

Usually, the developed models take into consideration the devices' physical behaviour and buildings' constructive characteristics, along with external factors, such as operation time, ambient temperature and energy tariffs, and the end-users' requirements (for instance, comfort level and general utilization needs). The amount of equipment characteristics and relationship between them varies depending on the accuracy level of the model, the type of equipment itself, and the type of model that is in development. Among many characteristics or relations, the developed model can be excessively complex. Thus, a large computational processing capacity may be required. Moreover, if different types of devices do not have compatible behaviour, namely the same output variables, their aggregation potential can be compromised.

In this context, there is a need to model a variety of household devices, in a way that provides the possibility of aggregation considering a defined number of input and output variables that can be mathematically treated. Although most residential loads operate with electricity, in some cases there can be other energy carriers involved in the process, such as biomass or natural gas. For instance, under the Portuguese context, many residential buildings have only event-based devices as loads that have potential to offer flexibility, such as washing machines, which is present in 93% of the Portuguese households, compared to electric heater (65%), electric water heater (16%), or electric HVAC system (7%) (Instituto Nacional de Estatísticas - Statistics Portugal, 2021). Furthermore, for the purpose of this work, electric vehicles are also seen as event-based devices and the considered case studies will focus on this type of device. To avoid the complex computational process and based on the new Portuguese legislation on the electricity system, this work proposes a different approach for the assessment of flexible loads in a REC operation context, and a novel methodology to share the electricity generated inside the REC borders, to directly increase the economic benefits for the members and decrease their carbon footprint due to RES used to produce energy locally.

Aiming to address the use of energy flexibility as a tool to increase the benefits of the association of energy users as energy communities, the work presented in this dissertation is focused on answering the following Research Questions (RQs):

RQ#1: How the electricity surplus can be shared in a given Renewable Energy Community to achieve economic and social benefits, both individually and collectively?

RQ#2: How the energy flexibility of shiftable loads can be represented in the context of a Renewable Energy Community, considering legal and technical frameworks?

To answer these RQs, two hypotheses (H) are proposed, in which *H#1* is related to *RQ#1* and *H#2* to *RQ#2*:

H#1: Dynamic energy sharing coefficients, varying in time and weighted by consumption, generation and socio-economic variables of the Renewable Energy Community members, are capable to allow electricity surplus sharing to achieve such benefits.

H#2: The energy flexibility potential of a shiftable load inside a Renewable Energy Community premises can be represented as a Virtual Storage Installation.

To verify the assertiveness of H#1 and H#2 to tackle RQ#1 and RQ#2, respectively, a series of indicators is selected, mainly focused on the user's perspective, namely: the energy virtually consumed, derived of the association of users as a REC compared to an individual performance, and the associated import costs of this association, also compared with the original considered scenario, namely the individual operation. Furthermore, for the experiments involving RECs, real consumption and meteorological data were considered to formulate the scenarios in terms of local generation and self-consumption management strategies.

1.3 Aimed Contributions

From the latest definitions of energy flexibility, and considering the literature review, the objective of this work is twofold: firstly, a complete assessment of the operation of a REC in terms of the management of locally generated electricity among the members. In this sense, there is a comparison of the different sharing strategies available in the Portuguese context with the proposed dynamic sharing strategy. Furthermore, an analysis of the developed energy sharing process considering the Portuguese legal framework is conducted, to point out the advantages and disadvantages of each sharing framework, to answer RQ#1 by validating H#1. The second objective is to explore energy flexibility potential of some electrical loads to enhance the performance of the REC in terms of increase the benefits of such entities for the members, according to (Entidade Reguladora dos Serviços Energéticos, 2023a), hence answering RQ#2 by the validation of H#2.

The devices considered for study, in experiments related with exploitation of energy flexibility potential of shiftable loads, are plug-in electric vehicles (PEV) for a complete assessment of the load shifting benefits and the impacts of unavailability of such devices to be managed. Regarding local generation units, PV systems are considered due to data availability for modelling the out power of self-consumption units and their penetration in Portuguese buildings.

The innovative aspect of this work regards the development of a process for the building's devices operation as flexibility sources, which may consider them as a virtual storage device given the impact of the exploration of their energy flexibility potential on the aggregated load diagram of a specific REC. Therefore, their energy flexibility is defined as the ability to alter their consumption, similarly as a traditional electricity storage device, with the option to pause the operation cycle if needed. This modelling is to be developed taking into consideration the black box-based model approach. By the parametrization of the inputs and, mainly, the outputs, the developed algorithm can make the necessary aggregation of a defined system, from a single building to a large cluster as a REC. The aggregation is also paramount when the cluster is participating in energy markets as a flexibility provider, consuming or generating energy, depending on the market's needs. Regarding the REC management entity, the main objective refers to the development a calculation method for a time-variant dynamic sharing coefficient, named "Dynamic Sharing Coefficient", which considers the instant power demand of REC members and the available power, locally generated by a given number of members, or even a generation facility owned by the formed REC. Furthermore, the proposed sharing coefficient is capable to comply with subjective parameters for its calculation, such as the level of energy poverty that a given REC member can be suffering. In this case, a mix of technical, financial, and social parameters can be used to calculate the electricity share of each member. To the best of the author's knowledge, no actual proposal and analysis of their impact are described in the existing literature. Some theorical proposals have been discussed in the past years, but no actual research is made to assess the impact of a time-varying sharing coefficient on the performance of a given REC.

1.4 Conducted Research

To achieve the proposed objectives for this work, a bottom-up approach is defined to describe the energy flexibility characterization of a selection of a selection of household devices, the potential to provide this flexibility for the system in which they are inserted, and the aggregation possibility, in the context of a cluster of buildings associated as a REC. The bottom-up approach is the chosen technique due to the facility of the study of smaller entities and the consequential adding process into bigger clusters. Therefore, the research starts regarding individual devices and will progressively end on a cluster, which size will be defined suitable to answer the research questions proposed on section 1.2 of this document.

The first task is to identify, on the literature, the state of art regarding the characterization of energy flexibility for household devices, and how these devices are used to achieve the defined objectives for the energy flexibility measures. Furthermore, the literature review has the objective to identify the recent endeavours of the association of buildings as RECs, and how the European and local legal framework comply with the needs of users and manager entities. These two topics are described, in the following chapters, separated, for a better understanding of readers. For the topic of energy flexibility, a collection of papers is made based on keywords, such as "demand response", "energy flexibility", "residential". The search of scientific papers regarding energy communities is made by using the same strategy, using keywords such as "renewable energy communities", "energy sharing", or "European Directive".

One of the objectives of this work is to characterize, based on the literature review, the energy flexibility potential of event-based household devices based on their electricity consumption or generation pattern. This characterization assumes that the devices can be modelled as black boxes. The main advantage of this model is the non-dependence of the physical behaviour of the device operation (Ljung, 2001), which can increase the complexity of the mathematical approach for the remaining work to be conducted on this research. The outputs of this model and consequential characterization will be designed to make possible the aggregation of the assessed devices. For the characterization development, it is important to define the electricity flexibility potential of each device, based on a considered number of variables. Due to the meteorological characteristics of Portugal, only shiftable loads will be analysed in this work case studies, as long with distributed energy generation and chemical energy storage installations. The characterisation of the energy flexibility potential of the shiftable loads will be formulated based on the modification on the building's load diagram caused by shifting and pausing occurrences of such loads, in a similar way as a storage installation.

The characterisation of the energy flexibility potential of shiftable loads is the basis for the development of an algorithm that can exploit this potential. This algorithm aims to manage shiftable loads based on the main identified characteristics of such devices. For a proper visualisation and monitoring of the available flexibility at any given time, the changing on the load diagram is the main parameter, and the management methodology is to consider this alteration as the operation of a storage device, called "Virtual Storge Installation". Regarding the REC management strategy, an algorithm that proceeds to the dynamic sharing of locally generated electricity among the members is also developed. The goals of this algorithm are to maximize the self-consumption of RES units present into the community boundaries, minimize the energy import on peak hours, to indirectly decrease the system's GHG-emission, based on a CO_2e (the equivalent amount of Carbon Dioxide, in the situation of other gases emission, which can cause the same effect in the atmosphere), and decrease of the cost of energy imported from the grid. For this, the time-variant energy sharing coefficient, named "Dynamic Sharing Coefficient" is the main component of this management strategy, based on the Portuguese framework for its development (Entidade Reguladora dos Serviços Energéticos, 2023a).

1.5 Document Structure

The following chapters of this document are structured as follows: Chapter 2 is dedicated to the governance of Renewable Energy Communities. Section 2.1 initiates with a literature review of the topic, also exploring the usage energy flexibility within the context of RECs (Section 2.1.1). Section 2.2 describe the legislative landscape, providing an understanding of regulatory frameworks shaping the operational contours of RECs in Europe and specifically in Portugal. The reason for choosing Portugal is the context of this work, which is based on part of the solutions developed for the Portuguese pilot of the Horizon 2020 project POCITYF (POCITYF Project, 2022). The points on the body of knowledge that need further investigation regarding energy management in RECs, i.e., the sharing strategies, are discussed in Section 2.3. The core of the chapter, Section 2.4, introduces the Renewable Energy Community

Management Framework, accentuating the permitted ways to calculate energy sharing coefficients as a structured approach to community-level energy management, and the proposition of a novel manner to share electricity among REC members.

Chapter 3 examines energy flexibility modelling for event-based and storage devices. Section 3.1 conducts a literature review, classifying devices (Section 3.1.1), describing energy flexibility objectives (Section 3.1.2), characterizing devices' energy flexibility (Section 3.1.3), and describing the knowledge gaps identified in this research, and how it is aimed to address them (Section 3.1.4). Section 3.2 explores the nexus between Event-Based Devices and their operation as a Virtual Storage Installation and how the energy flexibility potential inherent in such devices can be explored in the view of a consumer, to provide them economic benefits in terms of imported electricity import and associated values.

In Chapter 4, the dissertation presents the experiments and analysis of the empirical results achieved through simulation. Three distinct scenarios are systematically explored: the performance of diverse sharing strategies in a non-residential REC (Section 4.1), including the proposed time-variant sharing coefficient; the energy flexibility potential of Event-Based Devices by operating them as a Virtual Storage Installation (Section 4.2); and the impact of such devices' energy flexibility potential on energy sharing coefficients in a REC context (Section 4.3). Each scenario is underpinned by a set of performance indicators, providing a scientific and quantitative basis for subsequent discussions. For experiments described in Section 4.1 and 4.3, real consumption and solar irradiation data are used to assess the propositions of this work. On the other hand, in Section 4.2 simulated consumption data is used to design experiment #2, along with the same solar irradiation dataset used on the other experiments.

Lastly, Chapter 5 focuses on the description of the findings of the research conducted in this work. Section 5.1 provides an overview of the research work, summarizing key aspects of the investigation. Section 5.2 discloses primary findings and contributions, integrating the insights derived from the conducted study. The chapter concludes with Section 5.3, delineating possibilities for future research, thereby meaning the document's contribution to the ongoing scientific body of knowledge within the specialized domains of energy flexibility and Renewable Energy Community management.

2

Renewable Energy Communities

2.1 Literature Review

To increase the usage of locally generated energy, consumers and prosumers can be associated as energy communities, to share the prosumers' surplus energy after the individual self-consumption among the associated members. This association can function as a peer-to-peer (P2P) framework, in which the peers can buy or sell energy from each other, in a direct manner, without the interference of the network operator and/or suppliers (Zhang et al., 2018; Soto et al., 2021). When operating in a P2P trading platform, members which own generation units are able to trade a certain amount of energy with the remaining peers (Zhou et al., 2020). The management model of a P2P energy trading process can be made in different manners. The augmented model for coordinated energy management proposed by (Verschae, Kato and Matsuyama, 2016) allows the community members to manage their consumption and generation in a jointly manner, by a control feedback for the coordination schemes, which gives the community the ability to manage their resources. (Jing et al., 2020) states that P2P energy trading is a promising model for the evolution of the energy market. In this sense, an optimization-based trading tool for a fair energy trading between both residential and commercial buildings is proposed. Results shows that electricity and heating can be traded, and despite the achieved cost savings, the trade-off of the fairness among the participants must be taken into consideration when managing the energy trading. The P2P energy trading frameworks can also provide benefits for the energy network. (Paudel et al., 2020) utilize a P2P electricity trading mechanism which considers the grid power loss and network utilization fees to calculate the optimal price for electricity trading among members. The objective is to maximize social welfare by adjusting the trading prices and the generation and consumption demand, i.e., how each participant evaluates its own welfare among certain aspects, and to achieve a balance between supply and demand in the local market. The insertion of electricity storage devices on a P2P framework is assessed by (Rodrigues et al., 2020). They compare the impacts of an electricity provider and a user ownership of electricity storage devices on a P2P electricity trading process. Results showed that the net present value (NPV) is higher when the user owns the storage devices. However, when the P2P process is conducted with storage devices owned by the electricity provider, the context for prosumers to engage in P2P electricity sharing and achieve energy costs savings is favourable due to the presence of a storage device that is present in the system without the investment need by the participants.

Research regarding the implementation and management of renewable energy communities, assembled as stated by the Directive 2018/2001, has been increasing in the last years. (Botsaris et al., 2021) presented the business case and the entities involved on the development of a REC on a student's residence in a Greek University. The REC is formed by the Democritus University of Thrace, the Municipality of Xanthi and a local industry. The considered RES are wind turbines, solar PV, solar thermal, biomass boiler, and geothermal heat pumps. They also have thermal energy storage and electricity storage devices. This REC's objectives are to reduce CO_2 emissions and achieve energy bills reduction. The business model is based on the reduction of the University energy bills through self-consumption and to enable the REC to offer flexibility services by a P2P scheme. They also have an incentivization scheme, aiming to affect the student community to increase the RES usage by promoting the consumption of energy produced locally, by reducing the overall consumption, and by changing the demand profile, giving preference to use energy at the local RES generation peaks. The remaining members of the REC participates by purchasing the energy surplus generated by the University, which is negotiated individually by the REC manager entity, owned by the University. It is concluded that the end-users of this REC, despite not being able to achieve direct financial savings from adapting to the REC needs, can contribute to reduce the University energy bills and reduce CO_2 emissions. In a different context, (Ceglia et al., 2021) assessed a REC formed by two office buildings in an Italian city. Both buildings have installed rooftop photovoltaic systems, and one of the buildings has a PEV. Thermal energy demands are satisfied by two reversible air-to-water heat pumps. There is a local microgrid that connects the buildings and is in parallel with the distribution grid. In this case, the members are co-owners of the electricity generation devices. The considered case study compares the performance of the REC with the standalone operation of each member, in a situation in which they are not allowed to share the energy locally generated. Results show that the sharing ability can increase the usage of energy locally generated, with a consequential reduction on energy import, and provide benefits for both the REC members, by the reduction of energy bills, and to the energy grid, by reducing losses and postponing investments. However, the authors argue that there is a necessity for the development of business models, suitable at a local level, proceeding to a transposition of the published European legal framework for the implementation of RECs.

Regarding the sizing of a REC, (Fioriti, Frangioni and Poli, 2021) developed a business model in which the REC aggregator solves a optimization problem in order to maximize its own net present value when assembling the community, based on the users' constraints. There is a special constraint that specifies that the community NPV must be higher than the sum of each member one if the community is not assembled regarding the installation and revenues of generation units installed. In summary, the main objective of the REC aggregator is to increase the profit of each member to a point in which it is more advantageous the association than to operate their assets individually. There is a proposition, as case study, on different levels of operation, from the baseline without the assets needed to self-consume energy from renewable sources to a scenario when all the considered buildings operate as a single entity, namely a REC. Results address the viability of the association of buildings as a community, since their operation brings better results in terms of energy costs, considering the investment for assembling the needed assets. Also, the remuneration scheme proposed by the aggregator can lead to cost savings by a maximum of 24% higher than the operation of the buildings with renewable assets, but without cooperation as an operation as a community. The authors state that the proposed business model can bring benefits on a social, technical, and environmental point of view, such as an increase penetration of RES and self-consumption, and a decrease on the peak power of a distribution grid due to the increased self-consumption of energy generated from a local source. In theory, RECs can also be used, when connected to an electricity grid, to maintain the users' comfort level when there is a lack of electricity supply by the provider. (Mar, Pereira and Martins, 2021) studied how to use the energy flexibility of an energy community, when a power failure occurs, to maintain the service level of the end-users and to aid the system operator until the power supply is recovered. The considered flexibility for the study is the time displacement of washing machines, dryers, and dish washers of the community's buildings. It is considered that only one of the community's members has a local renewable energy source, which is a solar PV system. The changing on the devices' operation, and a disconnection of some of the controllable loads were needed to keep the community running when the only source of energy is the solar PV system, i.e., in a situation of a total failure of the network provider. When the failure is only partial, with a decrease of the available power, with the redistribution of the controllable devices' operation schedule, the community can address the failure and maintain the users' wellbeing.

One possibility of the association of buildings into an REC is the energy (or power) sharing among the members. This sharing is described as a possibility by the Directive 2018/2001, and modelled by (Martirano et al., 2021). They propose a model for a given local energy source to connect it to a cluster of users, which are then able to share the power generated by this source as a community, with the objective to minimize the electricity exchange with the grid and assess the economic aspects and impacts of this operation. This power sharing model is conducted by the management of a single point of connection assessed by the two buildings used as case study, in which only one of them has a local source of energy, namely a solar PV system. The point of connection is managed by a "Common Power Sharing System" and has the premise to avoid power exchange between buildings, by considering a unidirectional inverter as a connection between the users and the power sharing system. Thus, it is considered a common energy service in the context of the joint operation of the buildings considered as case study. This configuration leads to a greater self-consumption of the solar PV system generated electricity, avoiding selling and import from the grid.

(Mutani, Santantonio and Beltramino, 2021) considers a real REC, assembled in Italy, to study its technical-economic feasibility, based on the investment and economic incentives for the respective members aggregation to the REC. The considered REC is composed by the

Town Hall building, a warehouse, the public lightning system, a local industry, and a social housing system. This configuration is justified by the diversity of electricity demand profiles and to comply with local legal requirements for a REC association of buildings. There is a comparison of an individual and collective operation of the buildings, with the buildings participating in different manners in each considered scenario. It is also assessed the impacts of the installation of storage devices and energy efficiency measures proposition on the cost-benefits analysis. Results shows that the region in which the REC is formed, with abundance of renewable energy sources and buildings with low energy consumption, is favourable for the achievement of high rates of self-consumption and self-sufficiency of the REC members. Authors claim that batteries, despite increasing the considered indicators for the case study, have high environmental and economic costs, and their implantation must be carefully assessed beforehand. It is also evidenced that economic incentives for energy efficiency measures must be carried out by governments for the objective achievement. (Olivero, Ghiani and Rosetti, 2021) also assess the implementation of a REC in Italy. In this case, the energy is produced and exchanged locally between the participants, namely: one small artisan company, three residences, and four public buildings, including the Town Hall, in which a solar PV system, with 19.8 kilowatt-peak (kWp), is installed, feeding the building load, an PEV charging plug and sharing with the remaining participants. The charging plug can be freely used by the citizens. This only local source of energy can be responsible for approximately 55% of the total consumption of the REC members throughout a year. However, during the months with higher potential of solar PV generation, namely from April to September, almost all the generated energy is self-consumed by the participants. This production leads to an average decrease of 21% on the energy bills. Regarding technological devices to make the REC assembling viable, there is considered the installation of smart energy meters and a software for the energy management, which is capable of manage energy flows in real time, monitor power quality, optimize self-consumption, analyse the remuneration of self-consumed energy, and to proceed to demand response actions if needed.

The configuration of a REC is assessed by (Weckesser et al., 2021). This assessment focused on the sizing and positioning of generation and storage units to be installed for the participants using. For a possibility to provide grid services, the positioning of the collective storage units is also assessed in terms of impacts on the distribution grid. The specific objectives are the maximization of economic benefit of the devices' installation position, the reduction of peak power on the distribution grid, and the maximization of self-sufficiency based on the position of the storage units. The mentioned objectives are assessed regarding their impacts on the grid. Results shows that the levelized cost of electricity, despite having the lowest value when considering one large commercial consumer, the variation between the values in all the considered scenarios is relatively low (<6%). The storage position can cause an important impact on grid voltage. In this sense, the voltage deviation is larger when the storage device is installed at the end of the feeder. On the cases in which the storage is installed at the beginning of the feeder the deviation is approximately half of the previous situation. The mainly objective of the community also impacts the distribution grid. If the purpose of the community is to provide economic benefits for its members, the voltage between phases, at low-voltage (LV) level might be higher, due to generated peaks during night hours (in which energy prices are lower), comparing with other possible objectives. This configuration also has a great impact on the medium voltage (MV)-LV transformer in some configuration.

As will be covered in Chapter 3, it is important to have a formal definition of the energy flexibility potential of an energy system. In this sense, The IEA – Energy in Buildings and Communities (EBC) Annex 67, in the publication “Energy Flexible Buildings”, defines energy flexibility as "*the amount of energy generated and/or consumed by a building that can be managed, respecting restraints such as climate conditions, user needs, and the energy system requirements*" (Jensen et al., 2017). Furthermore, on the context of the IEA's "Energy in Buildings and Communities Program" (EBC), a research project called "Annex 82 - Energy Flexible Buildings Towards Resilient Low Carbon Energy Systems" aimed to "*gain important knowledge about the energy flexibility services that buildings and clusters of buildings may deliver to different types of energy networks*" (International Energy Agency, 2020). One of the outcomes of this research project is a study that assess the potential and limitations of energy flexibility at an aggregated level (Le Dréau *et al.*, 2023). This study identified the main barriers and limitations for the implementation of energy flexibility in aggregation of buildings, in a technical, economic, social and policy dimensions. Regarding legislation, despite the mapping of different legal mechanisms that empower and remove barriers for exploitation of energy flexibility and the participation of cluster of buildings in flexibility markets, in an aggregated manner there is still a lack of regulation documents that enables the creation of such markets. Furthermore, the limited access to wholesale markets by aggregated buildings and concerns regarding citizens privacy and cyber-security threats impose critical barriers for the enablement of infrastructures and implementation of business models coherent with such market. In this sense, the creation of knowledge share strategies, frameworks for enabling demand flexibility markets by aggregated buildings, development of novel pricing structures and the reinforcement of privacy protection are proposed.

The association of energy consumers as a REC can provide benefits for them, mainly related to economic benefits in terms of reduction of energy bills, by using locally generated energy individually or sharing a certain amount of this energy among them. Nonetheless, these benefits can be increased if the REC management entity uses members' load flexibility potential when operating the community. Implementing To this end, Demand Side Management (DSM) strategies play a crucial role, by considering the flexibility potential of flexible loads, and the scheduling of storage units' usage, both deterministic (Battery Energy Storage System - BESS) and stochastic (PEVs). The application of DSM measures provides a potential increase on the REC performance regarding economic benefits. However, environmental conditions causes impact on this performance, similarly to the consideration of a REC operating without flexible loads, due to some restrictions of the production of energy from local renewable resources.

(Reis et al., 2020) developed DSM exploitation strategies for a multi-purpose buildings energy community to maximize its self-sufficiency. The strategies are based in a multi-agent system, in which each agent is capable, through the dedicated algorithm, to decide how to behave under the given circumstances of the energy community operation to reach their goals, described by the maximization or minimization of an objective function. In this work, the agents are each residential and non-residential members of the energy community. The case study of this work comprises 100 residential agent, and 5 non-residential ones (3 small and medium enterprises (SME), and two cross-sectoral activities companies of public lightning services). There is also an energy community coordinator agent and a retailer agent. The residential agents have their loads distributed stochastically, which are divided in manageable loads, such as washing machines, tumble dryers, dishwashers, air conditioners, and electric water heaters. PEVs and BESS are also present among these agents. Regarding the non-residential buildings, since information on the installed equipment is not available for the acquired datasets, a general approach of load reduction measures is conducted during the simulations. For the public lightning services, the chosen techniques are "light-on-demand" and controllable dimmers. The simulations were conducted considering a 7-days horizon, both on summer and winter, to assess the impact of ambient conditions to the prosumers. Results clearly shows the impact of prosumer penetration on the available energy inside the community border. Furthermore, the diversity of agents in terms of energy consumption pattern is also an important factor when assessing the performance of the community. The more diverse are the agents, the better is the capacity of absorbing the energy generated by the prosumers. The interaction between residential agents, where peak load occurs during the night, and the SMEs, with a more intense energy consumption during daytime. Results also show a better performance in terms of minimization of costs during summer due to a more abundant renewable resources available.

Cluster of buildings can participate in flexibility markets via an aggregator entity, responsible for adding the individual potential of each building flexible loads and act as intermediate between the cluster (e.g., an energy community), and the flexibility market operator (Zhang, Good and Mancarella, 2019; Stede et al., 2020). In this sense, (de Villena et al., 2020) developed a model based on muti-agents capable to simulate a REC containing multiple flexible assets, such as loads and generation units, and a strategy for the activation of flexibility bids, allowing the REC to participate in flexibility markets. To assess this framework, the authors used real data from 20 flexible and 10 non-flexible consumers in Belgium. The simulated REC also contains a 48 MWp solar PV installation, with production simulated with real weather data from the same region. Results shows that the incorporation of flexibility into the REC operation can decrease the total system cost by up to 7%. It also increases the self-sufficiency and self-consumption ratio of the REC members.

Other objective of the application of energy flexibility is the reduction of peak load of a building or cluster of buildings connected as a community. That is the purpose of the study conducted by (Tomar et al., 2021), in which a Dutch university campus is considered for the application of the energy flexibility provided by heat pumps and air conditioners, called colling loads by the authors. The campus is composed by 14 heterogeneous buildings, with a distinct electricity consumption profile, with the presence of non-flexible loads in different proportions. The data considered for study is gathered in an aggregate way. For the controlling of the heat pumps and air conditioners a modulate method is proposed instead to simply turn the devices on and off, to avoid any adverse impacts on the users' comfort. Two flexibility indicators are considered to calculate the potential of the flexible loads. The first one considers the total energy used above a defined maximum power allowed, whereas the second one considers the total energy usage during peak and off-peak hours. Regarding the peak decreasing, there is a 16% reduction, without significant impacts on the energy usage, compared with the baseline. This economic difference depends on the voltage level of the connection between the grid and the main feeder of the community, since there are two distinct ways: directly to the transmission grid, through a MV-LV transformer, or to the distribution grid. These options lead to different tariffs.

The energy flexibility potential of an energy community can also serve to provide ancillary services to energy grids, namely electricity distribution grids. This is the approach of the study conducted by (Burgio et al., 2022), in which a considered number of solar PV systems installed in residences, along with BESS systems, in an energy community, is used to provide upward flexibility services. The developed heuristic method was designed to calculate a short-term upward flexibility potential, in a scenario in which the grid operator needs an urgent upward service in a considered area. The method is based by exploiting the surplus generation of the solar PV systems operating jointly with the BESS, using its state-of-charge (SoC) as the main input variable for calculation. The case study to assess this method considers real data from four energy meters of four modern houses. Each household also have a HEMS, responsible for measuring local power flows through the meters. The management of the solar PV systems with the respective batteries via Home Energy Management System (HEMS) can provide to the distribution grid 8 kW constantly for up an hour, if needed, based on grid needs.
In a similar way, a community-level energy storage system, formed by the association of individual residential batteries, is also used to provide ancillary services to the electricity grid, in a study conducted by (Nagpal et al., 2022). However, this service is complementary to the first

usage of this community battery, which has the primary objective to increase the energy community members' self-consumption and self-sufficiency indicators by sharing a part of the stored energy by each unit. The main goal is to share the community battery with the community members and the grid. The case study comprises a local energy community (LEC) formed by 15 residences, which one containing two 3.6 kWh batteries, forming a community battery system with 108 kWh of capacity. The real-time framework, along with the fixed and pre-specified time duration, turns the HEMS able to re-adjust the operating schedules of the flexible loads, and to quantify the available flexibility that the LEC can provide to the grid. There is a drawback in this framework, namely the compromising of the LEC profit when the flexibility is mainly served to provide ancillary services, due to the higher amount of electricity that must be imported, since the stored electricity is not using to fulfil the members' needs.

2.2 Legislation

The European Union (EU), in a collective effort to mitigate climate changes effects, which are mostly caused by the emission of GHGs, has been encouraging its Member States to increase the sharing of RES into their energy pool. These sources have, as main characteristics, the low level, or even the absence, of GHG emission during the generation process, and an intermittence of the energy generation pattern (Lopes *et al.*, 2018). The RES share in a given energy system is influenced by the extent to which government bodies enforce measures that actively incentivize the adoption and using of such energy, ensuring that renewable sources play a central role in meeting energy demands. The association of consumers and prosumers, to increase the usage of locally generated energy, through RES collective self-consumption is, in this context, one of the main tools that is used to achieve objectives regarding the usage of renewable energy and is encouraged over the last years.

This encouragement is performed by the publication of a series of legal propositions, in forms of Regulations, Directives, Decisions, Recommendations and Opinions (European Union, 2021), in which there are procedures that Member States should follow to achieve the proposed aims of the treaties signed by the EU. However, there is a difference between the legal propositions. The Regulations are binding legislative acts, and their instructions must be applied in its entirety. The Directives are legislative acts that set goals that all Member States must achieve by creating their own laws to specifically achieve these goals. The Decisions are binding, but only on those to whom it is addressed and is directly applicable. The Recommendations are not binding, and only suggest a course of action. Lastly, the Opinions are used for the institutions to make a statement without imposing any legal obligation. Regarding the energy self-consumption, both individual and collective, the EU states that it is an important measure to assure the goals set by the Directives 2018/2001 and 2019/944.

The Directive (EU) 2018/2001 (European Parliament and Council of The European Union, 2018), published on December 11th, set goals for the increasing of RES usage. On its "Preliminaries" is stated that there must be an encouragement investment in new, flexible, and clean technologies. It is also stated that all the EU Member States must consider the cost-effectiveness of RES integration and the impacts of the capacity increasing. The proposed measures might be of regulatory nature, such as market design or investments on flexibility sources, i.e., grid interconnections, energy storage, DR technologies and distributed and flexible generation units. On Article 3 of the document, titled "Binding overall Union target for 2030", it is stated thar the European Commission shall support the countries ambition regarding the increase of renewable energy technologies on the energy mix. This support must be made by enabling a framework for the use enhancement of Union funds, among other measures, by the incentive for development of programs and projects for renewable energy integration and flexibility increasing.

Regarding the electricity market, Directive 2019/944 (European Parliament and Council of The European Union, 2019), published on May 30th, focused on the common rules of the internal electricity markets, also states that the renewable energy usage targets should be met by the "creation of a market framework that rewards flexibility and innovation". In this way, the consumers must play an important role in achieving the flexibility for the adaptation of their electricity consuming devices, to achieve the increasing of renewable, distributed, and intermittent generation systems on the electricity grid. It also incentivizes the consumption, storage and selling of self-generated electricity, as means to participate on local markets, including the flexibility provision to the grid. In this context, the smart energy meters play an important role and should not be a barrier on the participation in electricity markets. Additionally, it recommends that the EU countries should proceed to a new framework of codes and rules for the electricity system to facilitate the implementation of flexibility measures. Such framework is suggested to have as an element the rights for entering electricity markets without the consent of other participants. On the other hand, there markets must have transparent rules regarding addition or removal of members and data exchange between them. There must be an obligation, on markets participants, to be financially responsible for every imbalance that are caused on the electricity grid. Lastly, a conflict resolution mechanism must be put in place for participants engaged in aggregation and other market models.

Both legal entities also incentivise the association of consumers, residential or commercial/industrial, to trade their flexibility and self-generated electricity into local markets. In this sense, the concept of REC and Citizen Energy Community (CEC) are developed to comply with this incentive. Despite the similarity among both definitions, namely: the free and voluntary participation by consumers, the ability to manage the energy generated inside their borders by local and renewable sources and the entitlement to access all electricity markets, either directly or by aggregation, there are some differences between these two entities. The main difference is the possibility, by the CEC, to own, establish, purchase or lease distribution networks, which is described on the number (2) item (b) of Article 16 of the Directive (EU) 2019/944. However, this possibility must be granted by the Member State and, in the case of a negative, both REC and CEC are a similar concept, and operates in a similar manner.

For a proper study of the behaviour of a REC, a national legislation must be chosen, for a proper design of the management algorithms. The choosing of the country to study can interfere with the results (Lage, 2022). To this end, for the specific purpose of this study, Portugal is chosen for the development of the algorithms for REC management. Furthermore, the research made during this work is inserted in the context of the Horizon 2020 project POCITYF, "*an EU-funded smart city project that will help historical cities to become greener, smarter and more liveable while respecting their cultural heritage. By implementing and testing Positive Energy District in its cities, POCITYF will support Europe in the race to become the first Carbon Neutral Continent by 2050*" (POCITYF Project, 2022).

Portugal, as one of the EU Member States, address the importance of the aforementioned legal framework (Directives 2018/2001 and 2019/944) by the publication of the Decree-law (DL) 15/2022 (Presidência do Conselho de Ministros, 2022), which approves the applicable legal regime for the renewable energy self-consumption, both individual and collective, transposing the Directives (UE) 2018/2001 and 2019/944, and the Regulation 815/2023, by the Portuguese Energy Services Regulatory Authority (Entidade Reguladora dos Serviços Energéticos, 2023a), the legal person governed by public law, endowed with administrative, financial and management autonomy which purpose is to regulate the electricity, natural gas and liquefied petroleum markets (Entidade Reguladora dos Serviços Energéticos, 2021). The Regulation

815/2023 has the purpose to regulate the electricity self-consumption, both individual and collective, and the relationship between the various stakeholders involved in this process. The DL 15/2022 propose a REC legal definition for the Portuguese context. It defines a REC as "*a collective body, constituted as stated in this decree-law, based on an open and voluntary member accession, partners and shareholders, which can be each one a singular or collective body, public or private, including, SMEs or local authorities*". Figure 2.1 show a possibility of association of buildings and energy assets as a REC.

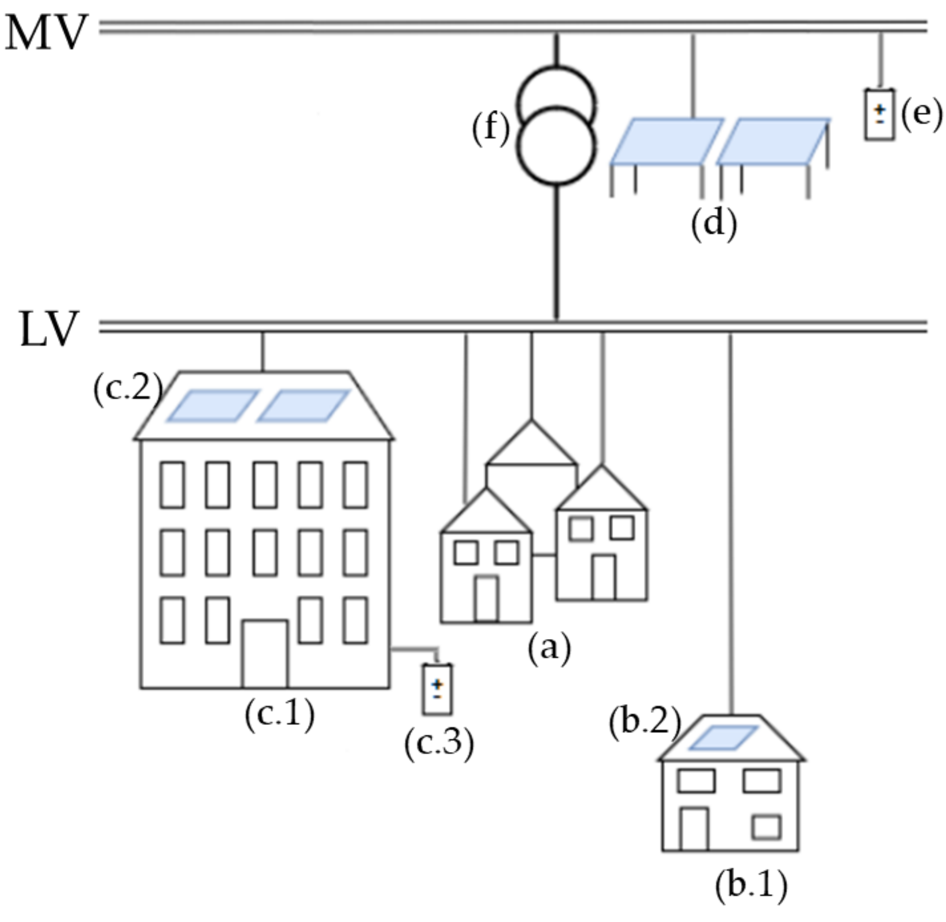

Figure 2.1 - A possibility for a Renewable Energy Community, adapted from (Fina and Auer, 2020)

In Figure 2.1, it is possible to visualize all the possible actors available to participate in a REC according to the Portuguese legislation. Those actors are (Entidade Reguladora dos Serviços Energéticos, 2023a):

(a) a given Consumption Installation (CI), a private electrical installation licensed according to (Presidência do Conselho de Ministros, 2022), for the usage of one or more clients, connected to the low voltage grid, registered to perform self-consumption, and connected to the public grid directly or via an internal network.

(b.1) a given CI which has a private Self-Consumption Production Unit (SCPU), a production unit which has as main primary source renewable resources, associated to one or several Consumption and Storage Installations (SI).

(b.2) the SCPU which belongs to (b.1).

(c.1) a given CI which has a SCPU and a SI.

(c.2) the SCPU which belongs to (c.1).

(c.3) the SSU which belongs to (c.1).

(d) the Production Installation (PI) which belongs to the REC, an electrical installation licensed under the terms of (Presidência do Conselho de Ministros, 2022) entitled to generate energy from renewable sources to one or several CIs, connected to the medium voltage grid directly of via an internal network;

(e) the SI which belongs to the REC, an electrical installation licensed under the terms of (Presidência do Conselho de Ministros, 2022) entitled to store energy generated from renewable sources. It can be one or several devices, both statics or by using plug-in electric vehicles' batteries, connected to the medium voltage grid directly or via an internal network.

(f) the MV-LV transformer that connected the PIs and SIs to the remaining assets of the REC.

2.3 Discussion

Directive 2018/2001 brings the definition of a REC, with the possibility of such entities to, among other operations, share part of the locally generated energy among the members. Despite this possibility, there is still a need to address the impact of different sharing strategies on the performance of RECs in terms of economic benefits, both individual and collective. P2P energy trading mechanisms are also a possibility. However, optimization reveals to be too complex since this mechanism is based on free trade among peers, which leads to potential conflict of collective interests. Regarding sharing strategies, the possibility of a management strategy that takes into consideration the instant variation in consumption and generation is not properly assessed in the existing literature, representing a knowledge gap.

In this context, this work proposes a framework for the management of RECs, considering a calculation method for a REC energy sharing coefficient that can consider, at any given time, a variety of factors, such as consumption, local production, and other factors related to investments and social aspects of REC members. Therefore, this work addresses the identified knowledge gap regarding the energy management in a REC in H#1. The proposed method is explained in Section 2.4 and experimented in Section 4.1 of this dissertation.

2.4 Renewable Energy Community Management Framework

In Portugal, to implement a REC, a Collective Self-consumption Management Entity (CSME) must be defined (Entidade Reguladora dos Serviços Energéticos, 2023a), which is responsible for the commercial relationships between the REC and the remaining stakeholders, including the electricity sharing process between the REC members and between the REC and the Distribution System Operator (DSO). Regarding the sharing process, it is important to highlight that the shared electricity is part of the total electricity, generated within the borders of a REC, assigned to a given member, by using a sharing coefficient. However, the energy sharing process among the members is made after the billing period, by analysing the respective energy meters and proceeding to a financial operation to share the electricity, based on the informed coefficients, due to the physical impossibility to drive the electricity instantly to whichever building that has an energy share assigned. This operation is made by the addition or subtraction of the measured energy, considering the available energy to share in a certain time interval (e.g., the billing period). After the sharing process, the electricity for billing is calculated considering the modified load diagram (Ministério da Economia e da Inovação, 2022; Entidade Reguladora dos Serviços Energéticos, 2023a). However, despite the sharing process being a financial operation conducted after the real consumption and generation of electricity, there may be an actual alleviation of the power grid during the operation of the local solar PV systems, either when the buildings are self-consuming, or on the occasion of electricity surplus exportation to the grid (Lopes, 2017). This procedure is in line with the ambitions of the

European Commission regarding the increase of the usage of renewable energy sources close to the consumption site (European Parliament and Council of The European Union, 2018).

One of the most important characteristics of RECs is the possibility to self-consume part of the locally generated electricity, which can lead to possible net-zero power that can be instantly achieved by one or more members. This situation allows a greater share of electricity for the remaining building which are not capable to achieve net-zero power. Such electricity can be generated both from private SCPUs of a given number of members or from a PI owned by the REC members.

For the general formulation of the electricity management in a building with local RES units, the presence of storage devices is considered. Otherwise, only the electricity surplus is considered, which is exported entirely to the low-voltage distribution grid when buildings operate individually. Figure 2.2 presents an algorithm illustrating the management of local RES generated electricity. In this Figure, for a given time instant "t", "$\boldsymbol{p_g}(t)$" means the local energy source's production, "$\boldsymbol{d}(t)$" represents the instantaneous total demand of a specific building, "$\boldsymbol{nd}(t)$" is the building's demand after the self-consumption, "$\boldsymbol{m}(t)$" means the energy surplus after the self-consumption, "$\boldsymbol{SoC}(t)$" means the state-of-charge of the SI, "$\boldsymbol{b}(t)$" means the charged or discharged energy of the SI, "B_{max}" means the instant maximum charged or discharged energy of the SI, and "CAP" means the storage capacity of the SI.

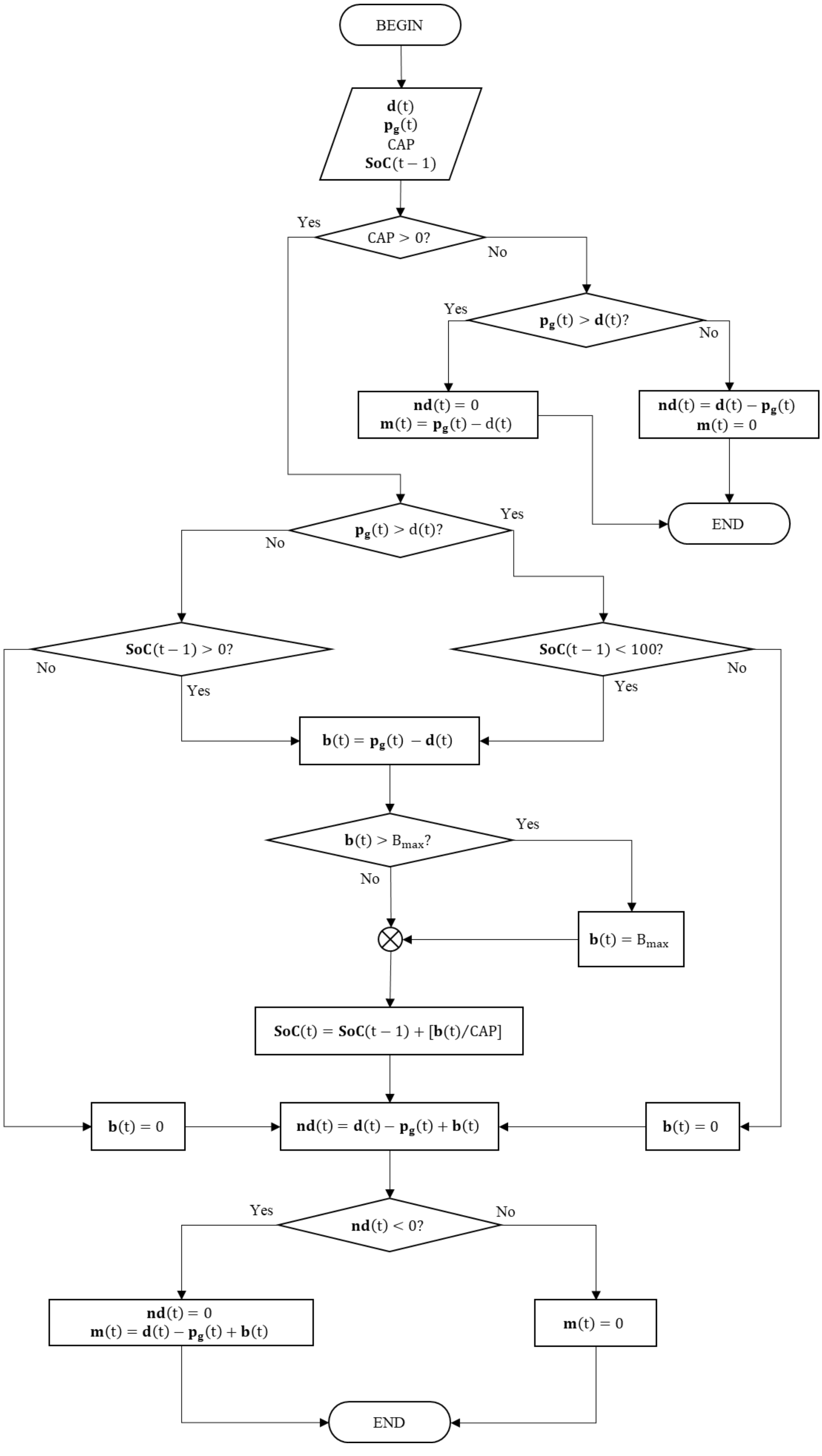

Figure 2.2 - Management algorithm for locally generated electricity

It is important to note that the algorithm showed in Figure 2.2 provides, at each time instant, the available surplus that a given REC member can contribute to an energy sharing framework in a REC context. Furthermore, the behaviour of the SIs present among the REC members is needed due to the duality of nature that this device presents. When it is charging, it behaves as a load (or a CI). On the other hand, in instants when the SI is discharging, it is equivalent to a SCPU. If there is no SI present on the building (characterised by the variable "CAP" equals to zero in the algorithm described in Figure 2.2), only the instant self-consumption of the locally generated energy is conducted.

The precise amount of surplus electricity available for sharing among REC members depends on the chosen operational strategy. For instance, if the REC manager allows members to self-consume a portion of locally generated electricity, the surplus available for distribution decreases accordingly. This rule-based algorithm considers solely the local conditions when determining the allocation of surplus electricity for self-consumption or export to the electricity grid. Furthermore, when considering storage units, different amounts of electricity are supposed to be available, due to instant charging and discharging processes of the storage units.

The variable "$\boldsymbol{m}(t)$" has its importance in this context as it incorporates the power readings obtained from the smart energy meters at building level. Positive values of "$\boldsymbol{m}(t)$" means instances where the local RES system generates an excess of electricity, capable of fulfilling the instantaneous needs of the building while also leaving surplus power for export to the grid. In such cases, the building's demand post-self-consumption, as indicated by the variable "$\boldsymbol{nd}(t)$", is reduced to zero. Conversely, when "$\boldsymbol{m}(t)$" equals zero, this indicates that the local RES system was not capable to generate adequate electricity to meet the building's full requirements at the considered time slot. In these instances, "$\boldsymbol{nd}(t)$" reflects the unfulfilled demand, representing the disparity between the initial demand and the local RES production ($\boldsymbol{p_g}(t)$), necessitating the import of electricity from the grid to bridge the gap. As mentioned before, positive values of "$\boldsymbol{m}(t)$" also means that there is energy available for sharing to the remaining members of a REC that, at the same time instant, have positive values of "$\boldsymbol{nd}(t)$".

When buildings operate as a REC, the collective self-consumption is made by sharing the electricity generated from its assets, namely the PIs and SCPUs. The share of each member is calculated by applying a sharing coefficient, which can be defined as the percentage that each member has from the summation of the electricity generated and/or stored by the REC's assets. It is important to note that, regarding the SIs, there is a duality when sharing the electricity: on the instants in which those units are charging, they are considered a CI and are entitled to a share of the electricity. On the other hand, on instants in which there are discharging of electricity to the members' CIs, they are considered as a PI (Entidade Reguladora dos Serviços Energéticos, 2023a).

The general rules of sharing energy described in (Entidade Reguladora dos Serviços Energéticos, 2023a) states that the sharing of the energy among the REC's CIs is made by the DSO on each 15-min interval according to the sharing coefficients which are defined by the CSME and informed to the DSO. The sharing is made based on the electricity exported to the grid by the PIs, SIs or SCPUs. When individual self-consumption is allowed, the CIs with SCPUs integrated to their grid are only entitled to receive a share of electricity when there is no electricity injection by its SCPUs. The sharing coefficients, in turn, are calculated, for each member, by the rules agreed upon by all REC members (Ministério da Economia e da Inovação, 2022; Entidade Reguladora dos Serviços Energéticos, 2023a). The current rules, according to the most recent Portuguese legislation, are:

I) Fixed coefficients, for a considered time frame, for each member. The values are freely decided by the REC members (they can be equal for each member or different among them) and informed to the DSO by the CSME. Regardless the type, they must be informed to the DSO prior to the sharing processes.

II) Variable coefficients computed by any valid criteria (for instance hierarchy or measured consumption) as agreed by all REC members and using the time interval defined on the Portuguese regulation (Entidade Reguladora dos Serviços Energéticos, 2023b).

The variable coefficient has, as main characteristic, the ability to adapt itself among the different circumstances of REC operation, such as situations in which, for instance, some of the CIs does not need to import electricity due to its prior self-consumption or to avoid sharing excessive electricity to a given CIs, compromising the REC operation. Therefore, there must be a way to calculate it at any given time instant. A general formulation for the calculation of this Dynamic Sharing Coefficient (DSC) on a given timestep "t" is showed in Equation 2.1.

$$\mathbf{DSC_j}(t) = \alpha \times \left(\frac{\mathbf{A_j}(t)}{\sum_{j=1}^{N\_BLD} \mathbf{A_j}(t)}\right) + \beta \times \left(\frac{\mathbf{B_j}(t)}{\sum_{j=1}^{N\_BLD} \mathbf{B_j}(t)}\right) + \gamma \times \left(\frac{\mathbf{C_j}(t)}{\sum_{j=1}^{N\_BLD} \mathbf{C_j}(t)}\right) + \cdots \tag{2.1}$$

In Equation 2.1, " α ", " β " and " γ " are the ponderation of each considered parameter; "$\boldsymbol{A_j}$", "$\boldsymbol{B_j}$" and "$\boldsymbol{C_j}$" are the chosen parameters for the sharing coefficient calculation, namely: each member's electricity demand, local generation pattern, private assets' characteristics, investment of each member in purchasing and installing the collective assets etc.; and "j" is the reference assigned to each REC member. Regarding the parameters, they can be objective or subjective, depending on the REC configuration. For instance, a large amount of the energy to be shared can be driven to members that are suffering from energy poverty, to alleviate their spending on energy purchase. For that matter, one parameter to assess the energy poverty is the percentage of the electricity purchasing cost over the total building income. A higher percentage of this ratio can pinpoint to a building in which its users are suffering from a certain form of energy poverty. In this case, a higher ponderation can be assigned to this parameter, which leads to a higher share of electricity to the respective building. It is important to note that this formulation is based on the possibilities described in the Portuguese legal framework. However, it can be used in any electricity-based REC, since the sharing process is made after the actual instants of consumption and local generation. For a proper use of this process, there must be a compromise, from the DSO, of establishing a communication streamline with the REC managers and/or members, to make possible the calculation of such sharing coefficients and the adjustments on REC members' electricity bills. This is a possibility for Portugal and is considered as a benchmark for this proposition, without loss of generality.

Despite the different framework for the operation of a given REC regarding the management of the electricity generated from the SCPUs, the same sharing coefficients' calculation formula, described in Equation 2.1, can be used. However, the input values will depend on the configuration and permissions of the REC regulation by its members. The consumption refers to the building demand power after the individual self-consumption procedure takes place if this procedure is permitted. When only the collective self-consumption is allowed, the consumption needs is represented by the sum of all the electric operating loads and the power available to share is the total power production of the locally installed solar PV systems. This framework leads to a difference on the amount of energy available for sharing among the REC members, which depends on how they decide to manage the locally generated electricity. If the decision is to proceed to an individual self-consumption before the sharing process, the available amount of electricity to be shared is lower than when only the collective self-consumption is made, since part of the generated electricity is consumed by the building users. Figure 2.3 shows the general process for the sharing process for a REC based on electricity, and Table 2.1 describes the variables involved in this process (Queiroz *et al.*, 2023). The management algorithm described in Figure 2.3 can verify, at each time instant, the consumption after the sharing process ("$\boldsymbol{nbd}(t)$"), the energy shared to each member ("$\boldsymbol{s}(t)$") and export of energy associated to each REC member ("$\boldsymbol{ep}(t)$") through the application of the respective export energy sharing coefficient ("$\boldsymbol{ESC}(t)$"). It is important to note that, except of "$\boldsymbol{ep}(t)$", all other variables involved in this process are internal to the REC boundaries and are treated every billing period by the CSME and the DSO. REC members must decide how to manage the exportable energy that was not used, instantly or by the sharing process. This decision is limited by the options allowed by the national legislation, e.g., enter in a flexibility market through aggregation.

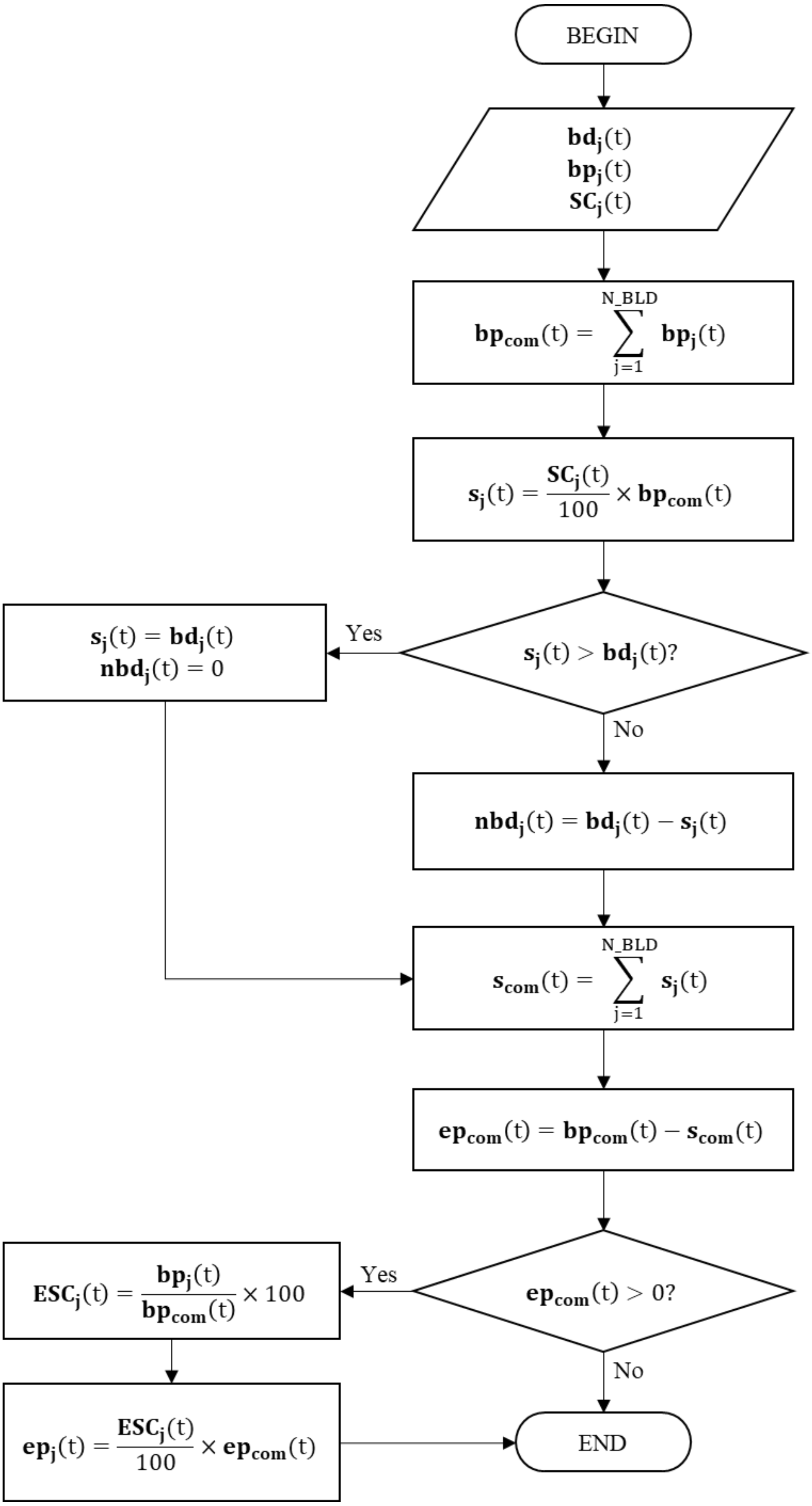

Figure 2.3 - REC energy sharing algorithm

Table 2.1 - REC algorithm' inputs and outputs

Parameter	Description	Unit
j	Index to reference a given REC member	-
com	Index to reference the REC as a whole	
N_BLD	Total REC members	-
	Inputs	
bd	Building demand in REC operation	kWh
bp	Building production available for sharing	kWh
SC	Energy sharing coefficient	%
	Mid-Process	
ESC	Export sharing coefficient	%
	Outputs	
s	Power to share	kWh
nbd	Building demand after sharing process	kWh
ep	Exported power	kWh

Another consideration regarding the sharing process of a REC is the importance to emphasize that the electricity shared within the REC constitutes a portion of the total electricity generated by its members. This shared electricity is subsequently allocated to specific members following the application of the chosen energy sharing coefficient, among the possibilities of the Portuguese legislation. However, due to physical constraints, the actual energy sharing process among the members is executed post-billing period by the DSO. This process involves an analysis of the data from respective energy meters and entails a financial operation based on coefficients provided by the CSME. The dynamic sharing coefficients, crucial for this process, are determined at 15-minute intervals, accounting for both energy generation and consumption. This calculation involves the aggregation or deduction of the measured energy, reflecting the available energy for sharing at each instance. Following the sharing procedure, the billing computation incorporates the adjusted shared energy (Entidade Reguladora dos Serviços Energéticos, 2023a). Despite the energy sharing process being primarily a financial operation conducted after actual electricity consumption and generation, it is essential to note that the operation of local PV systems can effectively alleviate both the power grid and the load diagram of the REC member. This alleviation occurs during instances of individual self-consumption within buildings or surplus electricity exports. Such a process closely aligns with the overarching aspirations of the EC, particularly its endeavours to promote the utilization of renewable energy sources in close proximity to the consumption sites (European Parliament and Council of The European Union, 2018).

Furthermore, it is essential to observe that in certain scenarios, REC members may opt for individual self-consumption of locally generated electricity. This choice can result in the possibility of achieving instant net-zero power balances and potentially a larger share of electricity for buildings unable to attain this status during a given time-step. Notably, while the algorithm showed in Figure 2.3 can be applied to RECs which permits the members' individual self-consumption prior to the sharing process and ones which only proceed to collective self-consumption, the input parameters differ. When individual self-consumption is permitted among REC members, the buildings' demand considering for the calculation of the sharing coefficients characterizes the demand following individual self-consumption procedures. In cases where only collective self-consumption is allowed, consumption requirements are defined as the sum of all electric operating loads, and the power available for sharing is equivalent to the total power production generated by locally installed RES systems. Similarly, the electricity available for sharing represents the power available at each time step. When REC operation is predicated on collective self-consumption, it means the totality of the power generated locally by all participating members.

This framework introduces a distinction in the quantity of energy accessible for sharing among REC members, contingent upon their choices regarding the management of locally generated electricity. Opting for individual self-consumption before the sharing process results in a reduced quantity of electricity available for sharing, as a portion of the generated electricity is consumed by the building users.

3

ENERGY FLEXIBILITY MODELLING FOR EVENT-BASED AND STORAGE DEVICES

3.1 Literature Review

As mentioned in Section 2.1, for the purpose of this study, the definition of "energy flexibility" as the possibility to manage energy consumption and/or generation in a given energy system (Jensen *et al.*, 2017; Le Dréau *et al.*, 2023) is considered. Regarding energy consumption, DSM may use the energy flexibility potential of devices to achieve their objectives (Du, 2017), which can be defined as policies and measures that can control and reduce electrical energy demand (Baghina et al., 2012). One of the DSM measures is DR, a methodology of altering the electrical energy usage by defined parameters such as instant prices, availability of local energy sources, end-users comfort requirements, incentives to reduce electrical energy bills, and to prevent the reliability compromising of the electrical grid (Baghina et al., 2012; Hu et al., 2016). For DR measures, there are two main approaches: direct control, which is direct modification of the electrical devices, and the indirect control, which utilizes incentives (Junker, Relan and Madsen, 2019). The authors also defined energy flexibility as the potential to contribute to a load demand response.

3.1.1 Classification of devices

For the specific purpose of this research, the electrical devices commonly used in buildings are divided by a criteria selection, divided by levels. The first level regards on the dependency of the user in the direct control of a considered device. Dependent devices are the ones in which the user have a direct impact on the consumption, and/or is actively used during its operation. Examples of dependent devices are TVs, computers, videogames etc. The remaining devices are independent, in which the user only starts and ends the operation, having no control during an operation cycle. This classification derives that, in this cluster of devices, most of them can be autonomously controlled, without the direct intervention on their starting and finishing status of operation. For this reason, these devices are also classified as "controllable" loads.

From the second level and on, the focus lies only on independent devices, since these are most used when energy flexibility strategies are applied and are extensively described in the literature. The second level regards on the manner that energy is consumed during an operation cycle. In this sense, devices are classified as event-based and storage devices. An event-based device (EBD) has an inflexible energy consumption pattern, which cannot be modified without compromising the quality of service. The energy flexibility potential is originated by the capability to change its operation instants. The most common EBD are washing machines, tumble dryers, and dishwashers. However, studies describing energy flexibility potential of electric pumps (Tan, Gan and Tan, 2016; Ji and Rajagopal, 2017; Rehman, Sajjad and Khan, 2018), PEVs (Ji and Rajagopal, 2017; Sousa *et al.*, 2018; Yahia and Pradhan, 2018; Terlouw *et al.*, 2019), electric water heaters (EWH) (Tan, Gan and Tan, 2016; Chipango, Popoola and Munda, 2017; Rehman, Sajjad and Khan, 2018; Yahia and Pradhan, 2018), refrigerators (Tan, Gan and Tan, 2016; Chipango, Popoola and Munda, 2017; Raman and Peng, 2018; Rehman, Sajjad and Khan, 2018), freezers (Chipango, Popoola and Munda, 2017), HVAC systems (Bai, Xu and Zheng, 2014; Tan, Gan and Tan, 2016; Raman and Peng, 2018) and light bulbs (Wang *et al.*, 2019) were also conducted, and these devices were classified and modelled as event-based. Regarding these other devices, from this research point of view, only the electric pump and PEVs' batteries can be studied as event-based. However, PEVs, due to the non-deterministic availability to act on the energy grid as an energy flexibility provider, can also be classified as storage device, but only in situations in which their batteries can discharge part of the stored energy to operate part of the remaining building's loads. Devices like EWHs, refrigerators, freezers, and HVAC systems convert electricity into thermal energy to change the temperature of a working fluid. This thermal energy can be stored for a postponed usage, providing energy flexibility. Therefore, they have a different classification than the event-based devices. Such devices are classified as "storage devices", based on their property to store a form of energy (thermal, chemical, or potential) for later utilisation, thus, the stored energy can be used in a more suitable moment, regarding the objective proposed in terms of energy flexibility exploration. Furthermore, these devices have a variable operation time at each cycle, depending on the user preferences such as setpoint temperature for HVACs and energy demand for batteries.

The third level is focused on storage devices, divided as their availability on the building premises. The ones that are always available to provide energy flexibility for its building are the deterministic devices. The remaining are defined as non-deterministic devices, due to the stochastic availability pattern. In this study, only the batteries of PEVs can classified as non-deterministic.

Lastly, the fourth level is dedicated to classifying both deterministic and non-deterministic as the form of energy that is manipulated during their operation. Regarding the deterministic, they are subdivided according to the type of energy that is stored: thermal, chemical, and potential. Deterministic thermal devices (DTD) use heat transfer to control the temperature of a fluid, namely room air or water for domestic purposes. According to the device's end-user needs, their operation can be adjusted, by power controlling and operation time, to achieve energy flexibility measures' objectives. The devices that comprise most of the studies are the EWHs and HVAC systems (De Coninck and Helsen, 2013; Reynders *et al.*, 2018; Clauß and Georges, 2019). Heat pumps, refrigerators, and freezers are also devices with some relevance. Gas boilers, as a studied device, and the building air or water thermal mass are also considered, on the fluid perspective. Deterministic chemical devices (DCD) are represented by the BESS. This type of device stores chemical energy, inside the battery and, on proper instants, converts it into electricity, for consumption inside the building boundaries. BESS can be used standalone or, for instance, as part of a solar PV system for self-consumption to store the surplus generated energy (Jin *et al.*, 2017; Blaauwbroek *et al.*, 2018; Favuzza *et al.*, 2018). Deterministic mechanical devices (DMD) store mechanical energy by giving kinetic energy to a spinning mass, which is connected to a generator axis, used to generate electricity. When the conditions are favourable, the spinning mass is connected to the generation unit, achieving a proposed objective. This procedure is mostly used on the supply side. Furthermore, to the best of the knowledge created by this research, no study was found that utilizes potential energy for energy flexibility at the demand side. Regarding the non-deterministic chemical devices (NDCD), the main feature is the stochastic behaviour of its availability to support the energy flexibility process. Unlike the other devices previously described, the non-deterministic has a component of partial unavailability during the considered time frame. The device that is classified as non-deterministic is the battery of PEVs. Due to the utilization of these vehicles by the end-users, its availability depends on the vehicle owner to stay in the building. This unavailability must be considered when characterizing the energy flexibility potential, among the other devices that participate in these assessments (Wang and Paranjape, 2017; Munshi and Mohamed, 2018; Park *et al.*, 2019). However, as mentioned, PEVs' batteries can only be classified as NDCD when Vehicle-to-Building (V2B) or Vehicle-to-Grid (V2G) are possible. Figure 3.1 summarizes the devices' classification. In this figure, terms in bold refers to the final classification of the usable devices for this research.

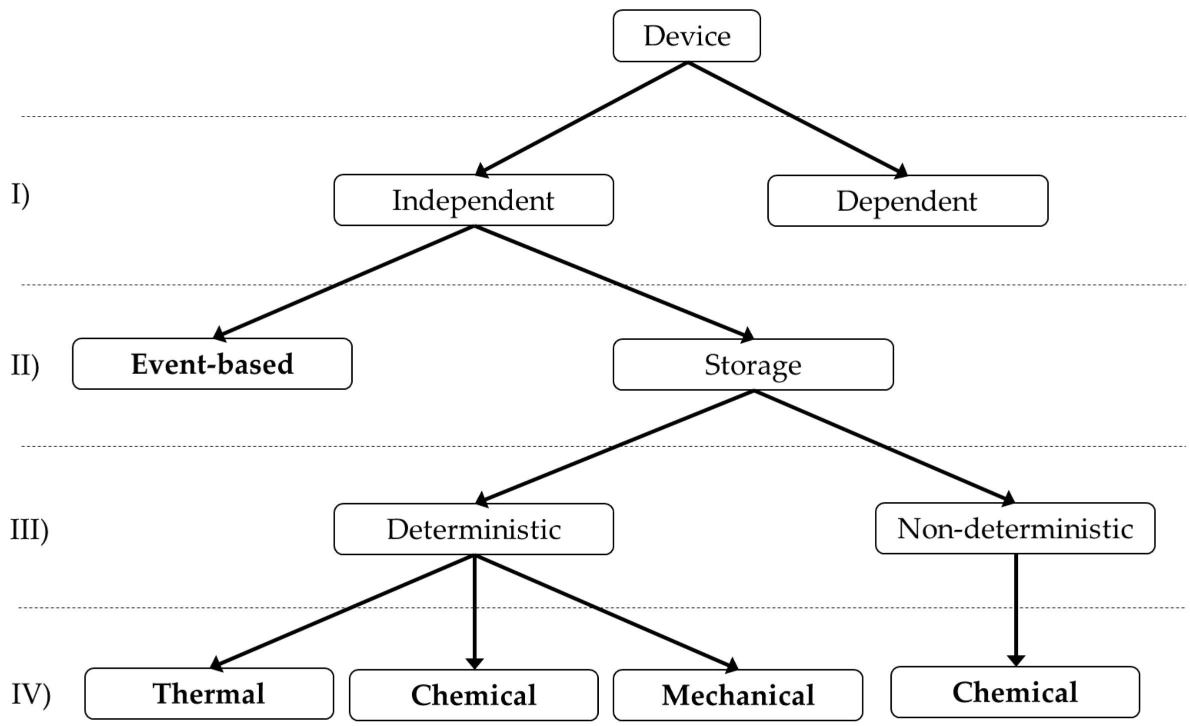

Figure 3.1 - Devices' classification for the identification of energy flexibility potential

3.1.2 Energy Flexibility objectives

There is a wide range of proposed objectives regarding measures that use energy flexibility. These objectives can be suited for a specific case (Morales-Valdés, Flores-Tlacuahuac and Zavala, 2014; Wang and Paranjape, 2017; Wang *et al.*, 2019) or generally developed to enable replication in similar cases (Heleno, Matos and Lopes, 2015; Degefa *et al.*, 2018; Chen *et al.*, 2019). They can be analysed for a single building (Althaher and Mutale, 2012; De Coninck and Helsen, 2013; Taddeo *et al.*, 2020) or for a cluster of buildings (Vlot, Knigge and Slootweg, 2013; Rehman, Sajjad and Khan, 2018; Shirsat and Tang, 2019). In the latter case, all participating buildings may share a common responsibility. The proposed measures converge towards an accumulated result, which leads to a greater achievement than the individual approach for each participant. However, a trend can be identified, regardless of the considered device. The most common objective among these works is to provide to the end-user an economic advantage, in terms of energy bill reduction or profit optimization for the surplus generated energy by local resources. To achieve this objective, the researchers mainly use the assembly of a cost function, which can estimate the monetary cost on the operation of the equipment. In turn, the cost function is manipulated for its minimization, that is, the minimum monetary value necessary for the operation of the equipment is calculated. This minimization is done, among other ways, by a series of methods, such as:

- forecasting the use of equipment within a limited horizon, and the consequent scheduling of the operation for times when energy is cheaper (Hu *et al.*, 2016);
- through its control by a dynamic programming development (Salpakari and Lund, 2016);
- by the restrictions analysis defined for study (Mohseni *et al.*, 2017);
- by the development of equipment stochastic models and the way that electricity prices are formed (Gazafroudi *et al.*, 2019);
- by the application of a cost function in conjunction with a multi-objective optimization models (Golmohamadi *et al.*, 2019);
- by the application of a cost function in conjunction with a multi-objective optimization models (Rajasekhar *et al.*, 2019); and
- by using the amount of imported energy as a constraint in a multi-objective approach (Terlouw *et al.*, 2019).

The assessment of DR measures is another common objective for the usage of the energy flexibility potential of building's loads. However, in this case, both supply and demand sides are considered for improvement since demand response has importance for the energy grid reliability. (Junyu Wang *et al.*, 2016) proposes an agent-based DR potential evaluation by a flexibility index of household devices. The proposed agent operates by sorting, internally, the devices by its flexibility, which is calculated by the operation time and power profile. After the flexibility calculation, the agent dispatches the devices' operation, respecting the user constraints. (Klein *et al.*, 2017) compares the flexibility provided by four different options in terms of energy storage: a fuel switch technique, characterized as the variation of the sequencing of heat generators in the low-level control; and the usage of water tanks, batteries, and the building thermal mass to store energy. The goal is to assess the grid improvement potential for load scheduling and energy efficiency. The control structure works on two levels, being the lower one responsible for control the setpoint charge. The higher control level calculates a load profile, through the setpoints controlled by the lower level, to be grid-supportive, when the building's electricity consumption profile coincides with the availability of electricity in the supply side. (Mohseni *et al.*, 2017) proposes a day-ahead energy management framework to activate a time-based DR program in a residential 15-households microgrid, respecting the households' devices constraints. For this, an integer linear programming problem was formulated, and grid and user constraints are inserted. The objective function has, as the main task, to impose the constraints to the Energy Management System (EMS) and calculate the optimal schedule for the devices, to avoid on-peak instants, which have the highest energy tariff values, and operating shiftable devices in instants of lower energy tariff (off-peak instants). In the case of an optimal power balance, the schedule is sent to the devices, for its proper operation. (Moreno *et al.*, 2017) described a proposition for a Demand Flexibility concept, which has a function to assess demand profiles, by analysing its flexibility. The assessment is made by selecting a variety of devices and calculating the flexibility with a stochastic model. (Blaauwbroek *et al.*, 2018) studied a framework for time shifting devices, by active power flexibility, to support the electrical grid with DSM measures to avoid operation limit violation. To achieve this objective, a general optimization of all considered devices functions is proposed, respecting the end-user and grid operator constraints.

Other important objective for energy flexibility, mostly motivated by the urgency to mitigate climate change effects, is the reduction of GHGs on the atmosphere. This objective can be achieved by changing the energy mix in a building, by utilizing local renewable resources or analysing the supply energy mix and schedule the operation of high energy-demanded loads to instants with a higher rate of renewable sources on the supply mix. (Jin *et al.*, 2017) assess, by using a modification of a single zone residential HVAC system, an EWH, and a local solar PV generation system, to reduce carbon emission associated with energy consumption, by the incentive of the using of the energy generated by the solar PV system. To achieve this, a multi-objective model with a predictive algorithm was developed. The emissions are weighted, after a survey, and the objective solver optimizes the devices' schedules, considering the emission as constraints. (Terlouw *et al.*, 2019) aims to minimize, along with the energy costs, CO_2 emissions during the system operation. The results compare an individual-building solution and a community-building one, to assess the aggregation effects on the proposed objectives. Two management systems work together. The first one controls the household devices individually, while the other one controls the community devices. The emissions are predefined, and the local solar PV systems supply the electrical energy households needs, while respecting the CO_2-emission constraints. (Taddeo *et al.*, 2020) considers day-ahead market information for CO_2 emission from the energy supply mix to minimize emissions by trading the electrical energy demand for the locally generated RES. The control system works based on the local energy generation profile prediction and a rule-based algorithm is used to achieve its objective.

Other objective which has an important role is the maintenance the end-user comfort level when using the energy flexibility potential of a building. In this case, the minimal requirements are defined by the end-user as constraints, and the developed systems aim to keep them between the upper and lower limits. However, the maintenance of the end-user comfort level works as an objective and as a system limitation. (Bai, Xu and Zheng, 2014) makes a sensitivity analysis on the end-user behaviour to define a benchmark for the control system to optimize the electrical energy usage considering the user's needs. To achieve community objectives, a game-theoretical equilibrium model is developed. (Chen *et al.*, 2019) assess the peak load reduction respecting the user's comfort range for an office building internal ambient temperature, by calculating the electrical energy flexibility that all considered devices can provide and, by an optimal control strategy, achieve the aforementioned objective. (Gerard and Papavasiliou, 2019), on the other hand, assess the effects of DR enabled solutions, on a single household, in the user comfort. The user comfort level and devices consumption profiles are perfect predicted, in a real-time context. The management system is bounded by the user requirements for the devices' usage. (Paudyal and Ni, 2019) defined a level of inconvenience, based on the user comfort level, to coordinate the controllers of the proposed method in managing the total load demand of a 25-house community. Based on the individual level of inconvenience, a global limit is calculated, allowing all the users to provide flexibility to the community energy consumption and have its comfort level fulfilled.

Several other objectives can be defined for energy flexibility usage. Despite its relative importance for the energy system, in comparison with the previously described, the following are relevant to the energy suppliers and can be contradictory concerning the end-users' interests, regarding the defined constraints to achieve the proposed goal. Among these objectives are the modulation of grid load peak (Hadis Pourasghar Khomami *et al.*, 2013; Favuzza *et al.*, 2018; Rehman, Sajjad and Khan, 2018), the balance between the supplied and demand energy in a specific interval (Hadis Pourasghar Khomami *et al.*, 2013; D'hulst *et al.*, 2015; Tan, Gan and Tan, 2016), the voltage balance in electrical energy distribution or transmission grids (D'hulst *et al.*, 2015; Blaauwbroek *et al.*, 2018). The increase of RES penetration (Hadis Pourasghar Khomami *et al.*, 2013) in the energy systems is another important objective, with importance for both the supply and demand players.

3.1.3 Energy Flexibility characterization

To assess the energy flexibility potential of an energy system, there is a need to understand how the loads operate during the considered time frame. this understanding is possible, among a series of techniques, by modelling the loads that have active participation in the flexibility potential assessment. to model the loads, key parameters must be taken into consideration. The process to define which parameters are important is part of the characterization of the energy flexibility potential of a load. Since several types of loads have a unique operation, it is essential to describe their behaviour when in operation.

A) Event-based Devices

As previously described, event-based devices have a fixed energy consumption profile, which only depends on the defined operation mode set by the end-user. Therefore, to provide flexibility to the system, the operation time frame of these devices must be modified. The energy flexibility characterization of this type of load is dependent on factors such as time interval to complete a task, the load power profile, and consequential energy consumption, or the interval in which the operation can be changed without jeopardizing the end-use comfort requirements.

- Time interval for a complete load cycle:

To develop an operation and planning model for distribution grids that takes into consideration the operation of wet devices (dishwashers, washing machines, and tumble dryers), (Karimi, Papadaskalopoulos and Strbac, 2017) use the devices operation time, associated with other parameters, such as voltage boundaries, the time duration of failures, the demand of uncontrollable loads, the customer power factor, the power of the controllable devices at a given time instant, the energy demand of an operation cycle and the time constraints for the device's operation, to calculate the inconvenience cost of the end-user. The flexibility provided by the devices is, in this case, dependent on the impact that the time-shifting can have on the end-users, which also limits the potential of using these devices to provide flexibility to the distribution grid.

(Chipango, Popoola and Munda, 2017) acknowledge that a flexible system must fulfil the end-user needs. Despite using several devices that, by default, cannot be controlled, the study considers the operation time of event-based devices to control the peak load of a distribution grid. The control is only occurring during peak hours. The loads are prioritized by the control system considering several factors. Among them, the device operation time, which is acquired and processed by the control algorithm to define the prioritization.

(Rajasekhar *et al.*, 2019), studying the impact of collaborative demand response management in the peak-to-average ratio on distribution grids and the penetration of local energy sources, use the aggregated coordination among customers of smart devices. To make the coordination possible, one of the indicators that are optimized is related to users' discomfort. In this study, a multi-objective optimization problem is considered for the customer, and the following variables are considered as objectives to be chieved: cost minimization, end-user discomfort minimization, interruption minimization (i.e., interruption of shiftable devices and set-points changes). The time-shiftable devices considered in this study are washing machines, tumble dryers and dishwasher, they are considered to have a particular consumption pattern and only the operation start can be scheduled.

The system proposed by (Wang *et al.*, 2019) uses a load aggregator controlled with an indirect scheme, namely the minimization of electricity cost by changing the electricity consumption behaviour of the users. The proposition is based on a price mechanism and has two distinct layers. The upper one aims to optimize consumer behaviour by the load aggregator entity issuing time-of-use (ToU) prices for the customers and receiving the load response, and the second to minimize the electricity cost of customers by reacting to the issued prices of the load aggregator. These interactions are modelled as a mixed inter linear programming problem. Due to the importance of the energy price in this study, the price composition has a factor that is directly influenced by the time interval in which the devices operate on each cycle.

- Load power profile:

(Hadis Pourasghar Khomami *et al.*, 2013) have the objective of providing the electricity systems operators with a way to increase the penetration of renewable energy sources without jeopardizing the reliability of the energy provided to its users. To achieve this goal, a load management algorithm was designed to convert the demand side into a more flexible system regarding energy consumption. The load management algorithm has, as inputs, the devices' operation time interval and duration, and their average energy power demand. The referred algorithm has, as management constraints, the users desired comfort level, based on the devices' operation. Since one of the specific objectives is to reduce the peak-to-average ratio, the device load power profile is important when scheduling them into a flatter and less expensive manner.

The main purpose of the (Blaauwbroek *et al.*, 2018) research is to design a solution for power systems operators to solve grid problems, such as violation of voltage limits during operation. The researchers enunciate that demand-side load management is not effective to solve grid operation problems due to lack of interface between the demand-side management applications and the network operator's monitoring applications. Taking this factor into consideration, they develop a time-shifting model for flexible devices that, among the earliest and latest time of the device's start, must have their load power profile through its cycle operation gathered with the remaining parameters to schedule its operation without exceeding the grid load limit, as an important aspect of the grid-supportive demand side management approach, applied to distribution networks developed in this study.

(Yahia and Pradhan, 2018), on their study about resolving a load scheduling problem taking into consideration the end-users' preferences, examined the factors that might affect the results. One of the defined parameters of influence is the rated power of the devices, since of the restrictions impose for scheduling the devices is the maximum cost that the user is willing to pay in a considered time frame, i.e., a day. This factor contributes with the scheduling results in terms of limiting the operation of all the controllable devices at a considered scheduling horizon, and has a significant importance on the electricity costs, which the minimization is one of the objectives of this study.

To propose an incentive-based demand management scheme for time shiftable devices, (Paudyal and Ni, 2019) aim to shift, in time, a series of devices, after separate them regarding its inconvenience level. Combined with a calculated level of inconvenience caused by the load shifting. The authors argument that this inconvenience may discourage the customers to participate in energy optimization programs, the proposed framework considers all the community devices to schedule them after the end-user inconvenience is properly measured. The developed system receives the demand limit from the utility, which is used to the definition of the maximum load that must be operated at the same time. Therefore, the load profile of each device is important to take into consideration in this case due to possible limitation of devices' operation caused by their demand power.

- Energy consumption:

The model proposed by (Bai, Xu and Zheng, 2014), based on game theory, aims to analyse energy consumption behaviour in a smart grid context. To maximize the cost savings using real-time pricing data, it is primordial to assess the end-user behaviour towards their devices, and the consequential energy consumption on a 24-hour cycle for each considered controllable load. On the mathematical model, the energy consumption of devices plays a major role, both individual and collective, as one of the decision variable restrictions. The proposed system minimizes the electricity costs by limiting the electricity consumption, scheduling their operation according to the considered restrictions, including a limit of the amount of electricity consumption at any given time unit during the time horizon of 24 hours.

(Tao, 2014) proposes a framework to develop a model for an optimal power flow, scheduling energy, and operating reserves by using the flexibility of loads. The named Energy Consumption Flexible Loads can adjust in time their energy consumption pattern based on a series of constraints, and its adjustment is used to create a reserve resource. Since they define a series of energy consumption requirements, one of the main variables that must be assessed is the energy consumption profile of each considered device. Results show that the flexible model can have a positive impact on energy consumption, and their used flexibility potential is able to level costs to consumers and smoothing the voltage profile of the distribution feeder.

The main objective of the study conducted by (Mohseni *et al.*, 2017) is to activate time-based demand response programs, namely the minimization of costs of energy import, the maximization of profits from exporting energy to the grid, by controlling the scheduling and sequence of devices' operation, managing the user's preference, and balancing supply and demand energy flows. To achieve the objectives of these programs, an energy consumption model of household devices is developed based on a set of sequential uninterruptible energy phases. Along with energy consumption, energy generation by PV systems and energy storage in batteries and PEVs are also considered. The interaction of these devices is analysed based on their energy consumption. The goal is to turn the consumers in active players on the DR program of the considered microgrid, by providing flexibility, with their devices' scheduling and by the energy that is generated or stored inside the home's boundaries.

(Degefa *et al.*, 2018) use a high-resolution measurement of data to model the flexible loads to balance electrical energy generation and consumption and increase the power system stability. By measuring energy consumption with a 1-minute resolution, according to the authors, the present method models the flexibility potential at any time of day. Using the probability of use-start of the devices, the consumption can be simulated in a 24-hour interval and the flexibility that the devices can provide to the energy grid to achieve the proposed objectives can be calculated. According to the authors, the probability of use-start approach removes the need for a base scenario to assess the flexibility potential of the controllable loads, and the effort is to extract information on the variability of devices' operation and their probability to operate based on 1-minute resolution consumption data.

- Time interval when the load can be shifted:

To investigate DR impacts and benefits under a residential real-time pricing context, (Althaher and Mutale, 2012) designed a tool to plan the measures and a control scheme to manage home devices operation, by the degree of flexibility that each consumer can provide to the grid. One of the mechanisms uses load shifting. Therefore, it is important to take into consideration the time interval in which the load can be shifted. The intervals are defined by the consumers, to achieve their comfort constraints regarding the devices' operation.

(Vlot, Knigge and Slootweg, 2013) aims to use DR of domestic devices to regulate grid power. It also calculates the economic value that can be achieved by controlling time shiftable devices. To assess the flexibility potential of domestic devices, namely washing machines, tumble dryers, and dishwashers, the model proposed by the authors has a variable that states the time operation, related to a variable that considers an operation after the time-shifting of the device. To calculate the maximum allowed time interval for shifting the device operation start, the end-users must define the interval in which the device can be shifted to maintain their needs satisfied.

The work developed by (Salpakari and Lund, 2016) uses the flexibility provided by a series of devices, including domestic shiftable loads. Their control mechanism aims to minimize electrical energy costs and maximize local RES consumption. Since the rule-based controls have an objective to minimize the selling to the grid, the generated energy must be used twofold, namely: immediately, following the generation profile or by storing it for future utilization. The load shifting is important in this context since the control mechanism must be able to schedule loads operation taking into consideration the time frame in which the loads can be shifted.

(Ji and Rajagopal, 2017) based their work on real-world data set to characterize and quantify the flexibility provided by domestic devices, by increasing or decreasing their energy consumption, to measure DR potential of these loads and optimize electrical energy costs. Defining the time of use and the maximum delay allowed by each studied time shiftable devices it is possible to design the control algorithm, and the scheduling problem is solved determining the optimal start time for the devices based on the defined constraints and proposed objectives.

The main objective proposed by (Strobbe *et al.*, 2014) is to develop an Information and Communication Technology (ICT) architecture able to connect a series of residences, with backend information of energy service providers, DSOs and flexibility aggregators. The proposed architecture comprises DR algorithms to balance renewable energy sources usage and to mitigate voltage issues on the distribution grid. The considered devices are the common time shiftable loads. They use real-time consumption measurements to calculate the energy flexibility potential provided by the devices. The load shifting time interval is defined by the start deadline, which defines the interval for the operation start and, consequently, the operation end. With the time frame defined, the control system can schedule all the devices, based on the time frame and the flexibility of each device.

B) Deterministic Chemical Devices:

In a similar manner to deterministic thermal devices, the chemical ones also can store energy. However, these devices store chemical energy to be instantly converted into electricity, to be consumed by a building's electrical loads when the conditions are favourable according to the designed control algorithms. The BESS, or simply "batteries", are the electric devices that are considered in this group. Regardless the technology, their function has the same premises. The main difference between their application relies on the presence of a local source of electrical energy, mainly RES, inside the building boundaries. In the presence of this device, the operation of a battery system normally has a strict relation with the generation pattern, storing the surplus generated energy for future consumption. However, if there is no local source of electrical energy on the considered building system, the battery has the main function to be charged when electrical energy prices are lower than a defined threshold and discharged on instants of a more expensive price. The characterization of energy flexibility of these devices has a variety of influence factors, and the more suitable ones are dependent of the design of the electrical system and the proposed objective to be achieved.

- Instant State of Charge (SoC):

(Salpakari and Lund, 2016) developed a control mechanism, which has the objective to maximize the self-consumption of the local generated electrical energy. To achieve this objective, since the considered PV system generates energy with an unbalanced pattern regarding the consumption, part of the surplus energy must be stored for future consumption. The design of the rule-based control algorithm is based on a simple storage model for the battery system. The surplus energy, namely the amount of generated energy available after the local usage is managed by storing into both electric and thermal storage devices. Regarding the electrical storage devices, its control is managed by the instant SoC. The control aims to avoid selling energy to the grid, and it only occurs when two conditions are satisfied, such as the storage devices are completely charged, and the electrical demand is met by energy generated by the local solar PV system. Therefore, the instant batteries' SoC must be constantly monitored by the control algorithm.

(Klein et al., 2017) use batteries that are discharged by the heat pump or the chiller and charged from the electrical grid when the residual load is low (according to the authors, the residual load is "the difference between the electric load and the generation of wind and solar PV plants, which provides a quantitative indication of the relative demand for conventionally generated electricity at a given time") or by the variable generator (the considered combined heat and power - CHP - unit when in heating operation). The discharge occurs when the residual load is high. Since the residual load varies constantly during a day and throughout the year, the batteries' SoC varies and must be monitored at any given instant for the objective achievement of electricity cost minimization.

The batteries are classified by (Blaauwbroek et al., 2018) as buffer devices, offering flexibility by its energy charging and discharging patterns over time. These devices must follow a calculated minimum "ON" and "OFF" times for energy flexibility purposes. According to the authors, a target SoC must be defined for a given instant. Since the buffer might have some energy stored when solicited, the monitoring of the instant SoC is also a requirement for the development of DR measures.

(Rajasekhar et al., 2019) consider a BESS operating as a part of a locally installed PV system. Their objective is to minimize the cumulative cost for the consumers and keep the electrical energy demand between the load peak-to-average ratio defined by the system operator. However, in this case, they are installed at the aggregator level. The proposed model considers, as one of the operational constraints, the SoC, which must be kept between minimum and maximum values.

- Charging and discharging power:

Regarding the use of a battery system along with a locally installed solar PV system, (Jin *et al.*, 2017) modelled its behaviour relating, throughout the time, the SoC with their charging or discharging power. Due to equipment's limitation, namely the solar PV system and inverter rated power, the charging power of the BESS must be limited. On the other hand, the discharging power is limited by the instant generated power by the solar PV system and the building electrical energy demand. These two variables are considered when calculating the overall energy balance of the building during the DR event horizon, occurring usually on cold winter mornings and hot summer afternoons, to test the HEMS performance in extreme situations.

The objective of (Gazafroudi *et al.*, 2019) is to maximize the profit from selling electrical energy generated locally. Therefore, it is important to measure all the interest variables of the battery system. The charging and discharging power are considered in the objective function designed to achieve the proposed objectives. Furthermore, there is a technical limitation considered when monitoring charging or discharging power, namely: the value must be under the maximum rate allowed by the manufacturer.

(Golmohamadi *et al.*, 2019) proposed to mitigate load congestion and peak loads. They also aim to maximize the profit of households. The objective function considers the maximum power rate of the battery system to model a factor that weights the battery participation on the objectives of maximizing the household payoff and minimizing the electrical energy cost.

On the other hand, (Terlouw *et al.*, 2019) propose a management control system with an objective to maximize the self-consumption of a local PV system. To achieve this objective, a battery system is a key component, storing electrical energy generated by the solar PV system and consuming it when it is convenient for the end-users. The charging and discharging power on the battery system terminals cannot exceed the manufacturer technical limits, in both situations. Also, the SoC calculation formula, used on the considered case study, depends on the values of the power at the battery system terminals, at any given instant.

- Energy storage capacity:

As stated by (Salpakari and Lund, 2016), their developed rule-based control "*maximizes PV self-consumption each hour by storing any surplus PV production to the electric grid*". Therefore, knowing the energy storage capacity of the BESS is of utmost importance. This value is the main parameter to evaluate the functionality of the control system. In the case study, batteries with different capacities were used to compare the results. Results show that increasing the battery size turns the electrical energy costs to be lower than the reference scenario. However, there is a non-linear trade-off relation of using thermal and electrical storage, which depends on the electrical energy prices during the experimentation interval.

(Mohseni *et al.*, 2017), while defining a device model assessed to develop a time-based DR program, constrain the energy stored in the BESS by the minimum and maximum storage capacities. These values are important during the DR event, managed by the developed program. The profit function designed has, as an output, the income related with the energy sold to the considered smart grid. Thus, this function depends on the charge or discharge power of the battery systems (the static and the PEVs). These powers are limited by the storage capacity of the considered devices. Also, the main objective is to minimize the proposed objective function, without the constraints violation, including the stored energy on the battery system, which is limited by its maximum capacity.

The building system assessed by (Rajasekhar *et al.*, 2019) contains a stationary BESS that operates as a part of a PV system. The BESS energy storage capacity is defined as an operational constraint to the system, and one of the constraints when formulating the multi-objective minimization of electrical energy costs and devices interruption at a customer level. The batteries and solar PV generation systems are installed, as states the case study, in some of the households of a considered smart community. Furthermore, the BESS participate in both customer and aggregation objectives. Therefore, it is important to take into consideration the energy stored in each step time, as well as the energy storage capacity, which influences the net energy demand of all community.

One of the objectives of (Terlouw *et al.*, 2019) is to minimize CO_2 emissions by maximizing solar PV generated energy usage. The devices that store energy, both thermal and chemical, have an important role in achieving this objective. The correct sizing of the storage capacity is an important variable to achieve the proposed goal. The higher is the thermal storage capacity on the water tanks, the lower is the needed electricity storage. The BESS' energy storage capacity is calculated with a formula that takes into consideration all aspects of the household energy storage possibilities. The authors state that optimizing the battery capacity is important to avoid a large and uneconomical sizing, i.e., during daily cycle operation, the BESS are almost never fully charged.

C) Non-deterministic Chemical Devices

The main difference between these devices and the ones classified as "deterministic chemical devices" regards its availability. Unlike the BESS, the batteries of PEVs can participate in energy flexibility programs only when they are present on the households. Hence, the non-deterministic classification. The presence pattern can be scattered and is strongly influenced by the end-user behaviour concerning PEV utilization. This situation derives a series of characterization variables, which must be carefully assessed and modelled to perform a reliable study with results that describe effectively the taken measures. However, not all the studies regarding PEVs take into consideration their non-deterministic aspect of the vehicles presence to be part of energy flexibility programs.

Among the studies that do not consider the non-deterministic aspect of plug-in electric vehicles presence at the building, (Strobbe *et al.*, 2014) utilizes shiftable devices to assess the designed ICT architecture for DR in a residential context. When considering the employment of PEVs, the authors state that they have a similar interface to the postponable devices, i.e., washing machine and tumble dryer, including the characterization variables, namely: operation start time, power profile, and operation time. In the case of the PEV, the operation is defined as charging its batteries. The only aspect that differentiates these two types of devices, according to the authors, is that the considered PEV operation (the charging cycle of its batteries) can be interrupted, instead of the postponable devices, which must end the operation cycle once it is started. (Park *et al.*, 2019) propose a community-scale EMS, appliable to a set of connected households, distributed RES (i.e., PV systems and wind turbines), and PEVs. This system aims to optimize energy resources and systems optimal scheduling. To understand how the power flows between the community and the electrical grid, the authors defined a power balance equation, considering the instant power of each element that transact electrical energy (by generation, consumption, or storage). Regarding PEV charging or discharging power, there is no consideration of their presence at a given time. Therefore, despite the PEV normal utilization for transportation, which, by definition, turns it unable to participate in the demand response activity, they are treated as stationary batteries. The case study of (Terlouw *et al.*, 2019) is relatively complete regarding the mix of devices used to achieve the proposed objectives, which are the cost optimization and the equivalent CO_2 emission (based on the hourly database of the energy generation mix) reduction. The studied system includes a local source of electrical energy generation and a variety of devices, such as shiftable loads, static battery system and PEVs as energy flexible loads. However, when describing the shiftable devices, it is only considered the PEV. The schedule is fixed, despite the defined interval in which the vehicles are available for charging, and the traveling distance is assumed constant. Therefore, PEVs are defined as electrical load and only participate in consuming electrical energy. The two-layer load aggregator designed by (Wang *et al.*, 2019) takes into consideration PEVs as one of the controllable loads. However, the energy flexibility characterization of these devices does not consider them as a stochastic load, defining if it is present at the household to be part of the DR measures. It is considered a deferrable load but is not clear if this type of load is present at the case study, neither the impact of its participation on the objectives' achievement.

Regarding the consideration of the non-deterministic aspect, (Clement-Nyns, Haesen and Driesen, 2010) address the impact of the penetration of hybrid PEVs on the electric distribution grid due to the raise of power needed to charge them. The main mentioned problems regard to power losses and voltage deviation. To mitigate these problems, it is proposed a charging coordination methodology, introducing a stochastic programming technique. The methodology takes into consideration the presence of the vehicle at the residences, where the charging of the devices is stipulated. However, the PEVs only take part as load and do not contribute to the energy flexibility discharging the stored energy on the electric system that they are inserted.

Specifically concerning PEVs' batteries, (Mohseni *et al.*, 2017) defined, as the energy flexibility characterization, the availability of the device when designing the proposed time-based DR program. Therefore, besides the constraints defined for the stationary BESS (the minimum and maximum storage capacities, the roundtrip efficiency of the battery, and the charging and discharging rate), the stochastic behaviour of the PEV battery is considered for the participation of such device on the DR strategies that are considered for the conducted study. The research of (Wang and Paranjape, 2017) also focus on the impact of PEVs on the distribution grid. However, the goal of this study is to calculate the trade-off between the electricity cost with and without the charging coordination schedule, and the defined dissatisfaction factor, a variable that indicates the predisposition of the vehicle owner in participating in the defined schedule. The dissatisfaction factor is associated with the delaying of the PEV charging. Therefore, the PEV availability at the residence, to have the charging time schedule, has a strong relation with the dissatisfaction factor. The penetration of such device on the studied electric system is also studied, and the impact of this factor on the proposed results (the peak-to-average power ratio, a variable defined to evaluate the uniformity of an electric system load profile, and the electrical energy consumption). The penetration of PEVs, according to the achieved results, has an important influence on the peak-to-average power ratio in a positive way. Furthermore, the dissatisfaction factor introduces a restriction on the charging instants for the PEVs, which is considered by the authors as a bottleneck to increase the PEV penetration on a considered electrical energy grid. However, when the PEV is charging it is considered a load, and their amount increase may raise the overall electric energy consumption. (Munshi and Mohamed, 2018) aim to define the PEV load pattern to provide smart grid operators resources to increase energy conservation and stability of the electrical grids in terms of charging of these devices. In this context, there is a definition of a flexibility index, which is calculated based on the probability of the increase or decrease of the PEV charging load. Furthermore, this index indicates the probabilistic change to its considered boundaries (0 and 1), and their values are symmetric with respect to 0.5, such as the conditions of a possible collective trend for the EV charging collective behaviour. Thus, as far as this index is to 0.5, greater is the system flexibility to achieve the best behaviour in terms of the grid operation. To extract the charging load behaviour pattern, the developed algorithm considers the charging power amplitude and the time in which the charging starts and ends. The extraction of the behaviour pattern shows the availability of the device for charging in a time interval. The probability of demand to increase or decrease is then investigated by using a Bayesian Maximum Likelihood method. The flexibility is defined as an index for the PEVs aggregated demand and a percentage level. The flexibility index measures the PEV utilization and provides a control system to perceive the number of devices that can be part of the measures of charging schedule. The PEV charging and discharging behaviour is considered by (Gazafroudi *et al.*, 2019) when maximizing the profit from selling locally generated electrical energy. The stochastic nature of these devices is considered on a case study, by addressing the probability of the device departure and arrival time, and the driving distance. In this way, along with the technical constraints of their batteries (the real-time stored energy, the minimum and maximum limitations for stored energy, and the charging or discharging power limits), the energy flexibility of these devices is calculated, taking values between 0 and 1, which defines the participation availability of such device on a HEMS. (Luo *et al.*, 2019) use PEVs as temporary energy storage facilities to ensure energy flexibility to the system and provide economic benefit for the users. The factors that may impact this usage are the behaviour and preferences of the PEV owners and priorities of the load schedule. Regarding the DR framework proposed, the PEVs can act in the proposed DR framework, in possible ways, namely: V2B and vehicle-to-neighbour (V2N) connection. In a general manner, V2N structures are also named as V2G. In the households where their occupants have PEV, it can provide power for the household devices on appropriate occasions, as a V2B connection. On the other hand, the PEV can also provide power to the households without energy storage units, as a V2N connection. To assess the PEV presence on the respective households, two binary variables are considered when calculating the power balance of the system. These variables can determine, at the same time, if the vehicle is available to participate in the DR program, and if it is charging or discharging. The binary variables are defined for all the users of the energy community, including the ones who do not have a PEV.

D) Other devices' characterization

The remaining storage devices are not considered for study in this work. However, it is important to address their characterization in terms of energy flexibility potential due to their compatibility of usage with the devices to provide flexibility to the demand of the buildings in which they are part of.

The main characteristic of DTD regarding the energy flexibility potential is the complete availability during the considered case study interval (the deterministic aspect of characterization) and the ability to store thermal energy for using when favourable conditions are verified. The electricity in this context can be used to modify the temperature of a working fluid, mainly air, in the case of HVAC devices, or water, when EWH are considered. The characterization of the energy flexibility for these devices has a relation with temperature changes. Therefore, the thermal behaviour of the working fluid and the boundary conditions are the common factors that are considered when calculating the potential of these devices to provide energy flexibility. The characteristics that are manipulated when these devices are modelled are thermal properties of the fluid, such as heat capacity and thermal resistance; the comfort range of the user, characterised by the upper and lower boundaries in which the working fluid temperature can vary; the ambient temperature, due to its close relationship with the indoor temperature, and the setpoint temperature, defined by the user, which also depends on their comfort preferences (Sossan, 2017; Finck, Li and Zeiler, 2019; Shirsat and Tang, 2019; Terlouw *et al.*, 2019). Regarding DMDs, the main example is the flywheel, composed by spinning mass which stores a certain amount of energy by varying the spinning speed of a mass. This device uses electricity to accelerate or decelerate this mass (Luo *et al.*, 2015) and offers excellent efficiency of storing energy at high cost. Their main usage regards on power quality improvement of electricity grid containing renewable energy sources due to their high stability. It is considered as a bridge to diminish the gap between demand and supply (Basit *et al.*, 2020) and an integral part of a wind power plant (Alam *et al.*, 2020). However, to the best of the researcher knowledge there is no practical application of such devices in the context of demand response and energy flexibility on the demand side.

3.1.4 Discussion

Regarding energy flexibility, the literature review conducted for this study identified, as variables commonly used for the characterization and modelling the energy flexibility potential of EBDs, the following: time interval for a complete load cycle, device's load power profile, energy consumption for a complete cycle and time interval when the device can be shifted. Furthermore, other variables were also used when studying the energy flexibility potential of these devices, such as the instant of a cycle start and the "ON/OFF" status of the device at a given time. This variable is paramount for the development of the proposed model.

In a given building, the application of DR measures is possible by considering different methods for implementing it using controllable devices. One possible approach is to install a device called a "smart" or "connected" device, which is equipped with sensors and communication technology that enables receiving signals from the power grid and adjust electricity consumption accordingly. For example, during times of high electricity demand, the power company may send a signal to the washing machine to delay the start of its cycle by a few minutes, which can help to reduce the overall electricity consumption cost of the device. Another approach is to use a HEMS that can communicate with controllable devices in the household. The HEMS can receive signals from the power grid and adjust the electricity consumption of the washing machine and other devices in response to changes in electricity demand. Furthermore, the HEMS can be locally programmed, to increase the benefits of devices' operation based only on the users' wishes and needs. This can help to improve electricity use and reduce the overall electricity consumption cost of the building.

However, it is not identified, to the best of this research's knowledge, any studies that consider the strategy management of a given EBD's operation based on the building's load diagram behaviour and the available surplus after the self-consumption of the remaining electric loads. Furthermore, any studies in which DR measures are applied in a REC context, altering the energy consumption pattern of its members in order to better manage energy consumption inside the REC borders does not consider the DR effect of the energy sharing process. This knowledge gap is addressed in this study by H#2. The theorical development of the proposition that address such gap is described in Section 3.2. Regarding experimentation, a proof-of-concept of the DR framework designed in this study is firstly experimented in a single building, with the respective results and analysis described in Section 4.2. The experiment that addresses the identified knowledge gap is described in Section 4.3.

3.2 Energy Flexibility of Event-based devices as a Virtual Storage Installation

The energy flexibility potential of EBDs can be quantified by considering the time shifting aspect, which allows for adjusting the start time of operation to align with surplus electricity from local RES. It is not effective to use load diagram alteration in this case due to the certain of the amount of energy that is supposed to be shifted, since the EBDs have, as one of their main operation characteristics, a strict pattern of power to fulfil their objectives in term of operation per cycle. In this context, the variable that has more impact on assessing the energy flexibility potential of such devices are the time interval in which the operation is shifted, considering as a baseline a certain uncontrolled usage of the device by the users.

To assess energy flexibility potential, the first analysis regards on the variables involved in its quantification. It is included, in this work, the usual time in which each EBD cycle starts, prior to any DR measure applied at building level. Then, rules regarding the time interval in which the EBD is supposed to operate in a shifted manner are defined, e.g., their availability inside the building premises and the instant power demand. The operation time represents the needed time interval for the EBD to complete a cycle. Energy surplus availability is also considered, as it is paramount in determining the potential for utilising it to operate the EBDs and therefore increase building self-consumption, also limiting the horizon for the possible load shifting (i.e., during the first hours in the morning and the last hours in the afternoon is not likely to have surplus due to the natural pattern of electricity generation of a PV).

The development of the EBDs' modelling in this study is made considers a manipulation of their operation that reflects in alteration in a buildings' load diagram similarly as a traditional SI, such as Li-ion batteries, as such devices are referred in the Portuguese regulation for the national energy system (Ministério da Economia e da Inovação, 2022; Entidade Reguladora dos Serviços Energéticos, 2023a), as one of the assets potentially present in a REC, showed in Figure 2.1. For this reason, the modelling of such loads is called "Virtual Storage Installation" (VSI). The VSI mimics the behaviour of actual energy storage devices in terms of altering the load diagram of a given building, collecting the benefits of exploiting the energy flexibility as the one provided by SIs under the Portuguese REC context. The main principle behind the VSI concept lies in its ability to manipulate the timing of energy consumption through DR measures in EBDs. This manipulation creates alterations in the load diagram of the building in a similar way that a physical storage device: when interacting with the distribution grid at energy meter level, in charging instants of a SI, the load diagram of the building increases, and in discharging instants the load diagram decreases. The VSI definition is made in a similar way, considering as its charging and discharging instants the effect of the EBD operation in the load diagram of the building. At the end, by visualising the load diagram of a considered building, the displacement of loads due to the exploitation of their energy flexibility potential is assessed similarly to the operation of a SI, focusing on the alterations in instants which the EBD operation is manipulated. Also, the management of EBDs under the VSI concept has similar rules as the common management strategies of regular SIs.

One of the characteristics of EBDs resides on the possibility of pausing their operation without immediately compromise the comfort of the user. Due to this factor, and similarly to management strategies of physical storage devices (Terlouw *et al.*, 2019; Dong *et al.*, 2020; Queiroz, Amaral Lopes and Martins, 2020; Gu *et al.*, 2023), the VSI can interrupt its charge by pausing the operation mid-process. This means that, depending on the conditions set for the shifting of the load's operation, it can pause if they are not fulfilled when the actual operation is supposed to happen. For instance, if a condition for an EBD shifting is to be operated in instants when there is surplus of energy generated from a local RES, the occurrence of a decrease in such generation can potentially trigger a momentary pause of the loads' operation. In conditions that favours the shifting of an EBD, after the device’s status is turned “ON” in a shifted manner, it only operates while the set conditions turn its operation available. Otherwise, the device is paused.

Regarding NDCDs (specifically the battery of EVs), literature shows that this class of equipment can also be modelled and managed as an EBD due to its inherent inflexible pattern of energy consumption during the charging process, limited by the battery capacity and the charging power of a given station. However, on the contrary of the remaining equipment classified as EBD (e.g., washing machines, tumble dryers and dishwashers), EVs are not always present to participate in DR measures, which impairs their flexibility potential. For instance, in a residential context, if one of the residents uses the EV for daily activities, during these usages it is not possible to consider the EV's battery as a load for the building. To this end, it is important to have a prior knowledge of the EV user behaviour to plan its participation. Furthermore, if a given charger has V2G and/or V2B capabilities, the VSI concept may not be an effective way to manage their charging and discharging during a time horizon, or at least must be adapted to this context, considering their non-deterministic status regarding their presence at the building's premises to participate in a such measure, and potential services for the building or the distribution grid.

The VSI operation encompasses the understanding of its definition and control variables. The first aspect is based on definitions of "energy storage" that are present in the literature. For instance, (Linden and Reddy, 2002) defines a storage device, or "storage batteries", or "accumulators", as "*a secondary battery (capable of being recharged) electrically connected to and charged by a prime energy source and delivering its energy to the load by demand*". In this sense, based on this definition, the VSI concept is "the transfer of the final use of electricity of a given device to a moment that differs from its originally intended instants". The account of such transfer is managed in a similar manner as the physical SI. Just as a physical SI stores energy for later use, the VSI "stores" energy by deferring or advancing the operation of EBDs to achieve the set objectives defined by a set of boundary conditions. However, on the contrary of what naturally happens with physical storage devices, the VSI will not self-discharge, which is a temperature-dependent phenomenon influenced by factors such as chemical activity, discharge rate, and time, and leads to the gradual loss of capacity due to internal chemical reactions, particularly notable at higher temperatures and during prolonged periods of disuse or high discharge rates (Linden and Reddy, 2002).

To this end, it is important to define the control variables that must be measured over time for a proper management of the VSI: its SoC, charging and discharging power, and capacity. The SoC of the VSI is defined similarly to a physical storage, namely the percentage of energy that is virtually stored in each moment. However, for the VSI the SoC also represents the percentage of the energy that is already consumed for a complete operation of the considered EBD. This concept is important to keep track of the operation cycle of an EBD, in instants which the non-verification of the proper set conditions, both usual and shifted, are identified. In this sense:

$$\mathbf{SOC_{V.St}}(t) = \sum_{n=0}^{t} \frac{\mathbf{e_{c,V.St}}(n)}{E_{T,V.St}} \tag{3.1}$$

In Equation 3.1:

- "$\boldsymbol{SOC_{V.St}}$" is the SoC of the virtual storage at a given timestep "t", since the beginning of the operation (when "t" is equal to zero).
- "$\boldsymbol{e_{c,V.St}}$" is:
  - For discharging: the energy not consumed by the EBD from the usual time since the instant in which the operation is supposed to start.
  - For charging: the energy consumed by the EBD from the beginning of the operation in a shifted start.
- "n" is the number of timesteps that occurred since the beginning of the shiftable load operation.
- "$E_{T,V.St}$" is the total energy that is needed to be consumed for the complete operation of the shiftable load.

It is important to define the instants in which the VSI is charging or discharging. To this end, their definition is made by the effect that the operation of the EBD has on the building's total power demand. Every instant in which the EBD is supposed to operate in a usual operation is referred to a discharging instant of the VSI, due to the consequent decrease in the building's load diagram, caused by the shifting process. Similarly, in every instant in which the EBD operates in a shifted manner, it is considered that the VSI is being charged, due to the increase of the load diagram comparing to a situation without the management of the EBD's operation. Other consequence of this definition is the possibility to learn when shifting the operation of the EBD is possible. At any given timestep, if the VSI is at full charge, one of two possibilities can be derived:

- The shiftable load already operates in a shifted way.
- The shiftable load has yet not operated and can be shifted if necessary.

Regarding the shift planning of such loads, it is important to determine which external variables, not directly linked to the operation of the EBDs, must be involved for the appropriate management algorithm development. In the case studies that are designed to validate this work, the main objective of the VSI is to operate mostly with generation surplus from locally installed generation RES units to increase the self-consumption of a given building. To this end, there is a need of data on historic energy consumption, and specifically disaggregated data on the operation of the available shiftable loads. Furthermore, for the development of such algorithm is necessary that a given EMS has means to acquire real-time data on local generation and on the building's energy consumption. These datasets serve as the basis for the decision-making algorithm embed to the EMS, regarding the effective timing of shiftable load operation, depending on the boundaries set conditions to be met. This process aims to decrease energy import of such loads during instants of low local energy production and/or high tariffs while improving consumption during instants of high availability of energy generated in-site. Figure 3.2 shows a proper visualisation of the VSI behaviour over a time horizon (24 hours), and the impact that its operation may cause to the overall load diagram of a given building and to the surplus of locally generated energy. It also shows the behaviour of the VSI itself, namely its SoC. Each action listed in Figure 3.2 represents the result of the strategic decision made based on the VSI concept for a more effective energy consumption pattern, e.g., increase of local generation energy usage and energy import cost decrease. It shows, in each line, the behaviour of the main variables involved on the development of the VSI concept, namely: the building's load diagram, the surplus of the local generation source after the self-consumption of the uncontrollable loads, the status of the VSI and its respective SoC. The columns refer to time intervals in which the status of such variables is displayed. Furthermore, for the sake of illustration, the local generation unit considered is a PV system.

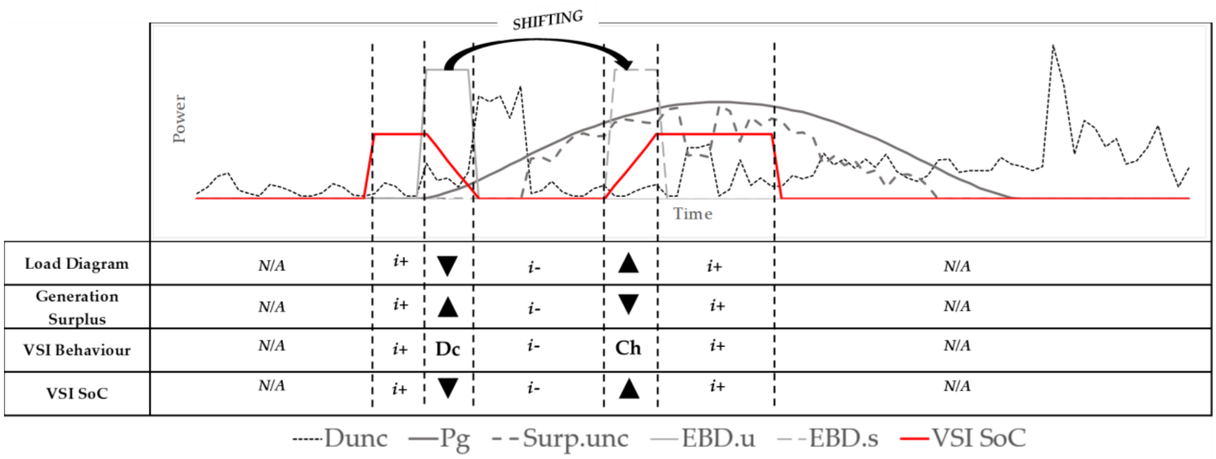

Figure 3.2 - Virtual Storage Installation's operation status

In Figure 3.2:

- *N/A*: means that the EBD is not available to contribute to the VSI (e.g., an EV is not connected to a charger station, or a dishwasher is not loaded with dishes).

- i+: the EBD is ready to contribute to a load shifting framework; the VSI is in an "idle" status, completely charged.
- i-: the EBD is present at the building but cannot contribute to any load shifting action; their functioning in the future it is already programmed; the VSI is in an "idle" status, completely discharged.
- ▼: the considered variable is decreasing:
    - The load diagram of the building decreases when the VSI is discharging; the EBD is not operating at its usual time.
    - The SoC of the VSI decreases over time on the horizon of the usual operation of the EBD.
    - The local generation surplus decreases during the operation of the EBD in a shifted horizon.
- ▲: the considered variable is increasing:
    - The load diagram of the building is increasing when the virtual storage is charging; the EBD is operating in a shifted way.
    - The SoC of the VSI increases over time on the horizon of the shifted operation of the EBD.
    - The local generation surplus increases on the horizon of the usual operation of the EBD due to the shifting process.
- Dc: a discharging instance of the VSI.
- Ch: a charging instance of the VSI.

Consider the following variables:

- $\boldsymbol{p_{d,unc}}$ – the demand of the uncontrollable loads.
- $\boldsymbol{p_{n,unc}}$ – the net demand of the uncontrollable loads.
- $\boldsymbol{p_{g}}$– the power generated by the local solar PV system.
- $\boldsymbol{p_{d,ebd}}$ – the demand of the considered EBD.
- ρ - the minimum percentage of the EBD demand the solar PV system must fulfil.
- $\boldsymbol{c_{ebd}}$ – the counter of the EBD cycle, in which after every time instant that the EBD operate, it is increasing in one unit.
- $C_{T,ebd}$ – the total number of time instants that completes one cycle of the EBD.

- $\boldsymbol{T_{present}}$ – a subset of the tariff structure, considering only the time interval in which the EBD is available to operate.
- $T_{present}(min)$ - the minimum value of $\boldsymbol{T_{present}}$.
- $t_{e,start}$ - time for the earliest start of the device.
- $t_{l,end}$ - time for the latest end of the device.
- Δt - time interval between two distinct instants "t" and "$(t-1)$".

The EMS's algorithm runs as shown in Figure 3.3.

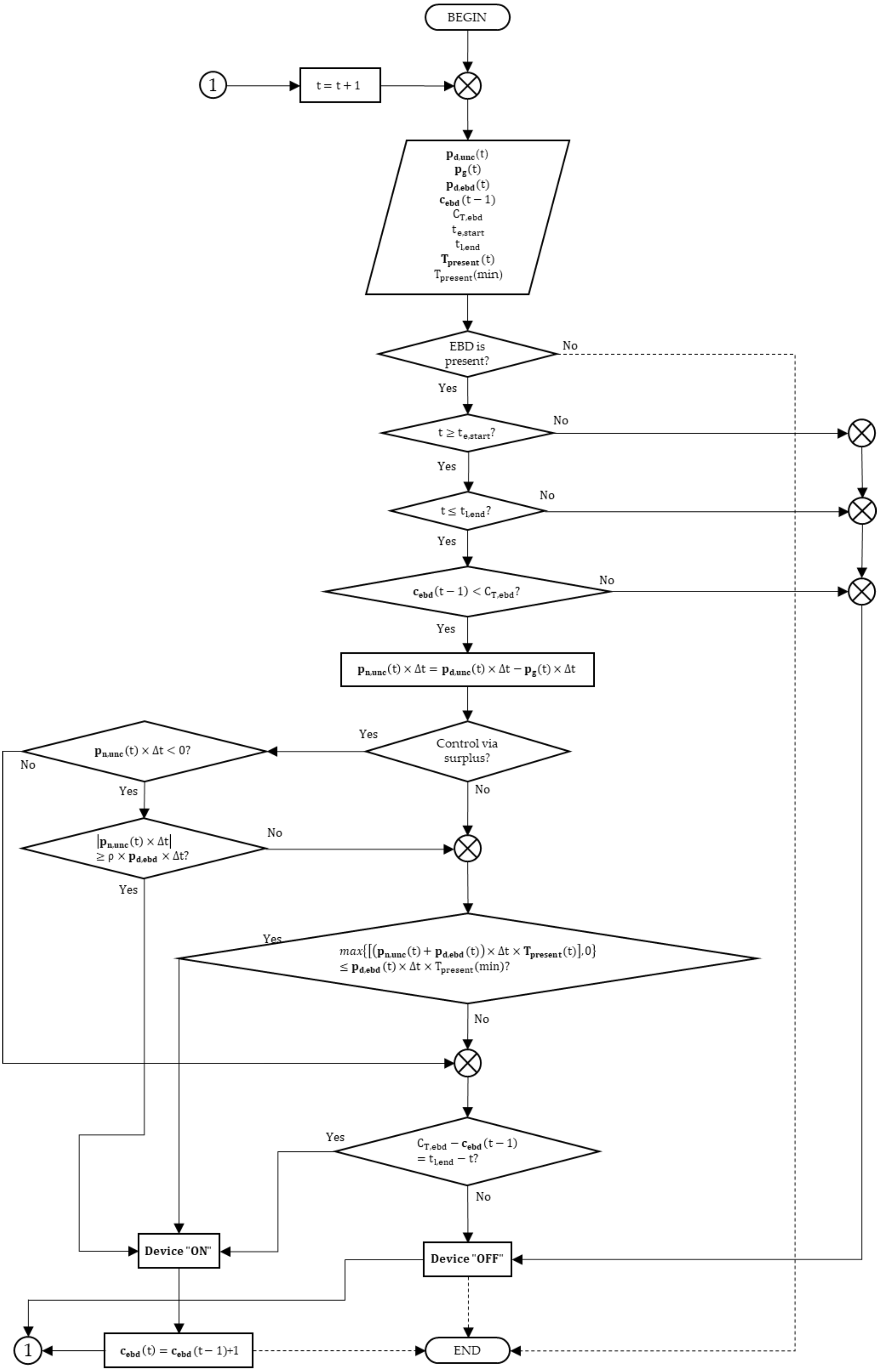

Figure 3.3 - EBD flexibility algorithm based on the VSI concept

The proposed algorithm functions by measuring, at each time instant, the summation of the demand of uncontrollable loads and the energy generated by the local source. Then, the self-consumption of the uncontrollable loads is conducted, and the net load is stored inside the algorithm. Prior to the beginning of the conditions favourable for applying this DR measure to increase self-consumption by shifting the EBD operation to an instant more favourable, i.e., with more available surplus. However, this increasing is limited by the user comfort, in the sense that there must be a declaration of the earliest start and the latest end possible for the completion of the operation cycle, according to the user needs, and their wishes regarding the percentage of energy generated from the local source that must fulfil the EBD operation, if possible. It is important to note that, regarding the earliest start and late end times, their choosing may vary. For instance, if the controlled EBD is a white appliance inside a household, such as the washing machine, even though the considered load is always present inside the premises to be controlled, the user must conduct a series of activities beforehand, namely fill the appliance with objects to clean. However, since EV batteries are considered EBDs for the purpose of this study, both earliest start and late end depends on the user usage, which varies the time horizon in which the vehicle is present to participate, as follows:

- If the charging of the EV battery is supposed to be controlled in the owner's residence, the time horizon depends on the usage of such vehicle and may have a variety of patterns, depending on the usage. In this situation, it can be potentially more difficult to control the charging to use locally generated energy.
- If the charging of the EV battery is supposed to be controlled in a non-residential context (for instance, an office building), the time horizon is usually stricter, depending heavily on the business hours that this building operates or the working hours of a given individual that uses an EV. This context can be potentially more favourable to control the charging of the EV battery to maximize the self-consumption of the building.

After the self-consumption of the uncontrollable loads is completed, the EMS verifies the control possibilities, namely the VSI charging with the generation surplus fulfilling part of the EBD's operation needs or by the difference of tariffs between the considered instant and the lowest tariff applicable to the building. This choosing is made by the user, depending on the characteristics of the consumption and generation pattern, and the tariff structure applied to the building. Note that in situations that only one tariff is applied during the whole billing period there is no possibility to use this strategy to control the EBD operation.

On the other hand, if the chosen management strategy is to use the surplus on the generated energy, the algorithm verifies, at any given instant, if the available surplus after the self-consumption of the uncontrollable loads is enough to operate the EBD or start it when the operation cycle is not started. Also, the counter of the operation cycle is verified, and the early start and late conditions for the operation are also assessed. Only when all conditions are favourable, the device is turned "ON” or is allowed to keep functioning. If at least one condition is not positively verified, the device is paused, or its turning-"ON" process do not start. Several variables can influence the overall performance of the exploitation of the energy flexibility potential of the EBDs, namely the building consumption in terms of uncontrollable loads, the operation pattern of the EBD (determined by the comfort of the end-user), the local generation pattern (the installed power of the generation system and other factors that can potentially impair their performance).

4

RESULTS AND ANALYSIS

To answer the research questions proposed for this study, a series of simulation in computational environment were conducted. For this purpose, a series of case studies were designed, and the results analysed. In this chapter, the case studies are described, as the results achieved through simulation, using MATLAB™, version R2019a. For these simulations, dedicated scripts were written, and specific functions were made for the self-consumption and energy sharing processes.

In Section 4.1, the first experiment regards on a comprehensive analysis of a REC composed by four non-residential buildings, to gain a deep understanding of the dynamics of energy sharing within this entity and to assess the impact of different energy sharing coefficients on community members. It uses real demand and meteorological data, exploring how different energy sharing coefficients impact members' electricity bills and comparing the fixed coefficients with the proposed Dynamic Sharing Coefficient. This experiment aims to answer RQ#1 by validating H#1. The second experiment, described in Section 4.2, focuses on the evaluation of a residential building which has an PEV as EBD to be controlled. This device's operation (the charging of the PEV battery) is controlled to perform the behaviour of the VSI concept described in Section 3.2. It can be considered as an intermediate experiment, in preparation for the third experiment designed for this study, in Section 4.3. This last experiment brings the evaluation of the influence of EBDs with energy flexibility potential on the calculation of energy sharing coefficients. The energy flexibility potential of the EBDs in this experiment are exploited by using the framework described in Section 3.2, hence they are considered VSI inside the REC premises and managed as such. The same REC described in Section 4.1 is considered. However, in this case, 2 EVs are added to the load of each REC member as EBDs. The objective of this last experiment is to answer RQ#2 upon the verification of the proposition stated in H#2. Regarding the assessment of energy sharing coefficients, throughout Section 4.1, a meticulous comparison of the three possible energy sharing coefficients will be conducted, with the focus on analysing their varying effects on the REC members. On the other hand, in Section 4.3 only the Dynamic Sharing Coefficient is considered as sharing strategy as this is the coefficient that tends to bring higher benefits to REC members.

4.1 Experiment Scenario: Sharing strategies in a Renewable Energy Community

The first designed experience has the objective to answer *RQ*#1 by validating *H*#1. For that purpose, a case study was designed to assess the performance of different energy sharing coefficients in a non-residential REC. This assessment is made considering the Portuguese legal framework for management of distributed energy resources, including the energy generated by REC members. Therefore, the framework described in Section 2.4 was designed in accordance with (Presidência do Conselho de Ministros, 2022; Entidade Reguladora dos Serviços Energéticos, 2023a), for the correct implementation of the REC by establishing a CSME. It is responsible for calculating metrics such as electricity consumption, generation, sharing, exports, and associated financial aspects, where applicable. This experiment encompasses structures within the Évora municipality, a historic city located in the heart of Portugal, as outlined below:

- Building 1 (Bld#1) – a versatile pavilion, serving as a venue for concerts, sports tournaments, and various events.
- Building 2 (Bld#2) – the City Hall market.
- Building 3 (Bld#3) – a public market.
- Building 4 (Bld#4) – a public school.

It is important to note that the data considered for this study were originally acquired for a selection of solutions developed on the scope of the Horizon 2020 project POCITYF (POCITYF Project, 2022). The data collection spanned the entire year of 2019, with a 15-minute resolution. This granular data was directly obtained from the DSO through a specific request by the building owners, following standard protocol for buildings equipped with smart meters in Portugal.

These selected buildings exhibit diverse electricity consumption profiles due to various influencing factors such as size, usage type, and year of construction. For example, Bld#4, being a school, experiences a significant reduction in electricity consumption from late July through the second week of September, corresponding to the summer holiday period for students and most school staff. In contrast, Bld#1, primarily used for concerts and events, exhibits a demand peak during the night-time. As a public market, Bld#3, on the other hand, witnesses its demand peak early in the morning. Despite the summer holiday period for Bld#4, its demand peak aligns with that of Bld#2, occurring around noon. These distinctive consumption patterns can have a direct influence on PV self-consumption and, consequently, on the REC's overall performance. To provide a visual representation, Figure 4.1 illustrates the normalized daily average electricity demand profile for each building, while Table 4.1 presents the respective contracted power, indicating the maximum power capacity contracted for each building.

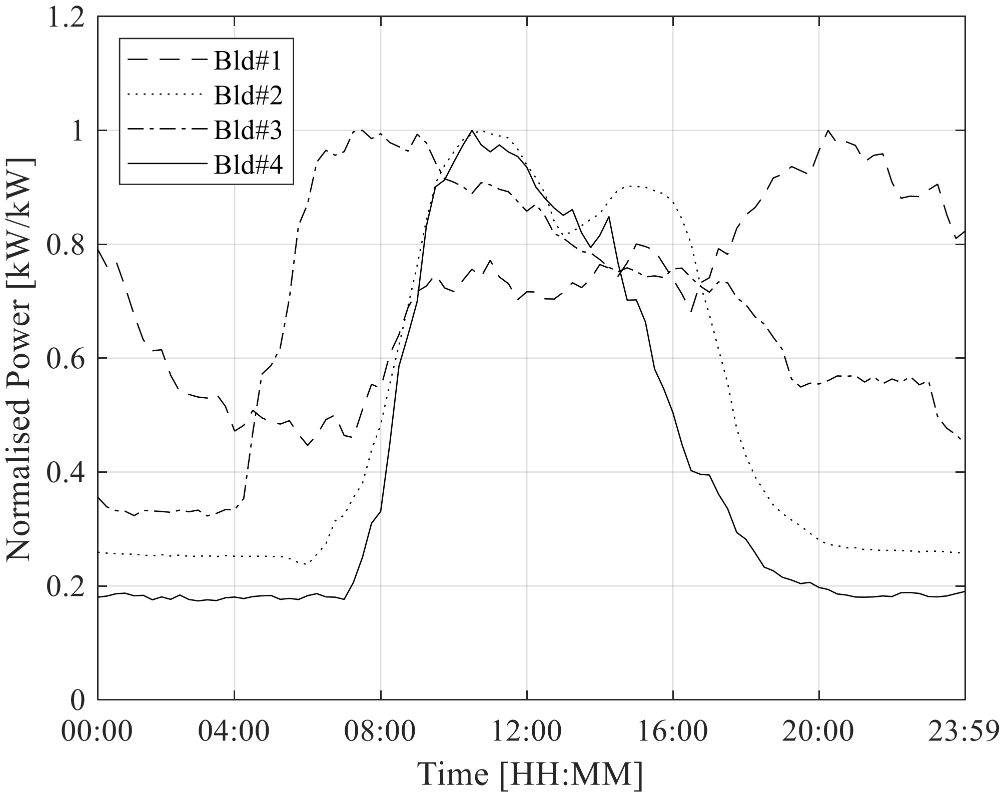

Figure 4.1 - Normalised buildings' daily average demand profile for experiment 4.1

Table 4.1 - Buildings' contracted power for experiment 4.1

Bld	Contracted power [kVA]
1	63.00
2	135.00
3	41.41
4	43.00

For an accurate simulation of the electricity generation when using solar PV modules, meteorological data is paramount for the needed calculation. Therefore, solar irradiance data were collected for the entirety of 2019 with a 1-minute resolution, utilizing a locally-installed meteorological station, in Évora area, also on the scope of the POCITYF Project. This station is equipped with a state-of-the-art two-axis fully automatic sun tracker, the SOLYS2, along with two CMP11 pyranometers to monitor global horizontal and diffuse solar irradiance. Additionally, it employs a CHP1 pyrheliometer for measuring direct solar irradiance. However, these data were acquired perpendicularly to the ground, which is not the inclination that the PV modules are supposed to be installed on the buildings. To align the solar irradiance values with the inclination of the solar PV modules, we applied the methodology outlined in (Duffie and Beckman, 2013). However, for the considered period (2019), real ambient temperature data were not available. To address this, a historic dataset was acquired with a 1-hour resolution from the Photovoltaic Geographical Information System (PVGIS). PVGIS is an online tool and database developed by the Joint Research Centre (JRC) of the European Commission (Joint Research Center (JRC), 2022). This dataset was then treated via a linear interpolation in MATLAB™ to achieve the needed granularity of this case study, namely 1 minute.

The PV modules are assumed to be installed with specific azimuth and tilt angles of 0º and 38º, respectively, to optimize annual generation. This configuration is designed to achieve a specific production of approximately 1,350 kWh per kilowatt-peak (kWp). Table 4.2 shows the characteristics of the solar PV models considered to be installed (Sunpower, 2009).

Table 4.2 - Solar PV module parameters for all experiments

Parameter	Value	Unit
Rated power	300	W
Am	1.63	m^2
η_{pe}	0.8	-
η_{STC}	0.184	-
φ	-0.0038	$ºC^{-1}$
$T_{c,STC}$	25	ºC
$T_{c,NOCT}$	45	ºC
$\theta_{a,NOCT}$	20	ºC
G_{NOCT}	800	$W.m^{-2}$

For further clarity and reference, Figure 4.2 presents this dataset, depicting the meteorological data throughout the year 2019, with their respective daily average values.

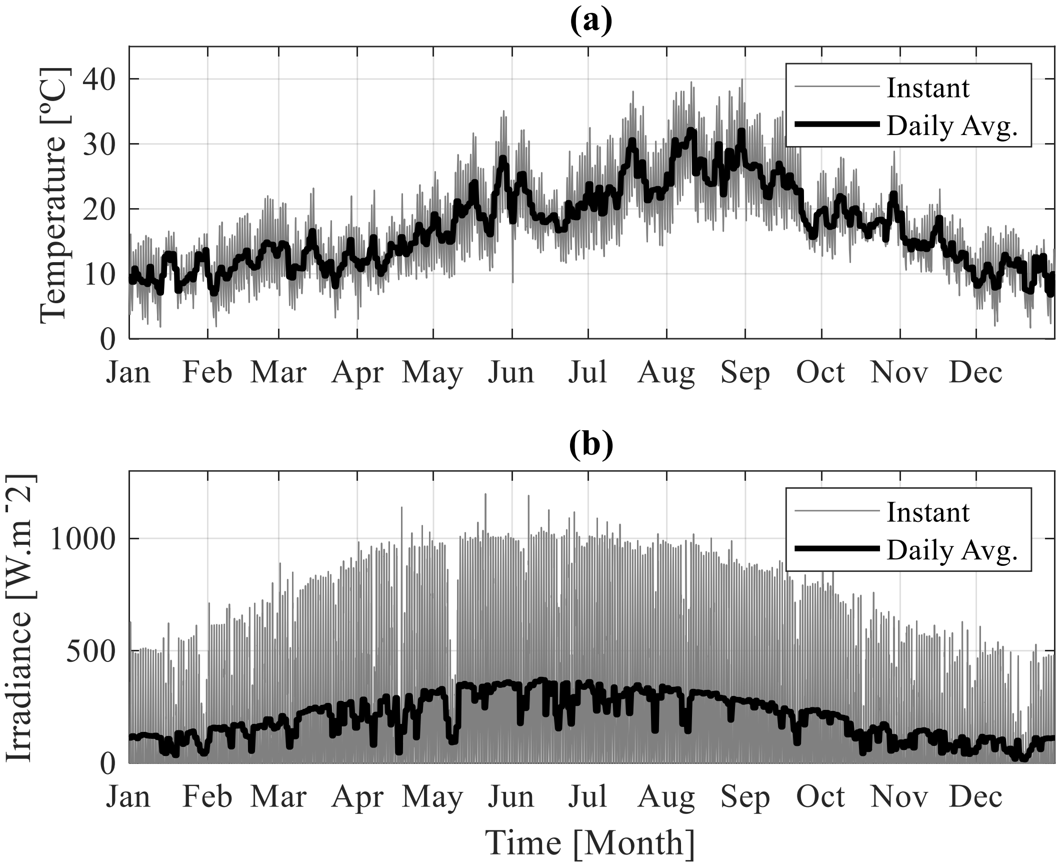

Figure 4.2 - Meteorological data: (a) ambient temperature; (b) solar irradiance, for all experiments

To ensure consistency and compatibility with the electricity consumption data already described, for this case study both solar irradiance and ambient temperature data were treated to achieve a standardized 15-minute resolution. The rationale behind this alignment lies in the need for a precise temporal synchronization between electricity consumption and meteorological parameters for the proper calculation of the generated electricity. The solar irradiance data was treated by calculating the average for each 15-minute interval, and the ambient temperature data were submitted to a linear interpolation, using a function embed in MATLAB™, to achieve the needed granularity for this study, namely 15 minutes. Those processed resulted in a comprehensive dataset for the year 2019, which encapsulates solar irradiance and ambient temperature readings at a 15-minute granularity.

With the information of the solar irradiance (Evans and Florschuetz, 1977; Evans, 1981; Duffie and Beckman, 2013; Lopes, 2017), it is possible to calculate a power output of a considered PV system. This is made by calculating the efficiency of the solar conversion to electricity ($\boldsymbol{\eta}_{sc}(t)$), made at the PV's modules, at a given time instant "t". It is given by Equation 3.9. In this Equation, "η_{STC}" is the efficiency of the solar conversion at the Standard Test Conditions (STC), "φ" is the decrease of the PV power output to the temperature, "$\boldsymbol{T_a}(t)$" is the ambient temperature, "$T_{c,STC}$" is the solar cell's temperature at STC, "$\boldsymbol{G_t}(t)$" is the total solar irradiance reaching the PV modules, "$T_{c,NOCT}$" is the cell temperature at the Nominal Operating Cell Temperature (NOCT), "$T_{a,NOCT}$" is the ambient temperature at NOCT conditions, and "G_{NOCT}" is the solar irradiance at NOCT. Usually, for the STC conditions it is normal to consider 15% for the efficiency and 25ºC for the temperature. Regarding the NOCT, the usual values for cell temperature is 47ºC, the ambient temperature is 20ºC and the solar irradiance is 800 W/m^2. The power output ($\boldsymbol{P_g}(t)$) can be calculated using Equation 4.2. In Equation 3.10, "N" is the number of modules of the considered solar PV system, "Am" is the useful area of each module, and "η_{pe}" is the average conversion efficiency of the power equipments, namely inverters, circuit brakers and cables. A real-life accurate value for this is 80%, considering balance-of-system losses from, for instance, power electronics equipment (e.g., DC/AC inverter), cables, or soiling in the modules (i.e., losses not related with η_{sc}) (Widén *et al.*, 2010). However, several factors can impact it, namely the quality of the equipment and the installation place regarding ventilation and exposure of the equipment to the weather.

$$\eta_{sc}(t) = \eta_{STC} \times \left\{1 + \varphi \times \left(T_a(t) - T_{c,STC} + G_t(t) \times \left[\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{NOCT}}\right] \times (1 - \eta_{STC})\right)\right\} \quad (4.1)$$

$$P_g(t) = N \times Am \times G_t(t) \times \eta_{sc}(t) \times \eta_{pe} \quad (4.2)$$

The solar PV modules installed follows the parameters accorded among the partners of the POCITYF Project. Table 4.3 shows the characteristics of the PV matrices considered for each of the buildings, describing respectively the number of modules, the installed rated power and the amount of electricity generated during the considered year. It is important to note that, despite the previously mentioned accordance, the selected buildings are situated within an architecturally sensitive area, namely the Évora city centre. Ongoing discussions with local authorities are focused on ensuring that the final PV system designs do not adversely impact the existing cultural heritage. Therefore, it's possible that the final PV system designs, including installed capacity, may undergo adjustments compared to the values presented in Table 4.3, specifically chosen for this study.

Table 4.3 - Buildings installed solar PV power and energy generation for experiment 4.1

Building	# of modules	Installed PV power	Annual generation
Bld#1	24 modules	7.2 kWp	9.74 MWh
Bld#2	285 modules	85.5 kWp	115.67 MWh
Bld#3	52 modules	15,6 kWp	21.2 MWh
Bld#4	135 modules	40,5 kWp	54.9 MWh

For this experiment, the considered sharing strategies possibilities are the ones permitted by the Portuguese regulation, namely (Ministério da Economia e da Inovação, 2022) and (Entidade Reguladora dos Serviços Energéticos, 2023a). To assess the benefits of the association of buildings as a REC, a baseline scenario is also considered, namely the buildings' operation without local generation units and no association whatsoever. Then, an intermediate scenario, in which these buildings have installed local PV systems, described in Table 4.3, but they operate individually, without any sharing strategies. The last two scenarios are the jointly operation of the buildings as a REC. In the third one, the buildings proceed to an individual self-consumption strategy, collectively sharing the surplus among them. The fourth and last scenario is the strategy of proceeding to a collective self-consumption strategy, then sharing the surplus. For the operation as a REC, with sharing the electricity surplus of the self-consumption regardless the chosen strategy, three coefficients are chosen, for comparison: two of them are fixed and one is the DSC, with its general formulation showed in Equation 2.1. Those sharing coefficients are described in Section 2.34. The fixed coefficients are calculated as follows:

- A Fixed and Equal Coefficient (FEC): this means that every building will receive the same amount of electricity ate any given time.
- A Fixed and Proportional Coefficient (FPC): the amount of electricity received by each member is proportional to its relative annual energy consumption on a previous time frame before the formation of the REC.
- The DSC: defined at each 15-minute time-step. The chosen parameter for this experiment is the relative energy consumption of each member at any given time interval.

The buildings under consideration exhibit specific attributes, providing a foundational framework for cost assessment for all the considered scenarios:

- **Voltage Level**: The voltage level governing electricity supply at the energy meter level, deemed relevant for tariff application, is consistently maintained at 400 V (line-to-line voltage). This ensures a uniform basis for evaluating and applying electricity tariffs.
- **Daily Billing Cycle**: The established billing structure adheres to a daily cycle, where the timings for the application of each tariff remain constant throughout the week. Consequently, there are no variations in tariff rates between weekdays and weekends. This standardized approach streamlines cost calculations and facilitates cost predictability for building owners and occupants.
- **Multiple Tariffs**: The billing framework encompasses four distinct tariffs, each designated for specific segments of the daily cycle. These tariffs are categorized as follows (Entidade Reguladora dos Serviços Energéticos, 2020):
    - **Peak Tariff**: This tariff is applicable during periods of high electricity demand, typically corresponding to times of the day when energy consumption reaches its zenith.
    - **Half-Peak Tariff**: The half-peak tariff applies to time intervals characterized by moderate electricity demand, typically falling between peak and off-peak hours.
    - **Normal Off-Peak Tariff**: This tariff comes into effect during off-peak hours, encompassing times when electricity demand is notably lower, such as late evenings and early mornings.
    - **Super Off-Peak Tariff**: The super off-peak tariff is relevant for periods marked by the lowest electricity demand, often occurring during the late night or early morning hours.

Regarding the tariffs' periods and values for this experiment, Table 4.4 describes them. Furthermore, in the process of determining electricity costs, there is an incorporation of a fixed tariff of 0.31 € per day. Additionally, it is applied a contracted power tariff of 0.49 € per kilowatt per day. To factor in the power demand during peak hours, there is also the consideration of the average of the demand power during these peak periods, amounting to 0.05 € per kilowatt per day (Entidade Reguladora dos Serviços Energéticos, 2024). The considered values of tariffs were acquired by analysing a real electricity bill, from January 2019, of one of the REC members used in this experiment. For the sake of simplicity, the same tariffs are applied to all members.

Table 4.4 - Daily cycle tariff intervals and values for experiment 4.2

Winter legal hours		**Summer legal hours**	
Peak (0.21 €/kWh)	09h00 – 10h30 18h00 – 20h30	*Peak* (0.21 €/kWh)	10h30 – 13h00 19h30 – 21h00
Half-peak (0.13 €/kWh)	08h00 – 09h00 10h30 – 18h00 20h30 – 22h00	*Half-peak* (0.13 €/kWh)	08h00 – 10h30 13h00 – 19h30 21h00 – 22h00
Off-peak (0.09 €/kWh)	06h00 – 08h00 22h00 – 02h00	*Off-peak* (0.09 €/kWh)	06h00 – 08h00 22h00 – 02h00
Super off-peak (0.08 €/kWh)	02h00 – 06h00	*Super off-peak* (0.08 €/kWh)	02h00 – 06h00

Experiment 4.1 considers the following scenarios: #1) a baseline operation, representing the current individual energy consumption of the buildings (no solar PV systems installed); #2) individual operation with solar PV systems installed at each building according to the information provided in Section 2.2; #3) REC operation with buildings able to perform individual self-consumption and sharing only the surplus of the locally generated energy; and #4) REC operation with buildings performing collective self-consumption of the total electricity generated by the considered solar PV systems. The performance are evaluated by the following indicators: the amount of electricity import ("E_{imp}") and associated costs ("C_{imp}") - related to all scenarios; the electricity self-consumed by the buildings ("E_{sc}") - related to scenarios #2 and #3; and the electricity exported to the grid ("E_{exp}") - related to scenarios from #2 to #4; and electricity shared to each member ("E_{sh}") - related to scenarios #3 and #4.

4.1.1 Scenario #1: Individual operation without local generation

In this scenario, characterized by the absence of local electricity generation, the concept of electricity sharing does not come into play. Instead, the focus is primarily on the calculation of associated costs, a process facilitated by the utilization of data and guidelines described in

Section 4.1. The total electricity imported from the grid and respective cost of import for the whole REC can be seen in Table 4.5.

Table 4.5 - Indicators for experiment 4.2 - scenario #1

Bld #	$\mathbf{E_{imp}}$ **[kWh]**	$\mathbf{C_{imp}}$ **[€]**
1	37,904	8,353
2	258,350	53,902
3	33,289	7,446
4	36,392	8,545
Total	**365,935**	**78,246**

4.1.2 Scenario #2: Individual operation with PV systems

As an evolution compared to the previous scenario, the solar PV systems described in Table 4.3 energy export becomes a necessity as a consequence of the unbalance between electricity consumption requirements and the locally generated power from the solar PV systems, managed using the algorithm detailed in Section 2.4. The quantification of power export is computed through the utilization of the algorithm depicted in Figure 2.2, with a detailed breakdown of relevant indicators presented in Table 4.6. It is worth mention that each building also contributes to its own energy self-consumption, thereby decreasing the dependency on imported energy and the associated costs. This reduction stems from the utilization of PV-generated electricity to meet the demands of building occupants.

The result of this consumption-generation mismatch manifests in a total electricity export accounting for 34% of the aggregate power produced by the local sources. The remaining 66% represents the proportion of electricity generation that is self-consumed by the individual buildings.

Table 4.6 - Indicators for experiment 4.1 - scenario #2

Bld #	E_{imp} **[kWh]**	C_{imp} **[€]**	E_{exp} **[kWh]**	E_{sc} **[kWh]**
1	30,157	6,685	1,994	7,747
2	165,900	33,673	23,225	92,450
3	21,102	4,643	9,054	12,187
4	16,781	4,149	35,224	20,154
Total	**233,940**	**49,150**	**69,497**	**132,538**

4.1.3 Scenario #3: REC operation with sharing of individual surplus

This configuration underscores a primary emphasis on individual self-consumption of locally generated electricity by the buildings from the solar PV systems. Any surplus energy, therefore, is reserved for sharing among those members who, during a specific time-step, couldn't meet their electricity demands using their respective PV systems. As a result, the available energy for REC sharing necessitates calculation at every time-step, involving the deduction of the energy self-consumed by each building from the total energy generated.

As previously mentioned, we consider three distinct sharing coefficients for the REC management strategies. In Table 4.7, it is shown the computed values for the designated fixed sharing coefficients: equal for every member (FEC) and proportional to each buildings' demand for a previous year before the formation of the REC (FPC). Please note that values for the variable sharing coefficient (DSC), which are unique for each of the 35,040 (96x365) time-steps of the used dataset, are not included here. Furthermore, the DSC is calculated considering only the instant consumption of each REC member, based on the general proposition described in Equation 2.1, to proceed to a fairer distribution of the shareable electricity. the calculation formula for the DSC in this case study is showed in Equation 4.3. This strategy is chose also considering that all members are owned by the same entity (the municipality of the city in study).

Table 4.7 - Fixed sharing coefficients for experiment 4.1 - scenario #3

Bld #	**FEC (%)**	**FPC (%)**
1	25	10.35
2	25	70.58
3	25	9.10
4	25	9.97

$$\mathbf{DSC_j(t)} = \left(\frac{\mathbf{D_j(t)}}{\sum_{\mathbf{j=1}}^{\mathbf{N\_BLD}} \mathbf{D_j(t)}}\right) \quad \textbf{(4.3)}$$

In Equation 4.3, "$\boldsymbol{D_j}(t)$" is the total consumption of the j^{th} REC member in a given timestep "t", and "N_BLD" is the total number of REC members. In this experiment "j" has values from 1 to 4, referring to each REC member considered in this experiment. The performance indicators are detailed in Table 4.8, where each indicator and energy sharing coefficient for a particular building is represented. It's important to note that the quantity of electricity self-consumed within this scenario mirrors that of scenario #2, owing to the prioritization of individual self-consumption before the sharing process commences. The specific values for self-consumed electricity can be referenced in Table 4.6.

Table 4.8 - Indicators for experiment 4.1 - scenario #3

Bld #	E_{imp} [kWh]	C_{imp} [€]	E_{exp} [kWh]	E_{sc} [kWh]	E_{sh} [kWh]
			(a) FEC		
1	28,118	6,300	1,830	7,747	2,039
2	161,454	32,780	22,720	92,450	4,446
3	20,375	4,513	7,900	12,187	727
4	16,715	4,138	29,769	20,154	67
Total	**226,662**	**47,731**	**62,219**	**132,538**	**7,279**
			(b) FPC		
1	28,913	6,446	1,657	7,747	1,244
2	155,677	31,684	22,871	92,450	10,223
3	20,752	4,580	6,999	12,187	351
4	16,754	4,145	26,125	20,154	28
Total	**222,095**	**46,855**	**57,652**	**132,538**	**11,846**
			(c) DSC		
1	28,005	6,275	1,594	7,747	2,152
2	153,876	31,347	22,545	92,450	12,024
3	20,454	4,527	6,570	12,187	649
4	16,756	4,145	23,937	20,154	26
Total	**219,091**	**46,294**	**54,646**	**132,538**	**14,851**

4.1.4 Scenario #4: REC operation with collective self-consumption

The main feature of this scenario lies in the fact that the PV systems are not allocated for individual self-consumption before initiating the sharing process. This fundamental distinction leads to a higher volume of electricity available for sharing among the REC members. Furthermore, there is no individual self-consumption by the members, for this reason the indicator "Electricity self-consumed" is not represented here. The subsequent stages of the energy sharing process mirror those of the prior scenario, including the values of the fixed coefficients, both fixed and proportional, as can be seen in Table 4.7. The overview of the performance indicators can be seen in Table 4.9.

Table 4.9 - Indicators for experiment 4.1 - scenario #4

Bld #	E_{imp} [kWh]	C_{imp} [€]	E_{exp} [kWh]	E_{sh} [kWh]
		(a) FEC		
1	24,056	5,491	5,126	13,848
2	211,161	43,448	60,844	47,189
3	17,883	4,014	11,178	15,406
4	17,429	4,291	28,906	19,057
Total	**270,529**	**57,244**	**106,084**	**95,500**
		(b) FPC		
1	26,888	6,045	2,968	11,015
2	152,580	31,006	35,249	105,770
3	21,765	4,777	6,473	11,524
4	24,638	5,900	16,738	11,848
Total	**225,871**	**47,728**	**61,428**	**140,157**
		(c) DSC		
1	27,344	6,157	2,641	10,560
2	148,328	30,201	31,358	110,022
3	21,848	4,828	5,758	11,441
4	21,571	5,121	14,891	14,915
Total	**219,091**	**46,307**	**54,648**	**146,938**

4.1.5 Experiment #1 Analysis

The findings derived from this experiment reveal that operating as a REC result in lower energy costs and a reduced reliance on imported energy, in contrast to the individual operation. This positive outcome can be attributed to the energy sharing dynamics among REC members, a feature present in both scenarios: the one which permits individual self-consumption and the one which embraces collective self-consumption. Notably, this shared energy approach also diminish the amount of electricity exported to the distribution grid. In contrast, the scenario in which PV systems are absent, exhibits the least favourable performance regarding costs and imported energy. This results only stress the importance of the distributed generation units considered for this case study. Furthermore, this procedure relies on most of the benefits for consumers, being the REC formation only an extra benefit, with a minimum amount of investment.

To support this analysis, Figure 4.3 provides a visual representation of the daily average demand profile of the REC, considering all possible sharing coefficients in experiment 4.1. In this figure, scenario #2 is included for comparative purposes, as it serves as a reference point for REC operation in the absence of specific energy sharing coefficients. scenario #1, due to its lack of local generation, is not incorporated into this comparison.

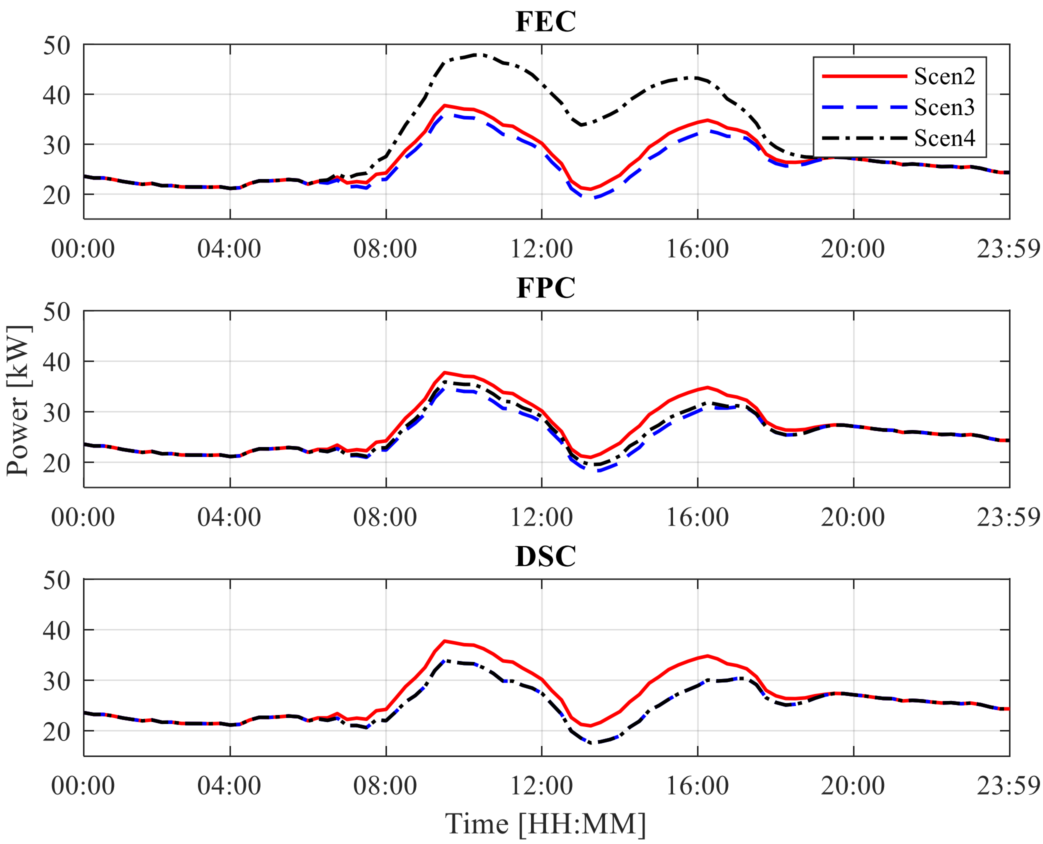

Figure 4.3 - Normalised REC average load diagram considering each sharing coefficient used in experiment 4.1

In regards to the sharing coefficients, it can be concluded from Table 4.8 and Table 4.9 that the optimal choice relies on the specific scenario and the individual demand profiles of each building. Nevertheless, it is discernible that the DSC tends to yield superior REC performance from a collective standpoint, characterized by reduced electricity costs and diminished reliance on imported electricity. However, an exception arises when individual self-consumption is allowed for REC members, as exemplified in experiment 4.2 - scenario #3. In such cases, the advantage of the DSC is diminished due to the inherent benefits of individual self-consumption and the corresponding reduction in electricity requirements at each timestep in which electricity sharing is performed. Contradictory, this scenario can enhance the overall sharing process, especially when the DSC is applied. It's important to acknowledge that in experiment 4.1 - scenario #4, which does not allow the members to proceed to an individual self-consumption from the solar PV systems, may pose challenges in terms of member engagement, considering a potential extension of the Return of Investments (ROI) by the members. This is especially evident when comparing REC operations with collective self-consumption (experiment 4.1 - scenario #4) against those permitting individual self-consumption (scenario #3). In such scenarios, the incorporation of the DSC can be advantageous when considering factors beyond the buildings' demand, such as investment costs, as outlined in Equation 3.1.

Another critical factor to consider is the variance in electricity demands and local generation among buildings. Table 4.10 provides an overview of the annual generation and demand for each building, along with the corresponding ratio between these values. In this context, the significance of Bld#2 in the sharing process is heightened due to its substantial electricity demands, rendering it the primary beneficiary of the DSC, as illustrated in Figure 4.4, which delineates the individual performance of each building across scenarios of experiment 4.1. Conversely, Bld#1 and Bld#3, with lower energy requirements, exhibit the most favourable outcomes when the FEC is applied, given that the volume of shared electricity remains unaffected by other members' electricity needs. Nonetheless, even with this disparity in demands, the DSC can enhance the overall performance of the entire REC, surpassing other methods of electricity sharing, as demonstrated in Figure 4.4. It is important to note that, according to the Portuguese sharing rules (Entidade Reguladora dos Serviços Energéticos, 2023a), this process, regardless of the chosen sharing coefficient, in a real environment does not reflect in actual changes on the respective members' load diagram. The energy sharing algorithm described in Section 2.4 perform the alteration on the load diagram for the sake of programming effectiveness. However, the achieved results are similar. Furthermore, to perform the application of the DSC, which alters at every time instant, this algorithm construction is made specifically for a proper leveraging on the advantages of the proposed sharing coefficient. In a real environment, the sharing process is made after the billing period, and it is made by adjusting the total building consumption. Figure 4.4 only shows the visual representation of the sharing process in each member and the impact on the energy consumed throughout the considered time horizon.

Table 4.10 - Annual generation and demand, and metrics' ratio, for experiment 4.1

Bld #	Generation [kWh]	Demand [kWh]	Generation to demand ratio [%]
1	9,741.03	37,903.75	25.70%
2	115,674.68	258,350.00	44.77%
3	21,240.85	33,289.00	63.81%
4	54,928.56	36,392.25	150.93%
Total	**201,585.12**	**365,935.00**	**55.09%**

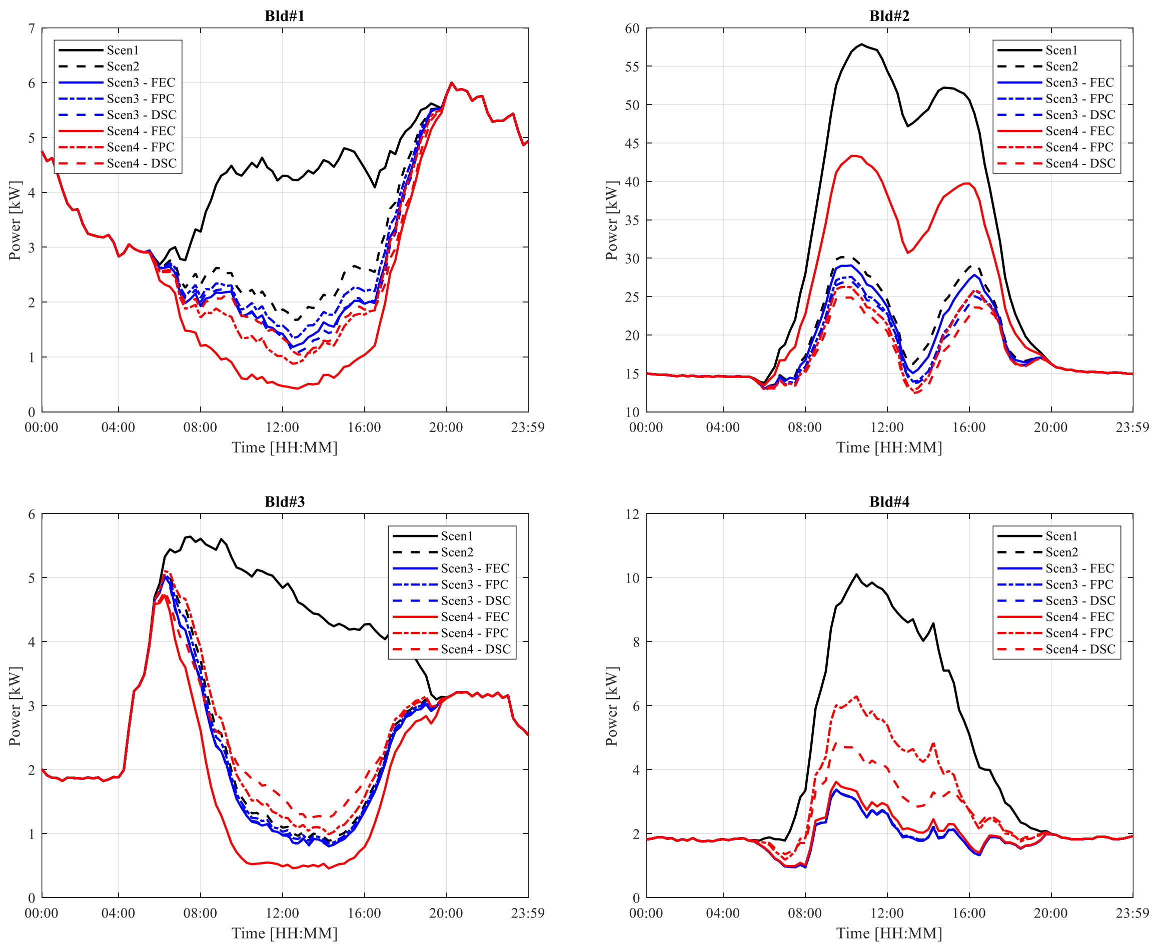

Figure 4.4 - Buildings' daily average demand profile per scenario in experiment 4.1

It is important to note that the operational framework described in this experiment is basically a financial operation, managed by the DSO, following the conclusion of each monthly billing cycle throughout the year. Regardless of the electricity sharing framework, each REC scenario involves the same quantity of electricity. The principal distinction lies in the methodology employed for sharing, which directly influences performance in terms of electricity costs. Lastly, despite the performance of the main indicators (i.e., electricity import and associated costs) are better at REC-level by using the DSC, individually other sharing strategies are better for a given member, e.g., if the REC proceeds to collective self-consumption, sharing the total amount of electricity generated by the members, all but Bld#2 have the lowest electricity cost by using the FEC, which is the worst strategy considering the whole REC. In this experiment, all the buildings belong to the same entity (the municipality of Évora, Portugal). In a situation in which REC buildings have multiple owners, conflicts may arise if the sharing strategy is not effective for every member. To address these conflicts, the Regulation of the REC, which must be approved by the grant entity in Portugal (Entidade Reguladora dos Serviços Energéticos, 2023a), must be clear in how to proceed in this situation.

4.2 Experiment Scenario: Energy Flexibility of an Event-Based Device as a Virtual Storage Installation

The main objective of this case study is to verify the energy flexibility potential of an EBD in a single residential building. It is not conducted to answer neither of the proposed Research Questions, but to serve as proof of concept of the management strategy that uses the energy flexibility potential of EBDs, resulting in a behaviour similar to a Storage Installation, the VSI. For this proof of concept, the load that is considered as flexible load is the battery of a PEV. Furthermore, other loads are also considered to form a typical consumption pattern of such building. These are lighting bulbs, a freezer, a refrigerator, a clock, a cordless telephone, a sound system, an iron, a vacuum cleaner, a personal computer, a printer, two TVs, a Blu-ray reader, a TV Box, a stove, a microwave oven, and a kettle. A dishwasher, a washing machine and a tumble dryer were also considered. Despite their classification as EBD, in this experiment they are not controlled. The reason is to use the same EBD throughout all the case studies, to maintain the logic of the study and a proper assessment of the results. Furthermore, since there is no option for considering any other devices classified as EBD in experiment #3, the decision made in this study is to artificially add the PEVs to the REC members described in Section 4.1 and control them as flexible loads.

The load diagrams were generated using the model developed by (Richardson *et al.*, 2010), with 1-min granularity, over 48 hours. Regarding generation data, it is considered measures from a local in the central region of Portugal, from 2019, presented in Figure 4.2. For this experiment, meteorological data from June 26th and 27th were considered. Section 4.1 of this document provides a detailed explanation on how to calculate the solar PV production considering a solar irradiation dataset (Equations 3.9 and 3.10). For the local solar PV system, a 2.5 kW-peak matrix is considered for calculating the power outputs. When devising strategies for scheduling the operation of flexible loads, it becomes crucial to monitor both the energy consumption of the residential building's loads and the generation profile of the local PV system. The relationship between these variables dictates whether the operation of flexible loads should be paused during unfavourable circumstances. Notably, this case study only considers internal variables, focusing on optimizing the flexible loads' operation within the residential building to reduce the cost with imported electricity, without explicitly addressing the needs and requirements of the DSO.

To create the behaviour of the EV charging, it is considered the following schedule of its use, for a 48-hour horizon, referring to a usage of a person who usually spends the day in the residence:

- Day 1:
  - PEV leaves at 9h13 and returns at 10h39; 36 km trip.
  - PEV leaves at 13h30 and returns at 14h09; 16.3 km trip.
  - PEV leaves at 14h33 and returns at 15h23; 21 km trip.
- Day 2:
  - PEV leaves at 6h00 and returns at 8h40: 66.3 km trip.
  - PEV leaves at 19h39 and does not return until the end of Day 2, due to a long trip.

The remaining characteristics of the considered PEV, generated by taking the average value of a series of commercial vehicles (Teleport Towers, 2024), are:

- Battery capacity: 52.7 kWh.
- PEV efficiency: 0.165 kWh/km.
- Charging power: 3.6 kW

Figure 4.5 illustrates the original residential building's load diagram and the PV generation pattern for a given summer day, and the load diagram of the EV charger for this considered 48-hour horizon, according to the described trips, is shown in Figure 4.6. It is important to note that Figure 4.5 displays the power of considered variables with a 15-min interval, as the average of the values in each considered interval, since it is the time interval used by the DSO to calculate the cost of imported electricity (Entidade Reguladora dos Serviços Energéticos, 2023b).

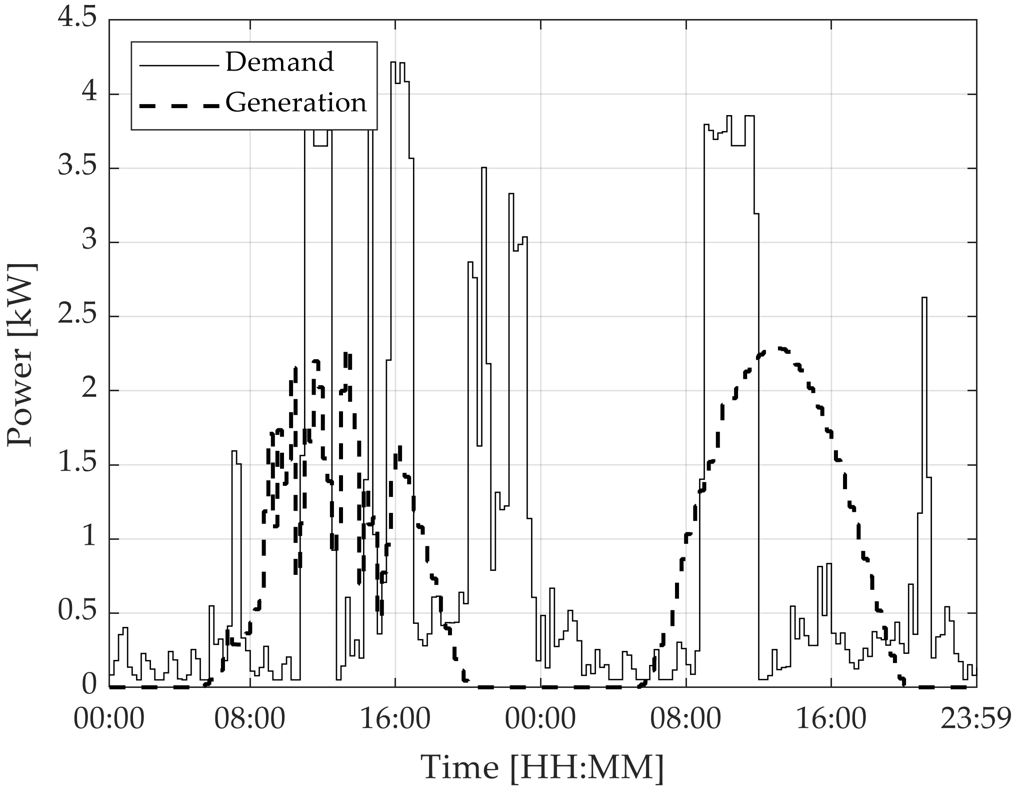

Figure 4.5 - Load diagram and PV generation pattern for experiment 4.2 - scenario #1

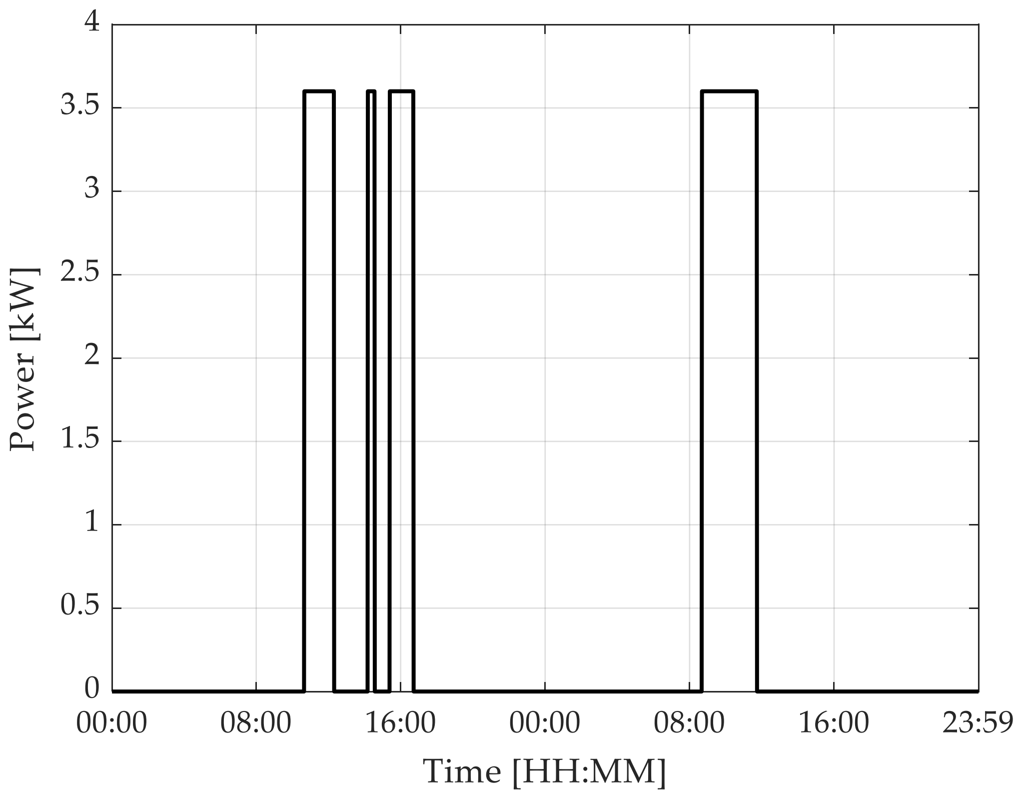

Figure 4.6 - EV Charger load diagram for experiment 4.2 - scenario #1

This experiment considers the following scenarios: #1) individual operation with solar PV systems installed at the building, with no control of the PEV charging: as soon as the user arrives at the residential building, the PEV is plugged to the charger and the charging process instantly begins; #2) programming of the PEV battery charging based on the tariff structure applied, choosing instants with the lowest possible tariff applicable on the instants in which the EV is present to be charged; #3) programming of the PEV battery charging based on the available surplus, after the self-consumption of the uncontrollable loads. The performance is evaluated by the following indicators: the amount of electricity imported and the associated cost.

The building under consideration exhibits specific attributes, providing the framework for cost assessment for all the considered scenarios (Entidade Reguladora dos Serviços Energéticos, 2020):

- **Voltage Level**: The voltage level governing electricity supply at the energy meter level, deemed relevant for tariff application, is consistently maintained at 230 V (single-phase voltage). This ensures a uniform basis for evaluating and applying electricity tariffs.

- **Daily Billing Cycle**: The established billing structure adheres to a daily cycle, where the timings for the application of each tariff remain constant throughout the week. Consequently, there are no variations in tariff rates between weekdays and weekends.
- **Multiple Tariffs**: The billing framework encompasses four distinct tariffs, each designated for specific segments of the daily cycle. These tariffs are categorized as follows:
    - **Peak Tariff**: This tariff is applicable during periods of high electricity demand, typically corresponding to times of the day when energy consumption reaches its zenith.
    - **Half-Peak Tariff**: The full tariff applies to time intervals characterized by moderate electricity demand, typically falling between peak and off-peak hours.
    - **Off-Peak Tariff**: The off-peak tariff is relevant for periods marked by the lowest electricity demand, often occurring during the late night or early morning hours.

Regarding the tariffs' periods and values, they can be seen in Table 4.11.

Table 4.11 - Daily cycle tariff intervals and values for experiment 4.2

Winter legal hours		**Summer legal hours**	
Peak (0.24 €/kWh)	08h30 – 10h30 18h00 – 20h30	*Peak* (0.24 €/kWh)	10h30 – 13h00 19h30 – 21h00
Half-peak (0.17 €/kWh)	08h00 – 08h30 10h30 – 18h00 20h30 – 22h00	*Half-peak* (0.17 €/kWh)	08h00 – 10h30 13h00 – 19h30 21h00 – 22h00
Off-peak (0.10 €/kWh)	00h00 – 08h00 22h00 – 23h59	*Off-peak* (0.10 €/kWh)	00h00 – 08h00 22h00 – 23h59

4.2.1 Scenario #1: PEV charging without control

The first scenario refers to the baseline which is showed in Figure 4.5. The performance indicators chosen for the assessment of this work are the amount of energy that is purchased by the building's users and the associated costs. These indicators were chosen due to the focus of this work being the users, and how the techniques described, when applied, can impact their lives by alleviating the cost of electricity, which is predicted to increase in the following years as stated in Section 1.1 of this document as one of the motivations for the research conducted in this work. The indicators scenario #1 are shown in Table 4.12.

Table 4.12 - Indicators of experiment 4.2 - scenario #1

Imported electricity (kWh)	26.5
Import cost (€)	4.69

4.2.2 Scenario #2: PEV charging control by the VSI - applied tariffs

The objective of this scenario is to assess the efficacy of the flexibility potential exploitation of the PEV battery, considered an EBD, as claimed in Section 3.1.1 by using the framework described in Section 3.2. To this end, the algorithm depicted in Figure 3.3 is implemented to control the charging of the PEV battery. The input variables for its implementation are described in Table 4.13.

Table 4.13 - Input variables for the management of the PEV battery charging process for scenario #2

$\boldsymbol{P_{d,unc}}$	The load diagram of the uncontrollable loads of the building
$\boldsymbol{P_g}$	The power generated by the PV system, shown in Figure 4.5
$\boldsymbol{P_{d,ebd}}$	The charging power of the PEV battery, which load diagram is shown in Figure 4.6
ρ	In this scenario, there is no control considering available surplus, therefore $\rho = 0$.
$t_{e,start}$	Day 1: 10h39, 14h09 Day 2: 8h40
$t_{l,end}$	Day 1: 13h30, 14h33 Day 2: 19h39
C_{ebd}	In this experiment refers to the variation of the PEV battery's SoC at any given time.
$C_{T,ebd}$	In this experiment refers to the total energy that is needed to charge after a given trip of the PEV.
$\boldsymbol{T_{present}}$	The tariff structure considered for this case study, described in Table 4.11.
$T_{present}(min)$	The value of the lowest tariff applied in each interval in which the PEV is present to be charged; in this case study, for Day 1 this value is 0.10 €/kWh, and for Day 2 this value is 0.17 €/kWh.

After the application of the energy flexibility algorithm, the load diagram of the PEV battery charging throughout the day changed considerably. The comparison of both load diagrams is shown in Figure 4.7, and the comparison of the building's load diagram, with the charging of the PEV battery with and without the application of the energy flexibility algorithm is showed in Figure 4.8. The performance indicators of scenario #2 are shown in Table 4.14.

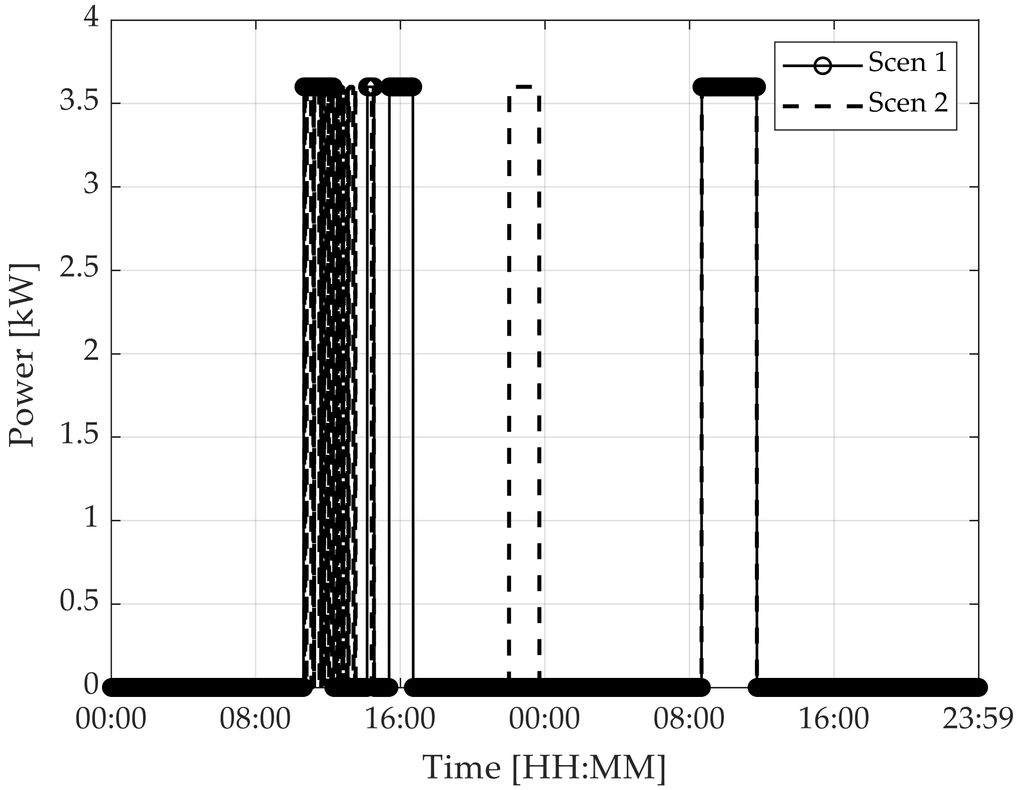

Figure 4.7 - Comparison of the PEV battery's load diagram in both scenarios #1 and #2 of experiment 4.2

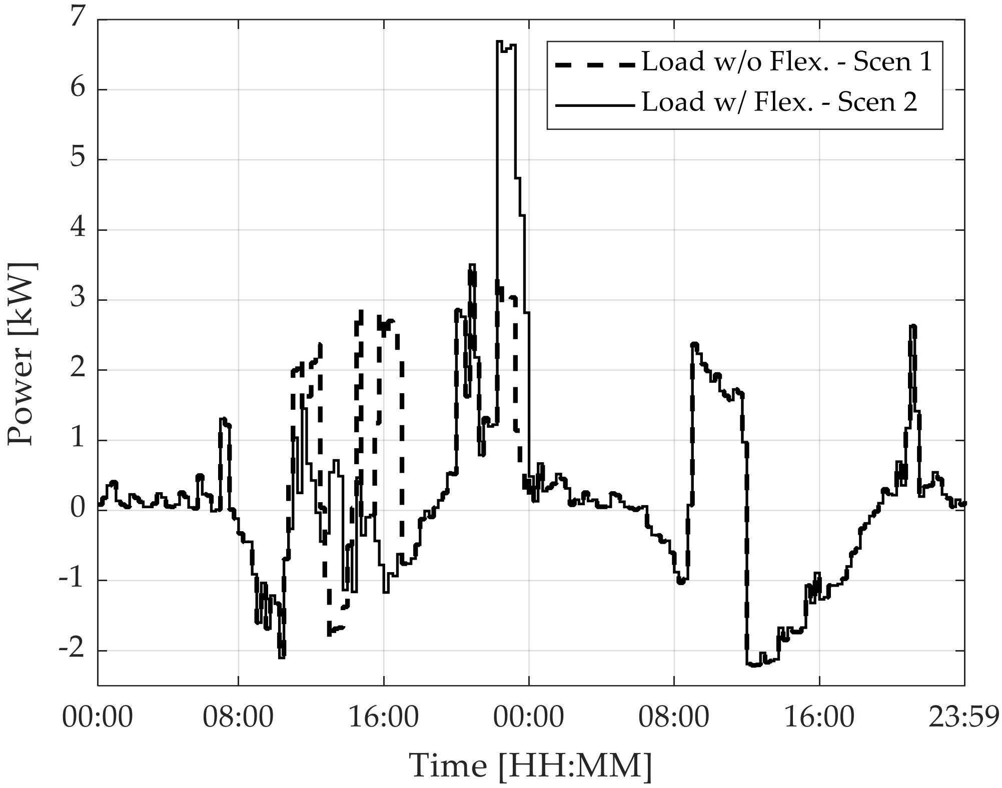

Figure 4.8 - Comparison of the building's load diagram at meter level in both scenarios #1 and #2 of experiment 4.2

Table 4.14 - Indicators of experiment 4.2 - scenario #2

Imported electricity (kWh)	26.7
Import cost (€)	4.17

4.2.3 Scenario #3: PEV charging control by the VSI - available surplus

On the contrary to what is conducted in scenario #2, the objective of this scenario is to assess a more restrictive condition for the EBD operation, namely the charging of the PEV battery with part of the available surplus after the self-consumption of the remaining building loads. This is possible as the branch in Figure 3.3 when, on the "Control via surplus?" decision box, the answer is "Yes". To this end, it is necessary to define the value of the variable "ρ", representing the percentage of the surplus in each time instant is needed for the charging. Despite the possibility of the whole range from zero to 100%, the chosen value can have the objective to minimize cost while increase the self-consumption of the building. To this end, let's consider the following parameters defined in Section 3.2, and their correspondent variable in this experiment:

Table 4.15 - Parameters for the calculation of the minimum surplus in experiment 4.2 - scenario #3

Parameter	Variable in this experiment
ρ	The chosen percentage of surplus to allow the charging of the EV battery
$P_{d,ebd}$	The charging power of the EV battery = 3.6 kW
$T_{present}(min)$	The lowest tariff on the interval in which the EV is present to be charged: - for Day 1 = 0.10 €/kWh - for Day 2 = 0.17 €/kWh
$T_{present}(max)$	The highest tariff on the interval in which the EV is present to be charged: - for Day 1 = 0.24 €/kWh - for Day 2 = 0.24 €/kWh

Only one percentage value is calculated per day, based on the difference between the highest tariff ($T_{present}(max)$) and the lowest tariff ($T_{present}(min)$) applicable in each day, during the interval in which the EBD is present at building premises and its operation is possible, namely the battery of PEV is not fully charged. In this sense:

$$T_{present}(max) \times \left[P_{d,ebd} - \left(\rho \times P_{d,ebd}\right)\right] \times \Delta t \leq T_{present}(min) \times P_{d,ebd} \times \Delta t \tag{4.4}$$

Some considerations regarding Equation 4.4:

- The inequality signal means that the price to pay is equal to the price to pay with the lowest tariff possible, at most.
- The term " $\rho \times P_{d,ebd}$" corresponds to the minimum amount of surplus in terms of the power demand of the EBD.
- For a single value of "ρ", it is possible to make both sides of Equation 4.4 equal, as:

$$T_{present}(max) \times \left[P_{d,ebd} - \left(\rho \times P_{d,ebd}\right)\right] \times \Delta t \leq T_{present}(min) \times P_{d,ebd} \times \Delta t \tag{4.5}$$

$$P_{d,ebd} - \left(\rho \times P_{d,ebd}\right) = \frac{T_{present}(min) \times P_{d,ebd}}{T_{present}(max)} \tag{4.6}$$

$$P_{d,ebd}(1-\rho) = \frac{T_{present}(min) \times P_{d,ebd}}{T_{present}(max)} \quad (4.7)$$

$$(1-\rho) = \frac{T_{present}(min)}{T_{present}(max)} \quad (4.8)$$

$$\rho = \left[1 - \frac{T_{present}(min)}{T_{present}(max)}\right] \times 100\% \quad (4.9)$$

Applying the values from Table 4.15 in Equation 4.9, the considered value for "ρ" is 58.33% for Day 1 and 29.17% for Day 2. The resulting charging profile of the PEV in scenario #3 is shown in Figure 4.9, in which it is possible to compare with the charging profile any control (scenario #1). Furthermore, the same comparison, now for the load diagram of the building, is shown Figure 4.10. Lastly, as per indicators, they are described in Table 4.16.

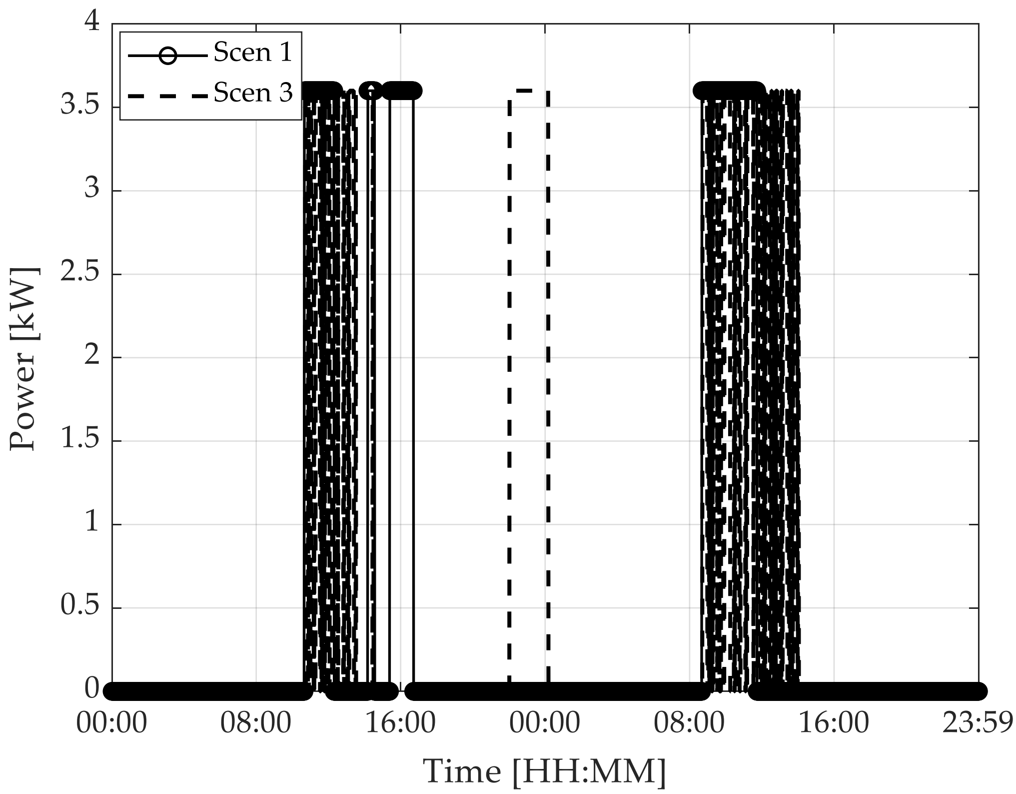

Figure 4.9 - Comparison of the PEV battery's load diagram in both scenarios #1 and #3 of experiment 4.2

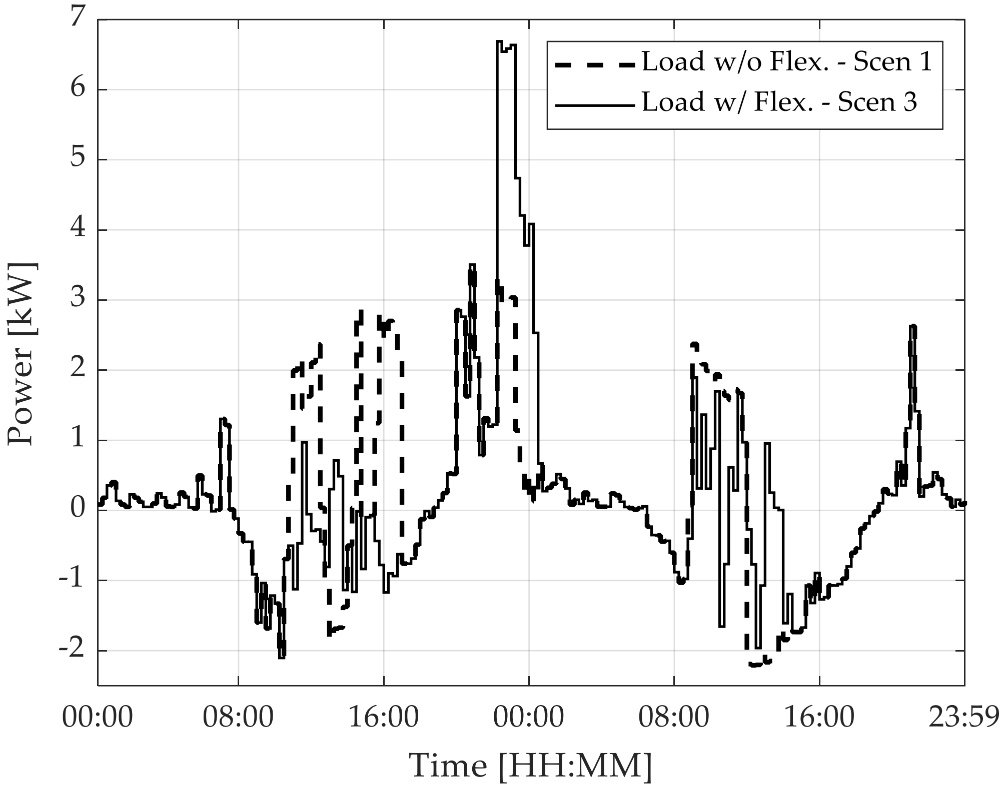

Figure 4.10 - Comparison of the building's load diagram at meter level in both scenarios #1 and #3 of experiment 4.2

Table 4.16 - Indicators of experiment 4.2 - scenario #3

Imported electricity (kWh)	24.9
Import cost (€)	3.67

4.2.4 Experiment #2 Analysis

By the comparison of the two first scenarios is possible to verify the effectiveness of the proposed approach. The analysis of Figure 4.8 and Figure 4.10 makes possible to verify that taking advantage of the energy flexibility potential of the PEV battery results in a behaviour similar to the operation of a Storage Installation, in line with the VSI concept described in Section 3.2, such as shifting of load peaks, that results in lower costs in both studied scenarios. Furthermore, due to the defined rules for the EBD operation, namely the charging of the PEV battery, valleys are presented in the load diagram, a consequence of the operation pausing of the device when conditions are not set. This behaviour is consistent with the operation of an SI in a building with PV system as local source of electricity (Queiroz, 2018) In scenario #2, the behaviour of the load diagram between midday and 18h, and after 22h during Day 1 is strongly impacted by the application of the VSI management strategy, exploiting the energy flexibility potential of the PEV battery as an EBD. However, it is not possible to control the PEV charging in Day 2 due to the instants in which it is present in building premises to have its operation changed and the tariff structure applied. On the other hand, since in scenario #3 the strategy is to control the charging by the availability of solar PV surplus, it is possible to control the EBD operation in both considered days. Furthermore, the loss of production in Day 1 due to shading on the panels is compensated by the clear sky generation pattern in Day 2, which leads to an overall better performance on the considered time horizon, comparing with scenario #2. Therefore, the exploitation of the flexibility potential of the PEV battery is more effective, achieving the best performance regarding the chosen indicators among the 3 designed scenarios. Figure 4.11 and Figure 4.12 detaches its behaviour, showing instants in which the equivalent VSI is charging and discharging during the considered time interval, namely 48 hours.

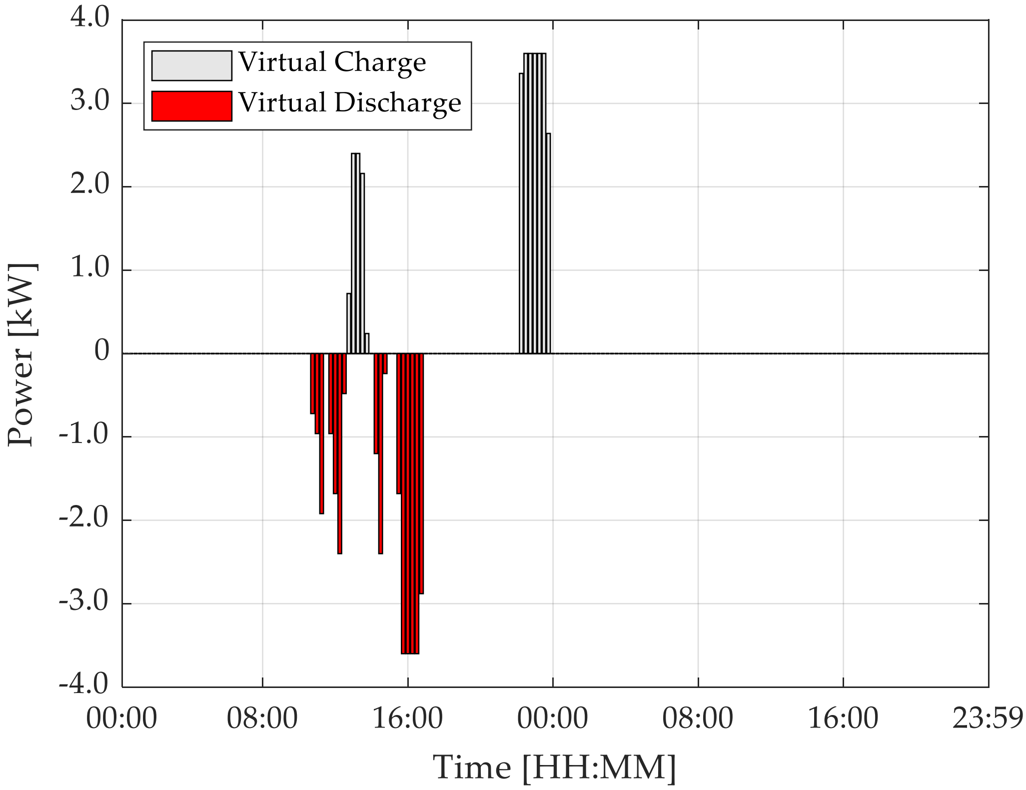

Figure 4.11 - VSI status in experiment 4.2 - scenario #2

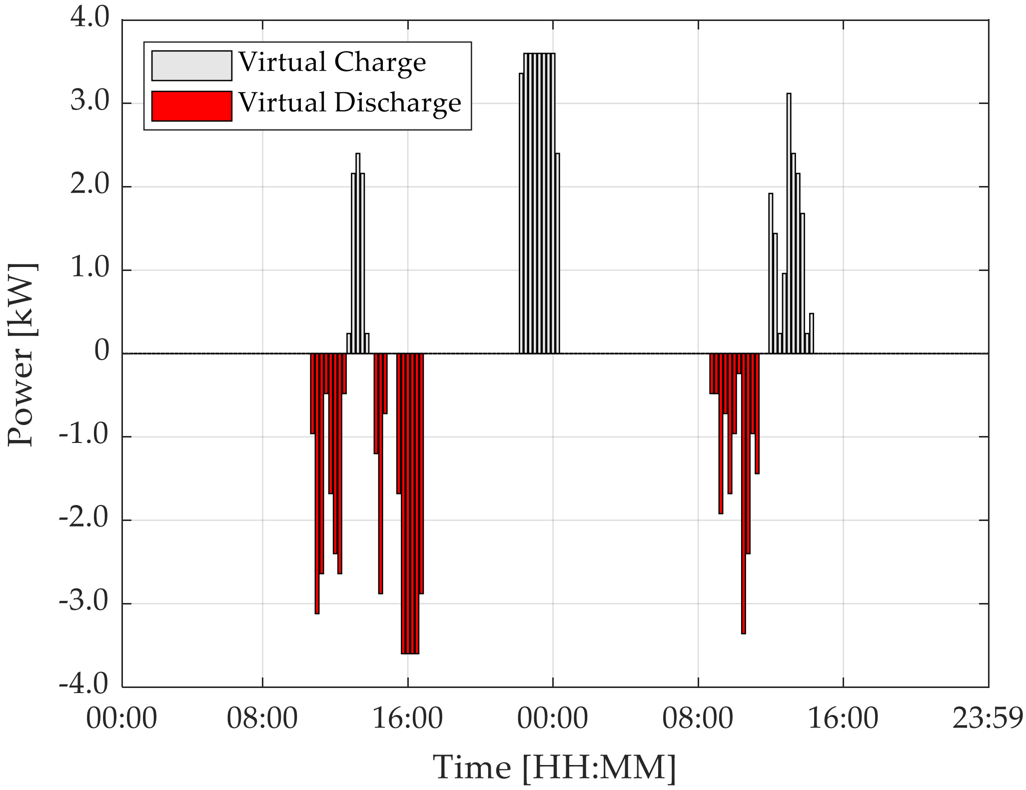

Figure 4.12 - VSI status in experiment 4.2 - scenario #3

It is important to note that, in scenario #2, there is no change on the load profile in Day 2 due to the difference of tariffs on instants in which the PEV is available for charging after its morning trip. Since the PEV is not available after 22h for charging, it is not possible to consider the "off-peak" tariff for its charging, compromising the performance of the charging control. Furthermore, in scenario #3, during Day 1, due to the imposed restrictions for the charging of the PEV battery, there is an increased consumption during its different usages, which leads to a more acute decrease in its SoC, compared with scenario #2, as can be seen in Figure 4.13. This figure also shows that, due to its perceived behaviour in scenario #3, there was a need to force the charging at 22h00, for the PEV battery achieve, at midnight, a SoC equal 100%, meaning that is fully charged. It is important to note that this situation did not occur in scenario #2, in which the battery is fully charged around 23h30 on Day 1. This also happens due to the flexibility exploitation in this scenario is made based simply on the difference of tariffs. Since after 22h, for this experiment, the tariff structure has its lowest value after this time, the management strategy naturally orders the charging of the PEV battery.

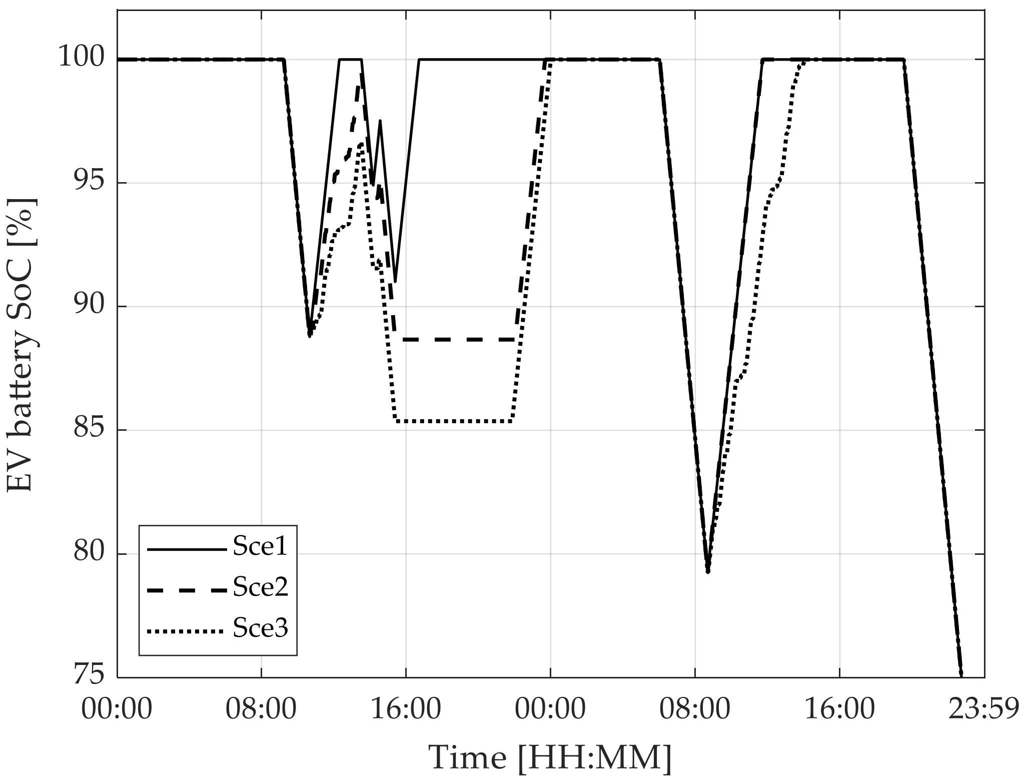

Figure 4.13 - Comparison of the PEV battery's SoC behaviour in experiment 4.2 scenarios

Moreover, since one of the main objectives of the PEV charging management is to decrease the imported electricity value, there was a need to take the import tariff into consideration, particularly in scenario #2, in which the only parameter of control is the tariff structure applied to the building. For this reason, the variables "$\boldsymbol{T_{present}}$", representing the tariff structure applied during the considered time interval, and "$T_{present}(min)$", the least expensive value of the same considered time, are applied. The energy flexibility control algorithm of the EBD is indirectly capable to map the instants in which it is more cost-efficient to charge the PEV battery when the control is made exclusively by the tariffs applied to the building. Figure 4.14 shows this mapping.

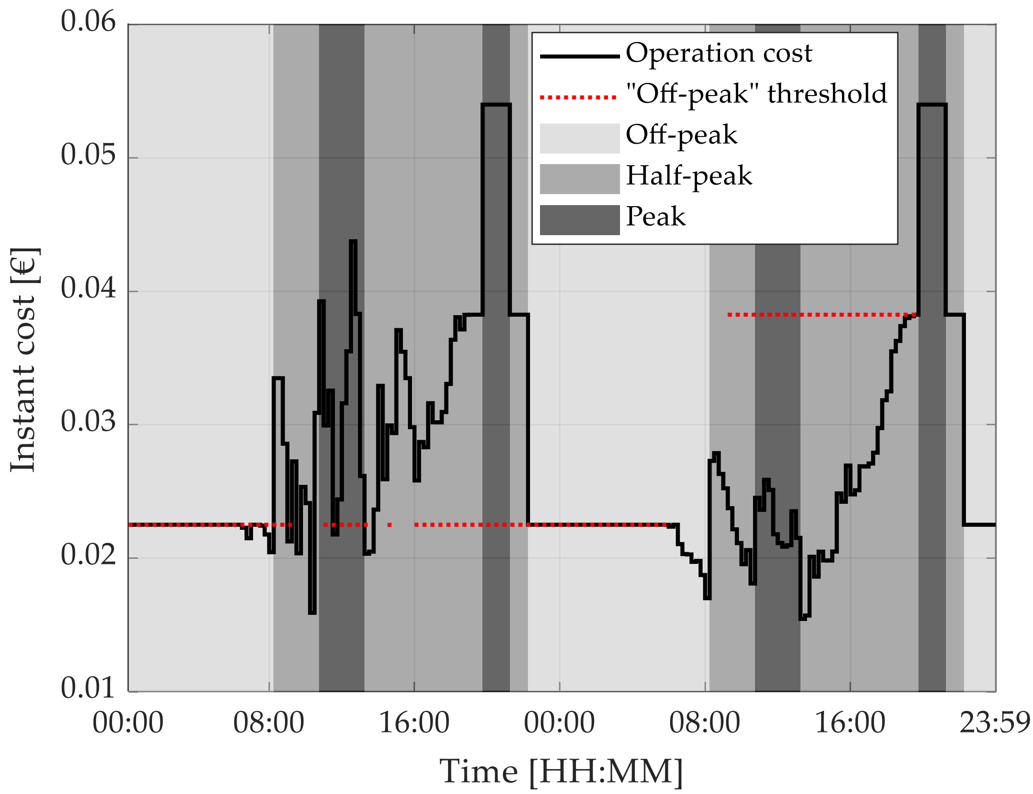

Figure 4.14 - Mapping of VSI operation cost for experiment 4.2 - scenario #2

In Figure 4.14, the dashed line refers to the value paid to charge the PEV at every 15-min interval when the tariff applied is the lowest possible, considering the time intervals in which the PEV is present in the building and its charging is possible, without considering any interaction with local generation units. The solid line refers to the actual value to charge the PEV at any given 15-min interval during the 48-hour horizon, considering the possibility to charge with the surplus after the self-consumption of the remaining building loads, when it exists. Therefore, based on the available local electricity surplus, it is more cost-effective to charge the PEV on instants in which the solid line in Figure 4.14 is below the dashed line. For that reason, the charging of the PEV did not have any modification during Day 2: since the PEV is not available, after its first trip in this day, in instants of lowest tariff applied ("off-peak", after 22h), this situation creates the red dashed line - the threshold, higher than the one in Day 1. That is reason that the PEV starts its charging as soon as it arrives in the building. This evidenced the need, by the end-user, to declare the late end for the operation of the EBD (in this case, the time when the PEV use is needed after a given trip).

Regarding the SoC behaviour of the VSI, Figure 4.15 show it for the 2 considered scenarios in which the flexibility of the PEV battery charging is exploited (scenarios #2 and #3), based on the proposition for the calculation of the VSI's SoC, summarized by Equation 3.1. In Figure 4.15 it is possible the verify every instance in which it was not possible to proceed to a complete operation shifting of the EBD, namely the time interval in which the VSI SoC cannot achieve 100%. For example, in Day 1, for both scenario #2 and #3, due to the constant usage of the PEV, and the restrictions imposed for the charging, after the first arrival, it is not possible to charge the totality of the energy spent, which is considered, for this load, that the shifting was not complete. Only at night, during the "Off-peak" instants, there is the completion of the operation shifting. This situation is easily perceived in Day 2 for scenario #3. The descending interval of the line representing the VSI SoC variation in scenario #3 represents the interval in which the PEV is supposed to be charged if any management structure is in place (scenario #1). On the other hand, the ascending one represents the actual charging instants, limited by the availability of solar PV surplus after the individual self-consumption of the remaining loads. It is important to note that, despite what is depicted in Figure 3.2, in this experiment the VSI operation was analysed based on the impact of the PEV battery shifting on the load diagram of the building at meter level. All the interactions (the individual self-consumption and consequential surplus, and the management structure for the PEV battery shifting) leads to different alterations in terms of demand power, despite the PEV battery has a constant charging power.

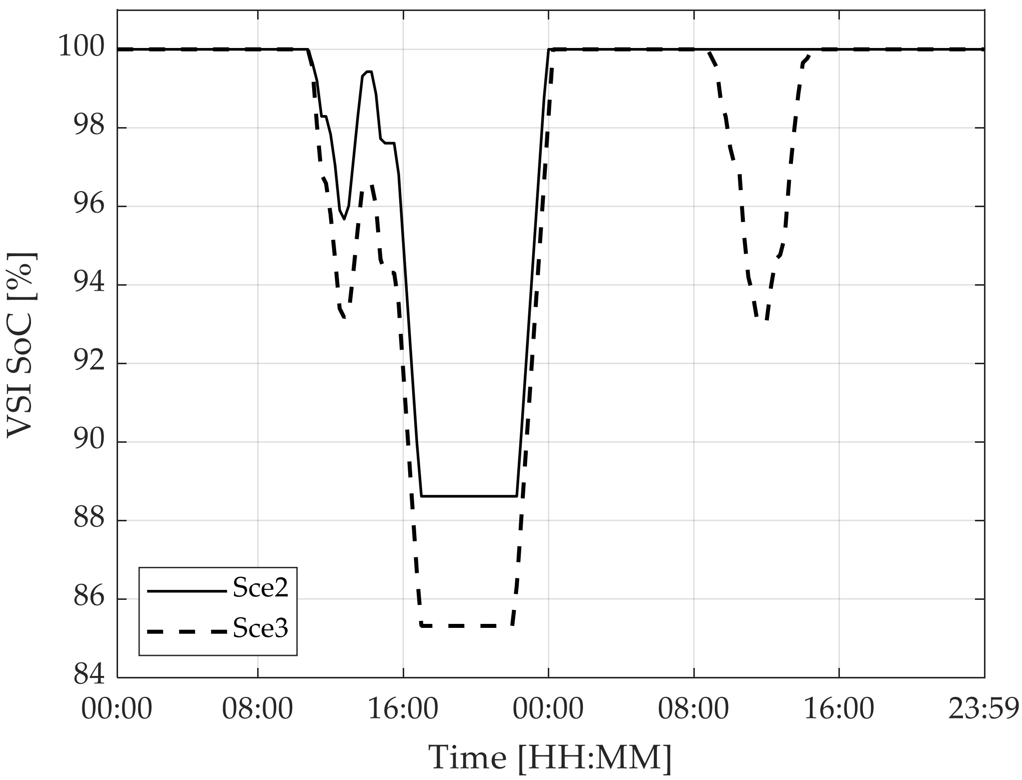

Figure 4.15 - VSI SoC behaviour in experiment 4.2, scenarios #2 and scenario #3

Experiment 4.2 does not aim to answer neither of the research questions proposed in this study, but only make a proof of concept of the Virtual Storage Installation management framework. The intent was to verify the feasibility of this concept in a smaller case study, in which is possible to verify detailed information on the behaviour of loads.

4.3 Experiment Scenario: Influence of EBD's energy flexibility potential on the DSC in a Renewable Energy Community

This case study focuses the exploration of the energy flexibility potential of EBDs in a REC context. To this end, the same REC assessed in experiment #1 is considered in terms of consumption (shown in Figure 4.1) and generation datasets (shown in Figure 4.2) of all 4 non-residential buildings. Furthermore, due to the nature of those buildings (non-residential) and the lack of disaggregated data, the EBDs that are considered in this experiment are PEVs. As stated in Section 3.1.1, the PEV can be classified as an EBD if there is no power flow from their batteries back to the grid. This is the assumption made for this experiment, since the only status that their batteries assume during the simulations are "charging" and "idle". Regarding this experiment:

- The same buildings are considered, namely: the pavilion (Bld#1), the City Hall building (Bld#2), the public market (Bld#3) and the public school (Bld#4).
- Two EVs are part of the fleet of each REC members
- The same tariff structure described in Section 4.1 is applied.
- The PV systems for local generation has the same modules considered in experiment #1, and their characteristics can be seen in Table 4.2 and production summary in Table 4.3.
- For the designed experiment scenarios, only the dynamic sharing coefficients (DSC) is considered for sharing strategy due to its better performance (see performance indicators in Table 4.8 and Table 4.9).

Regarding the EBDs, namely the PEVs, it is important to note that, due to the non-residential nature of the buildings, they are not available for the whole day to participate in this management strategy, which means that only in times that their users are present in the building the PEV battery can be charged. To simulate this non-deterministic behaviour, their arrival and departure time during workdays is randomly assigned for each day. For this experiment, all PEVs are modelled with the same characteristics described in Section 4.2. However, in this experiment the trip distance is fixed for every working day to simulate a normal usage of the EVs in this context of non-residential buildings (Automóvel Club de Portugal, 2023) such as this REC members. Table 4.17 shows the schedule of the PEVs in each REC member.

Table 4.17 - PEVs' schedules for experiment 4.3

		km driven/day	Arrival interval	Departure interval
Bld#1	**EV#1**	20	8h30 - 9h00	17h00 - 17h30
	EV#2	25	9h00 - 10h00	16h30 - 17h30
Bld#2	**EV#1**	40	8h30 - 9h15	16h30 - 17h15
	EV#2	50	8h15 - 9h30	16h45 - 17h45
Bld#3	**EV#1**	60	5h00 - 5h30	14h00 - 15h00
	EV#2	25	9h15 - 9h30	18h00 - 18h30
Bld#4	**EV#1**	30	7h15 - 7h45	16h00 - 16h15
	EV#2	60	9h00 - 9h45	17h45 - 18h30

The introduction of PEVs batteries' charging leads to changes on the demand of all REC members for this experiment. Figure 4.16 shows the new average demand of each member. This difference is due to the instant charge of the PEVs as soon as the vehicles arrived, and there's no influence of any management possibilities for exploring the energy flexibility potential of the PEVs' batteries. It is important to note that the average loads showed in Figure 4.16 are normalised using a base demand of the buildings without the need to charge the batteries, to provide a visualisation of their impact on the buildings' demand.

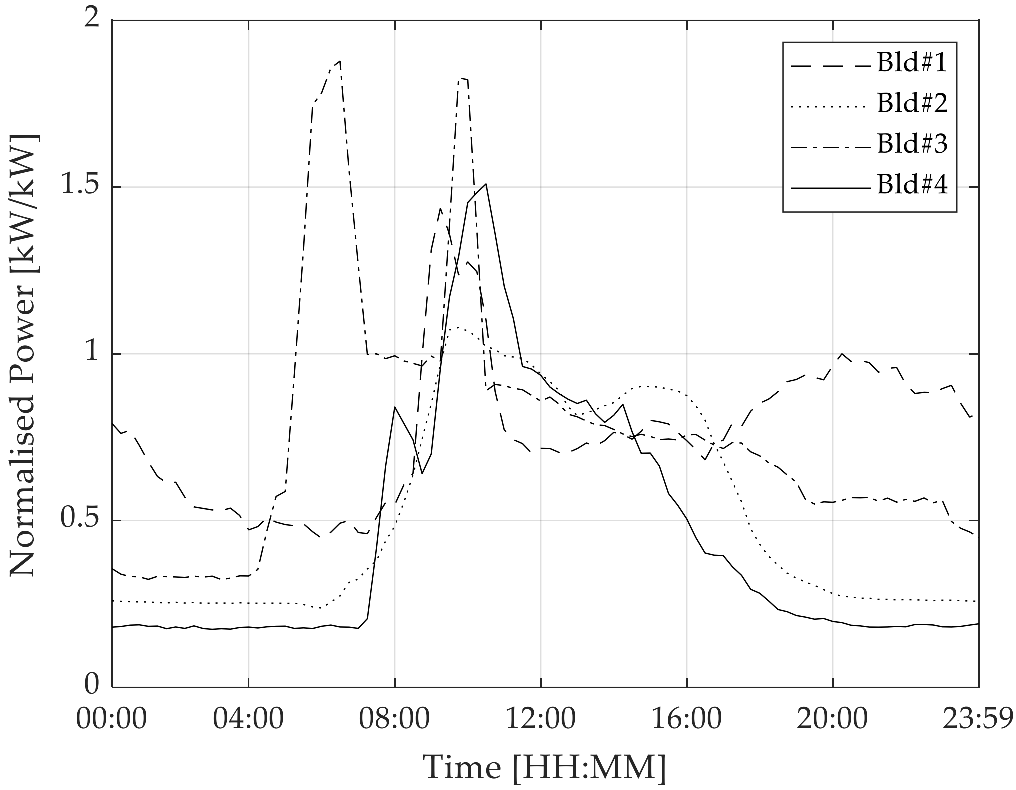

Figure 4.16 - REC members' demand with the addition of the PEVs

The main objective of this experiment is to assess the impact of the exploitation of the energy flexibility potential of the PEVs' batteries on the performance of the energy sharing strategy of a REC. To this end, this experiment considers the following scenarios: #1) REC operation with buildings able to perform individual self-consumption and sharing only the surplus of the locally generated energy; and #2) REC operation with buildings performing collective self-consumption of the total electricity generated by the considered PV systems. The performance are evaluated by the following indicators: the amount of electricity import ("E_{imp}") and associated costs ("C_{imp}") - related to both scenarios; the electricity self-consumed by the buildings ("E_{sc}") - related to scenario #1; and the electricity exported to the grid ("E_{exp}") and electricity shared to each member ("E_{sh}") - related to scenarios #1 and #2. Regarding the sharing strategies, only the usage of the DSC is assessed in this experiment due to its efficacy in comparison with the other considered possibilities, described in Section 0. Furthermore, by analysing the usage patterns of PEVs in each REC member, it is important to note that the majority of them are present for charging in members' premises during instants in which the tariff applied for electricity consumption is "half-peak", with some exceptions:

- The one and a half-hour period (in winter, between 09h00 and 10h30, and in summer between 10h30 and 13h00), in which the "peak" tariff is applied.
- For the PEV#1 of Bld#3, which has a different usage pattern, and is present in instants of "super off-peak" and "off-peak" instants.
- For the PEV#1 of Bld#4, which is present for a few minutes, in average, in instants in which the tariff applied is "off-peak".

Figure 4.17 and Figure 4.18 show the probability of the PEVs in each REC member, for winter and summer months respectively, based on the random simulation of their arriving and departure throughout the considered time horizon of analysis (one year). In both figures, the area shaded in green, yellow, orange and red refers to "super off-peak", "off-peak", "half-peak" and "peak" periods, respectively. Due to this context, the strategy of applying the VSI concept in this experiment is to manage the charging of PEVs' batteries considering only the available surplus of electricity generated by the PV systems, as it is one of the possibilities in the management algorithm shown in Figure 3.3. In this experiment, for both considered scenarios, the threshold to charge the PEVs' batteries when exploring their energy flexibility potential is the PEVs are only allowed to charge in instants that at least 60% of the surplus is available. That is the value chosen for the variable "ρ" when applying the Energy Flexibility algorithm, explained in Figure 3.3. The threshold can be freely chosen and is defined as a cost-effective balance between availability of local surplus and a certain degree of freedom of scheduling the PEVs' charging. Furthermore, it corresponds to the ratio between the production at REC-level and sum of the members' consumption disregarding the charging of PEVs, rounded up (see Table 4.3).

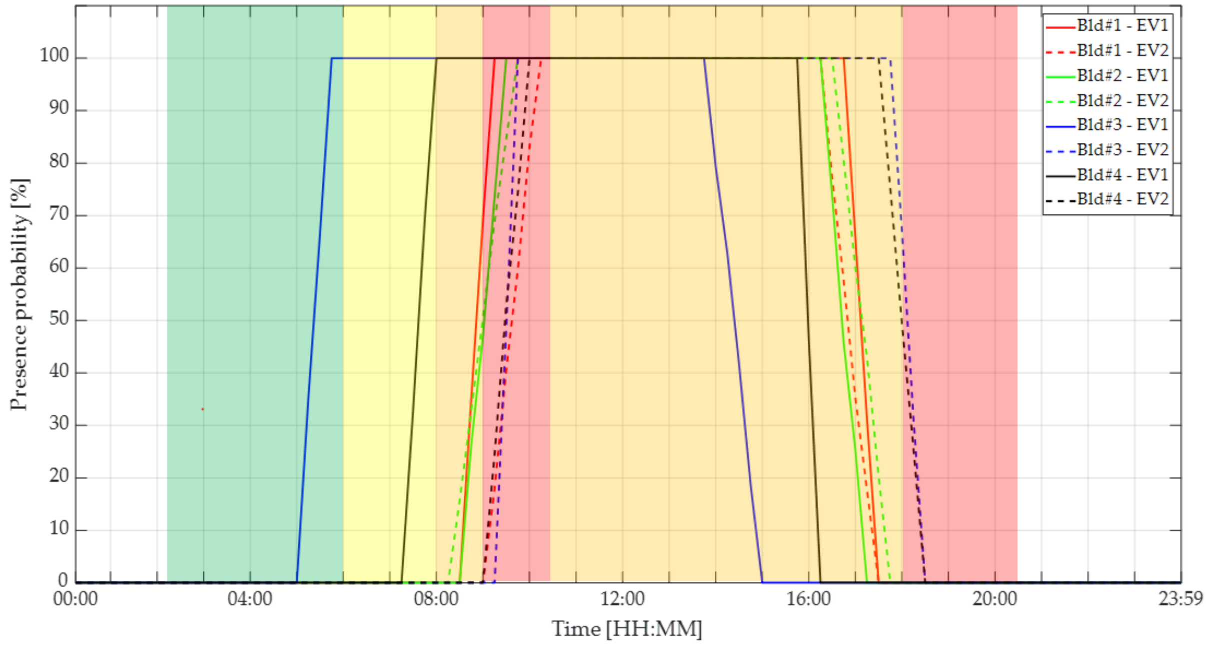

Figure 4.17 - EVs' presence probability in winter months

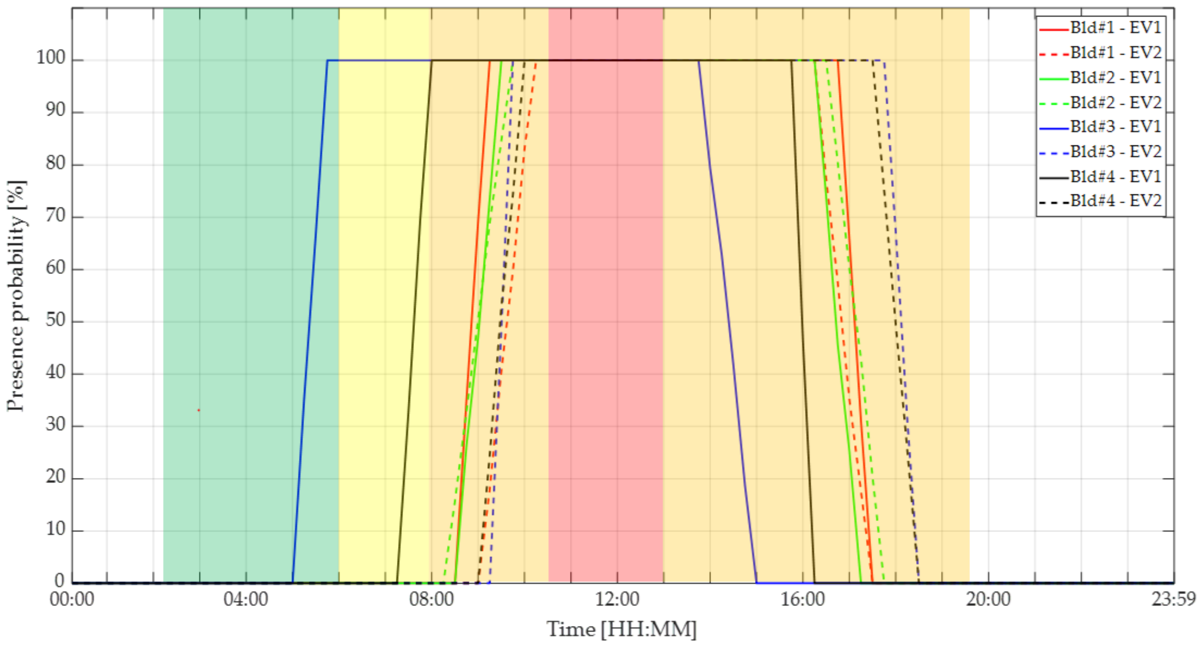

Figure 4.18 - EVs' presence probability in summer months

It is also important to note that, in this experiment, the load management of PEVs' batteries has the priority comparing with the REC energy sharing process at any given time instant. This priority is considered for a proper analysis of the load management impacts, under the VSI rules, on the behaviour of the DSC for each REC member. Other reason has a practical motive, because in a real environment that is the procedure for a proper relationship of the CSME with the DSO: the considered sharing coefficients, for each REC member, can be calculated at any given time. However, they can only be informed to the DSO, for the needed adjustments on the members' electricity bills under the Portuguese legal framework for REC management (Ministério da Economia e da Inovação, 2022; Entidade Reguladora dos Serviços Energéticos, 2023a) after the ending of a given billing period.

4.3.1 Scenario #1: Operation with sharing of individual surplus using the DSC

When the buildings are associated as a REC, the presence of the PEVs changes the performance of all members, due to change on the calculation of the DSC, strongly dependent of each member's consumption, as stated in Equation 4.1. This increasing on consumption directly influences the amount of electricity shared to members, depending on the interaction between the local generation, total demand and PEVs' charging needs. The shareable energy can potentially be less than in experiment 4.1. Furthermore, when exploring the energy flexibility potential of the PEVs' batteries, according to the strategy described in Section 3.2 (see Figure 3.2 and Figure 3.3 for complete details), there are some instants in which the available electricity to be shared among members are less comparing to a situation without it due to the shifting and/or pause of the PEVs' charging when the available surplus, after the self-consumption of the remaining loads is at least 60% of the charge power. Regarding the generalities of the REC management, the same rules described in Section 4.1 applies. As of results, Table 4.18 describe the performance of the members in this scenario, and Figure 4.19 shows the average load diagram of the PEVs' charging for each member.

Table 4.18 - Indicators for experiment 4.3 - scenario #1

	E_{imp} [kWh]	C_{imp} [€]	E_{exp} [kWh]	E_{sc} [kWh]	E_{sh} [kWh]
			Bld#1		
w/o Flex	29,939	6,778	1,511	8,230	2,449
w/ Flex	29,766	6,561	1,475	8,266	2,691
Δ	**-173(-0.6%)**	**-217(-3.2%)**	**-36(-2.4%)**	**+36(0.4%)**	**+242(9.9%)**
			Bld#2		
w/o Flex	159,055	32,586	22,354	93,320	10,929
w/ Flex	158,733	32,209	21,401	94,273	10,334
Δ	**-322(-0.2%)**	**-377(-1.2%)**	**-953(-4.2%)**	**+953(+1%)**	**-595(-5.4%)**
			Bld#3		
w/o Flex	24,253	5,124	6,242	14,999	707
w/ Flex	22,217	4,907	5,167	16,074	1,046
Δ	**-2,036(-8.4%)**	**-217(-4.2%)**	**-1,075(-17%)**	**+1,075(+7.2%)**	**+339(+48%)**
			Bld#4		
w/o Flex	19,058	4,767	22,721	32,208	45
w/ Flex	18,198	4,391	21,531	33,398	28
Δ	**-860(-4.5%)**	**-376(-7.9%)**	**-1,190(-5.2)**	**+1,190(+3.7%)**	**-17(-38%)**
			TOTAL		
w/o Flex	232,305	49,255	52,828	148,757	14,130
w/ Flex	228,913	48,068	49,574	152,011	14,099
Δ	**-3,392(-1.5%)**	**-1,187(-2.4%)**	**-3,254(-6.2%)**	**+3,254(+2.2%)**	**-31(-0.2%)**

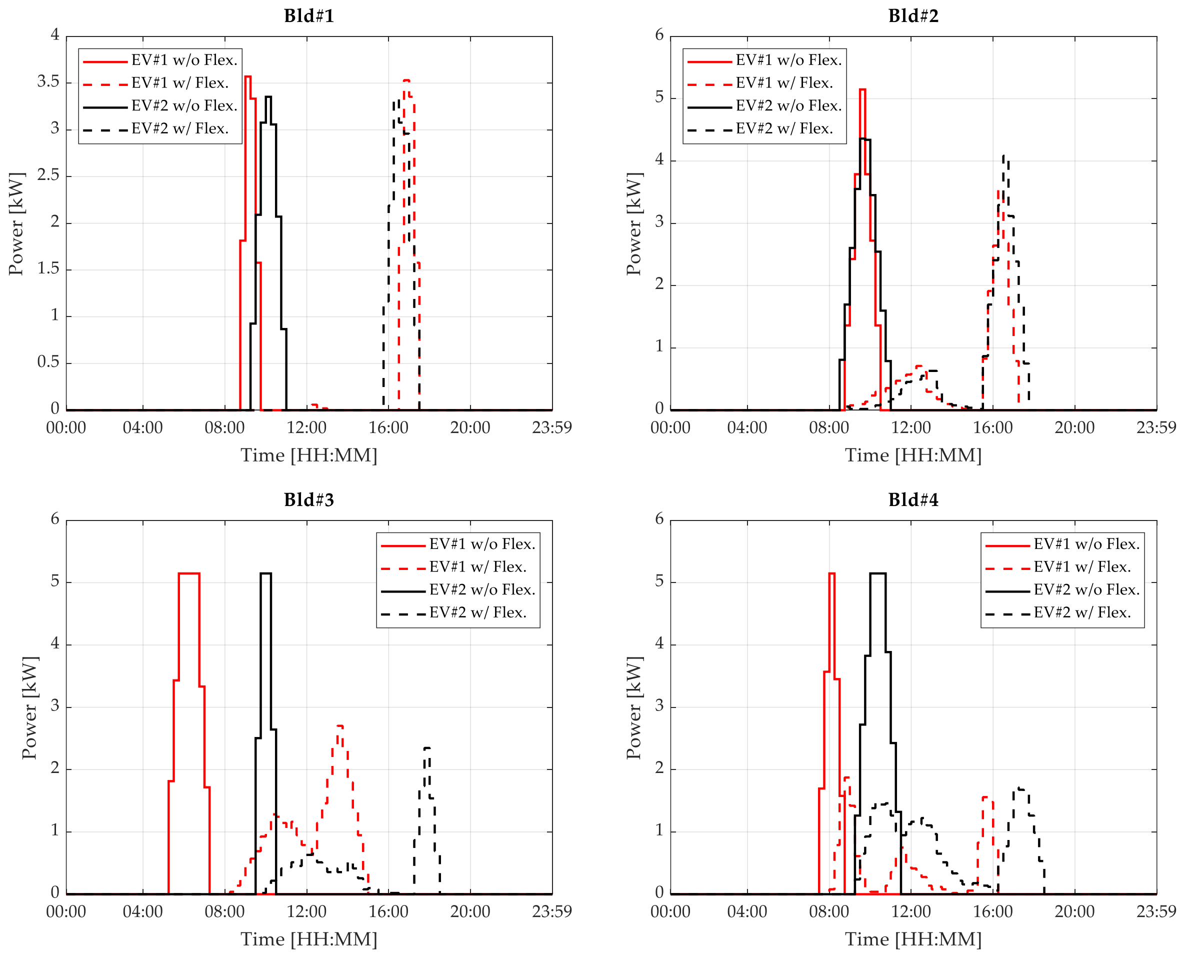

Figure 4.19 - Average load diagram of the PEVs' charging for each member in experiment 4.3 - scenario #1

4.3.2 Scenario #2: Operation with collective self-consumption using the DSC

On the contrary to the management strategy described in scenario #1, in this scenario the REC members are not allowed to proceed to individually self-consume part of the locally generated electricity, since they are also organized as a Collective Self-Consumption, characterised by the sharing of the whole production among the members, regardless the chosen sharing strategy (Entidade Reguladora dos Serviços Energéticos, 2023a). Therefore, there must be establish a framework to verify the satisfies the conditions to optimize the charging of the PEVs' batteries by shifting and/or pausing is:

- The CSME simulates the collective self-consumption and sharing behaviour of the members without considering the presence of the PEVs (the members' BMs must send real-time consumption and production values to the CSME).
- The CSME informs the simulated surplus of each member to their respective BMS.
- Members' BMS manages the charging of the PEVs based on the simulated surplus (it is used to optimize the charging by shifting and/or pausing if set conditions are not met).
- After the billing period, with the real consumption of the members considering the charging of the PEVs, the real sharing coefficient is calculated and applied to all REC members.

Due to the unbalance of the REC members in terms of consumption and generation patterns, when choosing a collective self-consumption framework there might be instants in which there's more surplus available than the minimum percentage that the energy flexibility potential of the PEVs' batteries is set to be explored. This allows that the operation of the EBD (in this scenario, the charging of the PEVs) can potentially be more restrictive, to maximize the usage of locally generated electricity when proceeding to the real collective self-consumption. However, as one can verify in Table 4.10 that the ration between consumption and generation in each REC members differs. Regarding the performance, the indicators are shown in Table 4.19 and the average load diagram of the PEV's charging in Figure 4.20.

Table 4.19 - Indicators for experiment 4.3 - scenario #2

	E_{imp} [kWh]	C_{imp} [€]	E_{exp} [kWh]	E_{sh} [kWh]
		Bld#1		
w/o Flex	28,759	6,539	2,553	11,494
w/ Flex	28,736	6,206	2,390	11,516
Δ	**-23(-0.07%)**	**-333(-5.1%)**	**-163(-6.4%)**	**+22(+0.2%)**
		Bld#2		
w/o Flex	153,816	31,533	30,314	108,762
w/ Flex	152,737	30,993	28,376	109,840
Δ	**-1,079(-0.7%)**	**-540(-1.7%)**	**-1,938(-6.4%)**	**+1,078(+1%)**
		Bld#3		
w/o Flex	25,513	5,394	5,566	12,005
w/ Flex	23,658	4,895	5,211	13,803
Δ	**-1,855(-7.3%)**	**-499(-9.3%)**	**-355(-6.4%)**	**+1,798(+15%)**
		Bld#4		
w/o Flex	24,217	5,797	14,395	16,497
w/ Flex	23,728	5,240	13,474	16,976
Δ	**-489(-2.0%)**	**-557(-9.6%)**	**-921(-6.4%)**	**+479(+3.0%)**
		TOTAL		
w/o Flex	232,305	49,263	52,828	148,758
w/ Flex	228,859	47,333	49,450	152,135
Δ	**-3,446(-1.5%)**	**-1,930(-3.9%)**	**-3,378(-6.4%)**	**+3,377(+2.3%)**

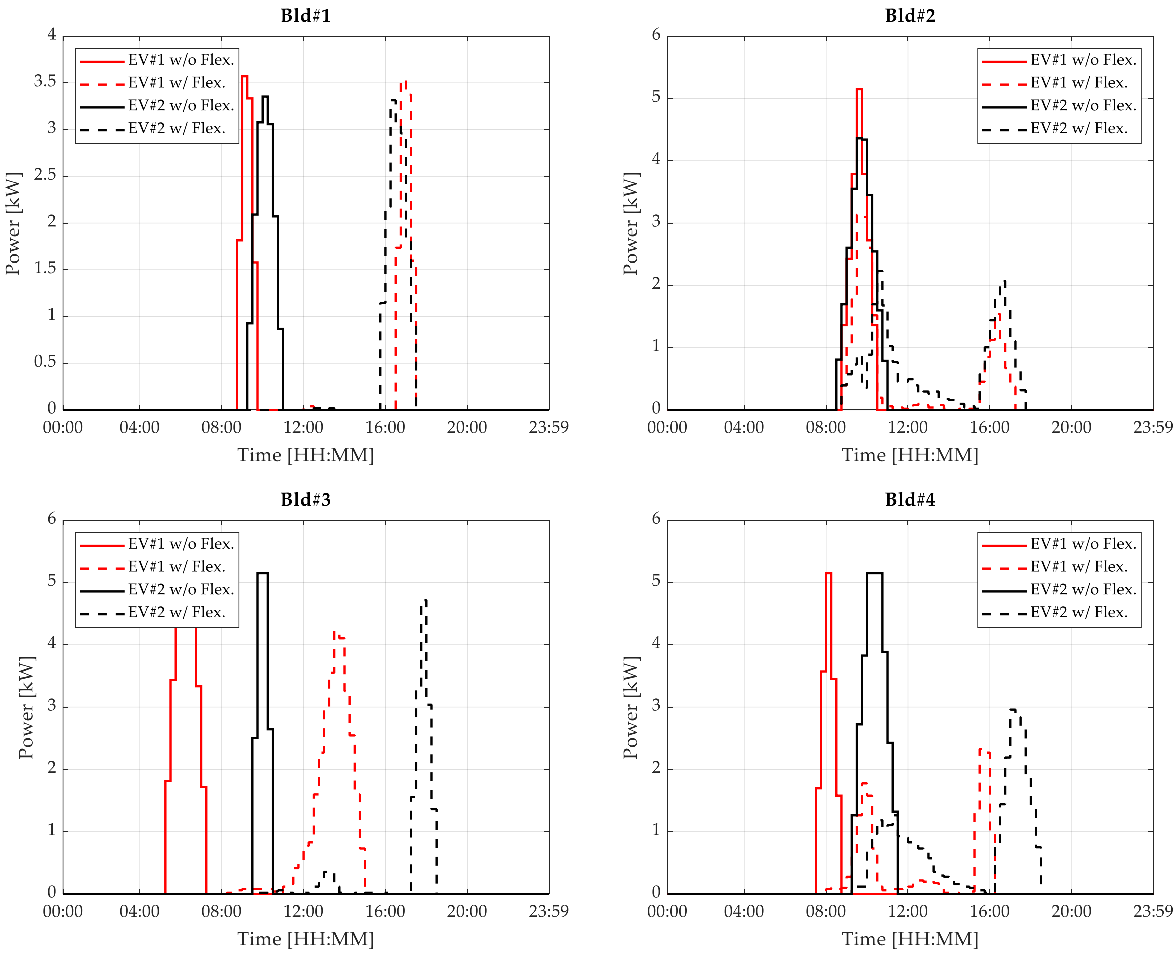

Figure 4.20 - Average load diagram of the PEVs' charging for each member in experiment 4.3 - scenario #2

4.3.3 Experiment #3 Analysis

When managing the REC by proceeding only Collective Self-Consumption and considering the DSC as management strategy, the individual performance of each member is worse than allowing members to individually self-consume their locally generated electricity (see Results from experiment 4.1). The addition of PEVs as manageable loads tends to diminish this lower performance because part of the load can be shifted, or paused, when the set conditions to operate the EBDs are not met. On the other hand, the increased surplus allows a less restrictive programming of the shiftable loads' operation, namely the charging process of the PEVs' batteries, which leads to a better performance than in experiment 4.1, when there is no energy flexibility potential to be explored.

Regarding the REC management strategies, the exploitation of the energy flexibility potential of the EBDs led to an increase on the self-consumed electricity due to the management strategy to only allow the charging of the PEVs when a certain amount of surplus is presented, which also led to a decrease on the exported electricity. Depending on the prices applied by the DSO in buying this surplus, the increase of the self-consumption increases the economic benefits of the exploitation of the energy flexibility potential of shiftable loads. As an example, Bld#3 has one of the PEVs with an unusual schedule comparing with the remaining PEVs of the REC. Its arrival time at the building is between 5h00 and 5h30. Despite the tariff applied in this time interval is "Super Off-peak", the tariff applied to most instants in which the PEV is planned to charge are "Half peak" instants, which is approximately 60% higher than the previous one (see Figure 4.19 and Figure 4.20). In this sense, the trade-off of charging is as positive as the available surplus to charge, for every time instants other than the one with the lowest tariff.

In scenarios in which the energy flexibility potential of shiftable loads is exploited, the energy sharing process when individual self-consumption is allowed turns to be fairer, as results in Table 4.18 shows, compared with the ones described in Table 4.19: the share of energy for buildings with higher consumption is diminished when the DSC is applied jointly with the management of the PEVs' batteries charging. This leads to a more interesting joining process of potential members with relative low consumption comparing with existing ones. Also, the fact both individual self-consumption and load management is made prior to the sharing of the solar PV surplus locally corrects some imbalances among members, due to the consideration to charge the PEVs solely with part of the individual surplus of each member. When it is time to proceed to the sharing process, part of the power demand of the members are already optimized, and the benefits of the REC energy management strategies is diminished. This phenomenon is more evident in both Bld#1 and Bld#3 analysing the indicator "shared energy". These are the members with a peak in the respective load diagram in instants outside the peak generation of the respective solar PV systems. The load management forces the charging of the PEVs to instants in which there is more local generation. Furthermore, Bld#3 has simultaneously the fact that the scheduling of one of its PEVs is non-usual, arriving the building premises between 5h00 and 5h30.

This behaviour is also perceived in the scenario when the collective self-consumption is the chosen strategy, but less effective. When the exploitation of energy flexibility potential of controllable loads is permitted by the CSME, Bld#3 has a decrease in the imported energy which is higher than Bld#2, even the latter having a higher consumption than the prior, disregarding the fact that the power demand of Bld#2 is significantly higher than Bld#3 and the DSC is calculated based on instant power demand. On the other hand, the decision to proceed to a collective self-consumption structure for managing energy inside the REC border leads to an increase on the shared energy for all members, even with the different performance among them: the increase is from 0.2% (in Bld#1), from 15% for Bld#3. In scenario #2, since the export share for each member is calculated based to its contribution to the total production, as shown in Figure 2.3, by the calculation process of the variable "$\boldsymbol{ESC_j(t)}$".

The impact of the exploitation of the energy flexibility on the DSC can be seen in Figure 4.21, which shows their average values in each REC member. Bld#4 is highly impacted by the sharing management strategy when it is possible to shift part of its loads. Due to its higher share of local generation proportionally to its consumption, the DSC is not capable to give back part of the electricity that is due to this building without changing its consumption pattern. However, when load shifting is possible, it can receive a higher share of electricity due to the manipulation of such loads, which led to a fairer sharing. By shifting part of its loads to instants with higher generation, it is possible to increase the collective self-consumption of the members, increasing the share of each one of them.

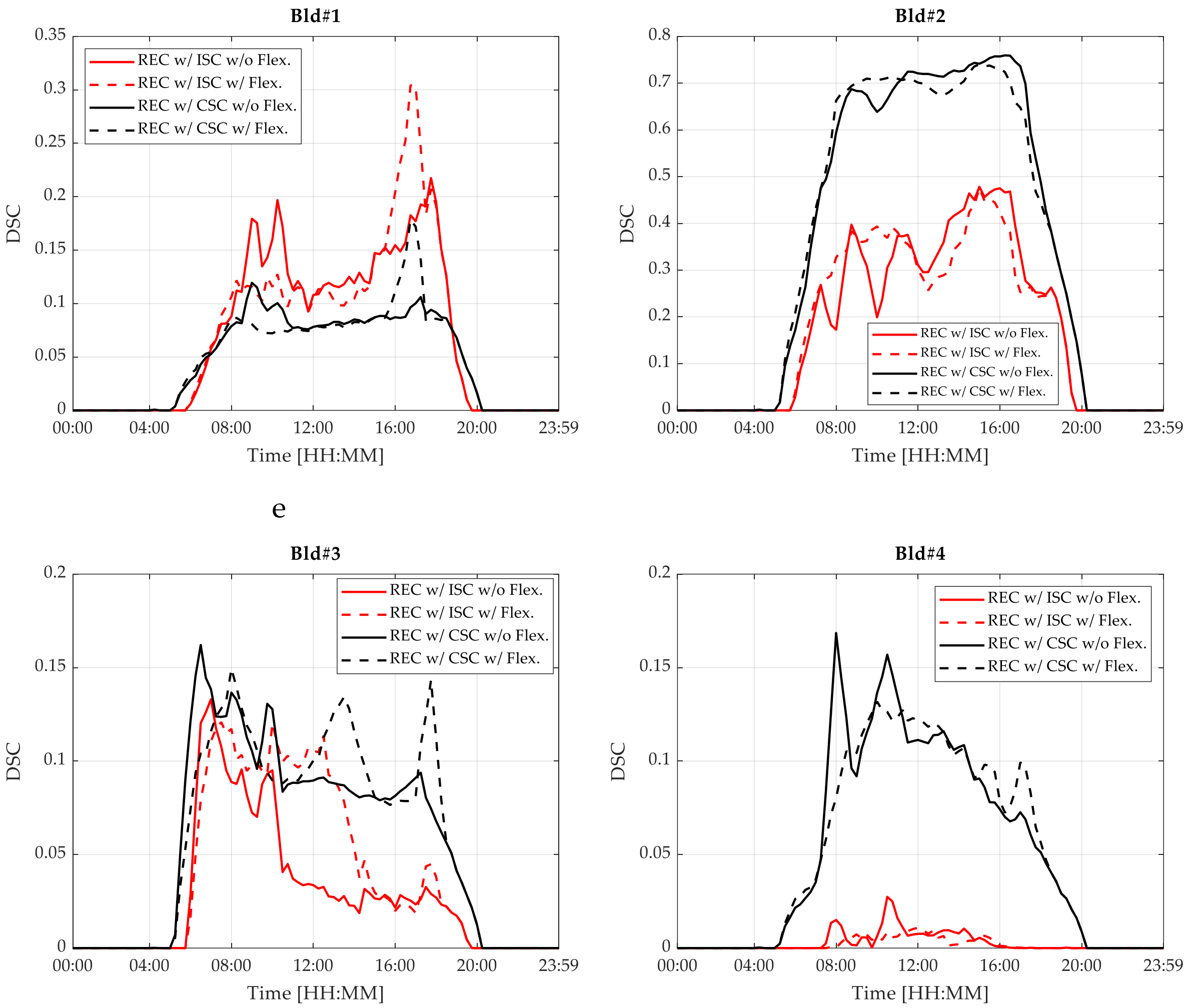

Figure 4.21 - Impact of the energy flexibility exploitation on the Dynamic Sharing Coefficient

Regarding the average behaviour of the VSI management strategy, despite the benefit in terms of energy import and associated costs, and based on the chosen strategy for allowing the operation of the EBD solely with available surplus of the PV systems, it is not optimized, as can be seen in Figure 4.22, for scenario #1, and Figure 4.23, for scenario #2. When managing the loads using the VSI concept, in scenario #1 an effective use of it was only possible in Bld#3, with an important share of the VSI charging occurring in instants around midday, meaning the PEVs were charged, on their majority, with energy surplus after the REC energy sharing process. On the other hand, in scenario #2, both Bld#2 and Bld#3 increased REC self-consumption as a whole, contributing with similar VSI charging instants, meaning that an equivalent amount of load was managed to operate in instants of PV systems' generation peak. In both scenarios, most of the load shifting occurrences is in Bld#3, due to the behaviour of one of its users, compared with the remaining PEV users, as can be seen in Table 4.17. The normal behaviour of this PEV user is the presence of the vehicle at the respective building in different hours, arriving and departing earlier than the other users, which provides to Bld#3 a higher potential to exploit its energy flexibility potential in terms of time horizon for load shifting.

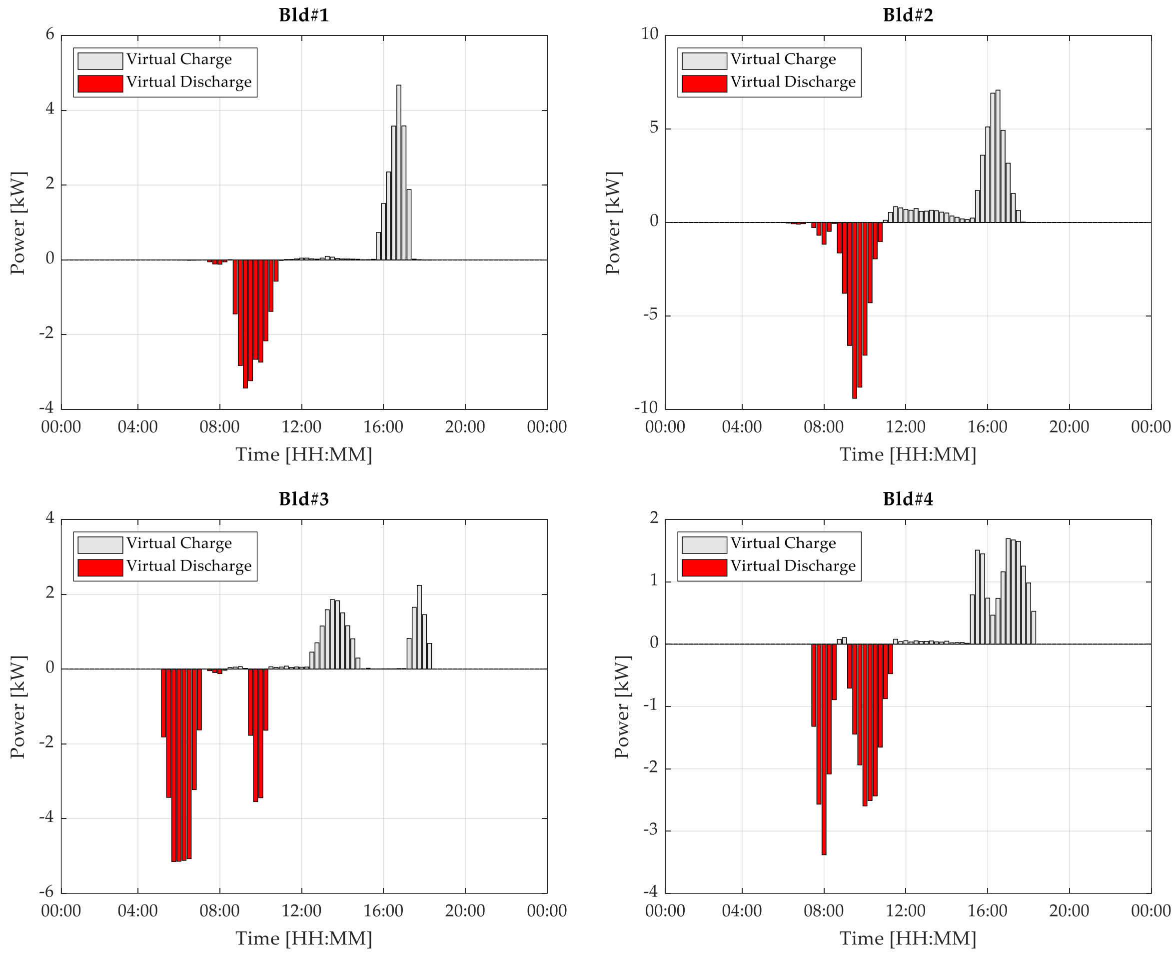

Figure 4.22 - Average VSI behaviour at REC member level for experiment #3, scenario #1

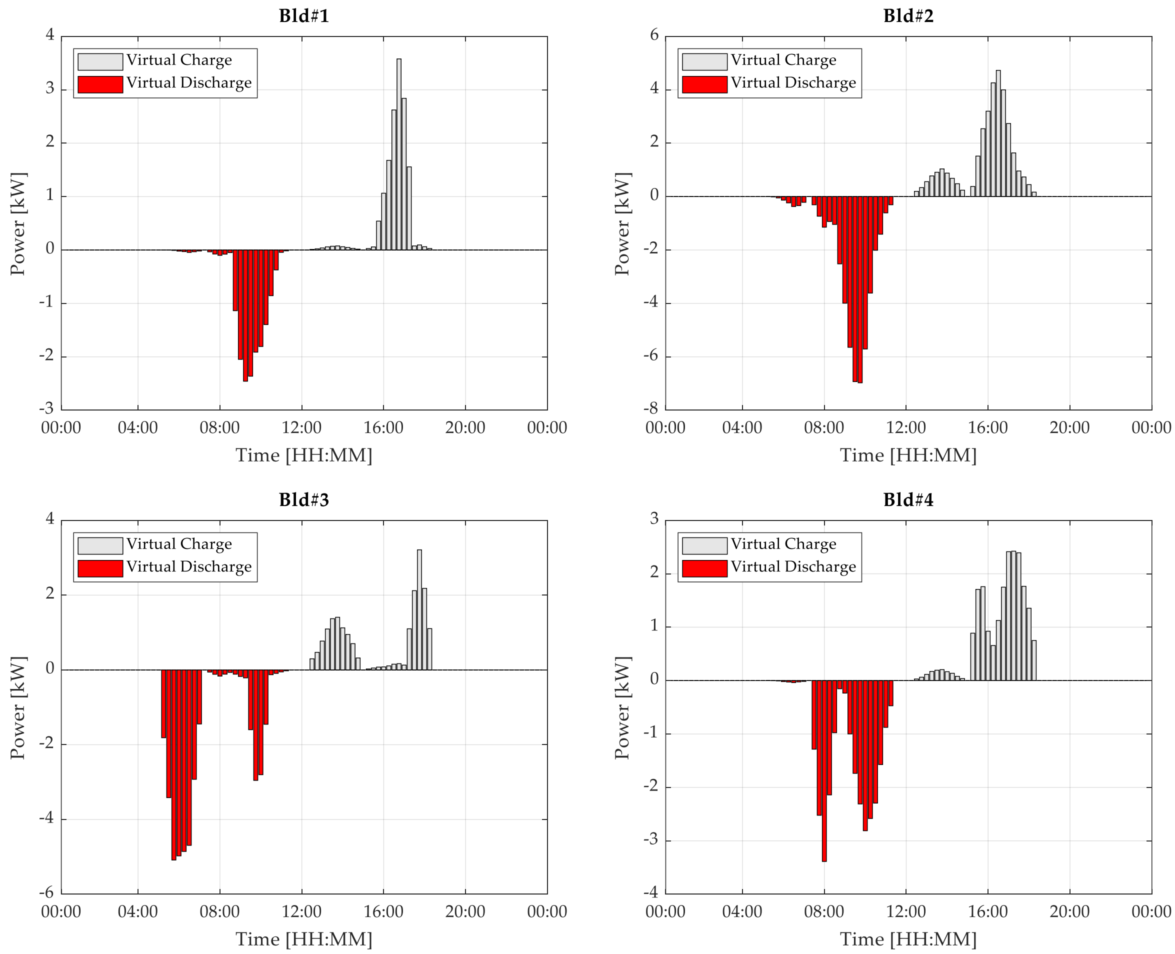

Figure 4.23 - Average VSI behaviour at REC member level for experiment #3, scenario #2

The boundaries considered for the implementation of the VSI framework, along with the imposed rules for the management of the energy to be shared inside the borders of the REC used in this experiment limits its effectiveness, as can be verified by analysing Figure 4.22 and Figure 4.23 in terms of the average VSI charging in the late hours of the afternoon. This behaviour is due to a procedure designed as a safeguard, to guarantee that the PEVs' batteries are fully charged (all the energy spent during the trip to the REC members is completed stored). However, an important outcome of the management of the PEVs' charging is the decreasing of the peak load of each REC member. When no load management strategy takes place, the EV chargers start the charging process as soon as the respective outlet is connected to them. This potentially increase the total demand of the building when multiple PEVs are connected at the same time, which can be visualised in Figure 4.16. However, the load management of PEVs' charging spreads the charging of the PEVs in different times instants, which decreases the average load peak of each REC member. This behaviour can be visualised in Figure 4.24.

Furthermore, a similar behaviour is perceived on the REC as a single entity, as shown in Figure 4.25.

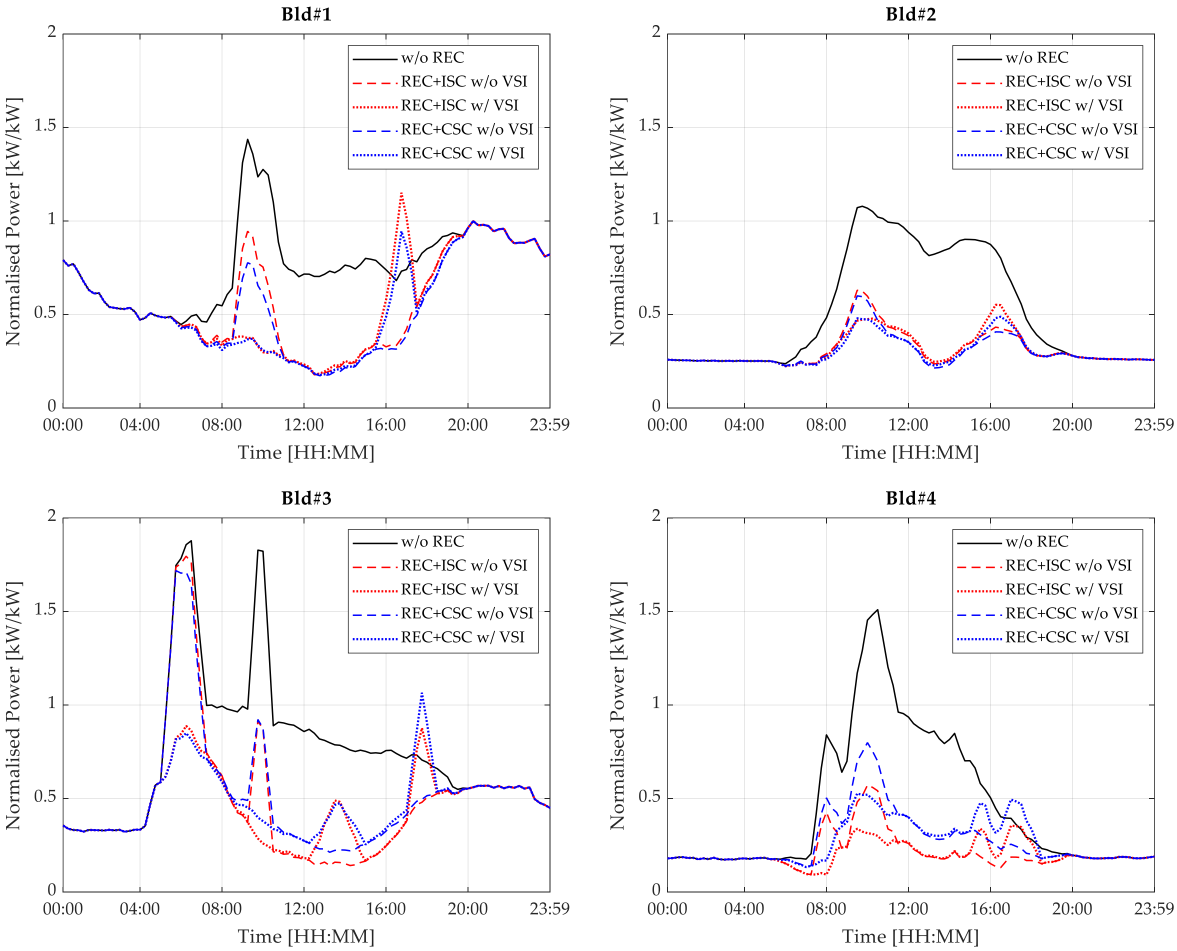

Figure 4.24 - Impact of the VSI on load diagram in each REC member

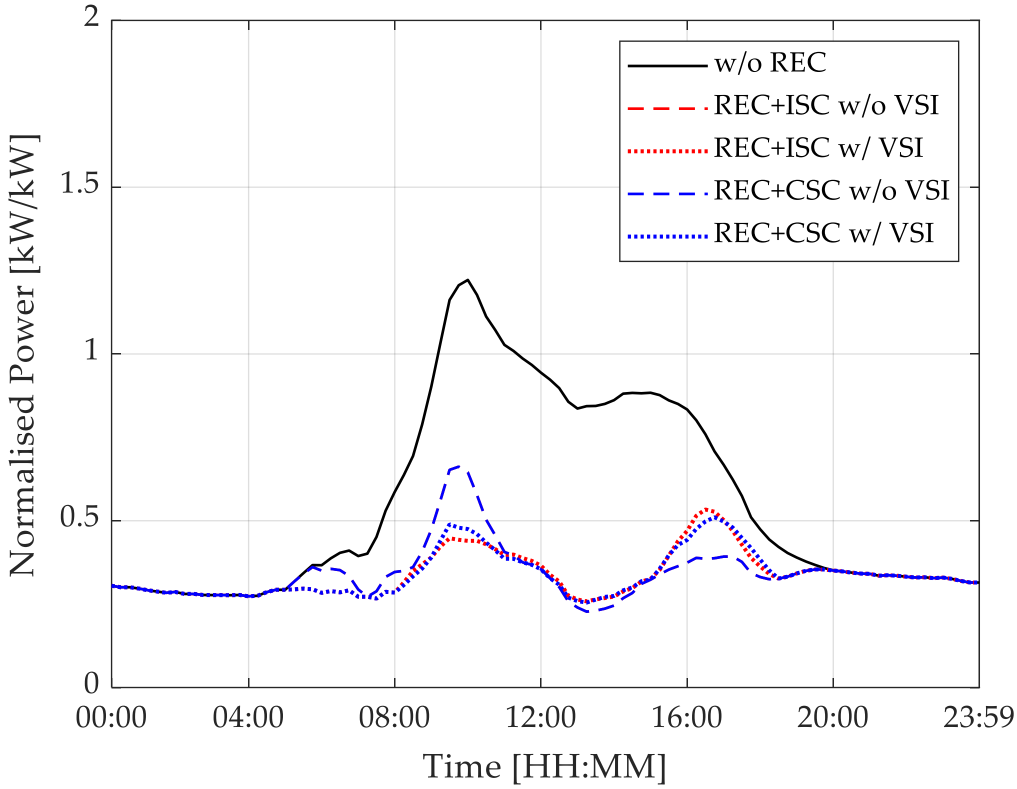

Figure 4.25 - Impact of the VSI on load diagram on the whole REC

It is important to note that, without considering any energy flexibility measure, the association of buildings in a REC does not impact peak load, as can be seen in Figure 4.4, regarding experiment #1, and Figure 4.25 for experiment #3, represented by an overlap of the load diagrams of both possibilities of self-consumption considered in this experiment, namely individual self-consumption of each member prior to the sharing of the surplus and the collective self-consumption structure, in which the total production of the PV systems are considered as shareable energy. On the other hand, the exploitation of the energy flexibility potential of the PEVs by the application of the VSI concept has an actual impact on the load diagram due to the displacement of their charging in time, even considering the pauses when set conditions are not met for a given time instant.

5

CONCLUSIONS

This chapter brings the conclusions of this study. Section 5.1 brings an overview of the conducted research that led to the found conclusions, Section 5.2 describes the main conclusions of this Doctoral Program, and their contributions to the Energy Management body of knowledge. Lastly, Section 5.3 points to some directions that future researchers can follow to cover the limitations of this study.

5.1 Research Work Overview

The European Union is making efforts to promote the increasing of energy coming from renewable sources, to alleviate the increasing effects of climate changes, which is partially cause by energy consumed from fossil fuels. To this end, Directive 2018/2001, from December 11th, and Directive 2019/944, from June 5th, were published. The first one brings, among several recommendations, the REC concept, which is planned to foster the usage of energy from renewable sources by end-users, by their ability to share part of locally generated energy between members.

However, there is not a clear proposition of optimal sharing techniques and strategies in order to maximize the benefits that the association of consumers in RECs can bring to them, namely economic, social and environmental-related. National transpositions of those Directives were also not able to propose fair sharing strategies, that cope with the diverse patterns of consumption of buildings. Furthermore, literature shows that the research in RECs is not fully aware of the gaining potential that energy sharing can bring to their members, focusing on optimizing assets and energy profiles. This led to the proposition of RQ#1. Given the increasing penetration of controllable loads in different businesses, their energy flexibility potential increases. Specifically, the increasing in EV selling over years is also a factor that can contribute to increase the energy flexibility potential of buildings in which this load is present. Their potential impacts inspired the proposition of RQ#2, which considers the nature of energy management strategies inside a REC, and the possibilities that national legislation on the topic can bring to their managers.

To propose a fairer sharing strategy for REC members, a dynamic sharing coefficient is proposed, which has, as one of its main characteristics, the ability to adapt itself to different conditions of the consumption/production relationship inside the borders of a given REC. This adaptation is made by its calculation at each time instant in which energy (in the case studies work, electric energy) is measured for billing purposes. This framework leads to a fairer sharing of energy between REC members, increasing their economic benefits throughout each billing period. Furthermore, the impact of load shifting frameworks in REC members is also assessed to study their potential of changing the behaviour of the DSC calculation process.

To this end, a series of experiments were conducted, to assess the different propositions of energy sharing coefficients brought by one of the European Union's Member State, Portugal, to test the proposed hypotheses. The first experiment focused on a REC formed by 4 non-residential buildings. The scenarios were designed to assess the efficiency of the DSC, and testing H#1. The results of this experiment are summarized in Table 5.1.

Table 5.1 – Results summary for experiment #1

Scenario	**Management Strategy**	**Electricity Imported [kWh]**	**Electricity Cost [€]**
1.1	-	365,935	78,246
1.2	ISC	233,940	49,150
1.3	REC w/ ISC + FEC	226,662	47,731
	REC w/ ISC + FPC	222,095	46,855
	REC w/ ISC + DSC	219,091	46,294
1.4	REC w/ CSC + FEC	270,529	57,244
	REC w/ CSC + FPC	225,871	47,728
	REC w/ CSC + DSC	219,091	46,307

The second experiment was designed to test the load shifting strategy that assess the changing on a building's load diagram as a virtual storage device. This experiment serves as a proof for the VSI concept, described in Section 3.2, and the results of the case study designed for this proof of concept are summarized in Table 5.2.

Table 5.2 – Results summary for experiment #2

Scenario	Management Strategy	Electricity Imported [kWh]	Electricity Cost [€]
2.1	w/o Flex	26.5	4.69
2.2	w/ Flex - tariff diff.	26.7	4.17
2.3	w/ Flex - % surplus	24.9	3.67

Lastly, experiment #3 assess the impact of the VSI implementation in the same REC designed for experiment #1, by adding two EVs in each member, with different schedules, and consequent availability on the REC member's premises for the exploitation of their energy flexibility potential. This experiment was designed to test H#2. Table 5.3 summarizes the main indicators of the considered experiments.

Table 5.3 – Results summary for experiment #3

Scenario	Management Strategy	Electricity Imported [kWh]	Electricity Cost [€]
3.1	REC w/ ISC + DSC w/o Flex	232,305	49,255
	REC w/ ISC + DSC w/ Flex	228,913	48,068
3.2	REC w/ CSC + DSC w/o Flex	232,305	49,263
	REC w/ CSC + DSC w/ Flex	228,859	47,333

5.2 Main Findings and Contributions

The results summarized in Table 5.3 shows that, despite the evident benefits that the association of consumers in RECs, the main benefit that can be achieved at local level is the presence of energy generated on their premises, such as the installation of solar systems in each building that is then form the REC under study. Therefore, in a situation of large penetration of distributed energy resources, the performance of local communities in terms of electricity imported and associated costs can be influence of their decision to form, or join, a REC, and the presence of flexible loads to proceed to the exploitation of their flexibility potential. In this sense, a diverse REC, as the one considered as the main case study of this work, can appropriate of the potential advantages that such association can bring to their member. Regarding the sharing strategies, regardless the possibility to exploit some energy flexibility potential, it is evident that the proposed DSC can bring the most impact on the performance of the REC members on indicators that directly impact the REC members' lives, namely the cost of electricity. On the other hand, the usage of a fixed share of energy for members can negatively impact the cost of electricity as up to 16% in a collective self-consumption framework. Furthermore, due to a more uncertain and changeable energy market, the possibility to increase locally generated electricity inside the boundaries of a REC by using the DSC can potentially increase the added value of such management strategy, as to foster the formation of this consumer and prosumer association.

As per the energy flexibility exploitation strategy, the proof of concept described in Section 4.2, derived from the framework from Section 3.2 is considered valid due to the direct impact on the electricity import cost of the given residence (up to 21% in a 48-hour horizon). However, since the strategy chosen for the loading of the PEV focused exclusively on the applied tariffs in that context, there was a drawback on the electricity import, increasing 2.5%. However, when the paradigm of scheduling the PEV charging changes, namely the focus on the available local generation surplus, applied on the considered REC in experiment #3, both indicators are positively impacted by the exploitation of the energy flexibility potential provided by the PEVs, achieving almost 4% when used jointly with a collective self-consumption framework for the REC. The aforementioned uncertain energy market also opens a possibility of a wider implementation of DR frameworks, allied by the energy management possibilities in a REC and the use of the DSC to protect consumers from this uncertainty and volatility in the future.

In summary, from this research's point of view, the results of the conducted experiments validated both H#1 and H#2, via experiment #1 and #3, thus answering RQ#1 and RQ#2, respectively. Furthermore, regarding the body of knowledge, the contributions of this research addressed the identified gaps as:

- The missing analysis of the energy management framework in RECs is addressed by the development of the DSC, in which the benefits of the energy sharing process in such entity is increased by the possibility of a higher amount of energy shared between REC members.
- The pausing of EBDs mid-operation, despite a possibility, is not properly assessed as a mean to explore the energy flexibility potential of such devices. The proposed VSI addressed this gap, becoming a possible framework for the management of such operation, when the conditions of the building's installation allow this procedure.

Lastly, this research contributed to the REC management and, indirectly, to the Distributed Energy Resources' field, as follows:

- The algorithm that manages the electricity generate inside the premises of a REC, including production, consumption, sharing and exporting features.
- The rule-based algorithm that harvests the energy flexibility potential of EBDs present in a building.

These contributions can be also evidenced by the publications described in Table 5.4. It is important to note that the assessment of the DSC in a real-life environment is ongoing since the approval of a pilot project, approved by ERSE in December of 2022, under the scope of one of the POCITYF project's pilots in Portugal, namely a REC formed by 5 residential members in a village near Évora.

Table 5.4 - Summary of publications of this Doctoral Program

Year	Authors and Title	Type	State
2020	Humberto Queiroz, Rui Amaral Lopes, João Martins. "Automated energy storage and curtailment system to mitigate distribution transformer aging due to high renewable energy penetration". Electric Power Systems Research, Volume 182. doi: 10.1016/j.epsr.2020.106199	Journal	Published
2022	Humberto Queiroz, Rui Amaral Lopes, João Martins, Luís Fialho, João Bravo Dias, Nuno Bilo.	Conference	Published

	"Assessing the Benefits of Renewable Energy Communities: A Portuguese Case Study". Technological Innovation for Digitalization and Virtualization DoCEIS 2022). doi: 10.1007/978-3-031-07520-9_2		
2023	Humberto Queiroz, Rui Amaral Lopes, João Martins, Filipe Neves Silva, Luís Fialho, Nuno Bilo. "Assessment of energy sharing coefficients under the new Portuguese renewable energy communities regulation". Heliyon, Volume 9. doi: 10.1016/j.heliyon.2023.e20599	Journal	Published
2023	Jérôme Le Dréau, Rui Amaral Lopes, Sarah O'Connell, Donal Finn, Maomao Hu, Humberto Queiroz, Dani Alexander, Andrew Satchwell, Doris Österreicher, Ben Polly, Alessia Arteconi, Flavia de Andrade Pereira, Monika Hall, Tuğçin Kırant-Mitić, Hanmin Cai, Hicham Johra, Hussain Kazmi, Rongling Li, Aaron Liu, Lorenzo Nespoli, Muhammad Hafeez Saeed. "Developing energy flexibility in clusters of buildings: a critical analysis of barriers from planning to operation". Energy and Buildings, Volume 300. doi: 10.1016/j.enbuild.2023.113608	Journal	Published
2025	Humberto Queiroz, Rui Amaral Lopes, João Martins. "Exploring load management capabilities of electric vehicles' batteries in renewable energy communities".	Journal	Submitted

5.3 Future Works

Regarding RECs, the continuation of this work can be conducted in two principal directions. The first one resides on the extension of the research on the DSC, in which different pondera-tion factors and parameters, to achieve different objectives than reducing electricity import and associated costs. For instance, a fixed share can be defined by members who's suffering from energy poverty in any of its aspects: impossibility to sustain heat comfort, the struggle to pay energy bills etc. A fair compensation for individual investments in assets for the REC can also be defined as a parameter, to provide financial justice among REC members.

The next main topic that can be studied based in this research is the comparison of sharing techniques, namely P2P trading versus energy sharing coefficients. In this sense, P2P can be considered a "competitive" strategy since each of the members seeks only for their individual benefit. On the other hand, the sharing strategy by using the DSC can be the "cooperative" one, and the benefits depends on the collective participation of all members. This comparison can be extended for the whole REC depending on the chosen strategy.

Lastly, regarding the exploitation of the energy flexibility potential inside the premises of a REC, one important research path for the future is the assessment of the impact of different Devices, based on the characterisation made in Chapter 3, Section 3.1.1, beyond Event-Based Devices, namely the Deterministic Thermal Devices, due to their management complexity regarding the work fluid temperature behaviour over time. Furthermore, Deterministic Chemical Devices are also important in this context of their impact on the REC performance due to their duality as generation and consumption device when discharging and charging, respectively. In this sense, initial research was conducted when the submission of the conference paper described in Table 5.4. However, deeper research is needed to cope with every possibility that DCD can bring to a REC, namely the impact of the sharing coefficients considering their duality. Furthermore, the uncertainty of the energy market regarding electricity prices over time can be added as an input variable for the management framework of the VSI. For this purpose, a prediction tool for the energy price (mainly in unregulated markets) needs to be developed in order to point instants in which the EBD can operate considering such volatile prices.

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