Universitat Politècnica de Catalunya

Master's degree in Energy Engineering

Implementation of second-life batteries as energy storage systems enhancing the interoperability and flexibility of the energy infrastructure in tertiary buildings

in cooperation with

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Greetings

Special thanks to my mother, Gloria, who supported me every single moment when I decided to begin this incredible academic journey two years ago at Kungliga Tekniska Högskolan (KTH) in Stockholm, Sweden, continuing at ESADE Business School and finishing at Universitat Politècnica de Catalunya (UPC) in Barcelona, Spain.

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Epigraph

Ïmagination is more important than knowledge. Knowledge is limited. Imagination encircles the world".

Albert Einstein

Symbology

V Nominal Voltage, in V

E_{spec} Specific Energy, in Wh/kg

$Weight$ Weight, in kg

E_{bat} Battery Energy, in kWh

$Ah - rate$ Ampere-hour rating, in Ah

$C - rate$ Charge-Discharge duration, in h

I Current, in A

P_{peak} Demand Power, in kW

P_{conv} Converter Power, in kW

P_{un} Fill Power, in kW

P_{PV} PV installation Power, in kW

P_{batmax} Maximum batterry power, in kW

E_{batmax} Maximum battery capacity, in kWh

SoC State of Charge, in $\%$

DoD Depth of Discharge, in $\%$

SoH State of Health, in $\%$

$cost_{bat}$ Battery cost, in €/kWh

$cost_{convbat}$ Converter cost, in €/kWh

$cost_{PV}$ PV cost, in €/kWh

$LCOE$ Levelized Cost of Energy, in €/MWh

Nomenclature

EU European Union

EC European Commission

H2020 Horizon 2020

JRC Joint Research Centre

IEA International Energy Agency

TSO Transmission System Operator

DSO Distribution System Operator

REE Red Eléctrica de España

IDAE Instituto para la Diversificación y Ahorro de la Energía

AEGE Asociación de Empresas de Gran Consumo de Energía

PNIEC Plan Nacional Integrado de Energía y Clima

VRES Variable Renewable Energy Sources

DSM Demand Side Management

DR Demand Response

DG Distributed Generation

O&M Operation and Maintenance

VPP Virtual Power Plant

kWh Kilowatt hour

MWh Megawatt hour

LEC Local Energy Communities

LES Local Energy Systems

IoE Internet of Energy

WSN Wireless Sensor Network

IoT Internet of Things

ICT Information and Communication Technology

SCRM Supply Chain Risk Management

WEC World Energy Council

WEF World Economic Forum

DER Dynamic Energy Resilience

NIS Network and Information Systems

ECSO European Cybersecurity Organisation

EECSP Energy Expert Cyber Security Platform

GDPR General Data Protection Regulation

EE Energy Efficiency

EEB Energy Efficient Buildings

SB Smart Buildings

GEB Grid-Interactive Efficient Buildings

BEMS Building Energy Management System

MAS Multi-Agent System

MPC Model Predictive Control-Agent

CI Computational Intelligence

AI Artificial Intelligence

ANN Artificial Neural Networks

FL Fuzzy Logic

ESS Energy Storage System

BESS Battery Energy Storage System

SLB Second-life Batteries

EOL End of Life

BMS Battery Management System

CAGR Compound Annual Growth

TAM Total Addressable Market

SAM Service Addressable Market

SOM Service Obtainable Market

PESTEL Political, Economic, Social, Technological, Environmental, Legal analysis

SWOT Strength, Weaknesses, Opportunities, Threats analysis

VP Value Proposition

BMC Business Model Canvas

EMS Energy Management System

ToU Time-of-Use

BIPV Building Integrated Photovoltaics

ADSM Automatic Demand Side Management

ReDR Reward from Demand Response

WSM Wholesale Market

AEC Annual Energy Costs

SGAM Smart Grid Architecture Model

IP Internet Protocol

TCP Transport Control Protocol

OCA Open Charge Alliance

OCPP Open Charge Point Protocol

SME Small-Medium Enterprise

TRL Technology Readiness Level

CRL Customer Readiness Level

BRL Business Readiness Level

Abstract

The main focus of this project is to evaluate the implementation of second-life batteries for a building stock enabling the energy flexibility schemes like Demand Response (DR). This project will focus particularly on how the building stock and its energy infrastructure (energy storage systems, legacy-assets, communication devices and grid architecture, among others) can participate as innovative energy solutions of the next generation of smart-grids, acting as virtual power plants (VPP) in order to deploy the distributed generation (DG) concept in the actual energy field and paving the way to unlock the demand response (DR) market in the distribution energy network. In addition, the implementation of these technologies will led to plan different business models and the scalability of them in the tertiary building sector.

Battery energy storage systems (BESSs) are already being deployed for several stationary applications in a techno-economical feasible way. This project focuses in the study to obtain potential revenues from BESSs built from EVs lithium-ion batteries with varying states of health (SoH). For this analysis, a stationary BESS sizing model is done, using the parameters of a 14 kWh new battery, but also doing a comparison with parameters if the same battery would be 11.2 kWh second-life battery. The comprehensive sizing model consists of several detailed sub-models, considering battery specifications, aging and an operational strategy plan, which allow a technical assessment through a determined time frame.

Therefore, battery depreciation and energy losses are considered in this techno-economic analysis. Potential economical feasible applications of new and second-life batteries, such the integration of a Building Integrated Photovoltaics (BIPV), self-consumption schemes, feed-in-tariff schemes and frequency regulation as well as their combined operation are compared. The research includes different electricity price scenarios mostly from the current Spanish energy market. The operation and integration of ICT-IoT technology upgrades is found to have the highest economic viability for this specific case study.

A detailed study for this project will enhance the relevant importance of these topics in the energy field and how it will be a disruptive solution for the initial problem statement. A general context is given in order to introduce the main and specific objectives thus to trace an adequate way to follow and achieve them. The development of this master thesis will be coupled with the Demand Response Integration technologies (DRIvE) [10] H2020 EU funded project, currently on-going, considering some of the energy consumption data and initial parameters from the selected case study at COMSA Corporación office building in Barcelona, Spain.

Preface

While the share of renewable energy in the electricity sector is growing continually, other sectors, such as transport, buildings and industry, still depend largely on fossil fuels. To decarbonise these sectors, they can either be electrified or the fossil fuels can be substituted by renewable gases such as hydrogen or other innovative energy solutions such as the implementation of Distributed Generation (DG). These technologies have emerged against climate change and they have been developed well in recent years to aim the adequate energy transition.

The attention focused on these particular topics has led into an important role of the distributed power generation in the modern network's security, stability and reliability, particularly the application and development of distributed generation using smart-grids. Adding stability to the system, it lowers the need for coal and gas fired spinning reserves, usually needed to run power plants by burning fuel continuously in order to be ready to supply power at short notice. This stability also decreases the need for local network investments, as it shifts consumption away from peak hours in regions with tight network capacity. In addition, improved grid reliability and power quality legislation are gaining more attention in economical terms because this could be an interesting tool to encourage more users to participate in a penalty-reward energy system against performance.

Moreover, the introduction of new telecommunication and digital technologies with encryption and remote inspection of assets, will increase the security of an electric grid and strengthen it. New grid architectures and new paradigms are needed to solve many technical problems related to that. In this context, autonomous or connected smart-grids represent a very interesting solution increasing the renewable energy penetration, improving energy efficiency and the resilience of the main electrical systems while contributing to a sustainable and competitive development in the countries. In the end, distributed generation working in parallel with smart-grids and energy storage will bring to the participants the ability to control energy consumption, using energy flexible schemes.

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Chapter 1

Introduction

According to Energy Performance of Buildings Directive (EPBD) [1], buildings are responsible for 40% of the energy consumption and 36% of the total CO2 emissions in the European Union (EU). More than 35% of EU buildings are very old and more than 75% of the total building stock is energy inefficient. Therefore, an important part of this consumption is mainly due to legacy equipment, which varies depending on the sector. For instance, in tertiary sector buildings, Heating, Ventilation, and Air Conditioning (HVAC) systems are responsible for the most relevant of the consumption, typically reaching up to a 40% of the overall energy profile.

During the next few decades, the strong uptake of electric vehicles (EVs) will result in the availability of terawatt-hours of batteries that no longer meet required specifications for usage in EVs systems. Finding applications for these still-useful batteries can create significant value and ultimately even help to bring down the costs of energy storage to enable further renewable-power integration into our electric systems as stationary storage applications in building stocks.

The European Commission [2] has reformed its electricity markets to facilitate the participation of energy storage in managing, supply and demand and also supporting new energy initiatives for batteries, distributed generation, Hydrogen economy, among others. Climate change and the need to integrate large amounts of clean renewable energy generation into the grid have been more significant drivers encouraging smart-grid and energy storage activities in the sector.

Electric systems already require a range of ancillary services to ensure smooth and reliable operation. Supply and demand need to be balanced in real time in order to ensure supply quality (e.g., maintaining constant voltage and frequency, large stations tripping offline, loss of an interconnection), avoid damage to electrical appliances and maintain supply to all users. For this case, energy flexibility gives the operators tools to rapidly restore the system equilibrium and making feasible to match these needs with the upcoming second-life battery market.

1.1 DRIvE H2020 European Project

The current proposed master thesis is a case study that COMSA Corporación can deploy as a continuation of the Demand Response Integration technologies (DRIvE) [10] H2020 EU funded project adding important value. Some of the data used for this case study about ESS The DRIvE project links together cutting-edge science in Multi-Agent Systems (MAS), forecasting and cyber-security with emerging innovative SMEs, making first market penetration in european DR markets. Market solutions are strengthened with lower Technology Readiness Levels (TRL), but also higher risk functionalities that develop the concept of 'Internet of Energy' and a collaborative energy network of prosumers.

DRIvE will unlock the Demand Response (DR) potential of residential and tertiary buildings in the distribution grid through a platform bridging the energy value-chain from planning and design of assets/buildings towards optimal operations in the next generation Smart Grids, and then will fully deploy the DR market in the distribution network. Therefore, a Multi-Agent Systems (MAS) will include real time operations and progress from a limited number of assets toward decentralized management of a larger number of assets providing DR services to prosumers, grid stakeholders and distribution system operators. Figure 1.1 shows the most important objectives of the DRIvE project:

Figure 1.1: DRIvE H2020 process map. Source: DRIvE H2020 (2018)

The benefits that DRIvE will generate in the local energy market will be valuable, for instance by unlocking the DR potential of the building assets, integrating advanced technologies such as ICT platforms, a proper smart grid architecture and communication to give local security, will led into the energy interoperability with also innovative load prediction and optimization algorithms.

Figure 1.2: Security in DRIvE. Source: DRIvE H2020 (2018)

Moreover, DRIvE will engage and stimulate customers to participate in DR programs through a consumer portal and these customers will track their personal assets such as home appliances and consumption from lightbulbs, washing machines, refrigerators, among others, as it is shown in Figure 1.3:

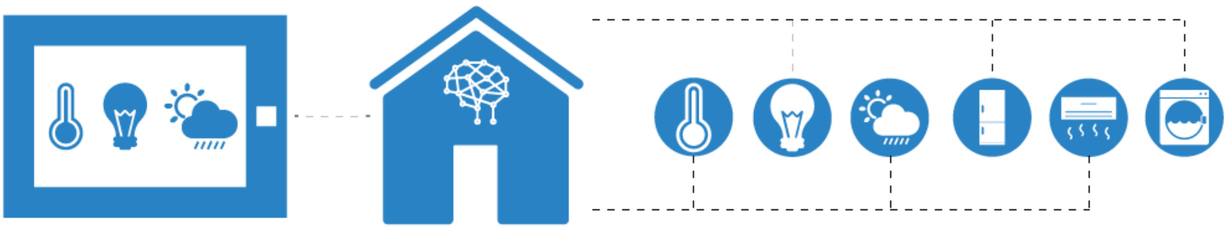

Figure 1.3: Customer's home appliances linked with DRIvE. Source: DRIvE H2020 (2018)

DRIvE H2020 project will create a substantial impact in different areas:

1. **Technological Impact:**

   The development of Demand Response (DR) enabling different energy technologies for residential and tertiary buildings, also, to enable a platform with information and selected data for flexibility optimization and market facilitation.

2. **Economic Impact:**

   One of the most important features of the DRIvE is to reduce the end-user's electricity cost after applying DR schemes. The energy innovation will be essential to develop local flexible markets and the reduction of DSO's investments in the grid balancing and reinforcement. Moreover, DRIvE will change the energy scenarios and enter in the local flexibility markets, while creating new business opportunities.

3. **Environmental Impact:**

   At a district level the local energy balancing will be enhanced and also a migration to this kind of technologies in order to promote clean and sustainable solutions and reducing the carbon footprint.

4. **Social Impact:**

   For the inhabitants of European smart districts in which DRIvE will operate, some social benefits related to the energy cost reduction will be increased.

5. **Policy and Standards Impact:**

DRIvE will impact the policy and standards stated by the EU, aiming a reduction of the GHG emmisions, and increasing the energy efficiency in buildings and districts. New strategies will come up from DRIvE in order to help into a clean energy transition.

6. **Energy Network Impact:**

   As mentioned in the economic impact, it will be a reduction in the grid reinforcement and at the same time an increased grid balancing due to the DRIvE initiative.

In the next chapters, the proposed master thesis project in co-relation with the DRIvE H2020 EU funded project [10], will explain how to enhance the application of the energy flexibility concept by having a high impact in the future power systems with high penetration levels of Variable Renewable Energy Sources (VRES). Nowadays, the new challenge is to unlock the remarkable potential of Demand Response (DR) in the distribution grid where the main sources of flexibility are the residential and tertiary buildings, particularly the Demand Response topic will be explained more in detail in the Chapter 2, Section 2.3.

1.2 Chapter description

This project has six main chapters that will interconnect different concepts related to the energy engineering, renewable energy technologies such as distributed generation with virtual power plants, microgrids and energy storage with batteries, also how all these type of technologies will help to participate in the flexible energy markets developing the demand response (DR) schemes with new business models. Moreover, the distribution of the main chapters will be:

- **Chapter 2. Building assets enabling energy flexibility**

  Chapter 2 analyzes the local market of building assets in a general context aligned with the Spanish legislation for energy flexibility and self-consumption. Different energy market services will be explained and linked to the specific objectives of this master thesis project. The chapter's sections will include the explanation of some key concepts such as VPPs, LECs, Microgrids, Internet of Energy (IoE) and cyber-security in the energy field. In addition, a co-relation with the EU project H2020 DRIvE, in which COMSA Corporación is being part, will be explained and how all those mentioned key concepts are essential for the development of a techno-economic analysis at COMSA Corporación building office in the next chapter.

- **Chapter 3. Energy storage for buildings using second-life batteries (SLB)**

  Chapter 3 focuses in the implementation of energy storage technologies in the project. Circular economy of batteries and its benefits for this project will be explained as well as other technical concepts related to Battery Management Systems (BMS), types of batteries and chemistries, charging and discharging parameters to be chosen. Moreover, an evaluation of the disruptive energy storage solutions that will open the energy market creating new business opportunities and revenue streams from them.

  Potential business models for the tertiary buildings sector are evaluated regarding the specific market to focus (Spanish market), taking into account the main focus of the EU H2020 DRIvE project. In addition, tools like Business Model Canvas (BMC), SWOT, PESTEL, market analysis, and a Value Proposition (VP) analysis are used in order to clarify and demonstrate the solution for the project.

  A techno-economic analysis using MS Excel and Matlab is done in order to show the potential results and savings by comparing two scenarios of energy storage in tertiary buildings. One scenario uses a new battery in the mentioned pilot and the other scenario uses a second-life battery. In the end, the results are shown and some learning outcomes are taken for later deployment. A tailormade solution for the COMSA Corporación case study must be implemented. The correct selection of the battery parameters will rely on the technical decisions made in this chapter.

- **Chapter 4. Energy Management System (EMS) and implementation barriers**

  Chapter 4 describes the importance of a proper Energy Management System (EMS) for this kind of applications. The architecture model of the study case and the interoperability concept aligned with the local energy legislation from Chapter 2 will be crucial to identify the potential barriers or risks associated to the implementation of the energy storage technology (second-life batteries) proposed in the Chapter 3. Theory and information about communication protocols, IoT devices on buildings and smart grids will be summarized here.

- **Chapter 5. Conclusions**

  In the Chapter 5, a summary of all the findings and assumptions from the project will be reported. Also, important discoveries about the research and future research questions will be developed. Some suggestions about advantages and disadvantages of this innovative study will be explained here.

- **Chapter 6. Environmental Impact**

  In the Chapter 6, an environmental impact will be discussed regarding the results and scope of the project and how the implementation of second-life batteries will be a better option in terms of sustainability for stationary storage applications in buildings.

- **Chapter 7. Budget**

  In the Chapter 7, a brief estimation of the budget for the development of this project is calculated. The computational tools, software and also the human resources are considered.

1.3 Objectives

1.3.1 Main objective

- Evaluate the implementation of second-life batteries as flexible assets for enabling buildings to participate in Demand Response (DR) programs.

1.3.2 Specific objectives

- Explain the role of the building stock enabling the energy flexibility in a specific context and market.
- Evaluate the scalability of new business models of second-life batteries for tertiary buildings applications considering regulatory frameworks of the local energy market.
- Determine the suitable battery parameters such as power, energy capacity, adequate chemistry, energy density, cyclability, among others for the interoperability of the case study at COMSA Corporación office building.
- Develop a techno-economic analysis taking into account all the variables and assumptions proposed for the implementation of second-life batteries in the proposed model of a VPP at COMSA Corporación office building.
- Calculate the Levelised Cost of Energy (LCOE) of each battery scenario and check the feasibility of the project implementation at COMSA Corporación office building.
- Analyze the energy infrastructure (devices, assets, controls, and other communication protocols) of a model Virtual Power Plant (VPP), regarding the DRIvE H2020 European project.
- Study the local security in this project and raise the awareness and maturity of security processes in it.
- Define the protection measures for mitigating the risks associated with the proposed model of VPP, following a Supply Chain Risk Management (SCRM) methodology.

Chapter 2

Building assets enabling energy flexibility

2.1 General context

According to the International Energy Agency (IEA)[3], the building and construction sectors combined are responsible for 40% of global final energy consumption and nearly 36% of total CO_2 emissions. Building sector electrical energy demand is growing at 5% per year, and for example once buildings become home to charging stations for electric vehicles, demand may increase by a further 15 to 20% per year. In fact, energy-related carbon dioxide (CO_2) emissions rose again in 2018 by almost 1.7% and increased above to an all-time high in the last decade.

One of the reasons of this phenomena is the extreme weather conditions that have raised the energy demand for heating and cooling, which together represented one-fifth of the total global increase in final energy demand in 2018. The use of less-efficient technologies, legacy assets, insufficient investments in sustainable buildings and lack of effective policies have affected the enormous potential of these assets to enable the energy flexibility. Transmission and Distribution are becoming more unreliable due to extreme weather events amplified by climate change and due to socioeconomic threats, but some energy systems and solutions have decreased sharply in price and now in the form of micro-grids, will allow buildings to self-generate and store electrical energy.

The concept of grid-interactive efficient buildings (GEBs), shown in the Figure 2.1, is the key to a decarbonized new energy future and how the societies are reshaping their energy consumption habits. The decentralized nature of these microgrid enabled buildings is a vital distribution feeder asset especially when they can be harnessed by a smart grid. These buildings can help utilities adapt to rapid changes in the grid, including the adoption of technologies like EVs, batteries for energy storage, smart devices as well as new policy directions like benefits in electrification. Also, they deliver substantial energy and emission reductions by using highly efficient materials and equipment.

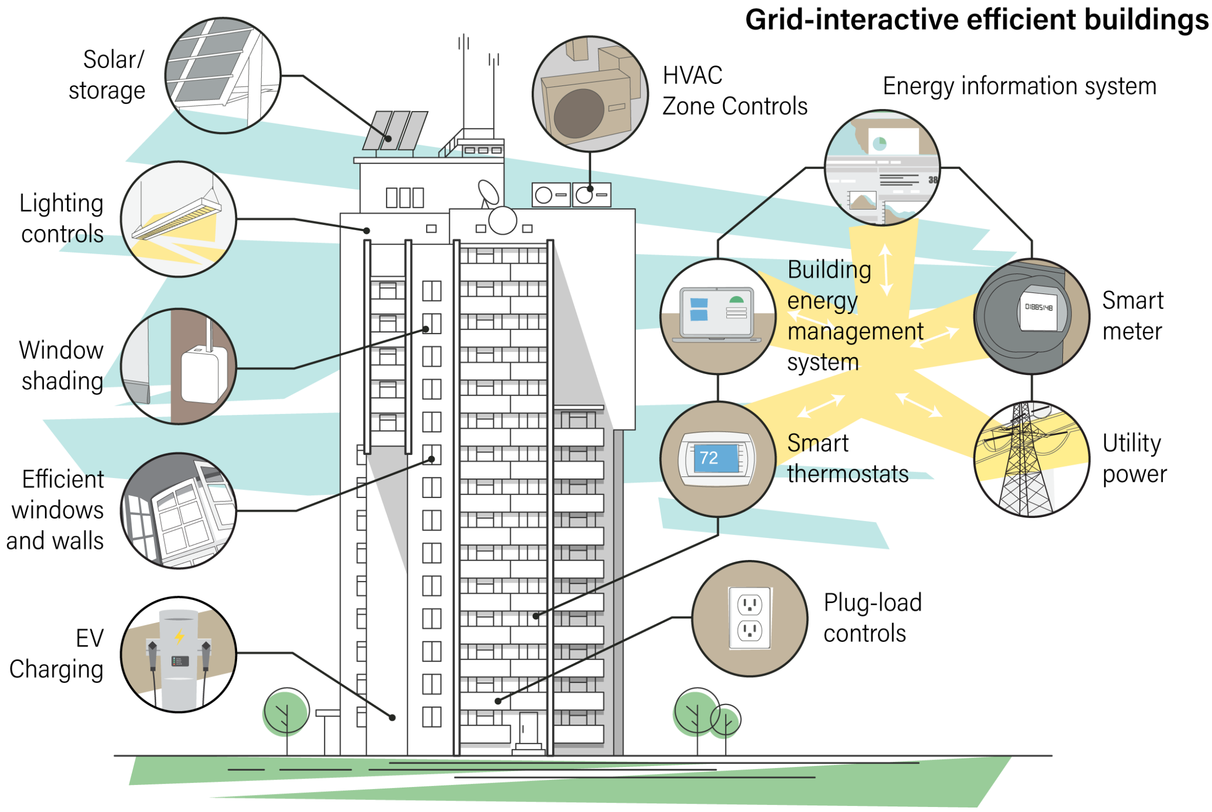

Figure 2.1: Grid-interactive efficient buildings. Source: ACEEE (2019)

The utility companies, consumers and users of grid-interactive efficient buildings would benefit greatly from creating programs that accurately value both energy efficiency and grid flexibility benefits. GEBs can also act as resources to the grid, by using less overall energy than a normal building and strategically shifting or reducing energy consumption during peak times. The true value of a distributed energy resource (DER) is about a more resilient energy future, where building owners and utilities profit from the self-consumption of locally available and affordable clean energy.

Figure 2.2 shows a graph that compares the energy efficiency (EE) versus the grid interactivity, while the complexity and level of technology integration increases. The programs showed are the ones that could be applied with a grid-interactive building, for example evolving from the concept of demand response (DR) programs to load flexibility and aiming the benefits of a smart energy management with the GEBs at the upper end of the scale. The demand response (DR) concept will be explained more in detail on this chapter, in the section 2.3.

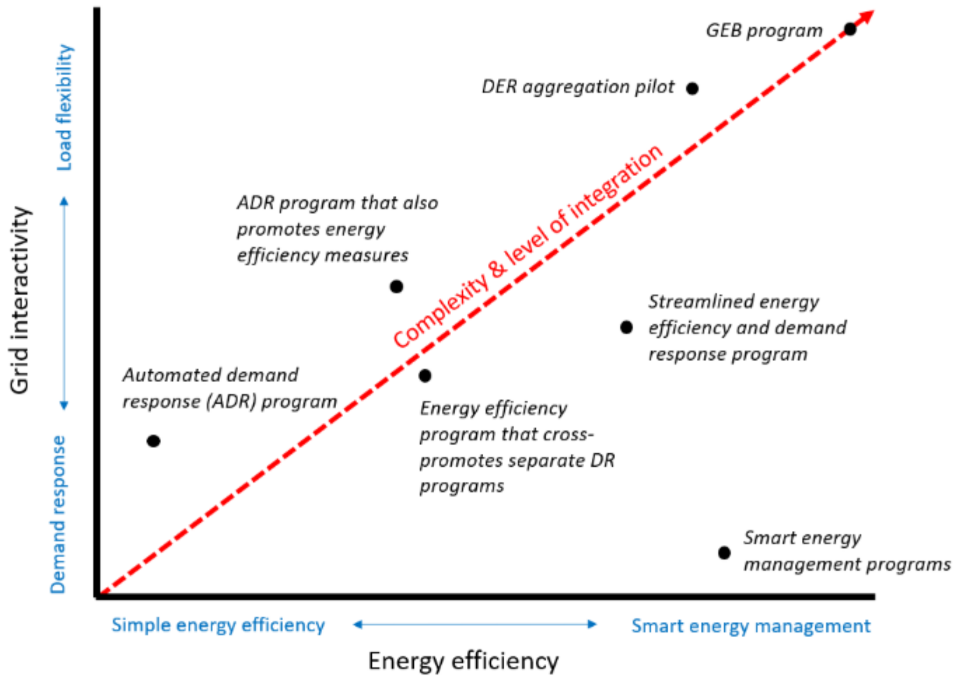

Figure 2.2: Energy efficiency vs Grid interactivity. Source: ACEEE (2019)

On the other hand, a lack of interoperability standards for residential and tertiary buildings, energy management and ICT-IoT systems to communicate with the grid, would not promote the coordination between energy efficiency and grid flexibility mentioned in the paragraph above. In this case, it is essential to upgrade the IoT infrastructure and EMS of the building to achieve these energy goals. The interoperability concept in this kind of applications will be developed in the Chapter 4, Section 4.2.

Furthermore, a proper energy management protocol will led the building owners and participants to introduce either rooftop PV and energy storage systems to manage their energy flexibility in terms of local loads and play an important role in the stability of the grid with services like voltage regulation and frequency response. In the end, a major shift away from the centralized one-way electrical grid is an opportunity for the massive real estate industry to explore the profitability of new business models, with the emerging grid-interactive and efficient building leading the way.

2.2 Demand Side Management (DSM)

Demand Side Management (DSM) involves different actions taken by electric energy consumers to change their behavior with the objective of improving the performance of the energy systems. The main techniques of DSM are energy efficiency, energy conservation, and demand response (DR). Since electricity is difficult and expensive to store, in most cases it has to be consumed at the same moment that is being generated and this causes a number of operational issues that have traditionally been addressed through services provided by common energy generators.

Nevertheless, in the last few years, the potential of consumers to address these operational issues through the modification of their consumption patterns have been increasingly recognized and valued. Therefore, electricity utilities and consumers have realized that it is important to implement an economic and affordable strategy to improve the competitiveness through the reduction of production costs. This section presents the concept of DSM, and explains how it can be a suitable strategy to solve issues related to the electricity demand from the consumer's point of view, either residential, commercial or industrial.

Throughout the day, changes occur in the demand curve: at the start of the working day, the closure of businesses at lunch time or people increasing consumption at home in the evenings are only some of the examples that explain why the demand curve is not uniform during the different hours of the day. There are, however, certain consumption patterns will help to determine some demand forecasts. Figure 2.3 shows the measures of a demand side management curve and the energy efficiency solutions:

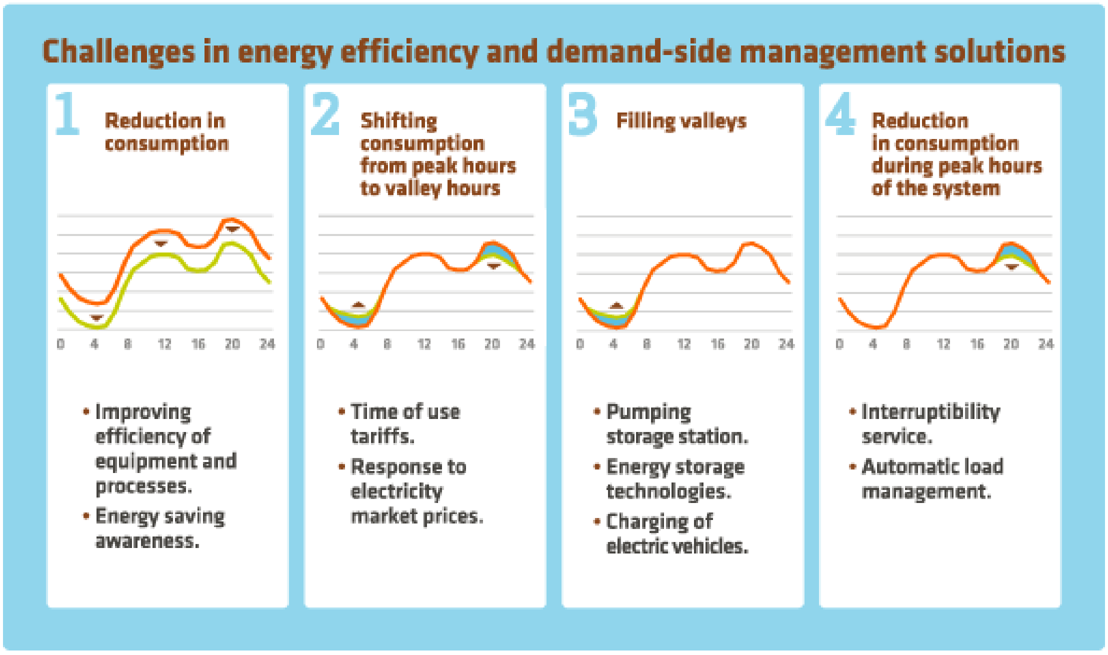

Figure 2.3: Demand Side Management curve(DSM). Source: Red Eléctrica de España (REE) (2020)

These measures contribute to a more efficient and sustainable management of the electricity system. Also, they are classified in four major groups depending on the type of impact they have on the demand curve.

1. **Reduction in consumption:**

While improving the efficiency of equipment, appliances and processes, the consumption will be drastically reduced.

2. **Shifting consumption from peak hours to valley hours:**

   An adequate response to electricity market prices and the time of use (ToU) tariffs from the energy market.

3. **Filling valleys:**

   The use of several energy storage technologies such as battery storage, charging and discharging of electric vehicles (EV), pumping storage stations, among others will contribute to a DSM during valleys.

4. **Reduction in consumption during peak hours of the system:**

   Some tools like the interruptibility services, and automatic load management are measures to reduce energy consumption during peak hours. These tools are explained more in detail in the Section 2.4.

Demand Side Management (DSM) can act as a cost effective balancing resource for variable renewable generation and also must balance the contradictions between the supply system and consumption, as an emerging power generation industry. DSM seeks a balance between energy demand and supply both on the side of utilities, system operators and consumers. Thus, it is very important to make a difference among the concepts of Demand Side Management (DSM) and Demand Response (DR), while DSM includes all demand-reducing measures, in other words, it includes both vehicles for its implementation, demand response and energy efficiency, that are part of the englobed concept of DSM. Figure 2.4 shows this conceptual difference between DSM, DR and EE:

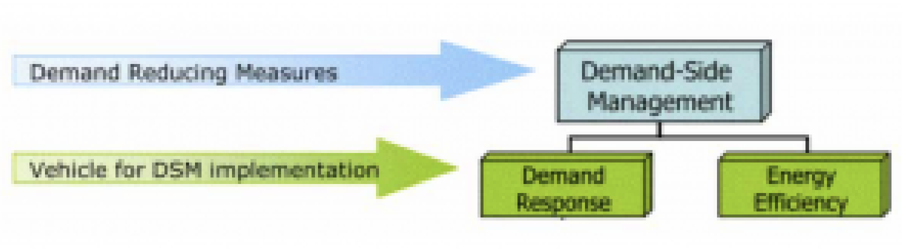

Figure 2.4: Demand Side Management (DSM). Source: EU Project RESPOND (2020)

2.3 Demand Response (DR)

According to the document, *"Demand Response status in EU Member States"*[11], Demand Response (DR) is a tariff or program established to incentivise changes in electric consumption patterns by end-use consumers in response to changes in the price of electricity over time, or to incentivise payments designed to induce lower electricity use at times of high market prices or when grid reliability is jeopardised. Demand response (DR) refers on how to increase a system's adequacy and to reduce the need for investment in peaking generation by shifting consumption away from times of high demand. Many opportunities from distributed generation can be taken to provide ancillary services such as reactive power and voltage support and improve the power quality, can add up improvements in the overall electric system reliability.

In terms of stability, unfortunately in many cases, demand and renewable energy availability are not favorably correlated, for example, periods of high (low) demand do not often coincide with periods of high (low) renewable energy production. Consequently, Demand Response (DR) aligned with energy storage applications can give several benefits to the potential consumers in the residential, commercial and industrial scenarios by providing them with the adequate energy management systems, controls and signals to adjust their consumption at specific times. It is most commonly implemented in the industrial sector, where energy use is high and peak energy demand comes at a significant cost to utilities and the grid itself.

However, as distributed energy resources and renewables become accessible, the demand response programs will play an increasingly important role in balancing energy demand within the tertiary building sector as well. Despite having a lower individual energy consumption per site, the potential to exploit demand flexibility for home appliances can contribute to grid load balancing and demand shaping. In order to promote investment on renewable-based technologies, the incentives through DR programs and the associate electricity pricing schemes can be effective. One of the most effective platforms for customer engagement is the participation in the electricity market. However, most end-consumers, especially in residential areas, they do not have access to dynamic price signals of electricity and therefore have been limited to their participation in energy markets.

In addition, DR aggregators play a fundamental role in tapping into the end-consumer market, by creating customized, automated controls for consumer loads and appliances that enable remote access, while taking into consideration preferences and behavioral patterns. These aggregators have the ability to bridge the information and technology gap that is currently being faced by power networks. The figure of an aggregator coordinates and manages the demand of the consumers and offers services of management of the demand to the system. Some of the main functions are:

- Responsibility for maximizing production with different and distributed sources in the supply area of the grid (residential, commercial buildings, among others.), cooperating with prosumers and facilitating the exchange of energy between consumers (balance between surplus and needs of energy). See Figure 2.5.
- Incorporating storage systems distributed in buildings and in each transformer station to model the energy load curve that negotiates with the network operator (upstream of the transformation center).
- Having the competence to develop, install and operate a network of charging points for electric vehicles, either in the public space or in private parking lots.

Therefore, some of the benefits that aggregation schemes offers are:

- Providing security and predictability to the system because it assumes the deviations in the technical and economic fields.
- Combining the interests of all the consumers and represents them, not only in front of the distributor, but also in front of the operator of the system.
- Managing the flow of energy according to needs, so it becomes a key element in the management of demand.
- A possible technological capability of, in certain situations, working in isolated mode and becoming a manager of a micro-network that maintains continuity in the supply. This mode of operation would allow the last step in supply quality, reducing almost to zero the total non-programmable supply chutes.
- Assuming the financial and technical risk of operating the micro-network, both in front the system operator and consumers.

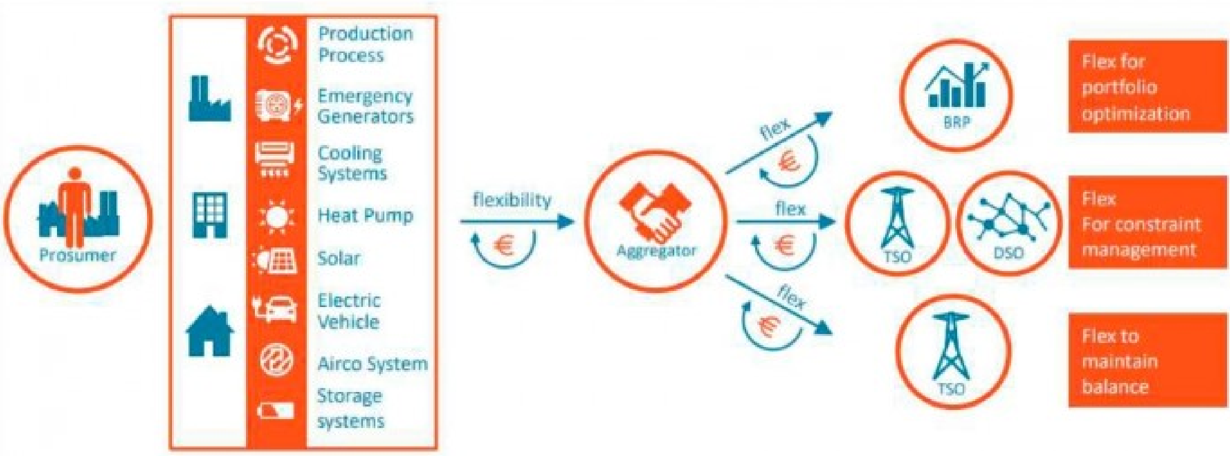

Figure 2.5: Aggregators-Prosumers value chain. Source: UFLEX (2020)

Consequently, the Demand Response (DR) programs can led to other several benefits such as:

1. **Generate income:**

   Participating in DR services enables the users to generate revenue simply by managing the energy consumption or generation in ways that support electrical grid of the country/region. The income-earning potential is significant and, in most cases, no investment or capital outlay is required. If the participants already have underused assets on site, it is good scheme to capitalize. Here is how the implementation of second-life batteries could play a key role on DR programs, and will be explained more in detail in Section 3.

   A range of DR balancing services is available, each with different payment regimes that are related to the required response times and duration of response. The level of income that the users can earn is linked to the speed of response required. Frequency response services, which require instantaneous action in response to frequency fluctuations on the network, pay the highest rates. Reserve services do not require an immediate response, and so offer lower payments. In Section 2.3.2, it will be explained how with the use of a Battery Energy Storage System (BESS) could make some revenue streams taking into account the operability of this energy systems.

2. **Improve asset maintenance:**

   To take part in DR services, it is necessary to maintain the energy generation assets in good working conditions. DR payments will help to fund essential regular maintenance of the assets, while frequent operation will keep them in better working order – helping to prolong their lifespan.

3. **Enhance the corporate-social responsibility:**

   Demand Response (DR) participation also incentivises improved energy efficiency (EE), since it requires energy consumption to be carefully managed and reduced at key times. The net result is that carbon emissions are reduced, supporting the environmental efforts and helping to meet regulatory obligations of the societies.

Finally, the implementation of demand response requires the installment of infrastructure allowing communication to the consumers (one direction or bidirectional), and also communication of consumer appliances able to adapt their consumption to the broadcast signals. This upgrade of the grid and of the consumer appliances is often associated with the notion of smart-grid. It must be important that a better understanding of a particular architecture of a smart-grid will be compulsory in order to give a tailormade solution based on energy consumption patterns. In this project, the model case study will be the architecture of COMSA Corporación office building (shown in Figure D.2).

2.3.1 DR market participants

Market players in DR programs can include producers, grid operators (Transmission System Operators (TSOs), Distribution System Operations (DSOs)), retailers, aggregators, Balance Response Parties (BRPs), policymakers, and consumers (building owners and occupants). New actors (aggregators) and new roles (e.g., retailers' aggregation service) appear in the energy market. The main relationships between actors in the DR market are shown in Table 2.1:

Actors	Offers	To
Aggregator	Pay for BRPs' energy loss	BRP
	Market access DR incentives	Consumer
	Ancillary services Tariff	Transmission System Operator (TSO)
	Network balancing services Tariff	Distribution System Operation (DSO)
Supplier/retailer	Incentives and contract package for the implicit DR program	Consumers
Regulator	DR incentives DR regulations DR awareness	All actors
Consumer	Demand profile	Aggregator
	Direct control	Supplier/retailer
	Large consumers can directly provide energy flexibility to the DR market	Demand Response (DR) market

Table 2.1: Actors in Demand Response (DR) programs. Source: Zheng Ma et. al (2017)

In the new decentralized energy market, these entities are referred to as market agents, players or stakeholders and are explained as follows:

1. **Consumers:**

   Consumers are the main users of electricity and they represent all different sectors such as industrial, commercial and domestic sectors. They can buy electricity in a traditional way from either the pool or future markets, or they may obtain their electricity through bilateral contracts from other market agents, such as producers or retailers. Bilateral contracts are energy arrangements between suppliers and consumers, which takes place outside the limits of energy markets. In such contracts, consumers can buy their energy directly from the producer, or through an energy retailer. Also, consumers have the option to participate in reserve markets, and they may need to participate in balancing markets if their consumption.

2. **Producers:**

   Producers are the market agents who have electricity generation units. They can sell energy in energy markets or directly to consumers or retailers, through bilateral contracts.

3. **Non-dispatchable producers:**

   Non-dispatchable generation refers to electricity generation units based on RES, such as wind or solar power.

4. **Retailers:**

   Entities which buy electricity from the wholesale market and sell to consumers, who are not interested or allowed to participate in such markets. Retailers do not have to own power generation, transmission or distribution assets.

5. **Market operator:**

   A nonprofit entity that provides a platform that enables the trading of electricity. In the day-ahead and intra-day markets, the market operator receives the sale and purchase offers from the sellers and buyers respectively through an online platform. Also, it is responsible for setting the market rules, receiving the energy bids from all market agents and then clearing the energy market.

6. **System operator:**

   A nonprofit entity which is responsible for the technical management of parts of the network. For example, the distribution system operator (DSO) is responsible for the operation and maintenance of a distribution network at a given area. Similarly, the transmission system operator (TSO), owns and operates the transmission network and ensure the secure transmission of electricity from the generation to the distribution sides of the network.

7. **Market regulator:**

   A governmental entity that ensures the fair competitiveness and trading of the energy markets.

8. **Balance responsible party (BRP):**

   An entity that is responsible for maintaining a continuous power balance between production and consumption. Also, a BRP can provide ancillary services to the system to maintain the system reliability and efficiency level.

2.3.2 DR programs

Several utilities have DR programs that provide financial incentives and price signals to customer owners of distributed generation units to make them available for electric system operators and also reduce their electricity consumption during peak demand periods. According to Zheng Ma et al [27], there are two types of DR programs: explicit and implicit demand response. The two types of DR programs are activated at different times and serve different purposes in markets. Consumers can participate in both programs. Consumers typically receive a lower bill by participating in a dynamic pricing program (implicit DR), and receive a direct payment for participating (explicit DR).

- **Implicit DR (Price-based DR program):**

  Implicit DR refers to the voluntary program in which consumers are exposed to time-varying electricity prices or time-varying network tariffs (such as a day/night tariff). Compared to explicit DR with direct load control, implicit DR provides less flexibility from the perspective of energy suppliers. Price-based programs depend on the cost of electricity production at different times, and on consumers own preferences and constraints.

- **Explicit DR (Incentive-based DR program):**

  Explicit DR is divided into traditional-based (e.g., direct load control, interruptible pricing) and market-based (e.g., emergency demand response programs, capacity market programs, demand bidding programs, and ancillary services market programs).

  In this program, demand competes directly with supply in wholesale, balancing, and ancillary services markets through services by aggregators or as single large consumers. Load requirements (size of energy consumption) need to comply to participate in DR programs. Therefore, small consumers only can participate by contracting with DR service providers. DR service providers can either be third-party aggregators or customer retailers. Through incentive-based programs, consumers receive direct payments to change their electricity consumption upon request (e.g., to consume more or less).

  In the end, Explicit DR is more flexible in terms of helping DR service providers acquire DR resources. Direct load control enables DR service providers to control appliances within a short notice. Explicit DR provides a valuable and reliable operational tool for system operators to adjust load to resolve operational issues.

2.4 Spanish legislation for energy flexibility

Electricity demand in Spain is highly variable, both within the same day, as between days. There are several factors that influence it, the most direct being the time, type of day and weather. This causes large differences to occur between the maximum peak, consumption peak, and the minimum of electrical demand, known as valley. The operation of the system must maintain a constant balance and in real time between consumption and generation. Low energy storage capacity and the limited international interconnections of the electricity system have led to dimension generation based on peak demand.

Solutions to avoid potential problems, both from the waste of energy resources such as the over-sizing of the system due to the great difference between the maximum and minimum demand, pass by applying strategies of active management of electricity demand. Active demand side management is the set of strategies and measures aimed at facilitating greater flexibility, as well as more active participation of consumers in the electricity markets and in the operation of the system, through economic incentives. On this section, this mechanism consists of the application of a system of prices and tariffs, both energy and the use of networks and other regulated costs, which reflect actual operating costs. The consumer responds in a way voluntary to market price signals by changing their habits of consumption.

The International Energy Agency (IEA) [4] refers that in Spain, the scarce interconnection capacity of the Iberian peninsula with the rest of Europe (2.8% instead of a minimum recommended by the European Union of 10%) and the remarkable penetration of variable resources (24% of total electricity generation in 2014) have created the need to improve the energy flexibility of the Spanish system, which so far has been facilitated by the involvement of large industrial consumers in direct load control programs. In 2013, these programs took the form of auctions managed by the Spanish TSO Red Electrica de España (REE) while in the previous framework the programs could be activated only for technical reasons, as in case of an emergency in the system, today the TSO has the possibility to activate them also for economic reasons, as when the curtailment option is cheaper than alternatives.

The market is characterized by seven DSOs and by three large firms covering more than 60% of the total electricity generation. The energy efficiency of the industrial sector is generally lower than in the rest of Europe, while energy intensity is much higher than in other countries (for example in the case of non-metallic minerals (42%), basic metals (82%), and chemicals (94%). The Spanish regulatory framework for distribution networks is based on a revenue-cap formula with four-year periods, taking into account also inflation and efficiency requirements, with incentives to improve continuity of supply and reduce energy losses.

In January 2014, the auctions covered a total capacity of 2.2 GW, and a recent paper by Asociación de Empresas de Gran Consumo de Energía (AEGE), (an association representing 12% of total peninsular electricity consumption and 30% of total industrial consumption), declared that a proper remuneration of interruptible programs was a measure to approximate competitive electricity prices for large energy-intensive industries, generally these industries belong to the basic industry, which is the one dedicated to the transformation of raw materials, and to guarantee security of supply and to improve the overall efficiency of the electricity system. Since July 2020, the interruptibility services of the Spanish electricity market has stopped working and now a new regulatory framework is being discussed in order to implement new measure that will help the residential, commercial and tertiary sectors in terms of energy self-generation and consumption.

2.4.1 Regulatory framework PNIEC 2021-2030

The new regulatory framework to be discussed in the 'Plan Nacional Integrado de Energía y Clima (PNIEC) 2021-2030' [9], aims for the integration of aggregation into the electric system and sets 2.5 GW as the objective for new batteries to be installed in such period, which could by far take into account of all the balancing services in the country. In fact, increasing the flexibility of the system is one of the actions that contributes to achieving the electricity generation objectives of renewable origin set forth in the PNIEC.

The contribution to a greater integration of the electricity market is addressed. Additionally, depending on the characteristics of the geographical areas, the rapid changes in the dynamics of consumption and generation can pose challenges for the management of distribution networks. In this sense, the use by the distributors of the services they can offer the energy resources distributed in a particular area, appears as a possible cost-efficient alternative for solving network congestion or other challenges at the local level.

If all the regulatory constraints regarding to the Demand Response (DR) schemes are cleared, the PNIEC will promote a proactive role for citizens in the decarbonisation, regulatory changes at Spanish and European level and technological development promote that citizens go from being passive consumers to actors and prosumers and can also participate in demand management through energy efficiency systems, the provision of recharging services for electric vehicles or other energy services. Meanwhile, those regulatory framework changes are in process, the structure of the ancillary services and capacity mechanisms will be the same in Spain as in the rest of Europe (Benelux, Germany and UK).

In addition, this new regulatory framework will accomplish the guidelines of the Energy Efficiency Directive 2012/27/EU and of the Winter Package. For these reasons, the analysis performed through other European markets already opened to DR programs via aggregation is useful to formulate a new alternative in the Spanish current energy legislation. In the end, the DR programs could be a cheaper and more environmental-friendly solution to reduce payments to peak power plants and decommission the older ones.

The Instituto para la Diversificación y Ahorro de la Energía (IDAE) [9] explains the self-consumption considerations that are mentioned in this new regulatory framework. The consumer figure is the consumer of electrical energy at a supply point that has associated facilities close to the internal network or facilities close to the network. It can be associated with individual self-consumption, or with collective self-consumption. In any form of self-consumption, it may be a natural or legal person different from the consumer and the producer. Thus, it is possible that the owner is an energy services company, a community of owners, building stock owners. For example, different modes of self-consumption are established in article 9 of Law 24/2013, and are again included in article 4 of Royal Decree 244/2019. Currently, the following modalities are distinguished:

- **Modality of supply with self-consumption WITHOUT surpluses:**

  When the installed devices prevent the injection of any surplus energy into the transmission or distribution network. In this case, there will be a single type of subject from those provided for in article 6 of Law 24/2013, of December 26, which will be the consumer subject. In facilities WITHOUT surpluses, the owner of the self-consumption installation will be the consumer. In the case of collective self-consumption, the ownership will be distributed among all associated consumers. Moreover, the figure of associated producer surplus does not exist, but the installation does not need to be registered.

- **Modality of supply with self-consumption WITH surpluses UNDER compensation:**

In terms of this project, this compensation mechanism will be the chosen for the analyses and calculations for the COMSA building in the next chapters. The energy from the self-consumption installation that is not consumed instantly or stored by the associated consumers, is injected into the grid. When consumers require more energy than the self-consumption facility provides, they will buy the energy from the grid at the price stipulated in their supply contract (PVPC or free market agreed with the marketer).

At the end of the billing period (which may not exceed one month), the compensation is made between the cost of the energy purchased from the grid and the value of the excess energy injected into the grid when generation facilities can (valued at average hourly market price less the cost of the deviations or the price agreed between the parties, depending on the supply contract to PVPC or the free market respectively). In addition, the figure of associated producer may be one of the associated consumers or another natural or legal person, and will act as the owner of the installation.

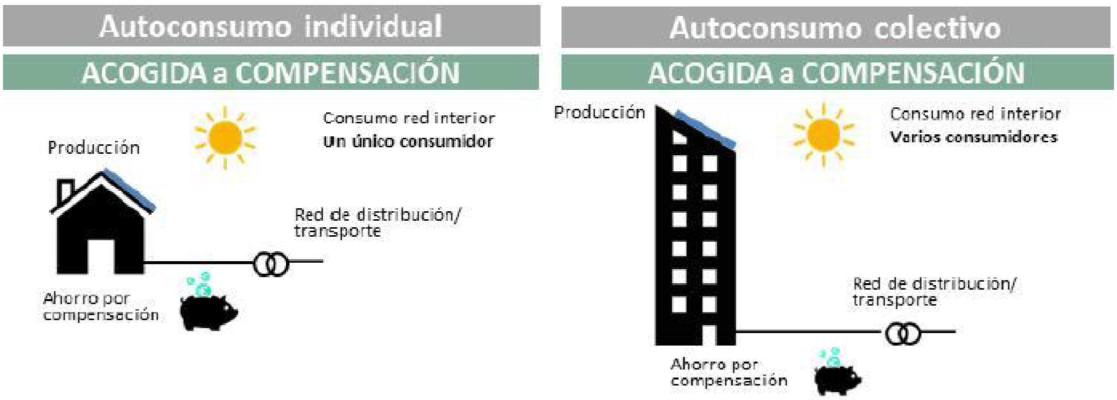

Figure 2.6: Self-consumption WITH surpluses UNDER compensation scheme. Source: PNIEC (2020)

Figure 2.6 represents the possible configurations for installations WITH surpluses under compensation, which will always be connections in an internal grid. The savings represented in these diagrams reflect the reductions in bills that are obtained thanks to the compensation of the energy discharged. To be eligible for the surplus compensation mechanism, the following conditions must be met:

1. The generating facility is from renewable sources
2. The power of the production facility is equal to or less than 100 kW
3. A single contract for consumption and auxiliary services has been signed
4. A surplus compensation contract is signed between producer and consumer
5. The facility has not been granted a specific additional remuneration scheme

Additionally to the self-consumption installations WITH surpluses that meet the above conditions, consumers associated with a self-consumption installations WITHOUT surpluses may benefit from the compensation mechanism. In this case (self-consumption WITHOUT surpluses), as it is a collective self-consumption facility, the associated consumers must agree on the energy sharing mechanism and sign a document that reflects it ("Distribution Agreement").

In August 2020, the Spanish Government via the PNIEC will destinate a fund of around € 300 million distributed in all the autonomous communities to the Building Retrofitting sector in order to improve the Energy Efficiency (EE), that is an important energy consumption share (30 %) in the country. Moreover, the application of this new regulatory framework will led to the creation of 48 000 new jobs and innovative SMEs boosting the green economy in Spain.

In the end, emerging self-consumption model in Spain opens new cost-containment opportunities for energy consumers therefore becoming active 'prosumers', but also for other consumers which are faced with high electricity prices, and allowing them to increasingly control their energy bills. Amongst residential consumers, new behavioral patterns are emerging ranging from in particular rooftop solar photovoltaic (PV) systems owned by individual households or third parties in buildings, to develop self-consumption plus energy storage projects.

2.4.2 Ancillary services - Balancing Market Services

As it was mentioned in the above Section 2.4.1, this project is going to evaluate a case study using Demand Response (DR) schemes in parallel with ESS applications on buildings. For this case study, the ancillary services model applied in the Netherlands will be used as a reference in Spain, taking into account the market opportunities, revenues streams and business scalability. In the present section, the Dutch ancillary services model will be explained in detail and afterwards in the Chapter 3, Section 3.3, will be applied in the Business Model Canvas (BMC) and techno-economic Excel Model.

Many studies have stated that the second-life batteries have enough functional capacity to be used for ancillary services such as area and frequency regulations at a much lower cost generating an income. Batteries can supply real power to the system very fast, therefore it can work along the generators for primary and secondary frequency control. Figure 2.7 shows that the frequency control can be categorized into three steps- primary, secondary, and tertiary:

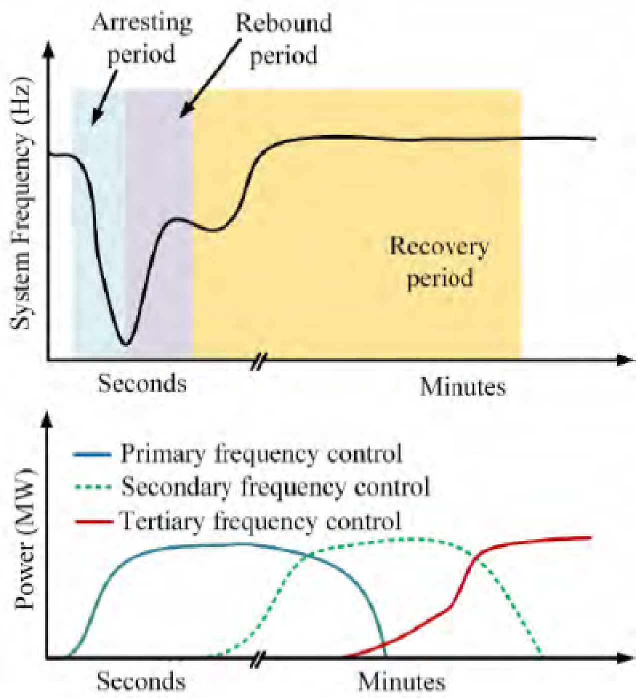

Figure 2.7: Frequency control schemes: primary, secondary, and tertiary. Source: IEEE (2019)

Moreover, demand response (DR) programs were limited in some ways since aggregation was only allowed in manual FRR (Secondary Control Reserve) for reserve capacity and RR (Tertiary Control Reserve) and not in FCR (Primary Control Reserve). However, according to the Dutch TSO TenneT, FCR is opened very recently after the successful pilot in the Netherlands. Other than these, automatic FRR (aFRR) and manual FRR (mFRR)for emergency power is available for load participation.

In other cases, demand response programs open to aggregation participation required a 4 MW minimum capacity (it has changed to only 100 kW minimum threshold) from consumers to participate. The advantage of this change is that new FCR programs will allow smaller aggregations to participate as well. On the other hand, regarding payments, RR considers only utilization, and FRR provides both availability and utilization incentives in the cases of emergency power and regulating capacity. Penalties for non-compliance are harsh, reaching up to 10 times the payment value. FCR will hold availability payments, with no extra fees for activation.

First, most assumptions of the Dutch market is that every customer (connection) is responsible for arranging his energy position, except small customers where the supplier is obliged to take this responsibility on board. Balancing, including FCR (Frequency Containment Reserve) and mFRR (Manual Frequency Restoration Reserves), intraday and day-ahead markets in the Netherlands are all open for demand response (DR). In the case of Spain, the FCR (Frequency Containment Reserve), primary reserve, is not possible yet due to the faster response that must be accomplished.

Aggregation relies on consistent contractual arrangements between consumer and supplier and between consumer and flexibility service provider. Larger consumers can arrange their own balancing responsibility and sourcing on the wholesale market or negotiate the terms and conditions of the use of their flexibility. A lot of different forms of contracts exist, there is not a one-size-fits-all contract. Smaller consumers rely on offers developed by various suppliers and will select the most attractive or a combination of offers for their specific situation, including the opportunity to market their flexibility. As a result of a consistent focus on market freedoms and a clear division of responsibilities, the Dutch electricity markets (including retail) have reached a significant level of maturity.

There is no separate FSP (Flexible Service Provider) market role defined. An FSP must take up the role of a supplier or sign a bilateral agreement with the supplier / BRP / customer on the connection. In order to do so the following actions need to be taken :

1. Connect to local Distribution System Operator (DSO)
2. Inform the DSO about your intention to enter the market
3. Plan and perform PQ test (test can vary depending on the services you want to provide)
4. Hand in PQ test report and necessary documentation (financial statements)
5. If requirements are met a BSP license (that needs to be renewed every 5 years)

According to Tennet, TSO from the Netherlands, both larger and smaller connections can be settled based on the 15 min measurements of the meter. Below there is a brief description of feasible services to provide for the Business Model Canvas (BMC) in the Chapter 3.

Frequency Containment Reserve (FCR): [5]:

- Minimum threshold of 1MW (changed in the Dutch market starting at 100 kW letting small aggregators to participate)
- Aggregation of multiple smaller units is allowed
- Minimum accuracy of the frequency measurement: 10 mHz or industry standard, whichever is better
- Insensitivity range of the FCR control: Maximum 10 mHz
- Activation speed: 30s for the full allocated volume (will vary between reserves)
- Frequency deviation for full FCR activation: + 200 mHz / – 200 mHz

Automatic Frequency Restoration Reserve (aFRR): Regulating Power [6]:

- Minimum threshold of 1MW (changed in the Dutch market starting at 100 kW letting small aggregators to participate)
- Two directions
- A BSP can offer at maximum three bids smaller than 4 MW. For smooth and efficient control of aFRR it is beneficial to have a mix of small and large bids.
- The ramp rate of the offered aFRR (up and/or down) volume should be at least 7% per minute of the bid volume.

- An observable power change is expected within 30 seconds after a setpoint change.

Manual Frequency Restoration Reserve, scheduled activated (mFRRsa): Power Reserve [7]:

- Minimum threshold of 1MW (changed in the Dutch market starting at 100 kW letting small aggregators to participate)
- Two directions
- The BSP must be able to receive a mFRRsa activation via the call-up screen
- A power measurement of the BSP must be made available to enable TenneT to monitor the mFRRsa supply.

According to the Penta Region energy markets [8], there is a separate flexibility service provider market role implemented. Other countries are in the process of defining the flexibility service provider market role and in some countries it is only possible for a flexibility service provider to become a supplier or to sell services to a supplier. Based on that, the following distinction between possible market models is proposed:

1. **Integrated/Broker Model:**

   There is no separate market role (needed) for an FSP. The FSP has the option to become a supplier (integrated model) or to become a service provider for the supplier (broker model)

2. **Contractual Model:**

   The FSP signs a contract with the customer and with the supplier/BRP at the connection. The actions of the FSP result in changes in the portfolio of the BRP of the supplier.

3. **Uncorrected Model:**

   The FSP signs a contract with the customer but not with the supplier/BRP. The actions of an FSP at the connection have an effect on the portfolio of the BRP but the effect is not neutralized. Financial compensation is organized bilaterally between BRP-Supplier and Supplier.

4. **Corrected Model:**

   In the corrected model, the meter reading is corrected by the amount of flexibility which is activated by the FSP. The customer pays the amount of energy to the supplier based on the corrected meter reading value. The FSP settles the amount of energy with the customer based on the difference between the real meter reading value and the corrected meter reading value. Financial compensation of the Supplier is organized via the customer at the customer's retail rate.

5. **Central Settlement:**

   In the central settlement model the amount of flexibility which is activated at the connection of the customer is financially compensated between Supplier and FSP via an intermediate party (TSO).

These new business models will led any market party (including new actors as aggregators) can obtain the necessary license to supply buildings and households or become a Balancing Responsible Party (BRP) active in the energy market. The figure 2.8 shows the types of business models mentioned above:

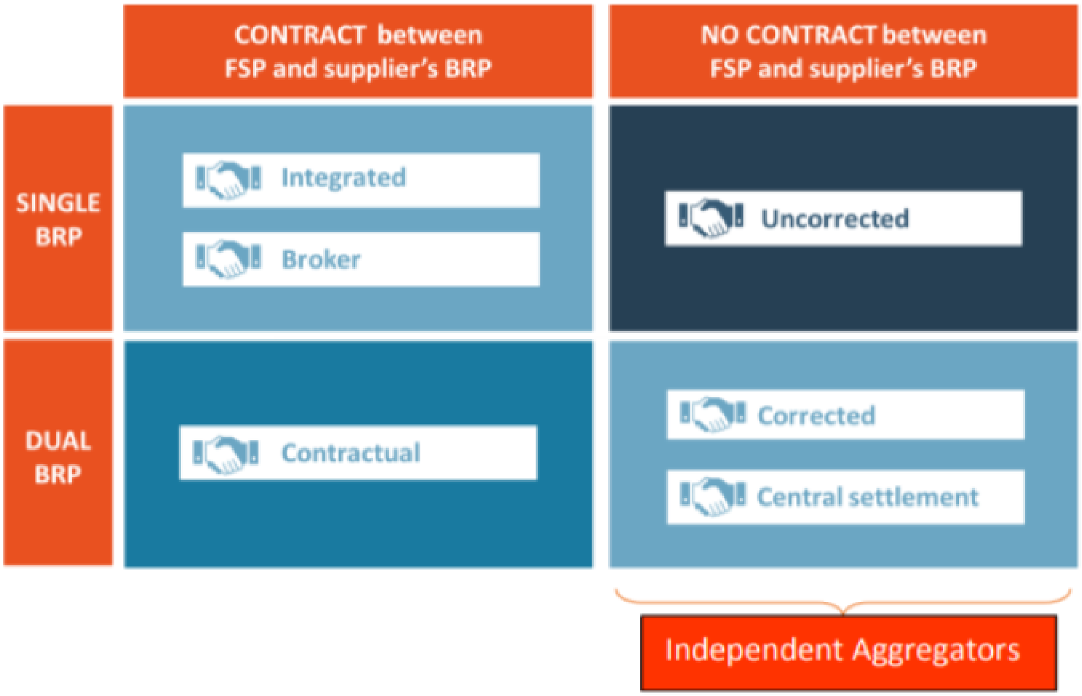

Figure 2.8: DR-Aggregator business models. Source: Benelux.int (2020)

As a reminder, these DR programs are now implemented in the Netherlands but since the Spanish energy market is changing its regulation framework, these schemes could be applied as well to develop some business models and in order to enter into the market soon as it starts. In the end, the Spanish energy market could led the participants to act on a supplier role (Integrated model), make arrangements with the consumer and its original supplier (Contractual model), and become a service provider for the supplier (Broker model). A complete table with all the Balancing Markets Services can be seen at the Appendix A.2, Figure A.3 with the description of each scheme applied nowadays around Europe.

2.5 Virtual Power Plants (VPPs)

Nowadays, the energy generation is changing from centralized control of production units and large conventional power plants to distributed generation that will displace these services. These type of conventional power plants will continue operating as backups units in the energy mix providing support services such as load following, frequency and voltage regulation and reserves. For those central power units some substantial investments, operational and maintenance (O&M) costs at both transmission and distribution levels must be taken into account. Therefore, in order to make the most of distributed energy resources (DERs), a new concept for power system operation in which the joint coordination of distributed generators and flexible loads can fully replace conventional power plants should be implemented.

In the book, *"Integrating Renewables in Electricity Markets"*[12], a virtual power plant (VPP) is a pool of several small and medium scale installations, either consuming or producing electricity. Individual small plants sometimes cannot offer services as balancing reserve or offer their flexibility on the power exchanges as their production or consumption profile varies strongly. It can be seen as a network of independent DER systems utilizing a cloud-based control system to perform like a single large capacity energy source while relieving the load on the grid by smartly distributing the power generated by the individual units during periods of peak load.

One of the main features of the virtual power plants is the energy flexibility, meaning the quick and versatile ability to balance the grid, and this is one of their most notable difference compared to large conventional power plants (thermal, nuclear, hydro, among others). A virtual power plant can deliver the same service and trade on the same markets as large central power plants or industrial consumers. Figure 2.9 shows an ideal virtual power plant concept using IoT systems and enabling the integration of the renewables energy sources.

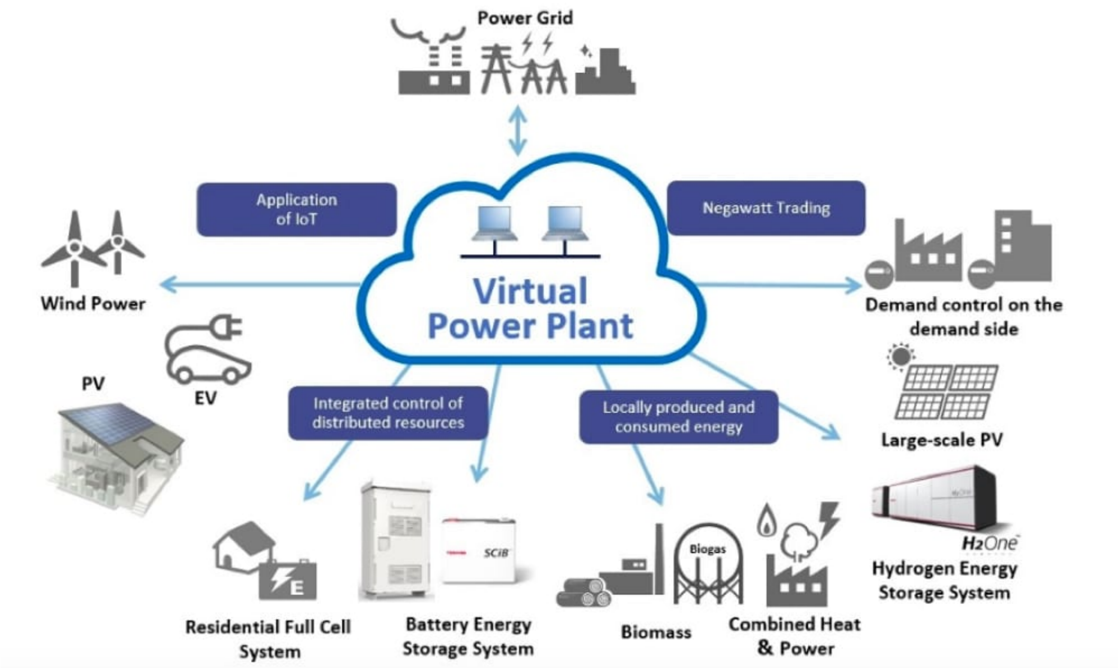

Figure 2.9: Virtual Power Plant(VPP) concept. Source: Toshiba (2020)

The implementation of the virtual power plant concept in the energy mix will allow the DERs to interact with the transmission system and participate in both energy markets and system management. Thus, enabling several consumers to participate in the future distribution grids and flexible loads. The VPPs can utilize the aggregated power to react to changes of the electricity price, quickly adapting to the existing supply of power in the grid and execute trades. Other important benefits that DERs will give to the energy generation are voltage control or VAR (reactive power) supply, ancillary services, environmental emissions benefits, reduction in system losses, energy production savings, enhanced reliability, power quality improvement, combined heat and power, demand reduction and standby generation.

On the other hand, the scheduling problem of distributed energy resources (DERs) is a very important issue in power systems nowadays and it is studied from various aspects such as modeling techniques, solving methods, reliability, emission, uncertainty, stability, demand response (DR) as mentioned in Section 2.3, and multi-objective standpoint in the micro-grid and VPP frameworks. Finally, the combination of several types of flexible production and consumption units, controlled by a central energy management system (EMS), is the concept behind a Virtual Power Plant.

2.5.1 Local Energy Communities (LECs)

Many energy experts and researchers have shown in different articles that the virtual power plant (VPP) and local energy community (LEC) concepts share some similarities between them. A community, in relation to an energy system, is a social network of people (and organizations) that collectively engage in energy related initiatives and projects, ranging from renewable energy generation, energy conservation and efficiency to energy management. This type of networks can be virtual (as explained in section 2.5)or sectoral and can include not only inhabitants or citizens, households owners but also other actors like local entities, companies and municipalities.

According to T. Van Der Schoor and B. Scholtens [14], the local energy communities (LECs) are defined as a number of residential households, industrial facilities and small power plants that aim at balancing energy demand and supply within a specific geographically bounded region. For curtailing load and optimizing electricity consumption for a mostly self-contained local energy community, appliances adapt their demand to the available electricity by shifting the load to times where, e.g., energy from photovoltaic power plants and wind power plants is available.

In addition, the article *"Trust-less electricity consumption optimization in local energy communities"* [15], states that optimizing energy consumption in local energy communities is one of the key contributions to the concept of a *'Microgrid'*. Such communities are equipped with rooftop photovoltaic power plants or other small power plants for local energy production. A number of appliances allow for shiftable energy consumption, e.g. batteries may act as buffers and some appliances such as heat pumps or electric vehicles (EVs) allow for relatively easy load curtailment, other appliances are less flexible. The ability to shift is, however, dependent on customer preferences and requirements.

2.5.2 Microgrids

The increasing interest in the development of distributed generation (DG) has heightened the need for the concept of *'Microgrids'* in the current energy mix. The study done by A. Hirsch et al. on their scientific article *"Microgrids: A review of technologies, key drivers, and outstanding issues"* [16] shows that deploying intermittent renewables in with co-located flexible loads and storage technologies in microgrids allows for small-medium scale local balancing of supply and demand makes widespread distributed renewable deployment more manageable.

The development and deployment of the building-integrated microgrids rely on some drivers to achieve like energy security, clean energy integration and economic benefits, also aligned with the growing investment in local, renewable production and an existing and operating electrical grid infrastructure that could be connected to other services like energy storage technologies in order to provide ancillary services like voltage control support, spinning reserves, load following, and peak shaving among others as mentioned also in the previous sections 2.5 and 2.5.1.

Most commercial and industrial buildings are connected to the main grid, but are increasingly adopting connected micro-grid solutions in order to maximize the auto consumption ratio, optimize the energy bill (tariff management and demand charge management) by leveraging the local resources and loads flexibility and participate in the mentioned demand-response mechanisms playing an active part in the electricity system balancing process. One appealing residential microgrid application combines market available grid-connected rooftop PV systems, electrical vehicle (EV) slow/medium chargers, and home or neighborhood energy storage system (ESS). During the day, the local ESS will be charged by the PV and during the night it will be discharged to the EV. The inclusion of an ESS alleviates overvoltages during the day due to excess PV power generation and undervoltages during the night caused by the huge current drained to charge the vehicle. The figure 2.10 shows a typical residential microgrid application:

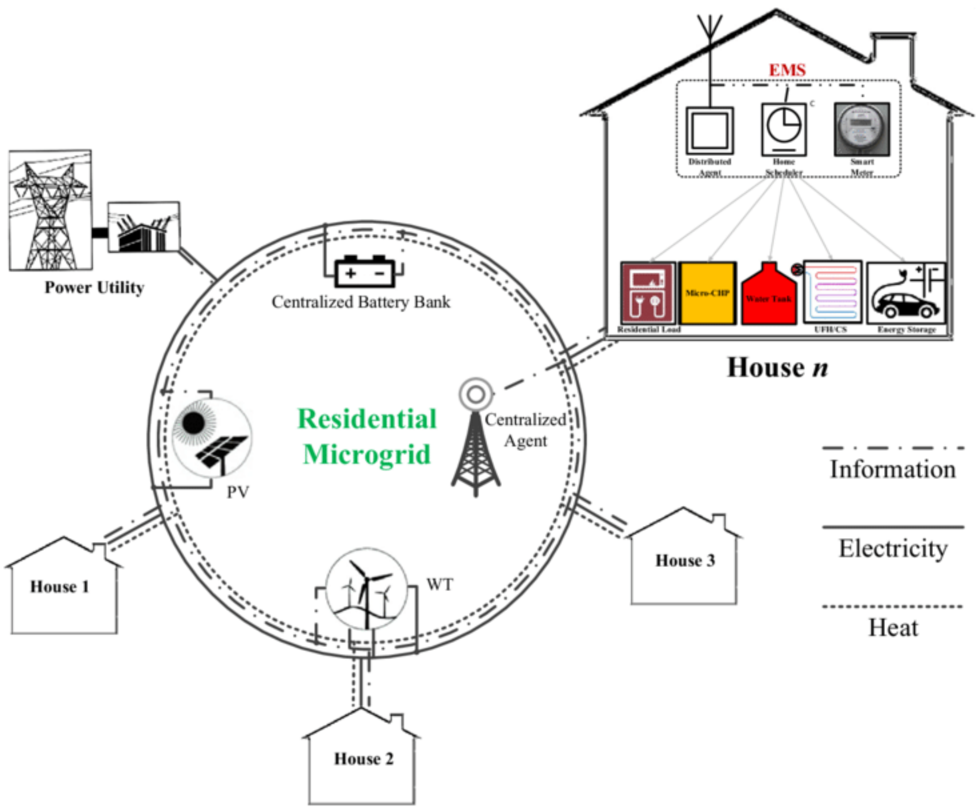

Figure 2.10: Microgrid concept. Source: researchgate.net(2020)

New technologies implemented in the energy sector can be coupled with the emerging revolution of IoT and Big Data, therefore the 'Smart building' (SB) concept proposes a multi-source, multi-load, and multi-storage system, all of it massively managed by software and communication systems and controlling all the assets such as micro-turbines, PV panels, wind turbines, fuel cells, energy storage capabilities, electrical vehicles and global building loads that will use information like energy market constraints (energy price), weather forecast, and other external and internal constraints to perform at the best point.

2.6 Internet of Things (IoT) in the energy sector

According to the article *"The Internet of Energy: Smart Sensor Networks and Big Data Management for Smart Grid"*[17], Internet of Things (IoT) technology is the interconnection of different networked embedded devices used in the everyday life integrated into the Internet. It aims to automate the operation of different domains such as home appliances, health care systems, security and surveillance systems, industrial systems, transportation systems, military systems, electrical systems, and many others.

Briefly explaining the Internet of Things (IoT), it has three system layers: the perception layer, the network layer, and the application layer as shown in Figure 2.11. The perception layer can detect objects, collect and exchange information via sensors, Global Positioning Systems (GPS), cameras, Radio Frequency Identification Devices (RFID) and other communication devices that could be sent to a nearby gateway.

Therefore, the network layer implement technologies such as WiFi, 2G, 3G, 4G, and Power line Communication (PLC) to carry the information for long distances based on the application. Finally, the upper layer is the application layer, where incoming information is processed to design better a power distribution system and energy management strategies. This will be explained more in detail in the Chapter 4. *'Energy Management System (EMS) and implementation barriers'*.

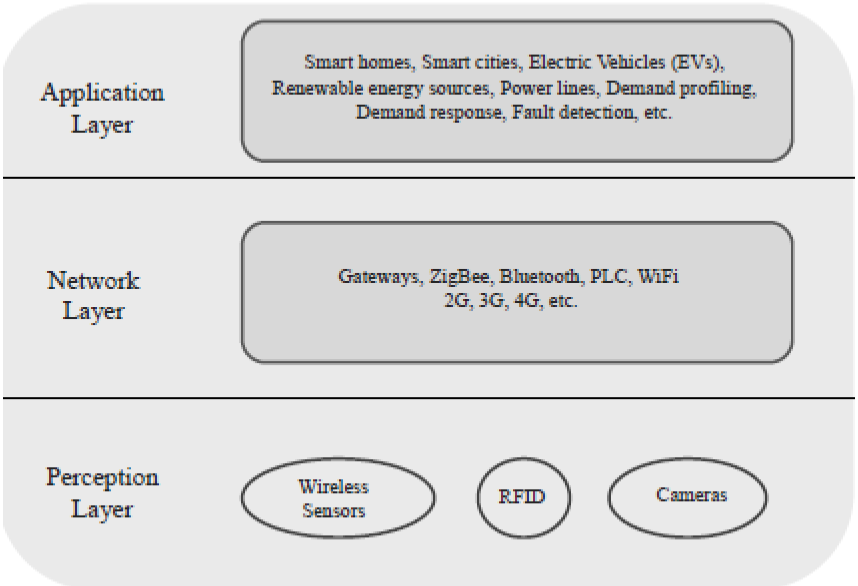

Figure 2.11: Internet of Things (IoT) architecture. Source: sciencedirect.com (2015)

IoT will help to realize the potential capabilities of situational awareness, smart control, cyber security, and online monitoring. These functions would improve efficiency, sustainability, and security of energy systems. Improving the productivity and presence of energy systems, efficient DER control, and effective customer engagement are among the benefits of IoT.

Furthermore, IoT technology will be linked to residential applications such as smart refrigerators, home security systems, lighting control, temperature control, and other electrical appliances to led the householders to control their houses as a whole unit, monitoring real-time data and predicting future activities to be prepared in advance for a more convenient, comfortable, secure, and efficient living environment. This application could scalable into smart communities as mentioned on section 2.5.1 as well as smart cities evolving into the concept of VPP (Section 2.5), changing the way to produce and control energy nowadays.

An increase in the electricity demand will put an important constrain on the current traditional and over stressed power infrastructure causing some serious network congestion problems and lowering the transferred power quality to the end-users. Moreover, a lack of efficient process monitoring, automation techniques and fault diagnostic will led into difficulties to integrate new distributed energy sources in the current infrastructure but also increasing the inflexibility of the energy services.

The smart-grids and microgrids technologies have emerged to tackle the challenges explained above, where a a new concept of intelligent energy infrastructure is already implemented. As it is known, in a smart grid a reliable and real-time monitoring is highly required to provide solutions quickly when for example natural accidents or catastrophes occur to prevent power disturbance and outage. This real-time and sensorial monitoring will assure the capabilities of the power grid enhancing rapid deployment, energy flexibility, and aggregated intelligence via parallel processing.

The Internet of Energy (IoE) concept is the result of the implementation of Internet of Things (IoT) technology with distributed energy systems. Its purpose is to optimize the efficiency of the generation, transmission, and utilization of electricity. IoT technology enables the IoE by creating networks of sensors that have numerous smart grid applications. These include demand-side energy management (DSM), distributed storage, and renewable energy integration, also a continuous monitoring of transmission line's status in addition to environmental behaviors and consumer's activities to send periodic reports to the grid control units.

Consequently, an example of how the IoE works for energy consumers is a system that combines a microgrid, intelligent energy storage, renewable energy generation, and smart devices. This system can be programmed to run energy prices are cheaper than usual or when there is a stored surplus of energy in an intelligent energy storage system. As a result, the energy costs can be minimized or virtually eliminated while plummeting the carbon footprint at the same time.

In the end, the concept of Internet of Energy (IoE) is an exciting new frontier in the development of the IoT. Implementing IoE technology will yield opportunities and efficiencies in the grid and electrical power systems carrying into several benefits for all participants and creating new business opportunities in the energy market.

2.7 Cybersecurity in the energy sector

The European energy system is undergoing to a fundamental transformation towards a model with a high share of variable distributed renewable energy, flexible demand, energy storage facilities and sector coupling. Electricity is becoming 'smart' with internet-connected appliances, smart homes, Advanced Metering Infrastructure (AMI) and ICT applications that can contribute to the management of the electricity grid and a better alignment of electricity production and demand, but they also present opportunities for cyber-attacks.

The production, distribution and use of energy is becoming increasingly digitalized and automated, a trend which will further increase with the transformation towards a distributed carbon-neutral energy system and the growth of the 'Internet of things' (IoT), which means that a growing number of networked devices and control systems will be connected to the electricity grid. This technological transformation in the sector will led to multiple opportunities for hackers and malicious actors to carry out cyber-attacks and inadvertent disruption on the energy infrastructure, creating a physical and a social damage. In addition, natural disasters such as storms, earthquakes, volcanic eruptions, floods and electromagnetic pulses can also cause serious disruption to energy systems, necessitating more resilient infrastructure.

According to an article from the European Parliamentary Research Service: *"Cybersecurity of critical energy infrastructure"* [18], the dangers are increasing, but the risk is doubtful to valued until a sizable attack takes place. The energy and the utility sector constitute a crucial part of a critical national infrastructure, that produces it an expensive target for state or non-state performers causing chaos and disruption. Disabling the energy grid can provoke civil unrest, disrupt chains of communication, degrade military readiness, and generally impede a government's ability to respond quickly and effectively in a crisis situation.

The potentially cascading impact of malicious cyberattacks on critical infrastructure is a rising concern for the sector and governments. The frequency and severity of cyberthreats in the power sector are increasing. Phishing remains the most common means of attack, but malicious actors are also deploying a more extensive range of methods such as credential theft and advanced persistent threats. The losses can include direct costs such as loss of revenue due to operational/productivity disruptions, costs associated with restoring operations and improvements to cybersecurity defenses, regulatory fines, and legal liability, as well as indirect costs such as regulatory fines and reputational damage.

2.7.1 Dynamic Energy Resilience

Since 2018, the World Energy Council has been developing a dynamic energy resilience framework for the purpose of helping energy firms and communities improve their approach to resilience to endogenous or exogenous shocks and disruptive innovations. It integrates three previously separate systemic and emerging risk themes:

1. Extreme weather or natural hazard
2. Digital or cyber risks
3. Food-energy-water nexus with a practical focus on risk identification and assessment, situational awareness and prevention-mitigation plans

In an article *"Cyber challenges to the energy transition"*[19] published by the World Energy Council, the concept of dynamic resilience is gaining popularity because it recognizes that if an attack occurs, the ability to isolate a problem, mitigate and restore to normal activities will define the future success of the correct energy supply chain. Nowadays, the conventional risk-based approach of reducing uncertainty is getting obsolete since resilience is no longer just about returning single assets or components to full operation after a disruptive event, but part of a coordinated approach to ensure the optimal recovery of the energy system as a whole. The figure 2.12 shows the process map with the main stages of dynamic resilience framework to be applied:

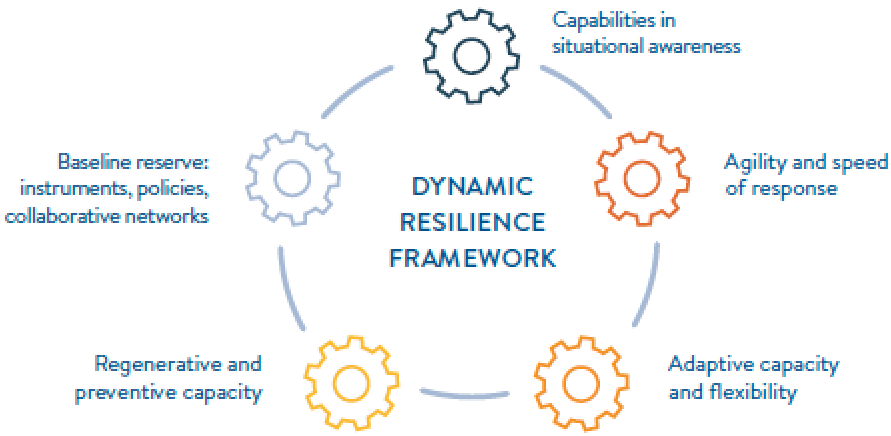

Figure 2.12: Dynamic resilience. Source: World Energy Council (2019)

- **Baseline reserves - instruments, policies and collaborative networks:**

  The systems, policies and processes in place are involved to strengthen resilience. This would involve a comprehensive cyber risk management framework that includes regularly tested incident response plans for the digital resilience. Skilled professionals in cybersecurity must be linked to networks that strengthen the digital and cyber resilience in a crisis.

- **Capabilities in situational awareness:**

  This is the ability to monitor, understand, assess, and continuously refresh the landscape of current and evolving digital and cyber risks, exposures, and potential impact on the organization and understanding the scope for cascade within and beyond the sector. It includes assessments of potential cyber-risk exposure and potential business impact (e.g., power outage and impact on revenue, net fuel, or energy margin basis) to help key decision-makers determine how to best allocate cyber-risk management resources and focus these resources in a crisis.

- **Agility and speed of response**

  It includes quick prioritization setting and coordination with key stakeholders. One of the most important benefits of an efficient event response system is the ability to react swiftly to a crisis and thereby decrease the severity of an event and lessen the reputational impact.

- **Adaptive capacity and flexibility**

This is the capacity and flexibility to evolve mitigation plans which are an essential feature of dynamic resilience. For example, determining clear governance structures in advance of any cyber event so that the organization understands who has the authority to determine a change in response plans during an ongoing cyberattack.

- **Regenerative and preventive capacity**

  This is the process to support a transformative approach that enables adaption and innovation of the cyber risk management framework and includes an assessment of existing resources, systems, and capabilities to prevent future comparable attacks and enhance normal operational function. For example, an immediate goal during an event is to return to 'normal operations' as swiftly and effectively as possible. However, lessons learned should be captured to evolve the response mechanisms and processes. A consistent review process should be established as part of dynamic resilience.

The digitization of the energy industry will continue. As the industry relies more on interconnectivity, the potential for cyberattacks to cause severe disruption to operations, loss of data, and financial losses should remain a key concern for energy executives. In response, building and maintaining dynamic resilience must be seen as a continuous exercise. A regular cadence of exercises will develop a pattern to respond and help identify when and how overall digital resilience can be strengthened.

In Chapter 4, Section 4.4, a supply chain risk management methodology will be studied and explained in order to develop the resilience of interoperability and communication in the energy infrastructure of the case study at COMSA Corporación office building.

2.7.2 European cybersecurity energy framework

Changes in the energy sector and the new digitalization era are making the energy grid very vulnerable to attacks. The European Commission (EC) promotes information sharing at a higher-level via dedicated events, protocols and fosters best practices among the EU Member States and has addressed the question of cybersecurity in energy sector also through the *'Clean energy for all Europeans package'* [20] among which the most important are:

- The new regulation on electricity on risk-awareness in the electricity sector makes EU Member States to develop national risk preparedness plans and coordinate their preparation at regional level, including measures to cope with cyber-attacks.

- The recast of Electricity Regulation gives a mandate to the EC to develop a network code on cyber security for the electricity sector in order to increase its resilience and protect the grid.

The energy sector report from the European Cybersecurity Organisation [21], emphasizes that in the last few years, legislations and policies related to cyber security for different sectors have been defined at an European level as a consequence of the recent changes observed in the energy sector. The main cyber security regulations are:

- The Directive on Security of Network and Information Systems (NIS) Directive was adopted by the European Parliament on 6 July 2016. It is a major component of the European cyber security strategy aimed at strengthening Europe's cyber resilience and cooperation across different sectors. The implementation of the NIS Directive in EU countries has been in effect since May 2018.

- The General Data Protection Regulation (GDPR): it was adopted in 2016 and defines requirements for the protection of personal data. The GDPR regulation has been in effect in EU Member States since May 2018.

- Regulation (EU) No 994/2010: the gas supply regulation aims at ensuring the security of gas supply. Member States shall establish at a national level a Preventive Action Plan and an Emergency Plan.

- The EU Cybersecurity package, including the Cyber Act, as presented in the joint communication to the EU Parliament and the Council *'Resilience, Deterrence and Defence: Building strong cybersecurity for the EU'* in September 2017, covers many aspects such as: a reinforced and permanent mandate of ENISA, a EU cybersecurity certification framework, a cybersecurity competence network with a European Cybersecurity Research and Competence Centre, developing Information Sharing and Analysis Centres (ISACs).

- Cybersecurity Network Code: in the context of the EU Clean Energy package (released on November 30th, 2016), the Cybersecurity Network Code proposes cybersecurity technical rules for electricity aiming at going beyond the NIS Directive obligations by addressing energy sector specificities.

The 2nd intermediary report [22], set up by the Smart Grids Task Force-Expert Group 2, was published in July 2018. The main components proposed in the 2nd draft for the Network Code on cybersecurity are:

- Early warning system in Europe for the energy sector

- Cross-border and cross-organizational risk management in the EU

- Minimum Security Requirements for critical infrastructure components

- Minimum Protection Level for energy system operators

- European Energy Cybersecurity Maturity Framework for Operators of Essential Services

- Supply Chain Risk Management for Operators of Essential Services

- National security strategies and legislations: beyond the definition of cyber security strategies in European countries, national legislations related to cyber security for critical infrastructure operators have been defined.

- Other initiatives have been initiated by the European Commission to strengthen existing cybersecurity policies and legislations.

Chapter 3

Energy storage systems (ESS) for buildings using second-life batteries (SLB)

The European Commission states on its article *"Energy Storage - The role of electricity"*[2], that energy storage is a key component in providing flexibility and supporting renewable energy integration in the energy system. Since the main energy market is changing, new players are involved in the energy scheme of balance centralized and distributed electricity generation. These new players are consumers becoming energy producers, aggregators and third parties managing demand and supply, in addition to utility planners and operators using demand response and energy storage technologies on the grids also contributing to energy security, flexible generation and provide a complement to grid development.

According to the *"Circular Economy Action Plan"* written by the European Commission[24], sustainable batteries and electric vehicles will enhance the energy and mobility sectors of the future. To progress the swift on enhancing the sustainability of the emerging battery value chain for electro-mobility and boost the circular potential of all batteries, the European Commission will also propose to revise the rules on end-of-life batteries with a view to promoting more circular business models by linking design issues to end-of-life treatment, considering rules on mandatory recycled content for certain materials of components, and improving recycling efficiency.

Nowadays, the 'Circular Energy Storage' term considers the rules on recycled content and measures to improve the collection and recycling rates of all batteries, ensure the recovery of valuable materials and provide guidance to consumers in order to enable integration of distributed storage solutions into the energy system and their commercial use. This initiative addresses the existing development needs by combining second-life batteries with an innovative local ICT-based Energy Management System (EMS) in order to develop a low-cost, scalable and easy-to-deploy battery energy storage system. In the end, energy storage can also contribute to the decarbonization of other economic sectors, and support the integration of higher shares of variable renewable energy (variable RES) in transport, buildings or industry.

3.1 Second-life batteries (SLB)

The IEEE states on its article *"A Comprehensive Review on Second-Life Batteries: Current State, Manufacturing Considerations, Applications, Impacts, Barriers & Potential Solutions, Business Strategies, and Policies"*[25], that the use of batteries after the have reached the end of their useful life (EOL) is called 'second-life'. Since the recycling technologies for Lead-acid (Pb-acid) batteries are substancially developed nowadays, the new market participant is the lithium-ion (Li-ion) battery type. The use of Li-ion batteries is increasing without any sign of declining, and in high-capacity applications such as electric vehicles (EV).

Developing business models supporting the extension of a batteries' lifetime in second life applications is a promising market: the European industry (car original equipment manufacturers/OEMs, battery producers and utilities) must seize the opportunity to maximize the residual value of these assets, while at the same time leverage their environmental stance into a competitive advantage. Consequently, a sub-cycle towards a circular economy starts with the second use of EV batteries after recycling, as showed in Figure 3.1, which supposes an enlargement of the battery useful life and a reduction of its impact per kWh exchanged.

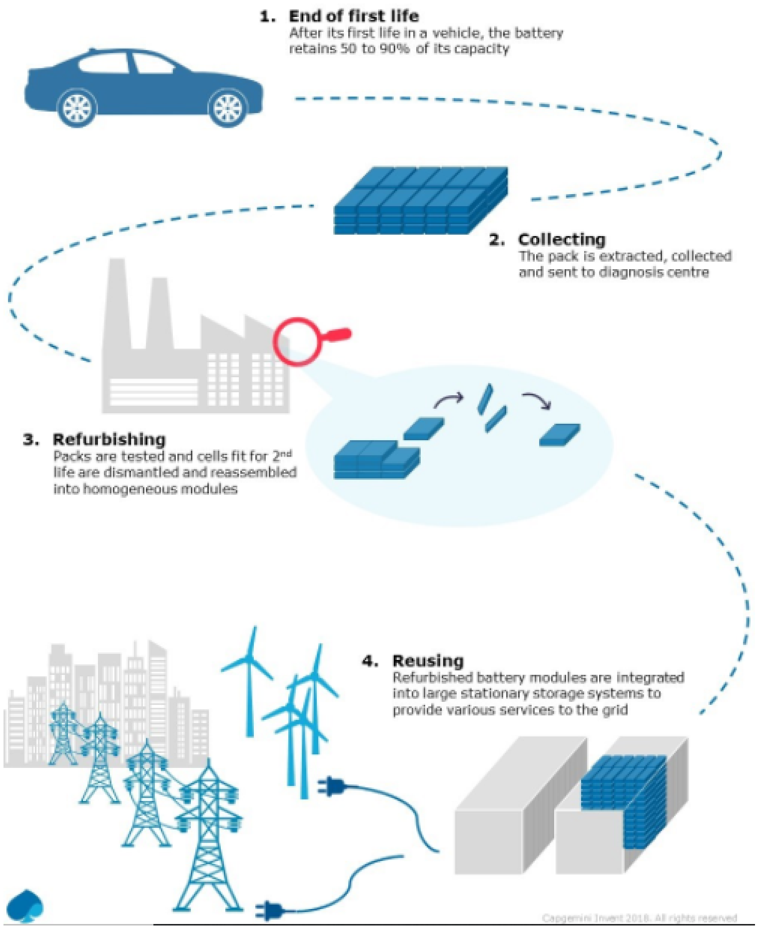

Figure 3.1: Battery life process. Source: Capgemini (2019)

The decreasing price of Lithium-ion batteries seems to be a good study subject because of the technological, economic and environmental potential applications that these batteries could develop after end-of-life (EOL) in electric vehicles (EV). Battery packs can be reused in stationary applications as part of a 'smart grid', for example to provide energy storage systems (ESS) for load leveling, residential, commercial and industrial power. These lower price batteries are supposed to bring business opportunities to renewable energy sources that see in batteries a good alliance, as mentioned, converging to post fossil carbon societies.

From a technical point of view, the focus in the second-life batteries (SLB) has predominately been on:

- Quality and remaining capacity in used electric car batteries
- Test and verification methods for determining reuse potential for batteries
- Battery Management Systems (BMS) in recycling applications
- Increase the potential lifetime of used batteries in other applications

A technical comparison between a new batteries (NB) and a second-life batteries (SLB) is shown in the Table 3.1, where the new batteries are focused as a Battery Management System (BMS) in electric vehicles applications, which their performance will depend on the driving mode, braking systems, periodicity of the use. On the other hand, the second-life batteries will be used with Energy Storage System (ESS) in frequency and voltage control, as well as peak shaving for stationary applications.

Category	New batteries	2nd life batteries
Nominal voltage level	~ 400 V	~ 800 V – 1000 V
Operating hours for 10a	~ 16 800 h (on)	max. 87 600 h (on)
Ambient temperatures	-40 -60 o C (in operation)	10 -35 o C (in operation)
C-rates	Continuous 2-3 C Peak > 5C	Continuous < 0.5 C Peak 0.5 -2C
Thermal management concept	Active (air or liquid)	Passive (active air or liquid only for specific use cases with critical temperatures)
Vibrations	Typical for vehicles in motion	None
SoH (Capacity begin of life)	100%	70-90 %
Control technique	EV Battery management system: depends on driving mode. Has regenerative braking etc.	ESS control: will depend on application: frequency regulation, voltage regulation, peak shaving etc.
Maintenance	Almost maintenance-free	Requires more frequent and careful maintenance
Size	EV rated sizes	ESS sizes
Capacity fade		~20%
Impedance		Increased impedance
Application	EV	Stationary use

Table 3.1: Comparison of new and second-life batteries. Source: IEEE (2019)

Rising adoption of Li-ion batteries on account of there enhanced energy stability across the ancillary services including load leveling, microgrids and distribution and transmission networks will drive the stationary battery storage market growth. Temperature stability, lower cost, energy efficient density and safe operations are some of the key parameters which will encourage the product penetration.

3.2 Market-Customer analysis

According to an article about second-life batteries by Capgemini [28], the lithium ion battery market is projected to grow over 25% by 2030 and about 3.4 million used electric vehicle (EV) batteries are expected to hit the market by 2025. Improved life cycles, gravimetric densities and high volumetric are the prominent factors which will encourage the product demand. In addition, large number of manufacturing facilities coupled with the declining battery costs by major industry players including Tesla will positively influence the industry landscape.

Growing consumer awareness toward establishment of energy efficient infrastructure along with the strengthening of microgrid networks will drive the local energy storage market share. Rising adoption of solar and wind technology along with upsurge in investments to stabilize the peak power demand will positively complement the business outlook. In addition, shifting trend toward clean energy sources coupled with the advancements and innovation in battery technologies will foster the stationary battery storage market growth.

3.2.1 PESTEL analysis

A PESTEL analysis is an analytical tool for strategic business planning, incorporating strategies and programs to reach the business goals. A PESTEL analysis is also used to identify and analyze the external key drivers of change in the business environment, as well as when plans to launch a new product, project or service into the market. For this project, a PESTEL analysis was carried out taking into account six important branches with an international focus, in order to aim the studied case to any country in the world. These six branches are showed in Figure 3.2 below:

P Political	• European countries alligned with Energy Transition EU policies – Winter Package • Changes in regulatory framework to allow energy flexibility and interoperability in Spain, rest of Europe, and overseas (LATAM, North-Africa) • Funding grants and initiatives to enhance renewable energy projects
E Economic	• Economic growth of regions, cities and countries due to integration of RE • Flexible taxation schemes and fees for developers and consumers • Higher profits and better payback periods in energy storage projects
S Social	• Adaptability of countries and societies to innovative technologies • New customer profiles and buying trends • Promotion of well-being and sustainability consciousness
T Tecnological	• New technology adopters with high interest in R&D energy solutions • Emerging energy technologies and maturity (Decreasing costs and availability) • Advances in Circular Economy, Energy Storage Systems and Sustainable Construction
E Environmental	• Climate Change, Sustainability and environment preservation awareness • Willingness to be part of Renewable Energy, Circular Economy and Energy Efficiency initiatives
L Legal	• Product/Service quality and safety standards • Consumers rights and laws in Spain and other countries • Clear terms and conditions of tailormade contracts

Table 3.2: PESTEL analysis. Source: Author (2020)

Some of the remarks enlisted in this analysis are part of the international/global context in which Spain and COMSA Corporación must take into account in order to compete. The political branch is crucial due to the changes in the regulatory framework to allow energy flexibility and interoperability in Spain as mentioned in the Chapter 2, Section 2.4. The Legal branch will be notable because a new customer figure will be part of the business model as a 'prosumer', so some legal aspects such as rights contract terms and laws must be noticed.

3.2.2 Market analysis - TAM SAM SOM

A top-down approach has been made for the market analysis, from global variables such as the Total Addressable Market (TAM), Serviceable Available Market (SAM) and the Serviceable Addressable Market (SOM). This analysis will give a better focus of the market volume:

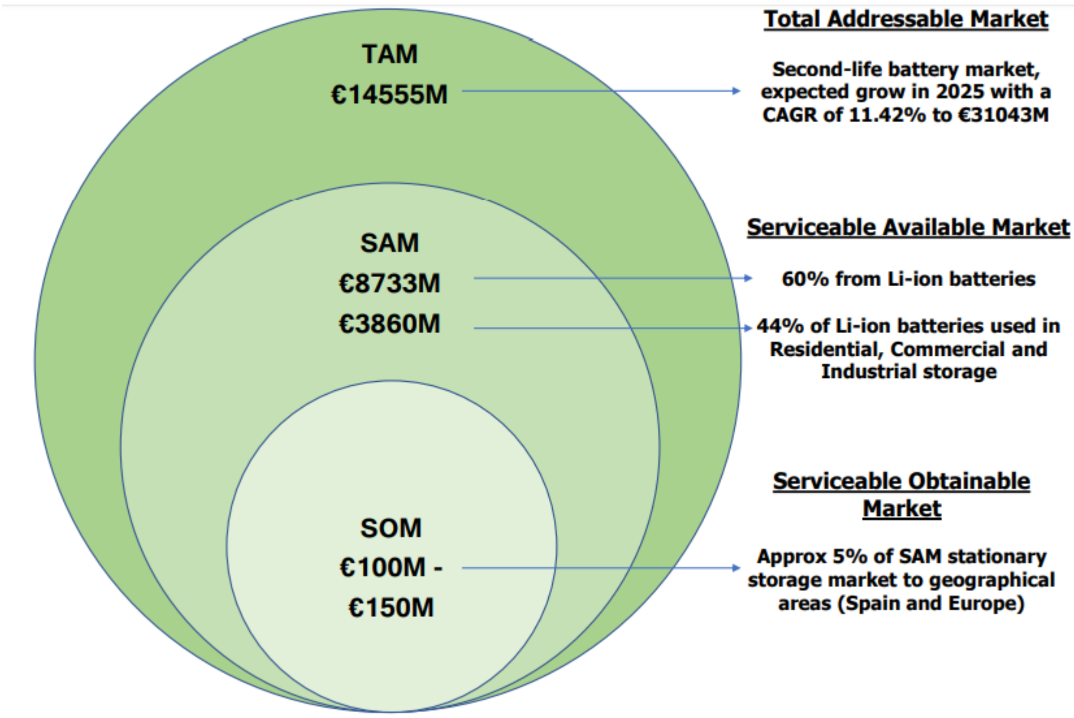

Table 3.3: TAM SAM SOM analysis for second-life batteries. Source: Author (2020)

- **Total Addressable Market (TAM):**

  TAM is the overall revenue opportunity that is available to a product or service if 100% market share was achieved, in other words, how much a company would make in sales per year if there were no other competitors. In the second-life battery market, it should be noted that there is an expected grow in 2025 with a Compound Annual Growth Rate (CAGR) of 11.42% to € 31043 million euros, since the market size at 2020 is € 14 555 million euros.

- **Serviceable Addressable Market (SAM):**

  SAM refers to the segment of the TAM which can be reached the market with our current business model. As it can be seen in the figure, 44% out of the TAM market size, corresponds globally to € 3860 million euros. This percent is just the share related to Residential, Commercial and Industrial applications in which COMSA Corporación would be interested to aim implementing second-life batteries.

- **Service Obtainable Market (SAM):**

  SOM is the share of the segmented market SAM, that COMSA Corporación can realistically aim and compete. This market size is delimited by geographical considerations in this case, Spain and Europe by the moment. According to the International Energy Agency (IEA), around 4-5% of the second-life battery manufacturing market is held in Europe and the stationary storage applications will be a share of around € 100 - € 150 million euros starting this year 2020.

Before entering to the Section 3.3 related to the Business Model Canvas some potential downstream markets for second-life batteries are evaluated. The following chart helps to visualize the various lithium-ion markets in terms of their energy density and cost of system downtime requirements as mentioned in the SAM and SOM market sizes:

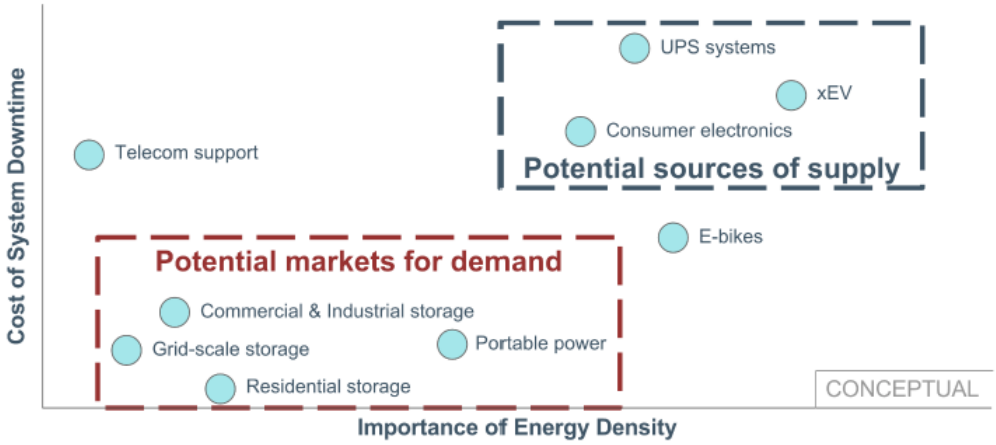

Figure 3.2: Comparison of Lithium-ion markets by downtime cost and required density. Source: Bartlett (2017)

As it can be seen in Figure 3.2, the potential markets for demand are Grid-scale storage, and Residential, Commercial and Industrial storage market (households, tertiary buildings and industrial applications). Therefore, the table 3.4 shows the potential applications of second life batteries (SLB) in the building energy storage sector:

Storage	Applications	Capacity
Residential	Load following	- One deep discharge and several shallow discharges per day - Typical discharge rate of C/3
	Back-up systems	- Up to 25 kWh for off-grid - Daily, moderately deep discharges (>50% DoD)
Commercial	Load following	- 75 to 100 kWh - Typical discharge rate of C/3 - One deep discharge and several shallow discharges per day
	Back-up systems	- Standby power - C/5 discharge, infrequent
	Peak shaving	- 3,000 to 4,000 kWh - C/2 to C discharge, daily
Industrial	Load levelling	- 100,000 kWh
	Renewables firming	- 1,000 to 10,000 kWh - C/5 discharge, frequent
	Spinning reserve/area regulation	- 5,000 to 7,500 kWh - C/2 to C discharge, infrequent
	Peak shaving	- 3,000 to 4,000 kWh - C/2 to C discharge, daily
	Transmission stabilization	- 140 kWh, 500,000 kW - 5 to 10 pulses per second, once/month

Table 3.4: Applications of second-life batteries. Source: IEEE (2019)

- **Residential Storage:**

  In the residential sector, the applications in which the second-batteries could be used include electrical appliances for water and space heating. The integration of the renewable energies will create a benefit, merging the consumption with for example PV devices to generate energy during the day and meet a daytime demand. During the evenings, when there is no electricity production by PV, batteries will be used.

- **Commercial Storage:**

  The commercial demand for electricity on average is much higher than the residential demand. The peak demand for the commercial sector occurs closer to midday in contrast to the residential sector, and thus the need to shift demand from the evening is not the main concern here. However, the PV generation being dependent on climate conditions such as rain and cloud prevalence necessitates the need for storage systems. The average commercial load being higher, load following and peak sharing applications may be more appropriate.

- **Industrial Storage:**

  The industrial sector is a demanding one since the demand for consumers is very much higher than the residential and commercial consumers. The peak demand occurs during midday and the PV generation is the highest during this time. Consequently, using a storage system can provide back up during low solar irradiance. The peak shaving application for industrial sector requires a similar amount of capacity like the commercial sector.

The market-customer analysis integrates the possible participants using second-life batteries (SLB) as energy storage systems. As it was mentioned before the key markets will be focused in residential, commercial and industrial storage. Figure 3.3 shows the applications of these markets:

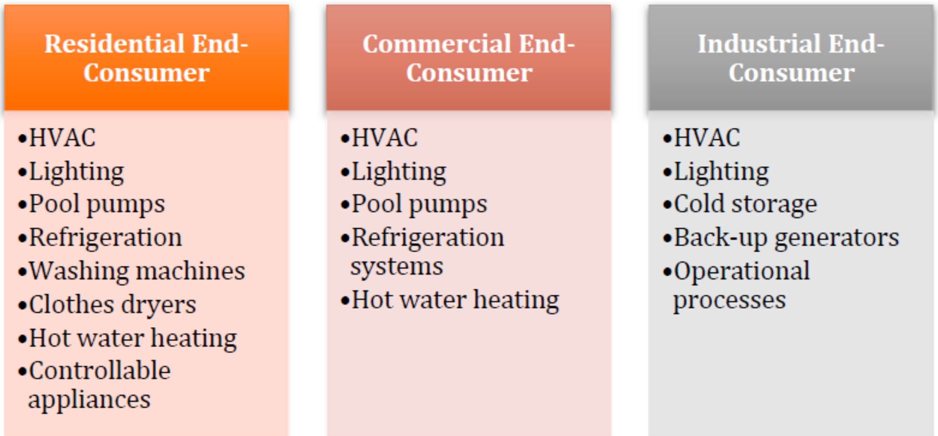

Figure 3.3: Potential participants in a demand response (DR) program using BESS. Source: Ponds et al (2018)

After completing the market-customer analysis, stationary energy storage applications stands out as the strongest option for a second-life battery business idea for COMSA Corporación. In addition, the cost structure for the reuse of batteries in these market sectors will rely on an efficient production chain in order to bring down the costs which is required as the batteries must be sold with a proper discount in relation to new batteries due to their shorter lifespan.

3.3 Business Model Canvas (BMC)

A key goal of this project is to present a research that can be used easily by companies or users who want to address the problem of the value gap. The analysis made in the previous section about potential markets for second-life batteries shows that could be applied to stationary energy storage applications and grid integration. By definition, a second-life battery has lower energy density than a brand-new cell, as some of the battery's ability to hold a charge has been degraded over time, but it still possesses the same physical weight and dimensions. Although there is still plenty of usable charge in the second-life cell. Figure A.2 in the Appendix A.1 shows the BMC proposed for this project using a Explicit DR scheme.

The proposed business model is one of energy storage as a service (ESaaS). One of the potential revenue streams could be that batteries can be leased to a building owners and customers, so they can use them for back-up, peak shaving and self-consumption systems. Monthly, the building owners will pay a lease that could be a 5%-10% of the initial battery purchase price in €/kWh. On top of the kWh installed for the owner, a certain amount is oversized that COMSA Corporación can use to sell balancing services to the DSO/TSO via an aggregator, as well as wholesale market (WSM) trading. The combination of different services and trading, also bilateral O&M contracts to ensure maximum use of battery capacity with aim to increase revenues. Both building owners and grid operators gain value from this installed battery capacity.

3.3.1 Value Proposition (VP) and Archetypes of BMC

After evaluating the possible value propositions for this business idea, the most important point to make clear is the potential application of the second-life batteries as Battery Energy Storage Systems (BESS) in buildings and take advantage of this new market niche. This value proposition could lead to a development of higher supply-demand flexibility matching also a decentralized coordinated control using DR programs aiming interoperability with external protocols. Figure 3.4 shows the value proposition analysis with all the variables to take into account for this project.

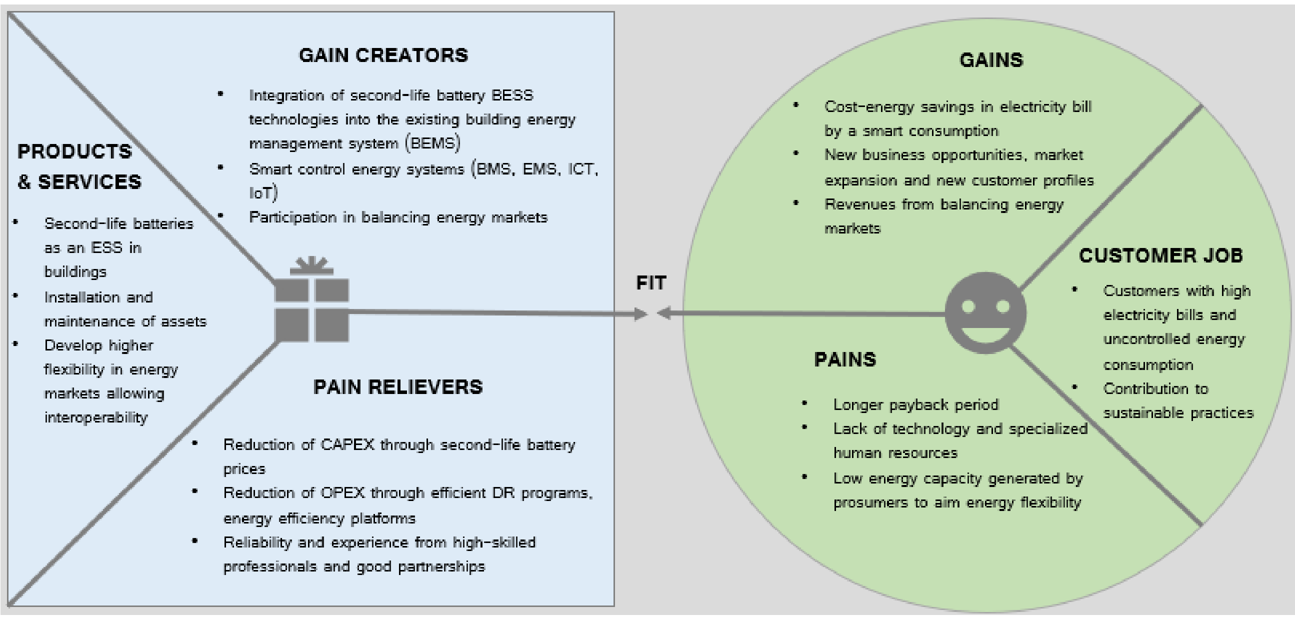

Figure 3.4: Value Proposition Model. Source: Author (2020)

It should be noted that the most important gains from this project will be new business opportunities regarding the BESS using second-life batteries, potential market expansion in other sectors and new customer profiles that could be interested. The inclusion of second-life batteries into this business model is to enhance the circular energy storage economy and be aligned with EU Commission goals settled in the Paris Agreement but also create new value from the ESS sector. On the other hand, some pains implied in the value proposition are CAPEX, OPEX, lack of technology and specialized human resources and from a technical point of view, the low energy capacity generated by prosumers to aim energy flexibility.

According to the Section 2.3.2, since the DR programs are divided in two: Implicit DR and Explicit DR, an analysis made by Burger and Luke [26] identified three business model archetypes for Demand Response (DR) and Energy Management Systems (EMS):

1. **Market-based capacity and reserve DR:**

   This Business Model Canvas (BMC) provides customers with EMS to control their energy consumption and potential generation. Furthermore, the DR businesses facilitate customer participation in DR market places through the EMS. Alternatively, the response of large customer loads may also be manual. Moreover, the profit for businesses in this BM type typically comes from taking a portion of the revenues from the sales of capacity and reserve services (brokerage fees) – and/or from subscription fees for the use of the energy management tools.

2. **Utility-based capacity and reserve DR:**

   According to Burger & Luke [26] businesses sell DR products such as firm capacity, operating reserves and mitigation of network constraints directly to regulated utilities (i.e. distribution or transmission networks or vertically integrated utilities). The participants benefit from getting a share of the revenues earned by the DR aggregator whereas the revenue for the aggregator comes through subscription fees from the utility or through brokerage fees.

3. **EMS service providers:**

   EMS providers, focuses mainly on the optimization of local energy usage in response to energy prices and local needs. These companies target especially the commercial, industrial, institutional and municipal customers and earn their revenues from shared saving arrangements, subscription fees (software), and asset sales (monitoring and control equipment).

The best archetype for a BMC is the one that could combines the features of the three ones mentioned above. Since, the idea of COMSA Corporación is to develop the aggregator concept as a new venture in which can be part of, entering into the flexible energy Spanish market taking advantage of the current DR programs and energy storage technologies such as second-life batteries in order to evaluate a future business expansion in the country. The Subsection 3.3.2 will explain more in detail these correlations in one BMC.

3.3.2 Buildings Access (Large Energy Consumption – via an Aggregator)

The focus of this business idea enpowered by COMSA Corporación is to engage the already defined customer segment that has in previous Engineering and Construction projects, since the legislation is changing as mentioned in the previous chapter, the customer segment with the best profile is the tertiary building sector, more specifically commercial (shopping malls, cinemas, supermarkets, office buildings, etc) and industrial (manufacturing plants, ports, airports, etc).

Large energy consumers will be mostly tertiary buildings and industrial sector as customer segments. In other words, buildings which already have or plan to have DERs (PV, micro-CHP, EV vehicles and EV charging stations) and are able to obtain direct payments by providing energy flexibility and COMSA Corporación participating with them. The volume threshold for power producers may prevent small DER owners to trade their energy individually. COMSA Corporación will be a bridge between the customer and DR aggregator and will aggregate DERs and flexible loads from these type of tertiary building customers to participate in the market with lower risk.

As it was mentioned in the Chapter 2, Section 2.3.2, DR programs usually integrate DERs such as rooftop solar photovoltaics (PVs) with a BESS and seeks to charge the battery storage during times of cheap electricity price or high surplus energy generation of DERs. The discharge of BESS during a congestion or peak price of electricity is considered by an aggregator to secure its contractual obligation of lowest price guarantee while making a profit from the higher energy price. In the end, end-consumers can obtain better benefits from their solar PV systems, with the assistance of an aggregator. This idea will be explained further in the section 3.5.1 about Time-of-Use (ToU) and how to take the benefits from it.

In addition, COMSA Corporación can engage with owners of EVs and vehicle-to-grid (V2G) systems for the purpose of capitalizing off of their available power and storage abilities. Although V2G is only in the pilot stage of development and are yet to be physically implemented in the market, they represent a very useful asset for the power system due to their flexible power outputs and storage abilities and are, therefore, set to be major players in the future. Customers with EV technologies should consider the nature of EVs operation which inherently means that they can 'ramp-up' and 'ramp-down' at high rates and quick response times. Furthermore, EVs by design can connect and disconnect from the grid for charging purposes using bi-directional charger stations.

DER owners can participate in different aggregation markets. For instance, due to response requirements for different markets (FCR, aFRR, mFRR with a minimum of 100 kWh taking the Dutch market as a reference), aggregation potentials that can be provided by DER owners depend mainly on the types of DERs integrated. In the customer relationships, a DR aggregator can provide customized market access strategies for different types of DER owners also because this will influence the DER owners' daily business or energy usage patterns to participate. COMSA Corporación must maintain good customer relationships with the participants through:

1. Customer service and technical support platform for any customer inquire
2. Provide accurate forecast information of supply and demand (Building occupancy, thermal inertia, HVAC, lighting, among others).
3. Training and energy consulting service, including DR knowledge and market information sharing.
4. Customized DR contracts based on customers' energy constraints and preferences.
5. Provide discounts on tailor-made user-friendly control systems to participate in the DR market.
6. Installation and maintenance services to customers to perform in the DR market.

Since the main reason for DER owners (customer segments) is to participate in the energy flexibility market is monetary benefits or income needs to be generated. Heating Ventilation and Air Conditioning (HVAC) systems and Electric Vehicle Charging Stations (EVCS) are identified as best Demand Response resources. Heating Ventilation and Air Conditioning systems are especially suitable for demand response as buildings can be viewed as energy storage systems in terms of thermal energy, being able to respond for a short period without compromising thermal comfort.

Thus, an efficient and fair payment system must be provide that can also enhance DER owners' satisfaction and engagement motivation. In the Appendix A.1, Figure A.2 shows this archetype of this business model more in detail.

3.3.3 SWOT analysis

This project outlines the implementation of second-life batteries in efficient buildings and how can COMSA Corporación could benefit from DR schemes in energy markets. Advantages and disadvantages of this new market participant from different aspects are based on a SWOT analysis [29], a strengths, weaknesses, opportunities, and threats analysis for a sample DR aggregator is presented. SWOT evaluates the internal and external aspects that are advantageous and unfavorable to satisfying the objectives of that business. The analysis from the figure in the Appendix A.1 represents a correlation between the potential Strengths, Weaknesses, Opportunities and Threats regarding this business idea.

- **Strengths:**

  This business case shows different 'Strengths' such as the implementation of new technologies in the energy infrastructure of buildings such as ICT-IoT technologies in order to upgrade it and make the buildings more adapted into potential changes regarding second-life batteries since the battery prices are plummeting year by year and also include EV chargers to provide fast response and higher power capacities.

  These strengths will led into cost reduction strategies, implementation of DER technologies with cutting edge control systems, increasing the number of prosumers willing to participate into a flexible energy mix. Additionally for COMSA, these strengths will led to deploy the technologies and grow in the current market faster than other competitors.

- **Weaknesses:**

  One of the most important weakness is the low capacity from prosumers to meet the required energy flexibility and participate, this due to a lack of knowledge of the proposed concept, but also not having the adequate energy infrastructure such as feasibility studies for battery installations, PV installation, correct communication protocols, EV technologies.

  A low awareness about the dynamic energy pricing will make difficult to engage new customers and offer tailor-made contracts and diverse payments schemes, but a good strategy will be the promotion of the business idea via webinars, seminars, and marketing campaigns to the customers to increase the potential benefits.

- **Opportunities:**

The services that COMSA can provide with this business idea like offer peak load services to system operators will maintain a grid reliability and also will increase the TRL levels of the business unit in the company as new venture.

The capacity to offer forecasting mechanisms by integrating end-consumer technology and behavior loads to provide flexible capacity and make profit from that.

- **Threats:**

  The regulation and framework barriers in some countries are creating uncertain business environments for the application of energy storage technologies. Another threat is the lack of energy infrastructure that can minimize potential economies of scale, slowing the ROI and payback periods.

  These threats need to be tackled and controlled to be able to have a fast and effective reaction when/if they occur. This is why a close and continuous tracking of regulatory and market tendencies needs to be implemented and then adjust scope approach as needed.

3.3.4 Value Chain analysis

In the following lines, the connection between the processes and actors of this value chain is described. It is an important fact to consider that no nonexistent elements interact in this value chain, which means that all the elements can be identified and connected to be able to continue developing the products. After evaluating a model of Value Chain for the business idea, the main areas to consider regarding technology maturity and related projects of the participant players are:

- **Second-life batteries (SLB):**

  This a key player in the value chain, the implementation of second-life batteries from battery manufacturers, transportation sector such as leasing car companies, and other fleet companies (buses, public transportation) would be important to consider.

- **EMS-BMS-EV Charging Stations:**

  Alternative energy saving solutions like envelope retrofitting, energy equipment replacement and renewable energies gaining market would have an effect in the acceptance of business idea. The improvement of new technologies linking energy storage solutions, second-life batteries will have a positive impact in the market.

- **ICT-IoT integration:**

  Software engineering and IoT technologies such as Machine Learning, AI are another part of the value chain that is controlled and provided directly by Energy Management companies. These profile companies will be in charge of providing its single front-end interface for the user's tool and connect easily with them.

- **Application of Second-life batteries (SLB):**

  Inside the application and operation of second-life batteries (SLB) phase it is possible to identify those activities related to hard operations, which include the installation and operation of the systems in buildings. Also the implementation of associated hardware (e.g. hardware engineering, communication protocols, BEMS, EMS, etc) is considered.

- **Ancillary Services:**

  The regulatory framework regarding the ancillary services could led into legal changes in regulations that put specific focus on the mentioned aspects or due to an improvement of competitiveness/performance of these alternative solutions. In Spain, since the regulatory energy framework is changing, COMSA could benefit from it and take an important advantage in the market offering the proposed services as a Facility Management services company.

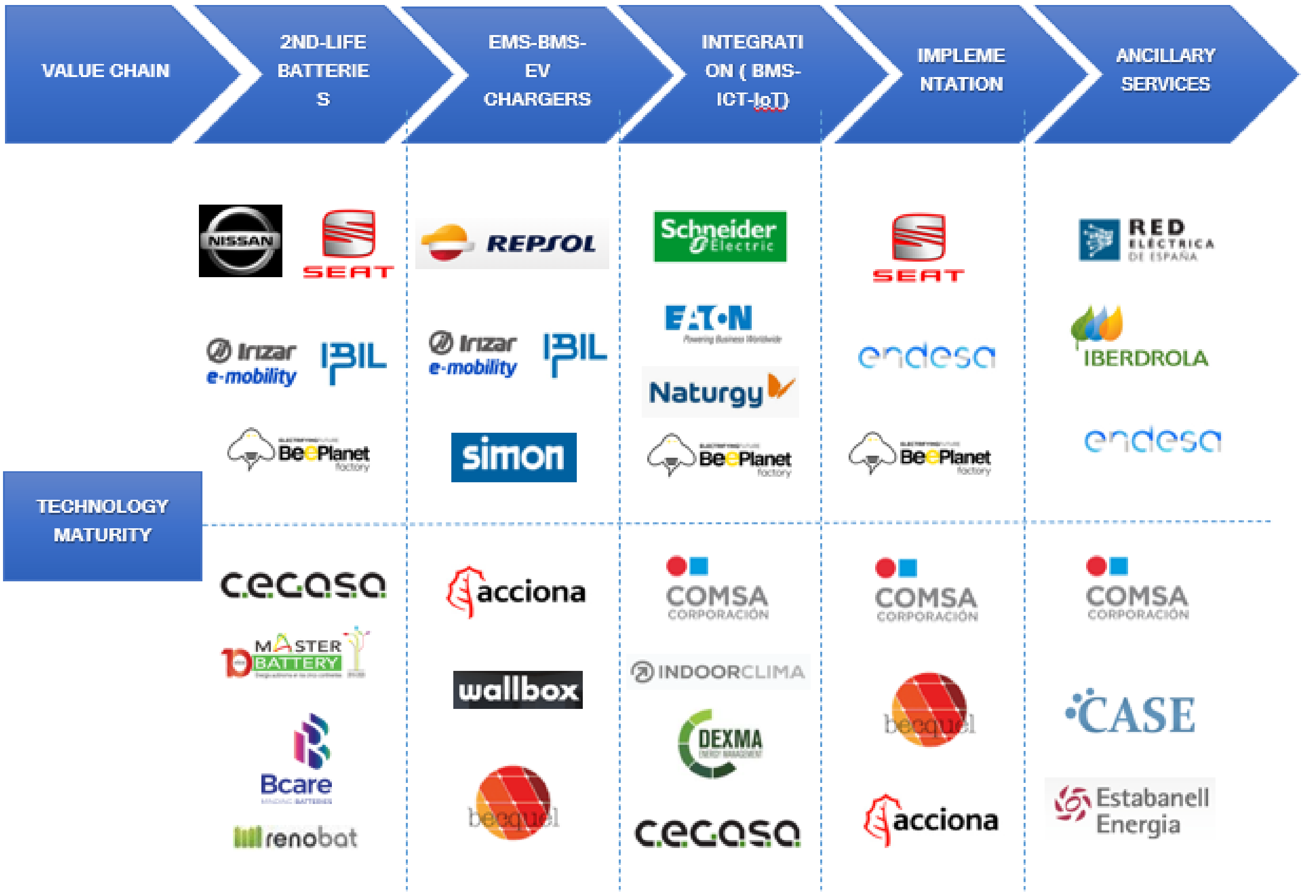

Figure 3.5: Value Chain Analysis. Source: Author (2020)

As can be seen in the Figure 3.5, the second-life market in Spain is analyzed from second-life manufacturers to potential ancillary services providers, also the position of COMSA Corporación in this map is considered due to its participation in the REFER Project in Barcelona. Also, the SUNBATT Project from Endesa and SEAT was evaluated to allocate this companies in this spot of the value chain.

The role of COMSA as a Facility Management company will implicate offering solutions to reduce the energy consumption by applying Demand Side Management (DSM) strategies to do so. These solutions will be increasingly automated, trying to minimize human intervention through self-learning software (AI, Machine Learning, etc). On the other hand, finding algorithms that accurately learn the cost of energy in real-time and with rapid response systems will enable the energy 'prosumers' to benefit by adjusting as far as possible the consumption curve to the production curve of the energy power plants and/or viceversa, resulting in economic savings for both parties (win-win), also assisting in energy purchasing to reduce the energy price.

Additionally, some factors related with energy, geography and technology are taken into account for COMSA as a valuable participant of this value chain:

- Current and expected evolution cost of electricity in Spain
- New energy consumption trends
- New types of energy sources to power HVAC systems of buildings
- Technology improvement(BMS-BEMS) and culture awareness of Facility Management services in the market

Finally, the COMSA proposal is a set of tools that enables tertiary buildings to face the challenge of reducing operating costs related to energy consumption by focusing on 2 strong vectors:

- Reducing energy intensity and usage by improving building efficiency (kWh/m^2/yr) with energy storage initiatives
- Reducing average energy unit cost (€/kWh)
- Percentage of economic reward from utility (TSO, DSO) for flexibility services.

From the customer's site some of the benefits perceive will be:

- Energy Use and balanced pricing awareness
- Facility efficiency increase (reduction of kWh)
- Price decrease (average €/kWh decrease due to second-life batteries)

3.3.5 Competition analysis

The competition map has identified the different competitors existing in the Spanish market and compare them with COMSA by locating the different companies in a two axis chart in which the technology maturity feature is compared. The comparison of them has allowed to graphically identify the position of these companies among the second-life battery (SLB) technology deployment in Spain.

In Figure 3.6, COMSA is located as a contender in the second-life market in Spain. The technology maturity development is something already known for COMSA as well as for other contenders in this analysis like BeePlanet.

Figure 3.6: Competition Analysis. Source: Author (2020)

It can be seen that the car manufacturers such as Nissan and SEAT have more advantages to re-use the second-life batteries into other applications, but some partnership with them or other manufacturers could be studied in the future in order to position COMSA as a Facility Management company in tertiary buildings.

3.4 COMSA Building Model

In order to validate the proposed business model from the Section 3.3, a battery sizing model was created. In this section, the different parts of the sizing model will be explained to give the reader an overview of the calculations and analysis. Appropriate sizing of the storage system (battery and power electronics) is a further criteria for system optimization, as for revenue maximization not only profits attainable but also the upfront cost for investments and potential replacement costs have to be taken into account.

3.4.1 Pilot description, assets and operational licenses

COMSA Headquarters office building is the chosen site to develop the case study. The building consists in a 2600 m^2 total surface across the 7 floors with different power consumption patterns each. Data from all controllable and monitoring systems is gathered, streamed and stored from 1- 15 minute resolution. The controlling systems of the building are:

- 77 individual HVAC indoor units (electric)
- 11 Outdoor HVAC VRF Units (electric)
- 180 kW Total HVAC Electric power installed
- 14 kWh battery (specifications explained below)

The monitoring and testing systems are:

- 22 electricity meters
- Weather station on roof (relative humidity, temperature, rain, barometric pressure, windspeed and direction, solar irradiation)
- 8 relative humidity and temperature sensors (by floor)
- 'Digital Twin' BIM testing model (electricity and thermal)

Other important systems and data:

- 22 kWp BIPV installation (not available right now, other external company manages this installation but for this project a PV energy production simulation will be calculated)
- 150 kW Contracted Power Demand (3 period contract)

In Figure B.1, Appendix B, the consumption values can be seen and for this sizing model analysis, the 4th floor is chosen. Particularly, the HVAC systems data of the 4th floor are used to develop this analysis and to select the battery that could perform without any issue. The overall consumption value of the building is 9730 kWh since the beginning of the current billing month and the maximum demand of the building is 360000 kWh/year. The average power consumption of the HVACs per floor is about 10 kW (For this case the data from January 2020 was taken for the analysis).

The system is made up of 4 main elements (3 DC / AC converters single-phase with a 7.2 capacity in total and 1 lithium-ion battery) with a three-phase power of 10 kW and a capacity of 14 kWh, in addition to other auxiliary elements (controller and DC busbar with fuses of protection). Figure B.2 in the Appendix B shows an example on how this system will be connected in the building.

Lithium-ion battery

An analysis of the building consumption, power demand and battery types were considered. The chosen battery is a lithium-ion modular battery from the car manufacturing company BYD. The modularity is showed in the battery packs in the Figure 3.7 and a possible parallel connection of them from 1 module of 3.5 kWh to a maximum of 4 modules reaching a total of 14 kWh capacity as this case. Moreover, Figure B.3 in Appendix B, shows the specifications of the BYD Battery Box L 14.0.

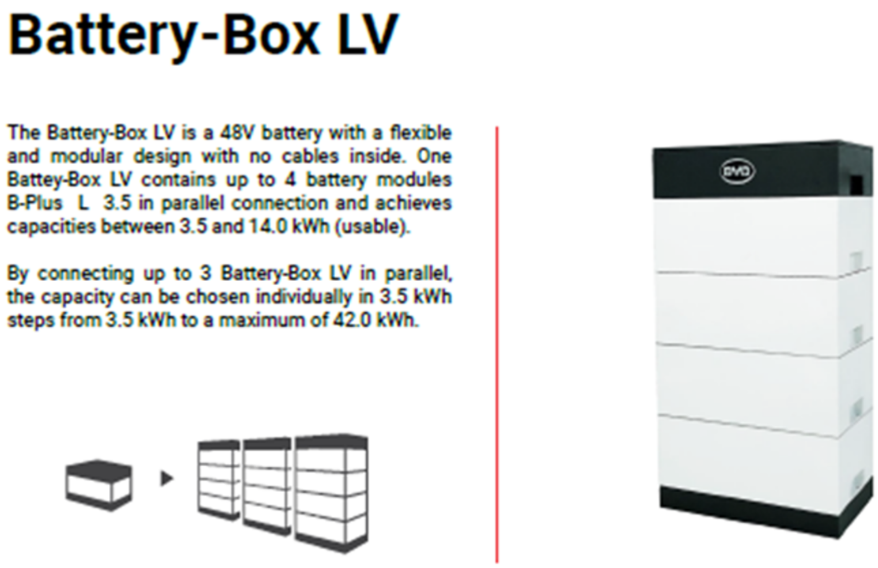

Figure 3.7: BYD Battery Box L 14.0 . Source: BYD Battery Box (2020)

The LiFePO4 cathode lithium ion batteries are a variation of the previous group with LiCoO2 cathode. Lithium iron phosphate is low cost, non-toxic, high iron abundance, very good thermal stability, and good safety characteristics with good electro-chemical performance for this type of applications. They are batteries whose greatest advantage is safety due to their great chemical stability and have a very good charge capacity and a longer useful life than the previous ones.

Advantages:

- High voltage open circuit, 3.3 V
- LiFePO4 is an intrinsically safer material cathode than LiCoO2
- They do not contain toxic products.
- It is the lithium battery that best tolerates high temperatures
- Exceeds 2000 life cycles and has a life of more than 10 years

- Charging time between 15 and 30 minutes
- Good ability to withstand overload
- Good specific energy and energy density

Disadvantages:

- They need additional electronic circuits
- Significantly lower energy density than LiCoO2

The specifications of the Lithium-ion battery for this case study were studied in detail. Some battery specifications are enlisted in the Table 3.5:

Table 3.5: Battery specifications - BYD Battery Box L 14.0

Type of Battery	New battery / Second-life	
Brand	BYD	
Model	B-Plus L 14.0 (14 kWh)	
Battery Type	LiFePO4	
Battery Capacity	14	kWh
Nominal Voltage	51.2	V (max)
Specific Energy	1891.55	Wh/kg
Weight	194	kg
Max Output Power	10	kW
Peak Output Power	15	kW
Current (I)	1433	A
Ampere-hour rate	7615.12	Ah
C-rate	0.2 C (5 hours)	h
Battery cycles	365	cycles
Scalability in parallel	42	kWh
Battery Lifetime (@ 0.2C) - Warranty	10	years

Other important data for the battery power sizing model is included in the Table 3.6, as the battery capacity, battery price per kWh, number of modules (packs) per battery installed in the building, number of floors per building:

Table 3.6: Battery power sizing model in COMSA building

nº of modules per battery	4	packs/battery
Usable energy size per battery module	3.5	kWh
Battery Unit - Max Usable Size Energy	NB - 14 kWh	SLB - 11.2 kWh
State of Health (SoH)	NB 100%	SLB 80%
Available battery storage size for COMSA	NB - 14 kWh	SLB - 11.2 kWh
Price of battery (€/kWh)	NB - 550 €/kWh	SLB - 275 €/kWh

Table 3.7: Battery physical configuration

nº of batteries in power shelf	1	batteries/shelf
nº of power shelves in cabinet	1	shelves/cabinet
nº of cabinets per column	1	cabinet/column
nº of columns per row	1	columns/row
nº of rows per floor	1	rows/floors
nº of active floors	7	floors/building

PV Converters

Regarding the specificacions of the inverter, the Figure B.4 in Appendix B shows the most important ones in order to be considered. The chosen inverter is the Victron MultiPlus-II 48/5000/70-50 with a converter power peak of 10 kW, Figure 3.8:

Figure 3.8: Inverter Victron MultiPlus-II 48/5000/70-50. Source: Victron (2020)

The MultiPlus-II can be used in photovoltaic systems, connected to the electrical network or not, and in other energy systems alternatives. It is compatible with both solar charge controllers and grid-connected inverters, as in the Figure 3.9. It will use the data from the external AC sensor or the energy meter to optimize self-consumption and, if desired, avoid the return of excess energy to the grid solar. In the event of a power failure, it will continue to power critical loads.

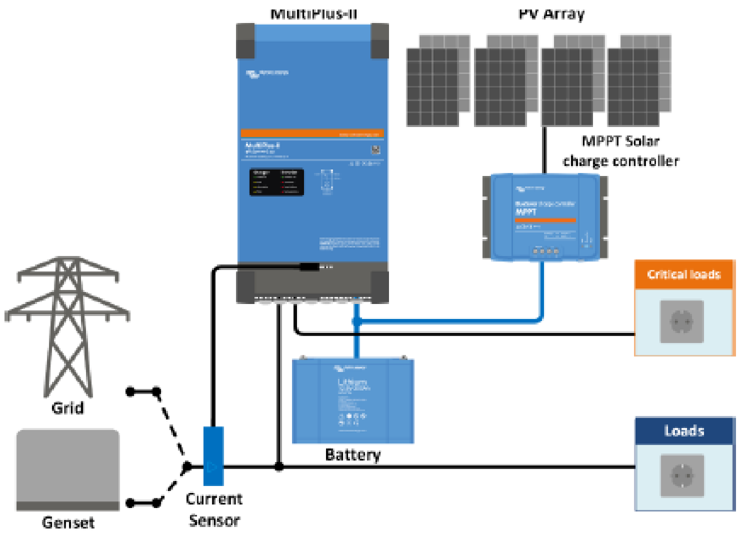

Figure 3.9: Inverter Victron MultiPlus-II in PV array configuration. Source: Victron (2020)

Moreover, another advantage of this type of inverter is the offered modularity to be placed in parallel in a correct configuration, as in the Figure 3.10:

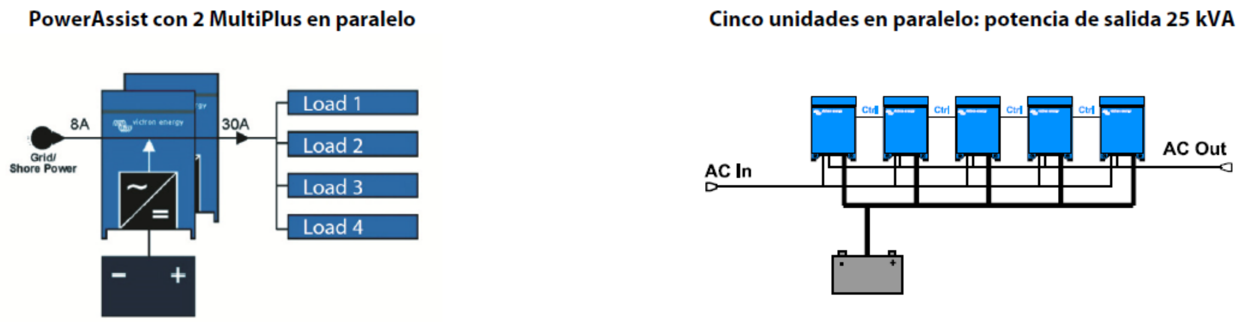

Figure 3.10: Inverter Victron MultiPlus-II parallel configuration. Source: Victron (2020)

Operational Licenses

Since the energy costs in tertiary buildings constitute a significant percentage of the total operating expenditures of the building sector, other kind of assets will be described ahead. The operational licenses to optimize both the energy consumption in kWh and the price paid in €/kWh will be an important reduction of these costs and a key part of this business case.

The main objective is to tackle this issue developing a set of tools that will, in different ways, enable optimal operation of the tertiary buildings aimed by COMSA and consequently reduce energy costs. The implementation of these licenses was taken as a reference from the document BEEST [37], and are gathered according with their features in different apps:

Table 3.8: Operational license apps:

Automatic Demand Side Management	ASDM	10 % savings of AEC
Reward for Demand Response	ReDR	5 % savings of AEC
Wholesale electric market trading	WSM	10 % savings of AEC

These licenses also have a specific amount of operational hours per year that must be considered in the business case. Table 3.9 shows the operational time per license:

Table 3.9: Operational hours of license apps:

Automatic Demand Side Management (ADSM)	24	hours/year
Reward for Demand Response (ReDR)	10	hours/year
Wholesale electric market trading (WSM)	10	hours/year

The use of these licenses apps in the business case will make easier the goals of COMSA in the value chain and also will benefit the tertiary buildings customer by:

- Adjust HVAC set points, while ensuring reasonable levels of comfort in the buildings.
- Disconnect non-critical loads (such as HVAC) when the utility makes a request or there is an opportunity by the aggregator to participate in the ancillary services.
- Reduce available capacity that is not used most of the time, reducing the energy consumption and balancing the electricity bill.

The operational license apps mentioned above will be included in the study, each of them with their initial investment in hardware (not necessary in every case), annual license costs, and impact on customer's energy cost savings. An estimation license costs of 0.15-0.30 €/m^2 is used, since the COMSA building has a surface of approximately 2600 m^2, keeping an average cost of 600 €/year for all the license apps. In the following paragraphs, details on each of the license apps will be given, taken as an example the BEEST project [37]:

- ***Demand Side Management (DSM):***

  DSM is based on the forecast data coming from the HVAC equipment by the Facility Management company (COMSA). Its purpose is to optimize operation of existing HVAC equipment while ensuring a reasonable end user comfort. In this particular case, the ADSM (Automatic Demand Side Management) will be the preferred option because the system overrides manual configuration of the BMS thanks to an integration and direct connection with the communication protocols.

  A prerequisite to implement this license app is a minimum building area of 2000 m^2 to ensure profitability in the business case for the customer, which takes into account the need for an initial investment. Also, an annual license fee and 2 hours per month are recurrent costs for the customer to use this license. This can be added in a operation and maintenance contract.

  Automatic energy savings actions (reduced total kWh), the system automatically adjusts to minimize the energy consumption. This will allow a much bigger gain to be achieved because very regular and fine-grained adjustments are possible which will not be feasible on a manual level.

The potential savings regarding this license app in the COMSA business case are about a 10 % of the Annual Energy Costs (AEC).

- ***Reward for Demand Response (ReDR):***

The energy purchaser will target this license app but also the Facility Management company (COMSA) will be aware of the impact in the building exploitation. The usage of this app implies availability for disconnection of non-critical equipment (HVAC) when is requested by the utility (TSO/DSO) or the aggregator. A prior implementation of a forecast assessment and the Automatic Demand Side Management (ASDM) app is necessary and a building minimum area of approximately 2000 m^2 is needed.

On the other hand, this license app does not work correctly simultaneously with the WSM license due to technical reasons. An annual license fee and 10 hours per year intervention to check DSM perfomance and economic rewards are other recurrent costs for the customer.

Providing a certain amount of flexibility capacity (e.g. kW of HVAC) for a maximal amount of interventions per year to turn down the power, would give a yearly upside DSM service fee towards the customer. The potential savings regarding this license app in the COMSA business case are about a 5 % of the Annual Energy Costs (AEC).

- ***Wholesale electricity market trading (WSM):***

The implementation of the WSM allows the corresponding energy retailer to bid for electricity at a lower price thanks to demand forecast assessment information and the use of the ASDM. The customer is rewarded with a reduction in average price of kWh. In the same case as ASDM and ReDR, an approximately minimum building area of 2000 m^2 is recommended to ensure profitability in the business case for the customer, which takes into account the need for an initial investment of the ADSM app.

The simultaneous use with ReDR app is not possible, in general, due to technical reasons. A prior implementation of a forecast assessment and the Automatic Demand Side Management (ASDM) app is necessary. Some recurrent costs for the customer are an annual license fee and the energy purchaser intervention for 10 hours per year and WSM revenue checking. One of the most advanced contract possibilities of the WSM app is a dynamic market contract (on the whole-sale market) and then be optimized by means of real time control of impacting energy consumption devices (HVAC). The potential savings regarding this license app in the COMSA business case are about a 10 % of the Annual Energy Costs (AEC).

3.5 Battery Sizing Model

In this section, the sample sizing model of this battery is explained. After deciding that the building will have one battery with the specifications showed above, a MATLAB code named ***Battery_ COMSA.m*** (Appendix D.1) indicates the charging and discharging behavior graphs related to the battery capacity *Ah*, voltage *V* and current *I*.

Peukert's law consists of a co-relation between the state of charge (SoC) of a battery and its discharge rate: the higher the discharge rate, the lower the capacity of the battery. Peukert's equation is as follows:

$$C_p = I^k \cdot t \tag{3.1}$$

Where,

C_p = No-load voltage (V),

I = Actual discharge current (A),

t = Actual download time (h),

k = Peukert's constant (dimensionless),

The previous equation can be reformulated considering H the theoretical discharge time of the battery:

$$t = H \cdot (\frac{C}{I \cdot H})^k \tag{3.2}$$

Theoretically, if we have a battery with a capacity of 7615.12 Ah, if we discharge it at an intensity of 1433 A, we will have a duration of 6 h approximately as shown in the Figure 3.14.

However, if we consider Peukert's Law the calculation is not so direct. If we assume that the battery has a Peukert constant of 1.2 for a Lithium-ion battery (a lead-acid battery has a k between 1.1 and 1.3) and we subject it to a discharge of 1433 A, we obtain:

$$t = 6 \cdot (\frac{7615.12}{1433 \cdot 6})^{1.2} = 237h \tag{3.3}$$

$$q1a = total - I \cdot \frac{1 - e^{-k \cdot t}}{k} + c \cdot I \cdot \frac{1 - e^{-k \cdot t}}{k} - c \cdot I \cdot t \tag{3.4}$$

The Shepherd Model allows us to calculate the state of charge of a battery from its internal parameters by measuring the voltage at its terminals. The equation used to model the battery is as follows:

$$E = E_0 - K \frac{Q}{Q - i \cdot t} - R \cdot i + A \cdot e^{-B \cdot i \cdot t} \tag{3.5}$$

Where,

E = No-load voltage (V),

E_0 = battery voltage constant (V),

K = Bias voltage (V),

Q = Battery capacity (Ah),

$i \cdot t$ = Instantaneous state of charge (Ah),

A = Voltage of the beginning of the exponential zone (V),

B = Inverse of the time constant of the exponential zone $(Ah^{-}1)$,

R = Internal resistance,

i = instantaneous intensity (A)

With the proposed model, when the battery is completely discharged and there is no current circulating, the voltage tends to 0. This model represents highly accurate results and also does not compromise the stability of the model.

The parameters used by the battery can be extracted from the discharge curves offered by the manufacturer. However, in the case of internal resistance, sometimes the value supplied by the manufacturer is not what makes the obtained curve fit more closely to reality. The nominal efficiency value used is around 93 % and 98%. It is for this reason that a method for obtaining internal resistance through efficiency has been determined:

$$R = V_{nom} \cdot \frac{1 - \eta}{0.2 \cdot Q_{nom}} \tag{3.6}$$

Where,

V_{nom} = Nominal voltage (V),

Q_{nom} = Nominal battery capacity voltage constant (Ah),

η = Round-trip efficiency,

Q = Battery capacity (Ah),

As part of the equation 3.5, the A value, B value, polarization voltage K, and constant battery voltage E_0 are enlisted in the following equations:

$$A = E_{max} - E_{min} \tag{3.7}$$

$$B = 3/Q \tag{3.8}$$

$$K = \frac{E_{max} - V_{nom} + A \cdot (e^{-B \cdot I \cdot H} - 1) \cdot (Q - Qnom)}{Q_{nom}} \tag{3.9}$$

$$E_0 = E_{max} + K + R \cdot I - A \tag{3.10}$$

The Figure 3.11 shows the battery capacity in Ah related to a charging time in minutes, with a current I value of 1433 A as stated in the Table 3.5. The equation 3.11 shows the behavior of the battery at these parameters:

$$E_2 = E_{min} - (E_{max} - E_{min}) \cdot \frac{q_{1a}}{Q} \tag{3.11}$$

Where,

E_2 = Charging voltage (V),

E_{min} = Minimum battery voltage (V),

E_{max} = Maximum battery voltage (V),

Q = Battery capacity (Ah),

q_{1a} = Battery capacity changing in time period (Ah),

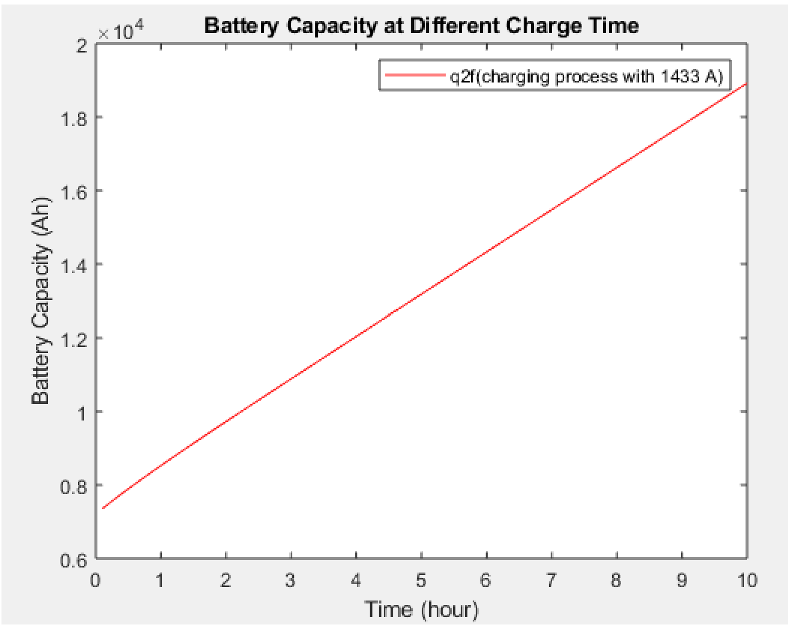

Figure 3.11: Battery Capacity (Ah) vs Charging Time (t). Source: Author (2020)

The Figure 3.12 shows the battery voltage in V related to a charging time in minutes, with a current I value of 1433 A as stated in the Table 3.5. After 6 hours the battery can reach a voltage value of 40 V approximately.

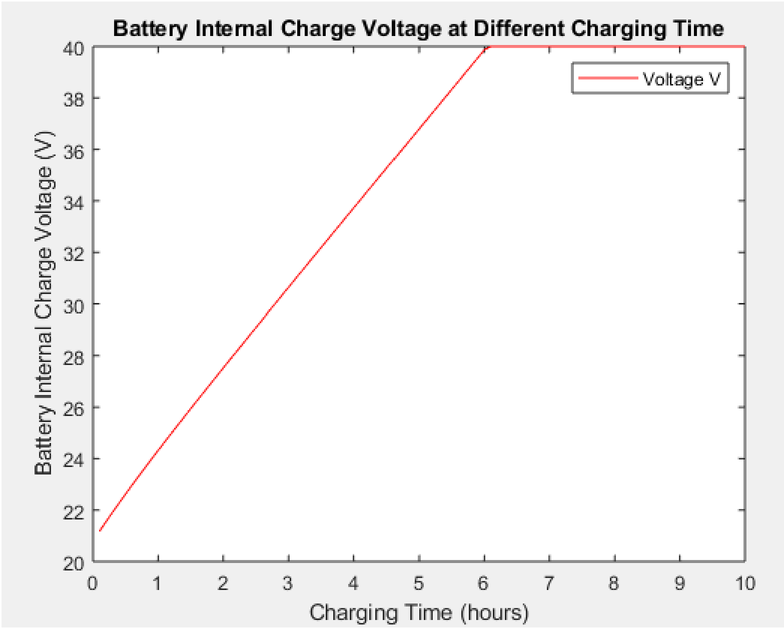

Figure 3.12: Battery Voltage (V) vs Charging Time (t). Source: Author (2020)

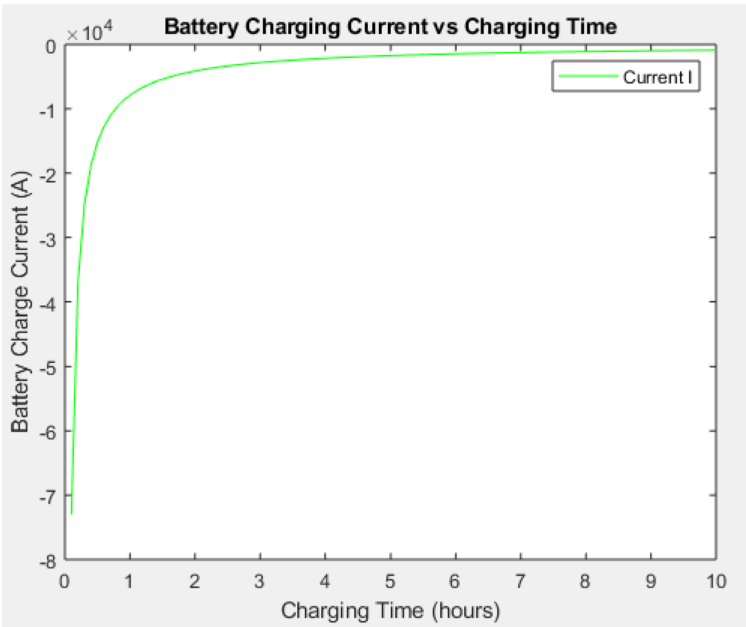

Figure 3.13: Current (A) vs Charging Time (t). Source: Author (2020)

The Figure 3.14 shows the battery capacity in (Ah) related to a discharging time in minutes, with a current I value of 1433 A as stated in the Table 3.5. The capacity in ampere-rate plummeted from 7000 Ah during the discharging time of the battery at a discharge current of 1433 A.

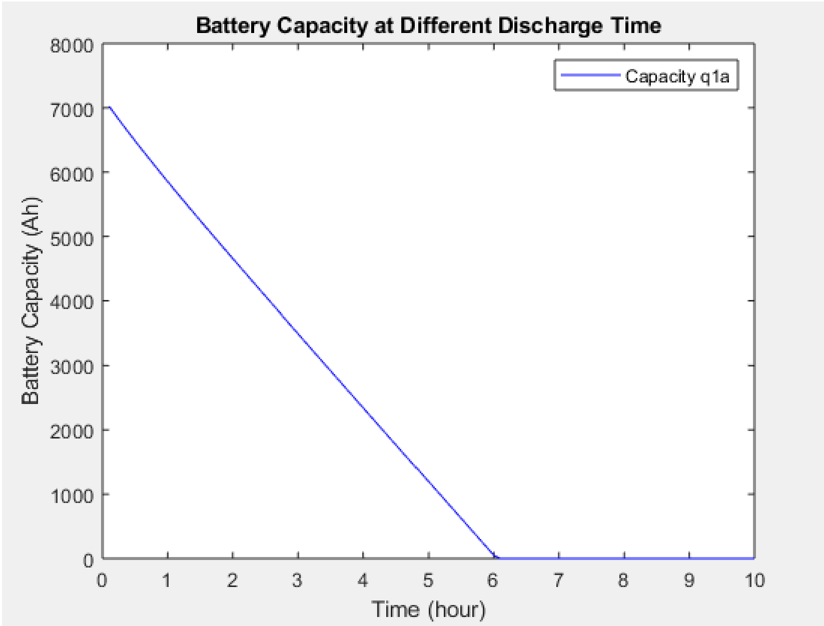

Figure 3.14: Battery Capacity (Ah) vs Discharging Time (t). Source: Author (2020)

Moreover, the Figure 3.15 gives the battery voltage in V related to a discharging time in minutes, with a current I value of 1433 A as stated in the Table 3.5. The battery voltage plummeted as well from a value of 59.2 V to 40 V during the 6-hour discharging time of the battery at 1433 A.

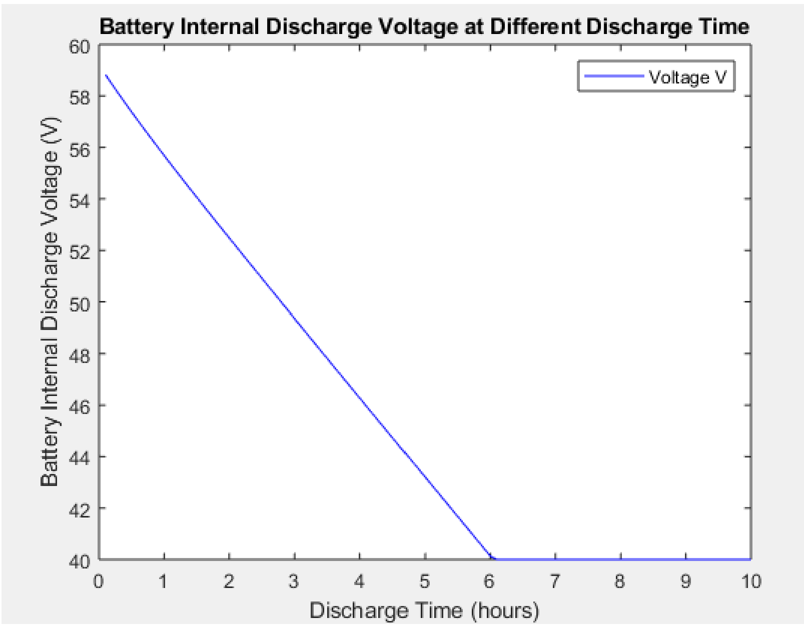

Figure 3.15: Battery Voltage (V) vs Discharging Time (t). Source: Author (2020)

Therefore, the equation 3.12 indicates how the discharging voltage decreases from a maximum to a minimum in the period of 6 hours:

$$E_1 = E_{min} + (E_{max} - E_{min}) \cdot \frac{q_{1a}}{Q} \quad (3.12)$$

Where,

E_1 = Discharging voltage (V),

E_{min} = Minimum battery voltage (V),

E_{max} = Maximum battery voltage (V),

Q = Battery capacity (Ah),

q_{1a} = Battery capacity changing in time period (Ah),

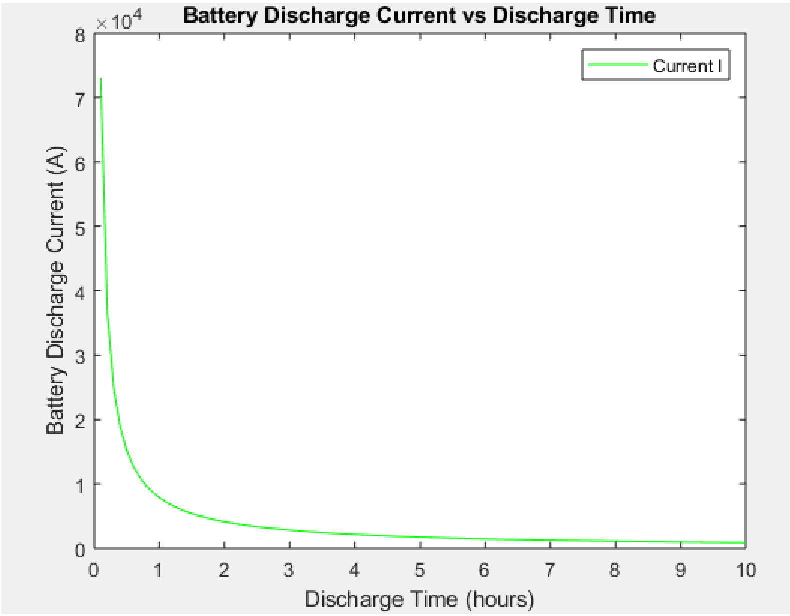

Figure 3.16: Current (A) vs Discharging Time (t). Source: Author (2020)

The MATLAB modeling code ***Battery_ Modelling.m*** (Appendix D.1) displays a simulation if more power is generated by the PV installation than is consumed, then this power is stored in the battery. Also, it shows a relation between the stored power in battery and the demand to cover from the HVAC reference system.

If more power is consumed than is generated, what is left to supply is extracted of the battery as long as the battery stores a set minimum power. In this case, the minimum has been set at 20% of the maximum capacity. The converter would restrict the value to the maximum it can regulate (in absolute value). The sign criterion followed is for power inputs to the battery and converter system, positive power values. For outputs, negative values.

The starting data stored in ***dataCOMSA.mat*** is the ratio of the current power it generates a BIPV installation between the maximum installed power respectively. The ratio between current demand to be covered by the battery and the assumed average HVAC power peak is also provided at 10 kW, but the values will vary between floors as it can be seen at Figure B.1, Appendix B.

Due to the COVID-19 lockdown COMSA building was closed, so the data used for calculations purposes was taken from one year calendar (May 2019 - May 2020). The data is a sample for every 15 minutes measure with a total of 31774 measures of the HVAC 4th floor system, taken from the data platform of the DRIvE H2020 project:

- **One year data:** From 01/05/2019 to 01/05/2020

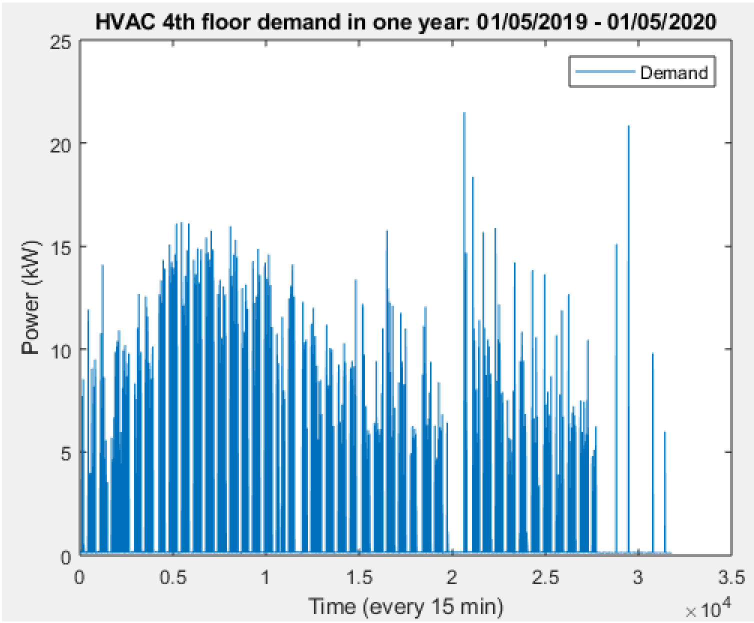

Figure 3.17: HVAC 4th floor Demand (kW), one year data - (01/05/2019 - 01/05/2020). Source: Author (2020)

- **One month data:** From 01/01/2020 to 31/01/2020

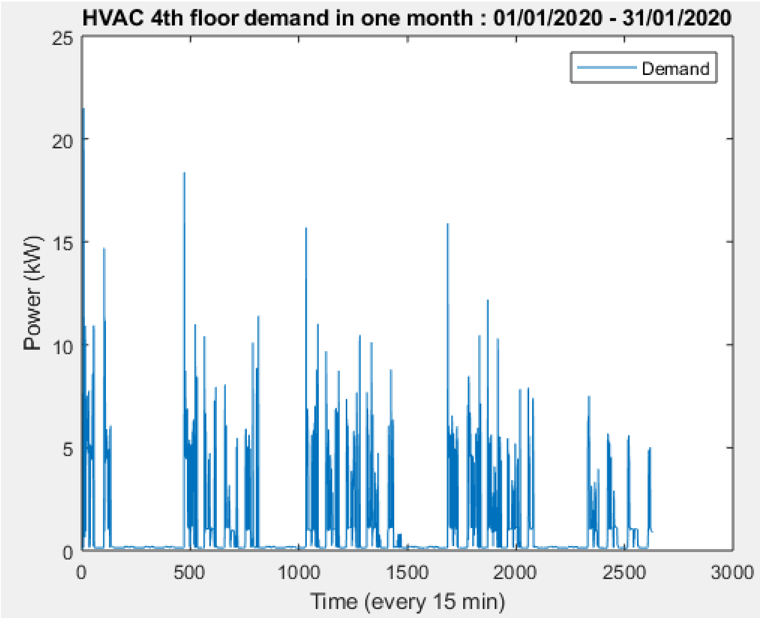

Figure 3.18: HVAC 4th floor Demand (kW), one month data - (01/01/2020 - 31/01/2020). Source: Author (2020)

- **One week data:** From 27/01/2020 to 31/01/2020

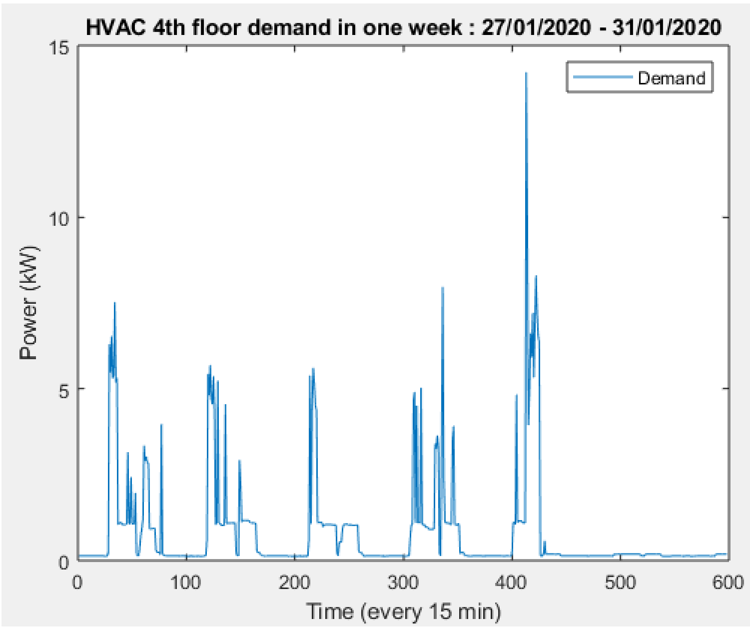

Figure 3.19: HVAC 4th floor Demand (kW), one week data - (27/01/2020 - 31/01/2020). Source: Author (2020)

- **One day data:** From 31/01/2020

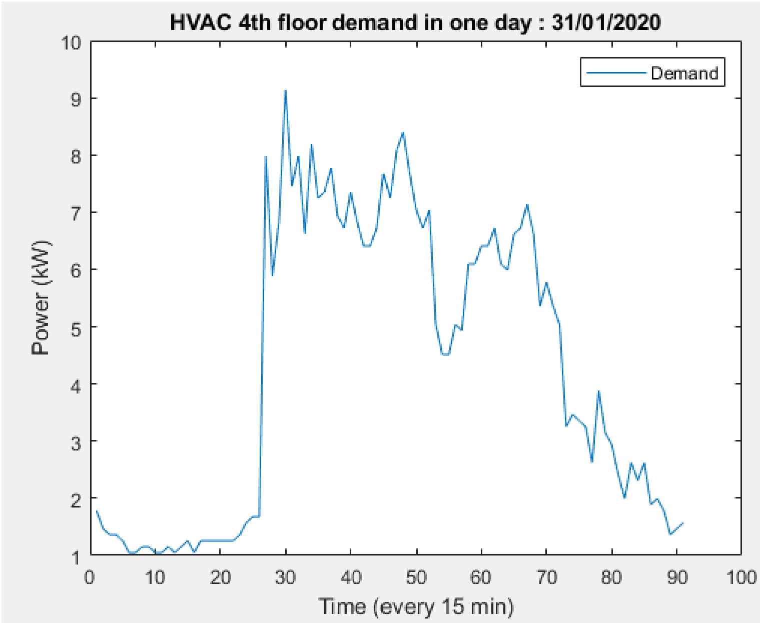

Figure 3.20: HVAC 4th floor Demand (kW), one day data - (31/01/2020). Source: Author (2020)

3.5.1 Time-of-Use (ToU)

The Time-of-Use (ToU) is a rate plan in which rates vary according to the time of day, season, and day type (weekday or weekend/holiday). Higher rates are charged during the peak demand hours and lower rates during off-peak (low) demand hours. Rates are also typically higher in summer months than in winter months. This rate structure provides price signals to energy users to shift energy use from peak hours to off-peak hours. Time-of-Use pricing encourages the most efficient use of the system and can reduce the overall costs for both the utility and customers.

Time-of-use windows can significantly affect demand charge savings. ToU windows that extend outside of daylight hours tend to decrease savings, whereas windows that are entirely within daylight hours tend to increase savings. Demand charges can vary by time of the day, by season, or can be based on more complex calculations of the building's demand. The process outlined on the next calculations use the simplest demand charge—ones that are assessed based on a building's monthly maximum demand (From January to December).

In the solar field, it is increasingly more important to show detailed financial savings versus system costs. With the decreases in system costs that we have seen over the last few years, a specific analysis to show return on investment (ROI) can help typical time-of-use (TOU) net metering projects sell themselves. Time-of-Use (TOU) rate structures have a tendency to favor Building Integrated Photovoltaic (BIPV) systems. This is due to the fact that energy that is delivered to the grid and net-metered will generally earn the system owner energy bill credits at the retail electricity rate when the electricity is delivered to the grid.

For this specific project, a BIPV installation is considered but due to the fact that this PV installation is being managed and rented by an external company at the moment of this project (not COMSA Corporación), an estimated monthly energy production was calculated using the online interactive tool PVGIS from the European Commission (EC) [38]. With this tool the user can choose the current location in which the PV installation can operate, in this case the COMSA office building located in Barcelona:

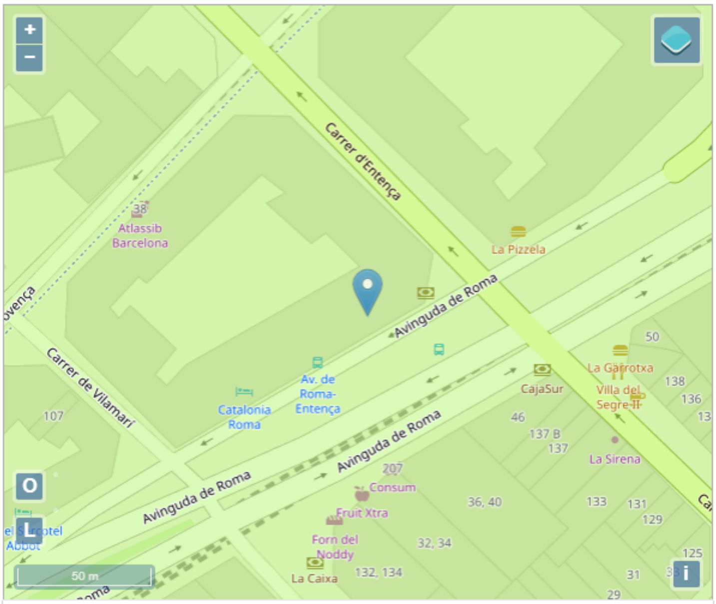

Figure 3.21: COMSA Corporación PV installation location. Source: PVGIS (2020)

The PVGIS interactive tool lets the user input some key data in order to get accurate results regarding the simulated BIPV installation. In this case, the BIPV installation is stated to have 5 % of the losses from the 22 kWp. The yearly PV energy production is around 36959.43 kWh as it is shown in the figure 3.22:

Provided inputs:	
Location [Lat/Lon]:	41.382, 2.146
Horizon:	Calculated
Database used:	PVGIS-SARAH
PV technology:	Crystalline silicon
PV installed [kWp]:	22
System loss [%]:	5
Simulation outputs:	
Slope angle [°]:	35
Azimuth angle [°]:	0
Yearly PV energy production [kWh]:	36959.43
Yearly in-plane irradiation [kWh/m^2]:	1996.17
Year-to-year variability [kWh]:	864.75
Changes in output due to:	
Angle of incidence [%]:	-2.54
Spectral effects [%]:	0.72
Temperature and low irradiance [%]:	-9.75
Total loss [%]:	-15.84

Figure 3.22: COMSA PV installation - PV inputs. Source: PVGIS (2020)

Using the online interactive tool PVGIS from the European Commission (EC) [38], a PV generation is calculated as stated in the Figure 3.23, where the Monthly energy output for one year is showed in the graph:

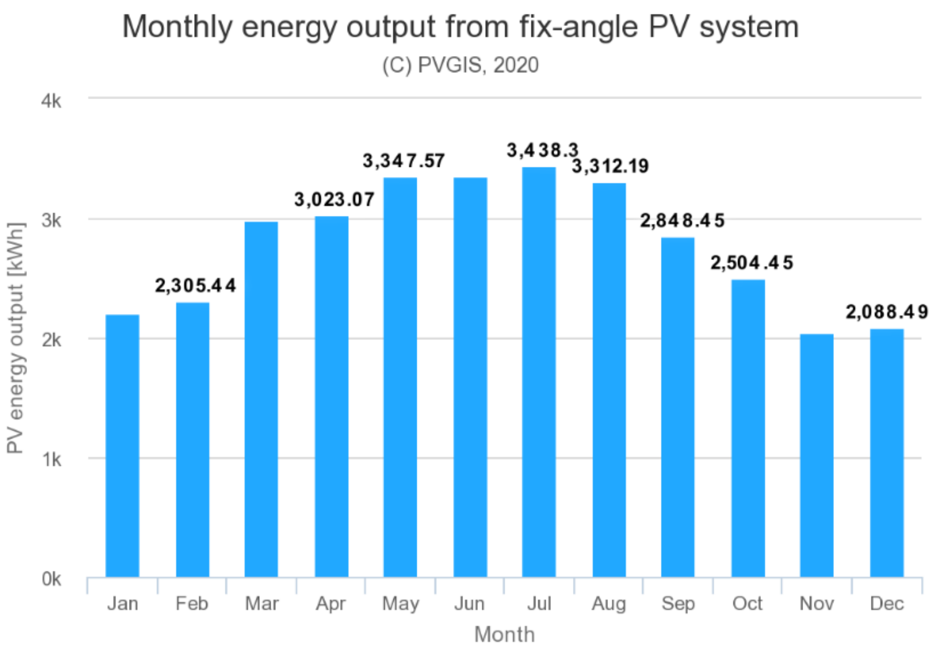

Figure 3.23: Monthly energy output. Source: PVGIS (2020)

In the Figure 3.24, the interactive tool calculates a PV generation for a complete year, using a 5 % losses as a design criteria in the installation. The maximum yearly energy produced is 36659.43 kWh/year and approximately 3079.95 kWh/month PV energy generation per month.

PV generation - JRC-PVGIS		
PV installation	22	kWp
System losses	5	%
Daily PV production	110.00	kWh/day
Weekly PV production	769.99	kWh/week
Monthly PV production	3079.95	kWh/month
Yearly PV production	36959.43	kWh
Year-to-year variability	864.75	kWh
PV production %	10.27	%

Figure 3.24: PV generation - JRC - PVGIS. Source: Author (2020)

Moreover, it is important to state that the percentage of the PV production regarding the total consumption of the COMSA building is calculated with the equation:

$$\%PV_{production} = \frac{PV\,Production_{yearly}}{BuildingEnergyDemand_{yearly}} \cdot 100 \tag{3.13}$$

$$\%PV_{production} = \frac{36959.43kWh/year}{360000kWh/year} \cdot 100 = 10.27\% \tag{3.14}$$

The calculations from the above equation 3.14 show that a 10.27 % is covered regarding the total yearly building demand (360 000 kWh). The monthly production that can be stored in the battery will depend on its capacity (New battery (14 kWh) or Second-life battery (11.2 kWh)).

Analyzing the case of implementing a new battery, in the Figure 3.25, taking the catalog specifications (cycles, C-rate, among others) from the new battery with a capacity of 14 kWh, the maximum yearly energy that can be stored is 5040 kWh/year and approximately 420 kWh/month PV energy generation per month can be stored.

PV generation - Stored energy in battery (Catalog data)		
C-rate	0.2	C
Charge-Discharge (h)	5	hours
Daily Battery cyclability	1	cycles/day
Yearly battery cyclability	365	cycles/year
Daily PV energy stored	14	kWh/day
Weekly PV energy stored	98	kWh/week
Monthly PV energy stored	420	kWh/month
Yearly PV energy stored	5040	kWh/year
Year-to-year variability	117.92	kWh
PV production %	1.40	%

Figure 3.25: PV generation - Stored energy in new battery (catalog data)

In addition, the percentage of the PV surplus energy stored regarding the total consumption of the COMSA building is calculated with the equation:

$$\%PV_{production} = \frac{PV surplus_{yearly}}{BuildingEnergyDemand_{yearly}} \cdot 100 \quad (3.15)$$

$$\%PV_{production} = \frac{5040kWh/year}{360000kWh/year} \cdot 100 = 1.40\% \quad (3.16)$$

The PV production could be monthly stored in the proposed lithium-ion battery (new battery or second-life battery) and the surplus can be sold at a price into the energy mix to have some revenues from the feed-in-tariff scheme. Figure 3.26 shows the reference tariff prices depending the period (Off-Peak, Mid-Peak, Peak) from ENDESA:

Rate Schedule	Tariff prices (€/kWh)
P1 - Peak (€/kWh)	€ 0.10787
P2 - Mid-Peak (€/kWh)	€ 0.10131
P3 - Off-Peak (€/kWh)	€ 0.07664

Figure 3.26: ENDESA electricity market tariffs. Source: Author (2020)

In the Figure B.5, in the Appendix section B.2, the calculations made for the PV surplus curtailed energy and yearly related savings considering a new battery are shown. The yearly ToU savings are the PV surplus energy per month (difference between PV generated and PV stored in battery) times the energy price rate plan (Peak price), then the sum of all months.

Additionally, the PV stored energy in the battery times the energy price (Off-Peak price), then sum of all months, represents the revenue from the ToU analysis. Peak indicates high price periods, Mid-Peak indicates moderate price periods, and Off-peak indicates low price periods. Since the battery operates 8760 hours/year, so a total revenue of 3829.41 €/year is accounted from this PV installation model using the energy price reference from figure 3.26.

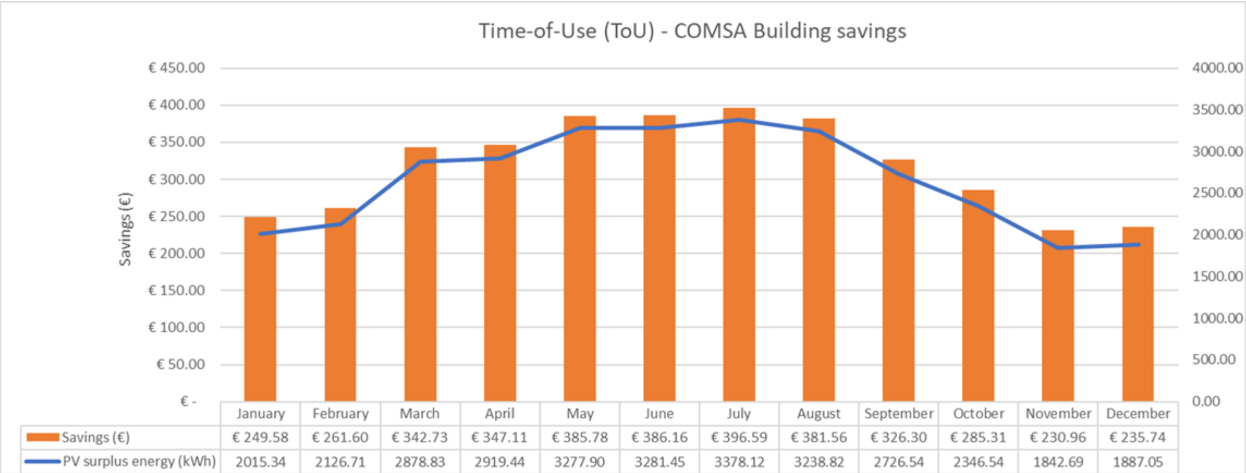

Figure 3.27: COMSA PV production - ToU savings curve using new battery. Source: Author (2020)

Finally, the Figure 3.27 shows the complete ToU analysis, with the monthly PV production and savings. The months with higher PV production are the summer ones (May, June, July and August), also the ones with higher revenues during one year analysis.

Analyzing the case of the second life battery with a capacity of 11.2 kWh, in the Figure 3.28, taking the catalog specifications (cycles, C-rate, among others) from the second-life battery, the maximum yearly energy that can be stored is 4032 kWh/year and approximately 336 kWh/month PV energy generation can be stored.

PV generation - Stored energy in battery (Catalog data)		
C-rate	0.2	C
Charge-Discharge (h)	5	hours
Daily Battery cyclability	1	cycles/day
Yearly battery cyclability	365	cycles/year
Daily PV energy stored	11.2	kWh/day
Weekly PV energy stored	78.4	kWh/week
Monthly PV energy stored	336	kWh/month
Yearly PV energy stored	4032	kWh/year
Year-to-year variability	94.34	kWh
PV production %	1.12	%

Figure 3.28: PV generation - Stored energy in second-life battery (catalog data). Source: Author (2020)

In addition, the percentage of the PV surplus energy stored regarding the total consumption of the COMSA building is calculated with the equation:

$$\%PV_{production} = \frac{PV surplus_{yearly}}{BuildingEnergyDemand_{yearly}} \cdot 100 \tag{3.17}$$

$$\%PV_{production} = \frac{4032kWh/year}{360000kWh/year} \cdot 100 = 1.12\% \tag{3.18}$$

In the Figure B.6, in the Appendix section B.2, the calculations made for the PV surplus energy and yearly related savings considering a second-life battery are shown. The yearly ToU savings are the PV surplus curtailed energy per month (difference between PV generated and PV stored in battery) times the energy price rate plan (Peak price), then the sum of all months.

Additionally, the PV stored energy in the battery times the energy price (Off-Peak price), then sum of all months, represents the revenue from the ToU analysis. Peak indicates high price periods, Mid-Peak indicates moderate price periods, and Off-peak indicates low price periods. Since the battery operates 8760 hours/year, so a total revenue of 3860.89 €/year is accounted from this PV installation model using the energy price reference from figure 3.26.

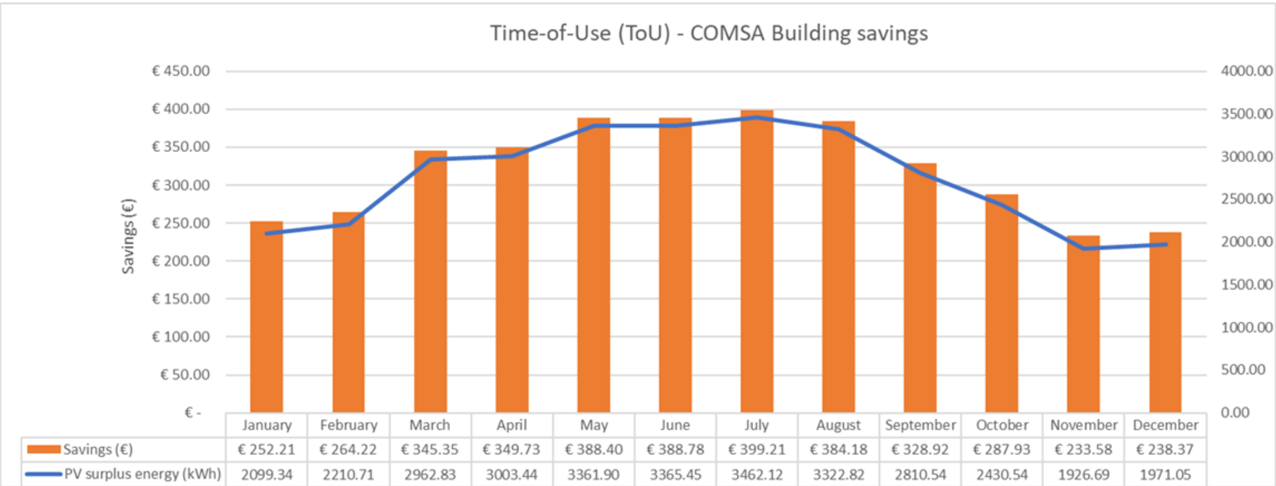

Figure 3.29: COMSA PV production - ToU savings curve using second-life battery. Source: Author (2020)

In the end, Figure 3.29 shows the complete ToU analysis, with the monthly PV production and savings. The months with higher PV production are the summer ones (May, June, July and August), also the ones with higher revenues during one year analysis. Since the capacity of the second-life battery is only 80 % of the total capacity of a new battery, the energy that can be stored is lower but the amount of surplus energy (curtailed generation) due to the ToU calculation is higher, the revenues using a second-life battery will be € 31.48 more than integrating a new battery in the installation due to the cyclability and State of Charge (SoC) of the second-life battery.

In the Figure 3.30, the graph shows the behavior of the HVAC 4th floor demand versus the PV modeled generation during the whole year as mentioned above. The PV generation is higher than the power demanded by the HVAC 4th floor systems at the COMSA building. The curtailed generation is evident, so the implementation of an energy storage system with the battery is a very good alternative to take an advantage of the PV energy generation surplus as mentioned in the last section.

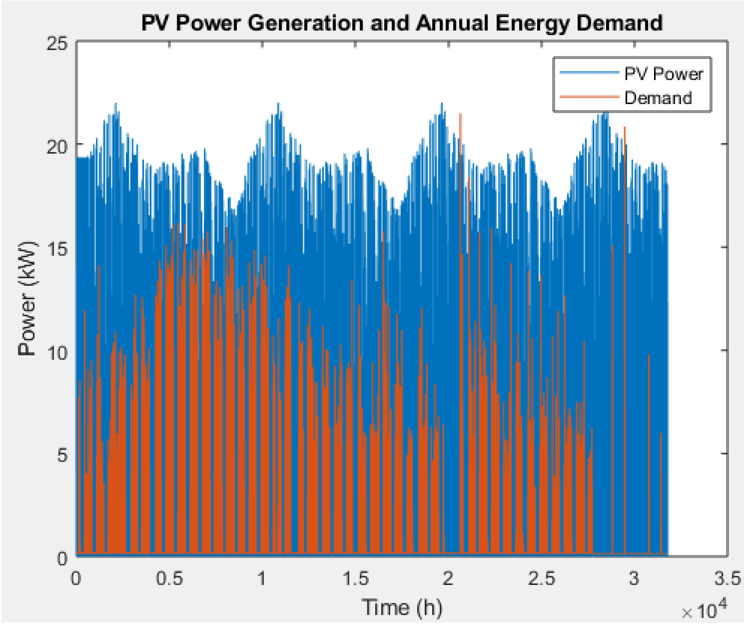

Figure 3.30: PV Power Generation and Annual HVAC demand

Finally, the specific cyclability behavior of this particular battery is out of the scope of this thesis since the installation and integration of it in the building is pending, but as a matter of fact, the cyclability data of the battery (new and second-life battery scenarios) taken into account for this calculation, is merely catalog data for the COMSA Model hypothesis. One cycle per day is the assumption regarding the lifespan (10 years) and daily operation of the battery is shown in the Figure 3.31, where there is the behavior between the HVAC 4th floor load demand (kW) and the battery State of Charge (SoC) in one day (31/01/2020):

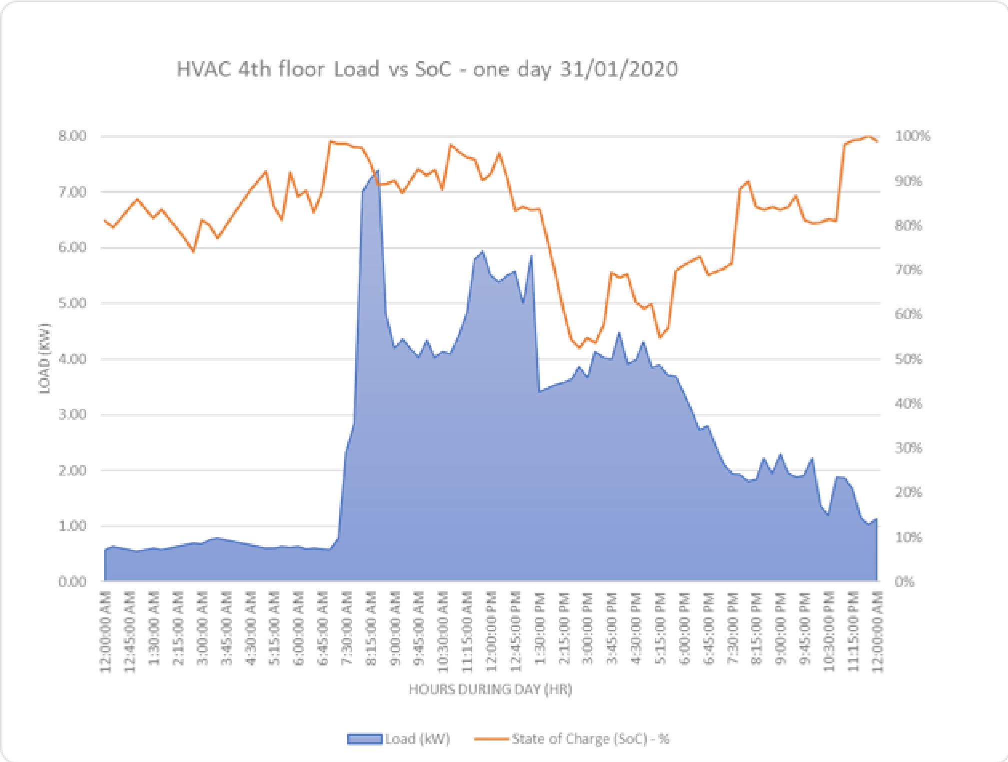

Figure 3.31: HVAC Load Curve vs Battery State of Charge (SoC) - One day. Source: Author (2020)

The operational schedule at COMSA building (4th floor) starts with a high demand peak between 7:30 am and 8:30 am, then starts to decrease until the midday hours when again there is another peak but lower than the one from the morning. It is interesting to see that during lunch time (1:30 pm - 3:30 pm) the load demand starts to decrease until the end of the working day (6:00 pm) and the state of charge (SoC) of the battery increases in parallel reaching a full-charge state again.

3.5.2 PV generation and energy storage system (ESS) analysis

Since solar and wind power are tied to environmental conditions there are a few hours each year where the environmental conditions are near-perfect for their production. As a result, a small amount of curtailment into their projects (i.e., solar inverters that clip excess production) during these periods of peak renewable production. In the end, the goal is to minimize the cost of the product and maximize its value to the customer. Figure 3.32 shows a simulation of the three 7.2 kW inverter system proposed to operate with the new battery in the PV installation and the peak load data from the project:

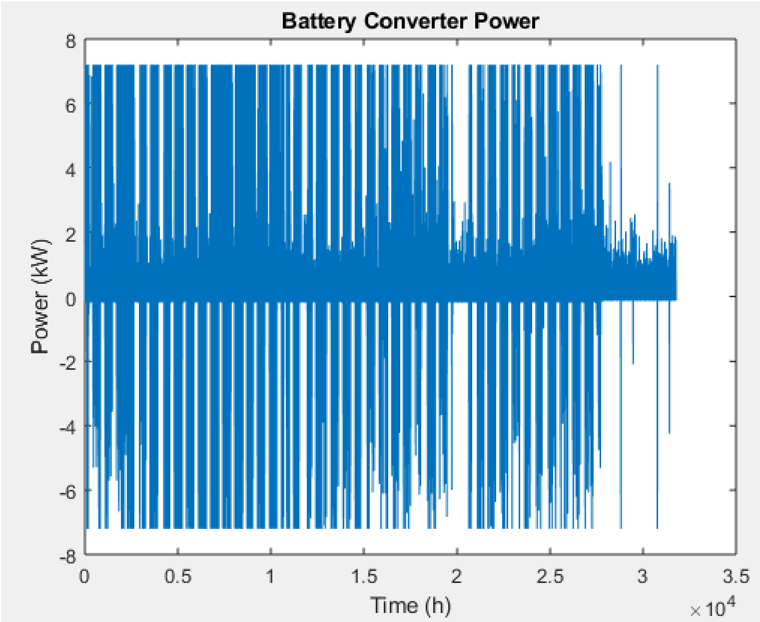

Figure 3.32: Battery Inverter Power 7.2 kW simulated in MATLAB modeling code using a new battery (NB) - One year. Source: Author (2020)

Figure 3.33 shows a simulation of the inverter used with the second-life battery in the PV installation and peak load data in one year:

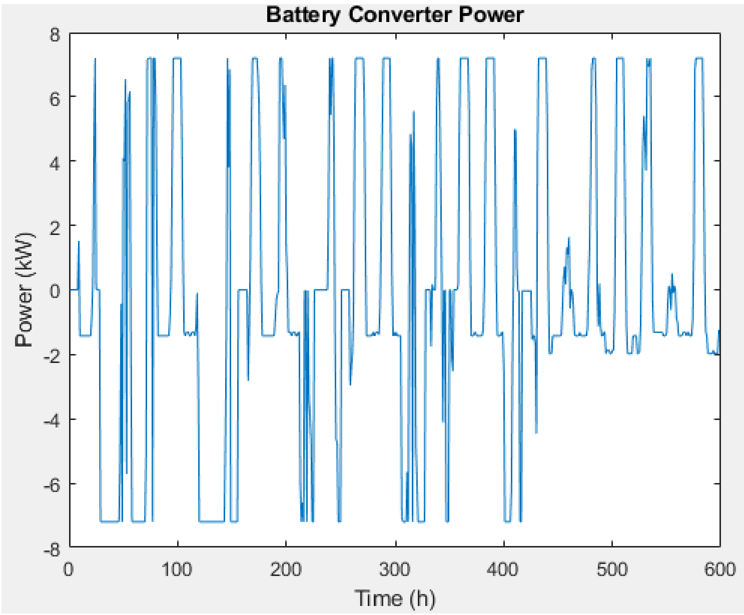

Figure 3.33: Battery Inverter Power 7.2 kW simulated in MATLAB modeling code using a second-life battery (SLB) - One year. Source: Author (2020)

The cost per kilowatt (kW) of the installed BIPV system, the inverter system and the cost per kWh of the battery are also data included in the optimization modeling code "***Battery_ Modelling_ Building.m***" (Appendix D.1). The function to be minimized is the total cost as mentioned above. This economic data is accompanied by the LCOE or the uniform cost of energy measured in lifetime the total cost between the required energy in the whole COMSA building. The service life of the proposed configuration either a new battery or second-life battery has been set at 10 years.

The input values of the LCOE algorithm calculation are showed in the Table 3.10:

Table 3.10: Input values:

$dload$	31774	nº data measures
$incT$	0.025	time increments
P_{peak}	110	kW
$cost_{PV}$	1300	€/kW
$cost_{convbat}$	300	€/kW
$cost_{bat}$	550	€/kWh (New battery (NB))
$cost_{bat}$	275	€/kWh (Second-life battery (SLB))

Once the system has been modeled and dimensioned based on different simulations in the previous subsection, it is proposed the need to minimize the LCOE cost as possible. The cost function is f_x:

$$f(x) = cost_{PV} \cdot x_2 + cost_{convbat} \cdot x_3 + cost_{bat} \cdot x_4 \tag{3.19}$$

In the Table 3.11, the study variables of the algorithm are:

Table 3.11: Study variables:

PV installed capacity - x_2	22	kWp
Converter power - x_3	7.2	kW
New Battery (NB) capacity - x_4	14	kWh
Second-life Battery (SLB) capacity - x_4	11.2	kWh

One of the restrictions of the model is the power balance. The difference between the power generated and the power consumed by the load is equivalent to the sum of power that regulates the converter and the power that is thrown.

$$a(t) \cdot x_2 + b(t) \cdot x_3 - c(t) \cdot P_{peak} = P_{conv}(t) \tag{3.20}$$

Moreover, the restriction on the value of the power of the converter, which in no case can exceed the value maximum allowed. Remember that for the project the total power of the converters system set is 7.2 kW.

$$-x_3 \leq P_{conv}(t) \leq x_3 \tag{3.21}$$

Another important restriction is the energy storage limits. The energy at the end of time iteration t is between the minimum and maximum of battery capacity (new or second-life battery).

$$E_{bat}(t) = E_{bat}(t-1) + incT \cdot P_{conv}(t) \tag{3.22}$$

$$k \cdot x_4 \leq E_{bat}(t) \leq x_4 \tag{3.23}$$

- The variable x_1 is the every 15-minute measures of the data model.
- Where a(t), b(t) is the ratio of photovoltaic and demand respectively. The variables x_2, x_3, x_4 are the value of the variables to be dimensioned.
- $P_{conv}(t)$ is power that the converter regulates and curtailed power in the time *t* from the PV generation.
- $E_{bat}(t)$ is the energy in the battery at time *t*.
- The constant k that is taken to determine the minimum battery capacity that can fit is 0.2.
- The increase in time, *incT*, and the peak power P_{peak} are also constant. For convenience, will henceforth be called the total demand at time *t*.

$$C(t) = c(t) \cdot P_{peak} \tag{3.24}$$

A key part of the model regarding the battery types, is to check the LCOE costs evaluating the proposed scenarios in the MATLAB modeling code ***Battery_Modelling_Building.m*** (Appendix D.1). After evaluating the sizing model, the results for both scenarios are given in the next tables:

Table 3.12: New battery (NB) sizing model results:

New Battery capacity (Ebatmax)	14	kWh
Battery converter power (Pbatmax)	7.2	kW
Total building Power Peak Demand (Ppeak)	110	kW
HVAC Power Peak Demand (Ppeak)	10	kW
Power BIPV installation (PPV)	22	kWp
PV curtailed generation per year before storage	36959.43	kWh
PV stored energy in battery per year	5040	kWh
PV surplus energy per year after storage	31919.43	kWh

Table 3.13: Second-life battery (SLB) sizing model results:

Second-life battery capacity (Ebatmax)	11.2	kWh
Battery converter power (Pbatmax)	7.2	kW
Total building Power Peak Demand (Ppeak)	110	kW
HVAC Power Peak Demand (Ppeak)	10	kW
Power BIPV installation (PPV)	22	kWp
PV curtailed generation per year before storage	36959.43	kWh
PV stored energy in battery per year	4032	kWh
PV surplus energy per year after storage	32927.43	kWh

Therefore, as stated in the Figures 3.25 and 3.28, the amount of energy stored per battery type (new battery and second-life battery) will vary due to the capacity of each one. To demonstrate the behavior of the battery storage system and correlate this analysis with the one done in the Subsection 3.5.1, referred to time-of-use (ToU). The results of the energy stored in a new battery (14 kWh) are showed below in a yearly, monthly, weekly and daily basis:

- **PV energy stored in a new battery (NB), one year (From 01/05/2019 to 01/05/2020):**

  The amount of energy stored in the battery is around 5040 kWh per year. In the figure, the behavior during this period of time is showed:

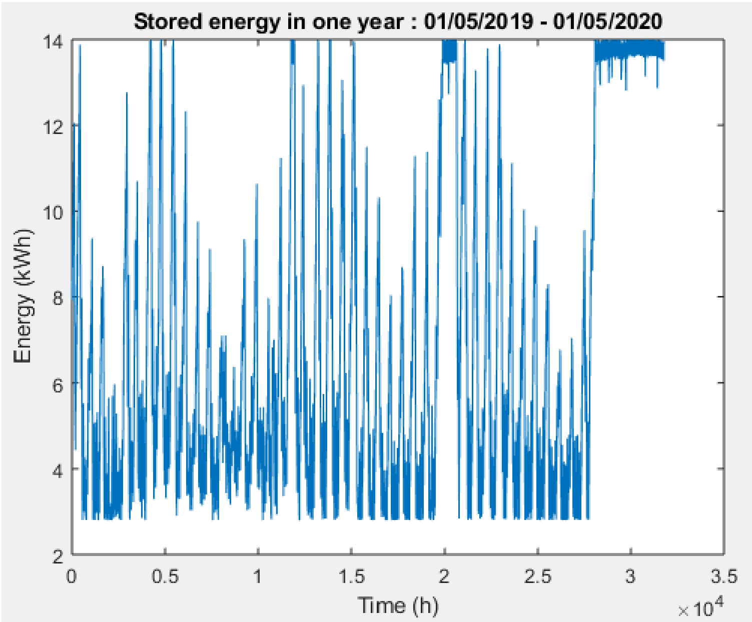

Figure 3.34: PV energy stored in a new battery, one year - (01/05/2019 - 01/05/2020). Source: Author (2020)

- **PV energy stored in a new battery (NB), one month (From 01/01/2020 to 31/01/2020):**

  The amount of energy stored in the battery is around 420 kWh per month. In the figure, the behavior during this period of time is showed:

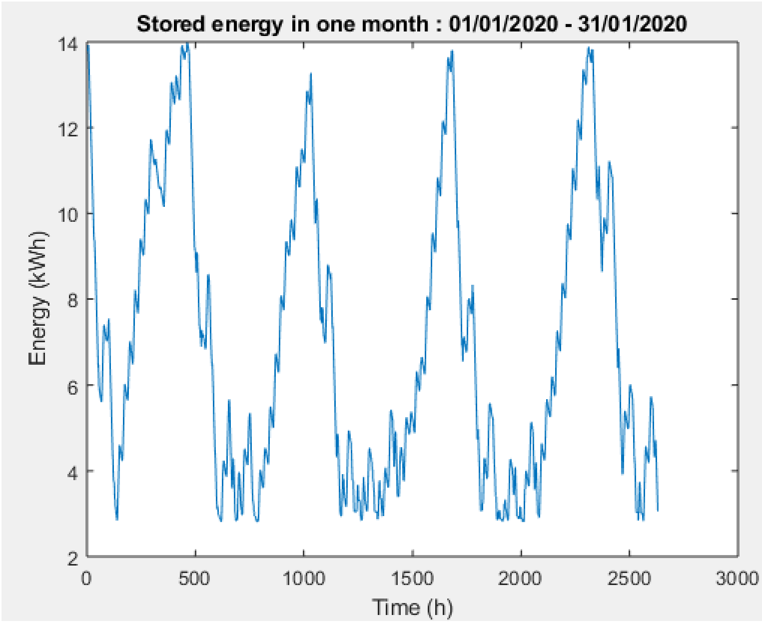

Figure 3.35: PV energy stored in a new battery, one month - (01/01/2020 - 31/01/2020). Source: Author (2020)

- **PV energy stored in a new battery (NB), one week (From 27/01/2020 to 31/01/2020):**

The amount of energy stored in the battery is around 98 kWh per week. In the figure, the behavior during this period of time is showed:

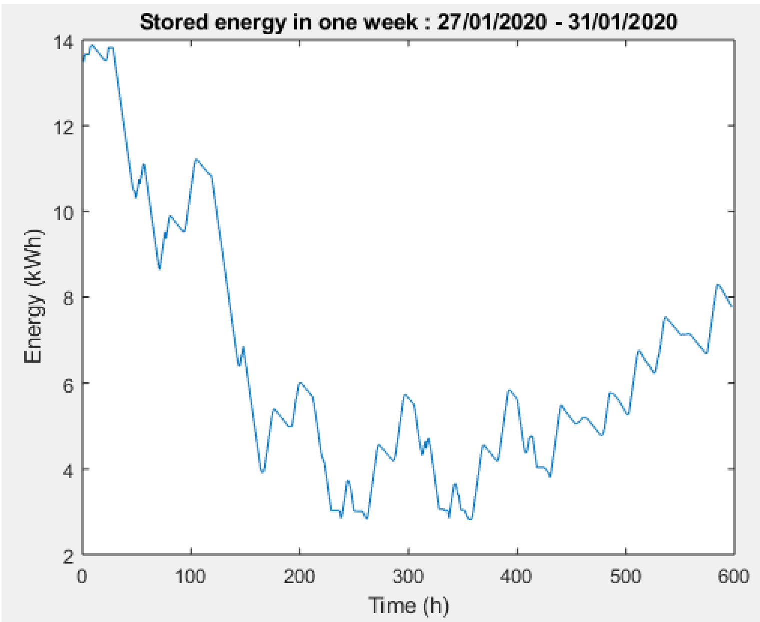

Figure 3.36: PV energy stored in a new battery, one week - (27/01/2020 - 31/01/2020). Source: Author (2020)

- **PV energy stored in a new battery (NB), one day:** 31/01/2020

The amount of energy stored in the battery is around 14 kWh per day. In the figure, the behavior during this period of time is showed:

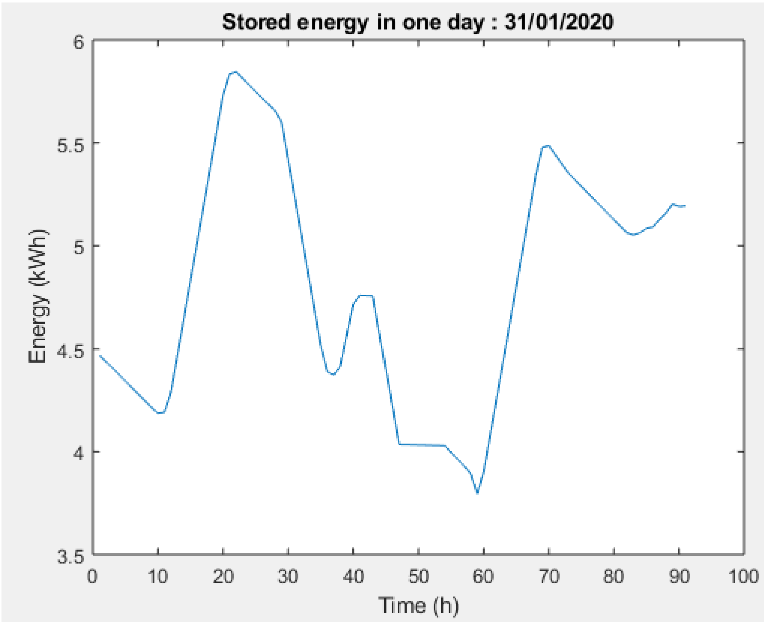

Figure 3.37: PV energy stored in a new battery, one day - (31/01/2020)

On the other hand, to demonstrate the behavior of the second-life battery (SLB) storage system and correlate this analysis with the one done in the Figure 3.28, referred to time-of-use (ToU), the results of the energy stored in this type of battery (11.2 kWh) are showed below in a yearly, monthly, weekly and daily basis:

- **PV energy stored in a second-life battery (SLB), one year (From 01/05/2019 to 01/05/2020):**

The amount of energy stored in the battery is around 4032 kWh per year. In the figure, the behavior during this period of time is showed:

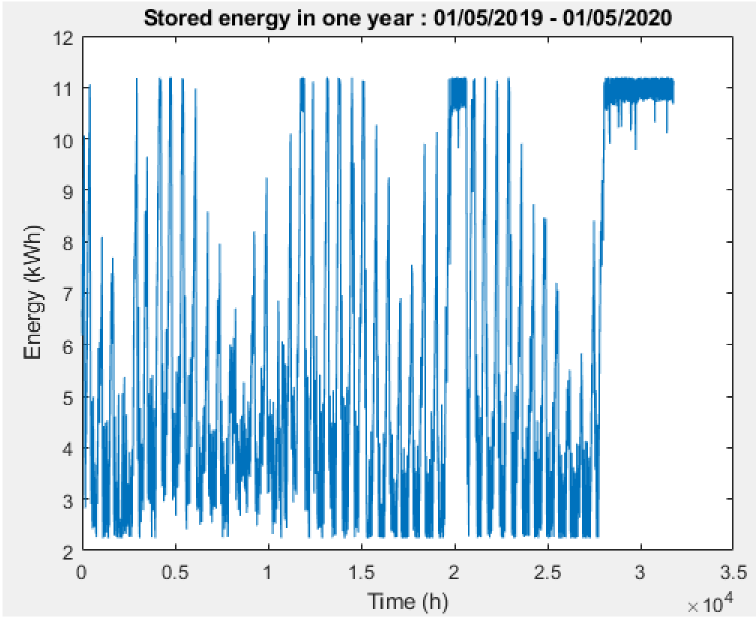

Figure 3.38: PV energy stored in a second-life battery, one year - (01/05/2019 - 01/05/2020). Source: Author (2020)

- **PV energy stored in a second-life battery (SLB), one month (From 01/01/2020 to 31/01/2020):**

The amount of energy stored in the battery is around 336 kWh per month. In the figure, the behavior during this period of time is showed:

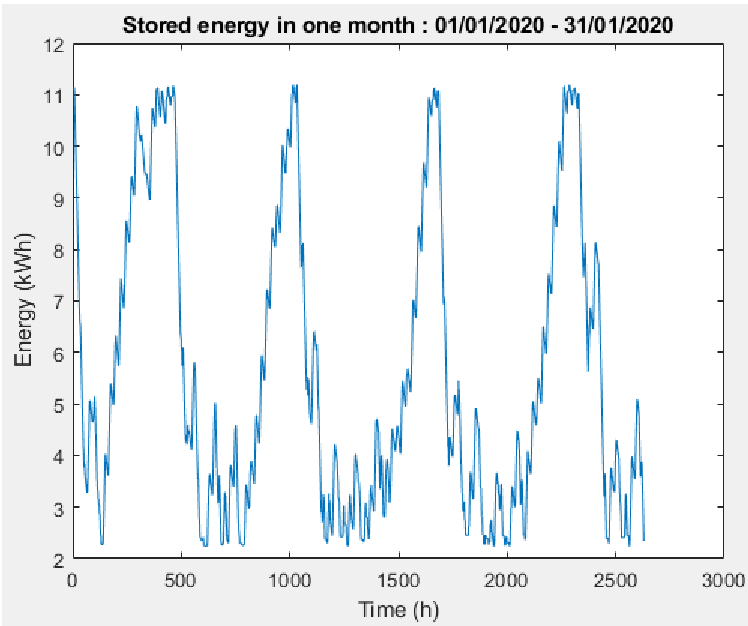

Figure 3.39: PV energy stored in a second-life battery, one month - (01/01/2020 - 31/01/2020). Source: Author (2020)

- **PV energy stored in a second battery (SLB), one week (From 27/01/2020 to 31/01/2020):**

The amount of energy stored in the battery is around 78.4 kWh per week. In the figure, the behavior during this period of time is showed:

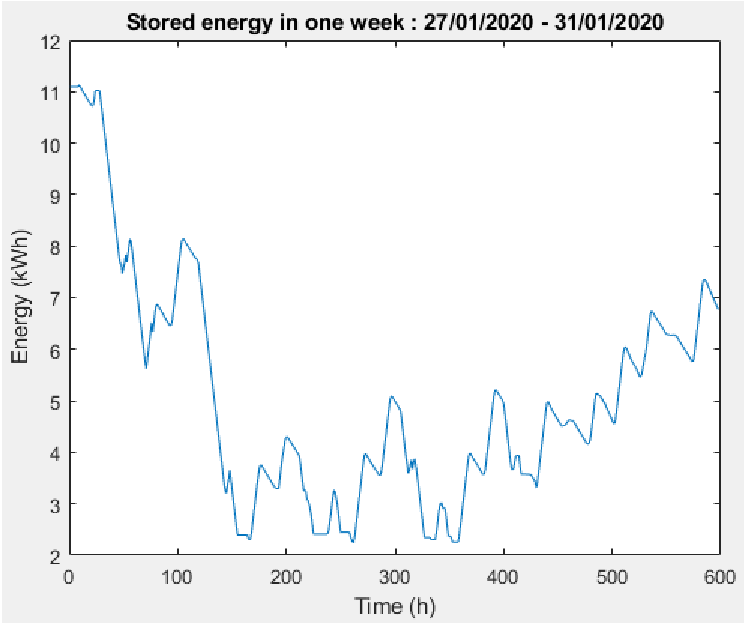

Figure 3.40: PV energy stored in a second-life battery, one week - (27/01/2020 - 31/01/2020). Source: Author (2020)

- **PV energy stored in a second-life battery (SLB), one day:** 31/01/2020

The amount of energy stored in the battery is around 11.2 kWh per day. In the figure, the behavior during this period of time is showed:

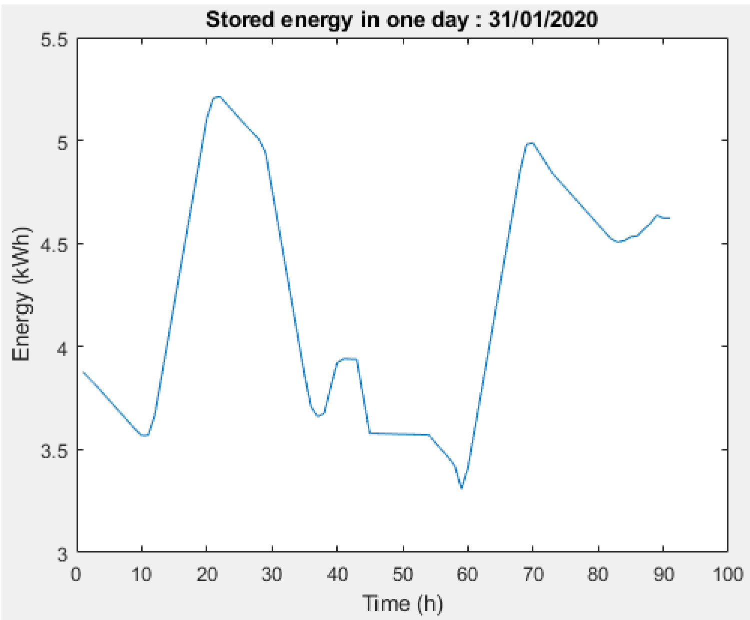

Figure 3.41: PV energy stored in a second-life battery, one day - (31/01/2020)

3.5.3 Levelized Cost of Energy (LCOE) analysis

The Levelized Cost of Energy (LCOE) is considered a cost metric which compares energy storage systems with different characteristics on a comparable basis. For instance, these systems have unequal lifetime, capacities, rated power, capital cost and efficiencies. The LCOE represents the lowest cost at which energy should be sold out so as to realize break-even over the storage life cycle. This approach allows for a fast and simple assessment of various energy storage systems.

The LCOE approach is widely used to value and compare energy storage systems with different characteristics. This method defines a unit cost of electricity generation over the life of the system. It determines the price per energy unit, which balances out the total costs of the system. The LCOE is calculated by dividing the total capital cost of the storage, over the expected energy output while talking into consideration the time-varying value of money.

As mentioned in the previous subsection 3.5.2, the possibility to store the surplus energy generation from the PV energy production in the proposed lithium-ion battery will help to minimize the LCOE of the installation and create a better synergy increasing energy production and reducing project total costs, considering a time period of 10 years and whole year demand database (31774 measures). From the MATLAB modeling code ***Battery_ Modelling_ Building.m*** (Appendix D.1), the equations below show how to calculate the LCOE of the system:

$$Enetot = sum(dload) \tag{3.25}$$

$$lifetime = 10years \tag{3.26}$$

$$LCOE(MWh) = \frac{cost}{(1e-6 \cdot lifetime \cdot (31774/length(Ebat)) \cdot Enetot)} \tag{3.27}$$

The analysis has a levelized cost of generation, or of discharge, which means dividing all the project costs or leveling all the project cost by the discharged energy, you get to a levelised cost of electricity number that represents the price you need on a megawatt-hour basis to recoup all of costs and then hitting the equity rate targets for the project. This LCOE analysis is merely a technical approach from the evaluated battery scenarios using a 22 kWp BIPV installation and a total building power peak demand of 110 kW:

- **LCOE - New battery (NB) storage system + BIPV installation:**

Table 3.14: LCOE new battery (NB) + BIPV installation results:

New battery capacity (Ebatmax)	14	kWh
Battery converter power (Pbatmax)	7.2	kW
Power BIPV installation (PPV)	22	kWp
System Costs	38.46	k€
LCOE (MWh)	37.56	€/MWh
LCOE (kWh)	0.03756	€/kWh

- **LCOE - Second-life battery (SLB) storage system + BIPV installation:**

Table 3.15: LCOE second-life battery (SLB) + BIPV installation results:

Second-life battery capacity (Ebatmax)	11.2	kWh
Battery converter power (Pbatmax)	7.2	kW
Power BIPV installation (PPV)	22	kWp
System Costs	33.84	k€
LCOE (MWh)	33.05	€/MWh
LCOE (kWh)	0.03305	€/kWh

- **LCOE - only BIPV installation:**

Table 3.16: LCOE only BIPV installation results:

Battery capacity (Ebatmax)	0	kWh
Battery converter power (Pbatmax)	0	kW
Power BIPV installation (PPV)	22	kWp
System Costs	28.6	k€
LCOE (MWh)	27.94	€/MWh
LCOE (kWh)	0.02794	€/kWh

A comparison of all LCOE scenarios is illustrated in the next table:

Table 3.17: LCOE comparison between scenarios:

LCOE new battery (NB) + BIPV installation (MWh)	37.56	€/MWh
LCOE second-life battery (SLB) + BIPV installation (MWh)	33.05	€/MWh
LCOE only BIPV installation (MWh)	27.94	€/MWh

The LCOE values from the Table 3.17 are compared with the LCOE benchmark values from the International Renewable Energy Agency (IRENA) [39] from figure 3.42 where the global average weighted LCOE in 2019 was 68.40 $ /MWh (57.84 €/MWh):

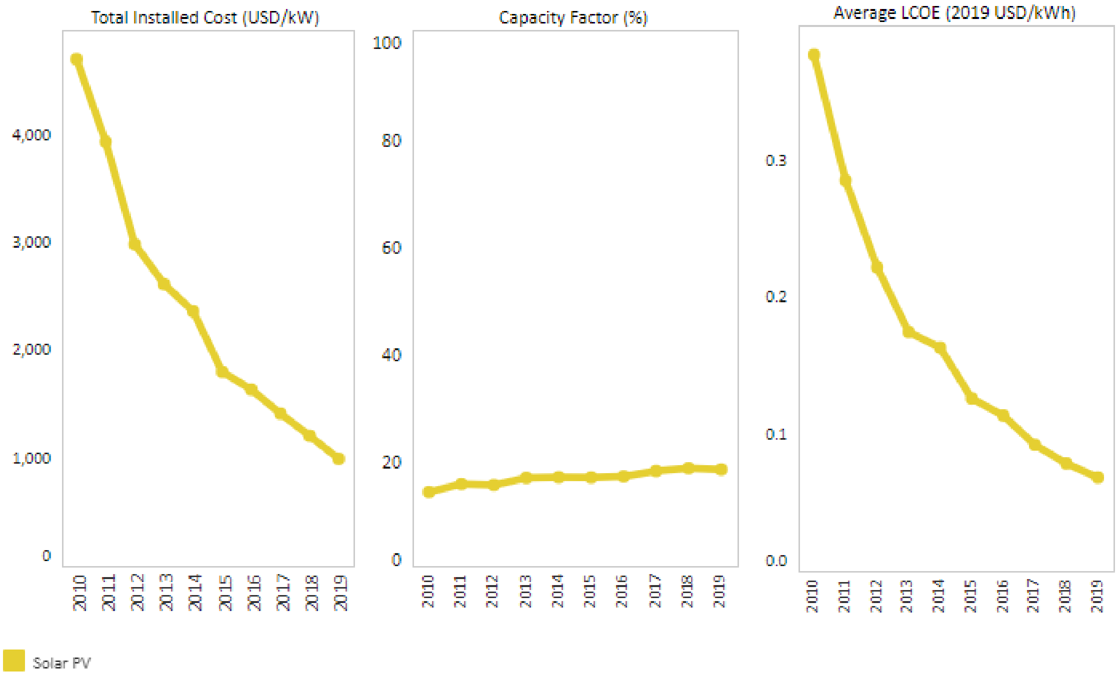

Figure 3.42: LCOE benchmark for Solar PV - 2020. Source: International Renewable Energy Agency (IRENA) (2020)

Consequently, the LCOE values from the calculations are lower than the average LCOE value from IRENA [39]. The cost of electricity from utility-scale solar PV has been decreasing since 2010 around 82 % until nowadays and the capacity factor increased until 18 %. In addition, the total installed price of a solar PV is 995 $ /kW (850 €/kW) approximately but in terms of this project, an installed price of 1300 €/kW is considered for the LCOE analysis because of a Building Integrated Photovoltaic (BIPV).

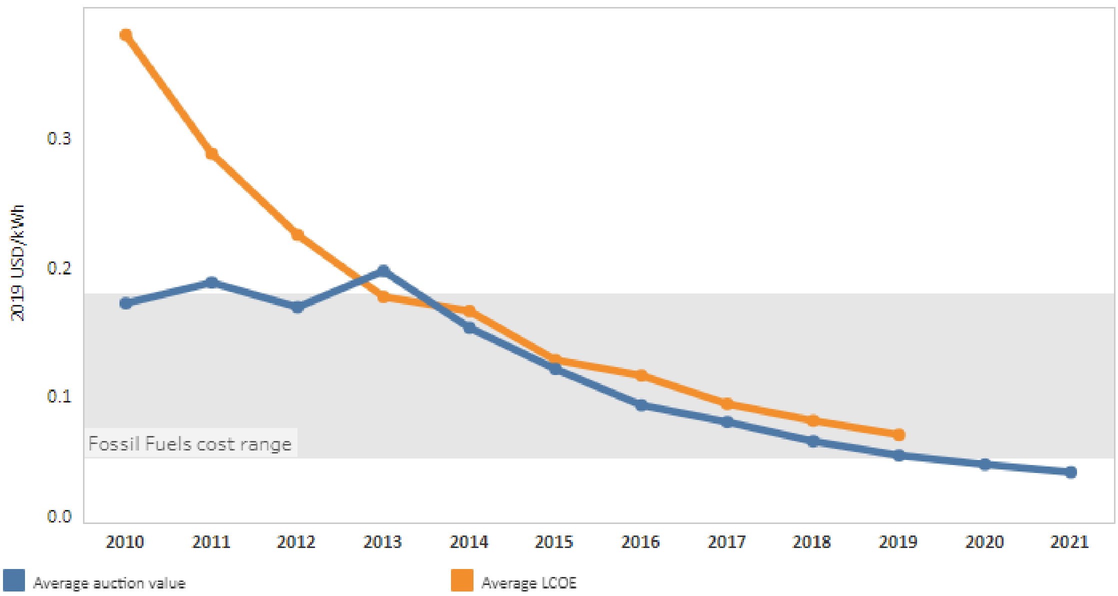

Figure 3.43: LCOE auction benchmark for Solar PV - 2020. Source: International Renewable Energy Agency (IRENA)(2020)

From Figure 3.43, in order to correlate the analysis from the Section 3.5.1 about ToU, energy storage system modeled and the LCOE values from the Table 3.17, the most adequate option for the project is the LCOE second-life battery (SLB) + BIPV installation, because of its LCOE value of 33.05 €/MWh compared to LCOE auction value of 38.40 €/MWh for this year 2020. It is inferred that with this lower value the project will have many technical and economical benefits applying these technologies on it. In addition, it is expected that for the year 2021 the LCOE auction value will decrease until a value of 33 €/MWh making these projects more profitable.

3.6 Techno-Economic Model

In the next sections, an analysis of the battery implementation will be held, so the main cases will take into account a new battery (NB) installation in the COMSA building pilot site versus a second-life battery (SLB) installation, so the initial investment, battery prices, input parameters, flexible markets revenues, and other details will be studied and compared in order to check the feasibility and profitability of the both business cases.

In this analysis, the total costs of the power systems were annualized, and these include investment repayments, fixed and variable operation and maintenance (O&M), integration and implementation costs. The Excel model offers the possibility to analyze both cases (New battery and Second-Life battery) changing some input parameters. In the Table 3.18, the main CAPEX costs are considered in the analysis:

Table 3.18: General initial investment costs (CAPEX)

New Battery (14 kWh)	7700	€
Second-Life Battery (11.2 kWh)	3080	€
3 Inverters Victron Energy (7.2 kW)	3180	€

In the Table 3.19, the main OPEX costs are considered in the analysis. The maintenance costs and battery charging costs are included per year, also a linear battery depreciation rate of a 10 % /year is considered according to the battery capacity cost and if it is a new battery or a second-life battery.

Table 3.19: General initial investment costs (OPEX)

Battery + inverters maintenance costs	400	€/year
Battery depreciation cost rate	10	% /year
Battery depreciation cost - New battery	770	€/year
Battery depreciation cost - Second-life battery	308	€/year
Estimated licenses operational cost	600	€/year

3.6.1 Licenses cases

After the description of the licenses in the Subsection 3.4.1, some cases related can be described in order to understand better the potential revenues. This licenses cases will be analyzed for both alternatives using either a new battery (Subsection 3.6.2) and a second-life battery (Subsection 3.6.3).

Table 3.20: License apps cases

Base Case AEC	AEC	No Licenses, No ToU
Case 1	ToU	ToU yearly revenues
Case 2	All Licenses	All Licenses yearly revenues
Case 3	All Licenses + ToU	All Licenses and ToU yearly revenues

- **Base Case Annual Energy Costs (AEC):**

The Base Case only takes into account the current situation at the COMSA building pilot. An Annual Energy Cost (AEC) of 36360 €/year without any update or implementation of ToU to reduce the electricity bill.

- **Case 1 - ToU:**

  In the Case 1, the implementation of the ToU is good way to see the potential yearly savings. In fact, in the Subsection 3.5.1 these potential ToU savings will be explained and how the ToU is calculated taken as an example an estimated PV installation using the COMSA data of the 22 kWp and the battery that COMSA is willing to install.

- **Case 2 - All Licenses:**

  Integrating all licenses in the model would be another strategy to reduce the AEC. The licenses are Automatic Demand Side Management (ADSM), Reward from Demand Response (ReDR), Wholesale electricity market trading (WSM) and each of them will provide some annual revenues (ADSM 10 %, ReDR 5 %, WSM 10 %), according to Table 3.8.

- **Case 3 - All Licenses + ToU:**

  Case 3 will be another potential profitable case by integrating all licenses in the model plus the ToU analysis to mitigate the Base Case AEC and have extra revenues from the solution.

3.6.2 New battery (NB) scenario analysis

The goal of this section is to show the potential techno-economic advantages of installing a new battery (NB) in the project, and furthermore this case will be compared with a second-life battery (SLB) one. The results of the financial calculations of this scenario are given below. The NPV is calculated using an interest discount rate of 0%. It is clear that break-even is reached and the project does seems very profitable in the shape it is in applying different case combinations. Figure C.5 in the Appendix C, Section C.2 shows the initial investment of the new battery case.

According to the Subsection 3.6.1 about the license operational apps, in this analysis it will be studied the benefit of the implementation of the assets (battery, inverters, PV installation) and the license apps in order to demonstrate the final potential revenues using a new battery (NB) in the COMSA pilot:

- **Base Case Annual Energy Costs (AEC):**

  The Base Case only takes into account the current situation at the COMSA building pilot. An Annual Energy Cost (AEC) of 36 360 €/year without any update or implementation of ToU to reduce the electricity bill.

- **Case 1 - ToU:**

  In the Case 1, the implementation of the ToU is an useful method to see the potential yearly savings.

Economic Indicators No discount rate	Building Type COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 15,696.16
Internal Rate Return (IRR) - %	20.7%
Payback Period (PP) - years	6.10
Benefit Cost Ratio (BCR)	1.44
Average yearly revenue	€ 2,659.41

Figure 3.44: Case 1 - Economic indicators without discount rate, New battery (NB). Source: Author (2020)

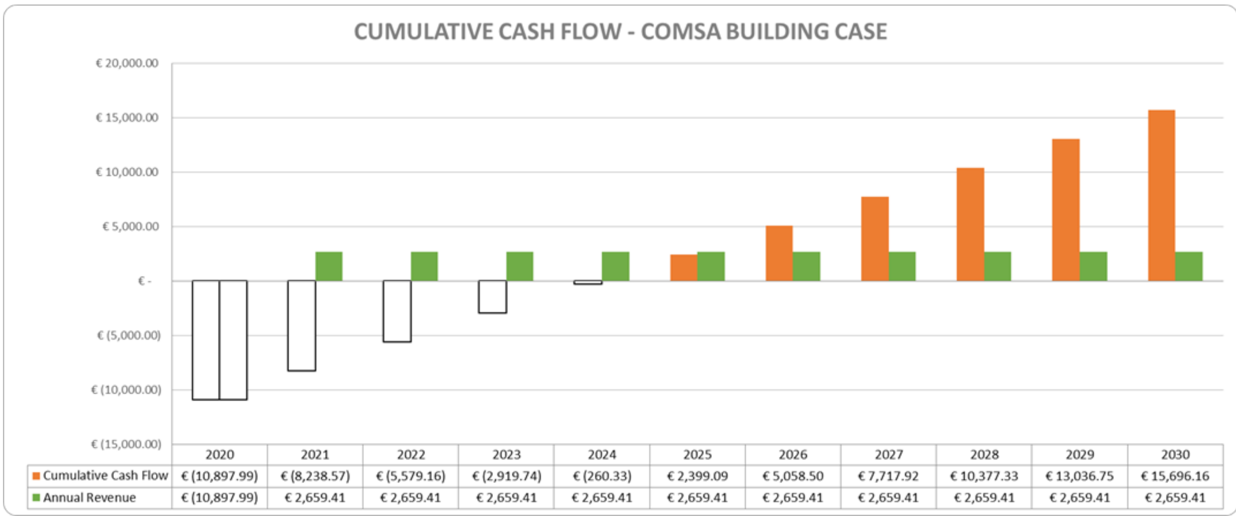

Figure 3.45: Case 1 - Cumulative Cash Flow graph, New battery (NB). Source: Author (2020)

In the Figure 3.45, the amount of € 10897.99 in the first year, corresponds to the initial investment considering the new battery and the inverters only. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

- **Case 2 - All Licenses:**

In Case 2, integrating all licenses in the model would be another strategy to reduce the Annual Energy Costs (AEC). The licenses are Automatic Demand Side Management (ADSM), Reward from Demand Response (ReDR), Wholesale electricity market trading (WSM) and each of them will provide some annual revenues (ADSM 10 %, ReDR 5 %, WSM 10 %), according to table 3.8. This licenses can provide around 15 % savings in total from the AEC value.

Economic Indicators No discount rate	Building Type COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 26,021.00
Internal Rate Return (IRR) - %	31.9%
Payback Period (PP) - years	4.94
Benefit Cost Ratio (BCR)	2.41
Average yearly revenue	€ 3,684.00

Figure 3.46: Case 2 - Economic indicators without discount rate, New battery (NB). Source: Author (2020)

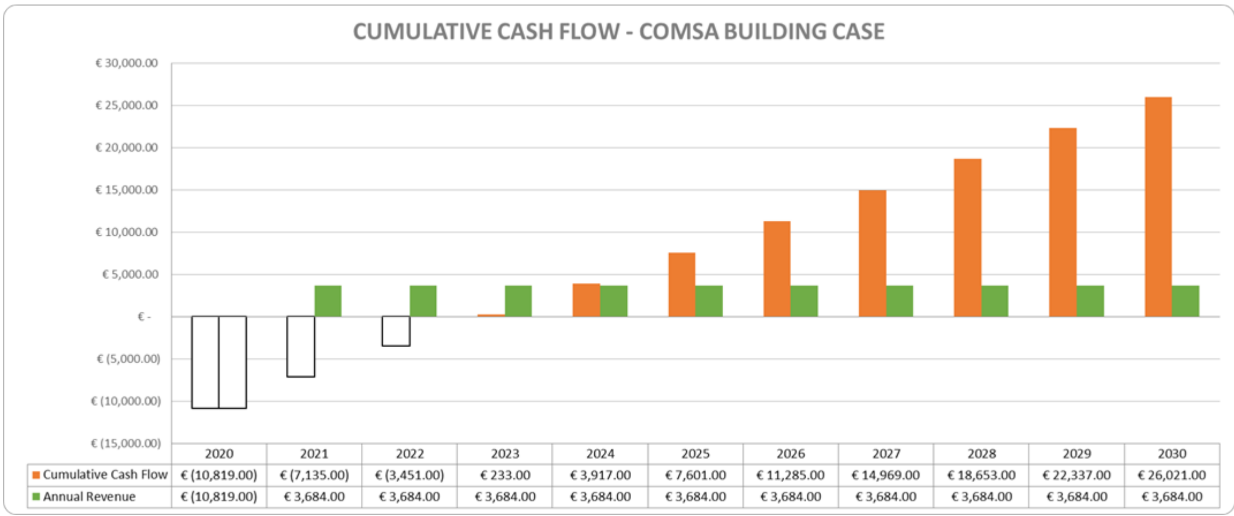

Figure 3.47: Case 2 - Cumulative Cash Flow graph, New battery (NB). Source: Author (2020)

In the Figure 3.47, the amount of € 10819 in the first year, corresponds to the initial investment considering the new battery, inverters and also the licenses (ADSM, ReDR and WSM) included in the solution. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

- **Case 3 - All Licenses + ToU:**

  Case 3 integrates the Automatic Demand Side Management (ADSM), Reward from Demand Response (ReDR), Wholesale electricity market trading (WSM) licenses in the analysis and adding the ToU scheme. This licenses can provide around 15 % savings in total from the AEC value plus the yearly revenues from the ToU.

Economic Indicators No discount rate	Building Type COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 65,067.16
Internal Rate Return (IRR) - %	74.3%
Payback Period (PP) - years	3.34
Benefit Cost Ratio (BCR)	6.46
Average yearly revenue	€ 7,513.41

Figure 3.48: Case 3 - Economic indicators without discount rate, New battery (NB). Source: Author (2020)

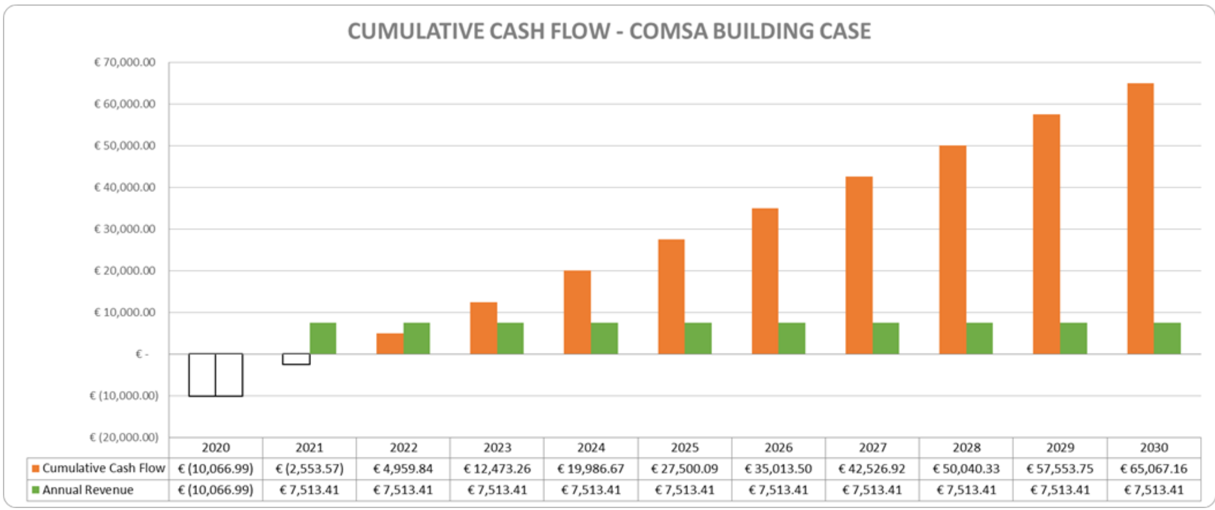

Figure 3.49: Case 3 - Cumulative Cash Flow graph, New battery (NB). Source: Author (2020)

In Case 3, Figure 3.49, the amount of € 10066.99 in the first year, corresponds to the initial investment considering the new battery, inverters and also the licenses (ADSM, ReDR and WSM) included in the solution. The integration of the Time-of-Use (ToU) led to yearly savings included in the analysis. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

3.6.3 Second-life battery (SLB) scenario analysis

The goal of this section is to show the potential techno-economic advantages of installing a second-life battery (SLB) in the project. The results of the financial calculations of this scenario are given below. The NPV is calculated using an discount rate of 0%. It is clear that breakeven is reached and the project does seems very profitable in the shape it is in now applying different case combinations. Figure C.7 in the Appendix C, Section C.2, shows the initial investment of the second-life battery (SLB) case.

According to the Subsection 3.6.1 about the license operational apps, in this analysis it will be studied the benefit of the implementation of the assets (battery, inverters, PV installation) and the license apps in order to demonstrate the final potential revenues using a second-life battery (SLB) in the COMSA pilot:

– **Base Case Annual Energy Costs (AEC):**

  The Base Case only takes into account the current situation at the COMSA building pilot. An Annual Energy Cost (AEC) of 36 360 €/year without any update or implementation of ToU to reduce the electricity bill.

– **Case 1 - ToU:**

  In the Case 1, the implementation of the ToU is good way to see the potential yearly savings generated.

Economic Indicators No discount rate	Building Type
	COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 25,720.83
Internal Rate Return (IRR) - %	53.5%
Payback Period (PP) - years	3.84
Benefit Cost Ratio (BCR)	4.43
Average yearly revenue	€ 3,152.89

Figure 3.50: Case 1 - Economic indicators without discount rate, Second-life battery (SLB). Source: Author (2020)

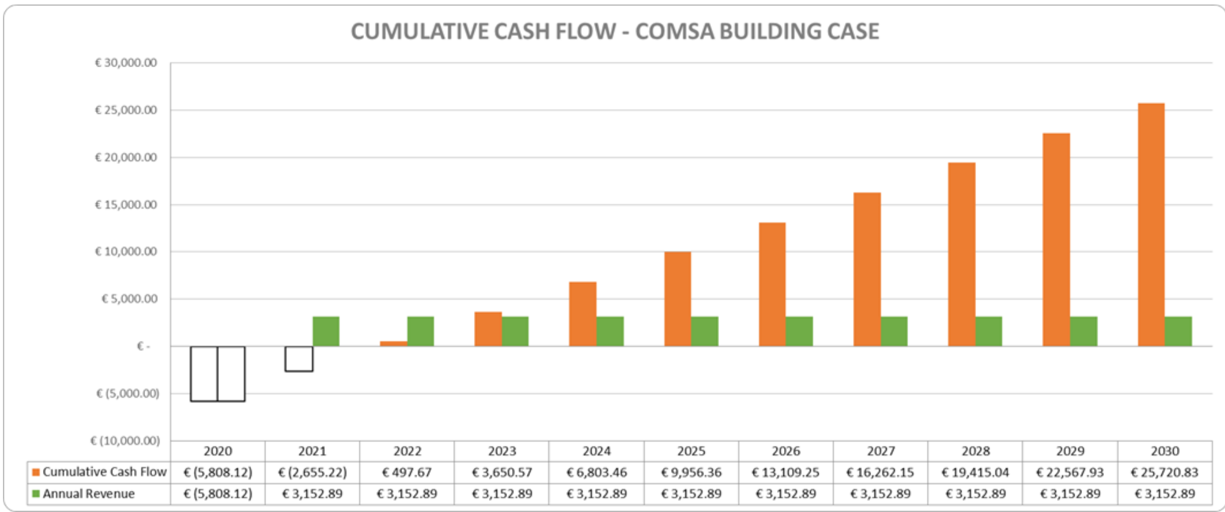

Figure 3.51: Case 1 - Cumulative Cash Flow graph, Second-life battery (SLB). Source: Author (2020)

In the Case 1, Figure 3.51, the amount of € 5808.12 in the first year, corresponds to the initial investment considering the second-life battery and inverters only as in the new battery analysis. The initial investment value implies a reduction in the battery cost since is a second-life battery. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

– **Case 2 - All Licenses:**

In order to reduce the AEC, the integration of all licenses in the model would be an useful revenue strategy. The licenses are Automatic Demand Side Management (ADSM), Reward from Demand Response (ReDR), Wholesale electricity market trading (WSM) and each of them will provide some annual revenues (ADSM 10 %, ReDR 5 %, WSM 10 %), according to Table 3.8. These licenses can provide around 15 % savings from the AEC value.

Economic Indicators No discount rate	Building Type COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 35,723.00
Internal Rate Return (IRR) - %	71.9%
Payback Period (PP) - years	3.38
Benefit Cost Ratio (BCR)	6.23
Average yearly revenue	€ 4,146.00

Figure 3.52: Case 2 - Economic indicators without discount rate, Second-life battery (SLB). Source: Author (2020)

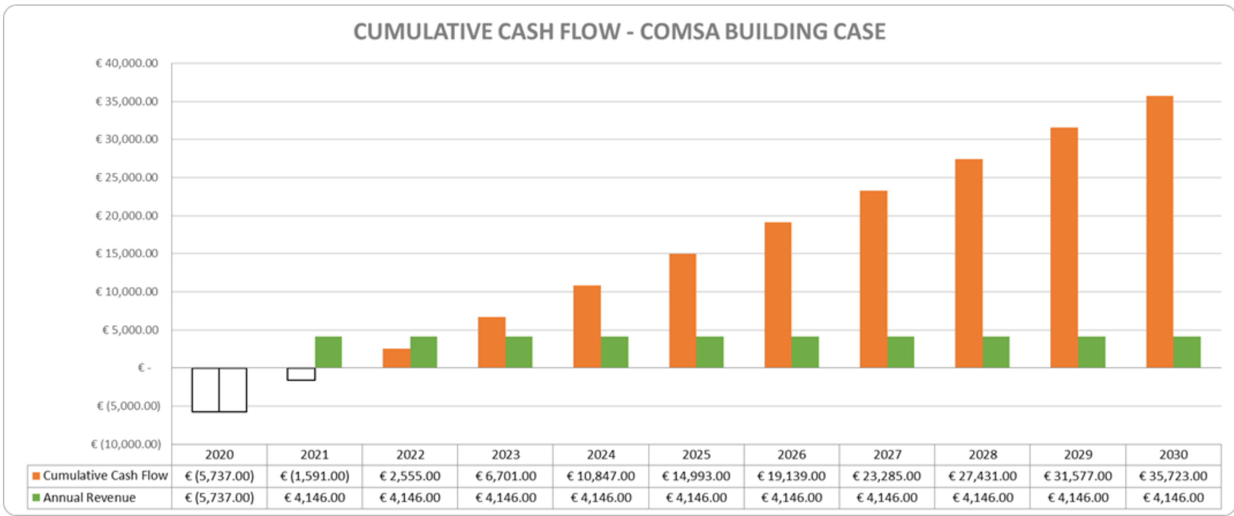

Figure 3.53: Case 2 - Cumulative Cash Flow graph, Second-life battery (SLB). Source: Author (2020)

In the Figure 3.53, the amount of € 5737 in the first year, corresponds to the initial investment considering the second-life battery, inverters and also the licenses (ADSM, ReDR and WSM) included in the solution. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

– **Case 3 - All Licenses + ToU:**

Case 5 is a potential profitable case by integrating all licenses in the model plus the ToU analysis would be another alternative to mitigate the Base Case AEC. These licenses can provide around 15 % savings from the AEC value plus the yearly revenues from the ToU.

Economic Indicators No discount rate	Building Type COMSA Building
Discount Rate - %	0%
Net Present Value (NPV) - €	€ 75,091.83
Internal Rate Return (IRR) - %	160.9%
Payback Period (PP) - years	2.62
Benefit Cost Ratio (BCR)	15.09
Average yearly revenue	€ 8,006.89

Figure 3.54: Case 3 - Economic indicators without discount rate, Second-life battery (SLB). Source: Author (2020)

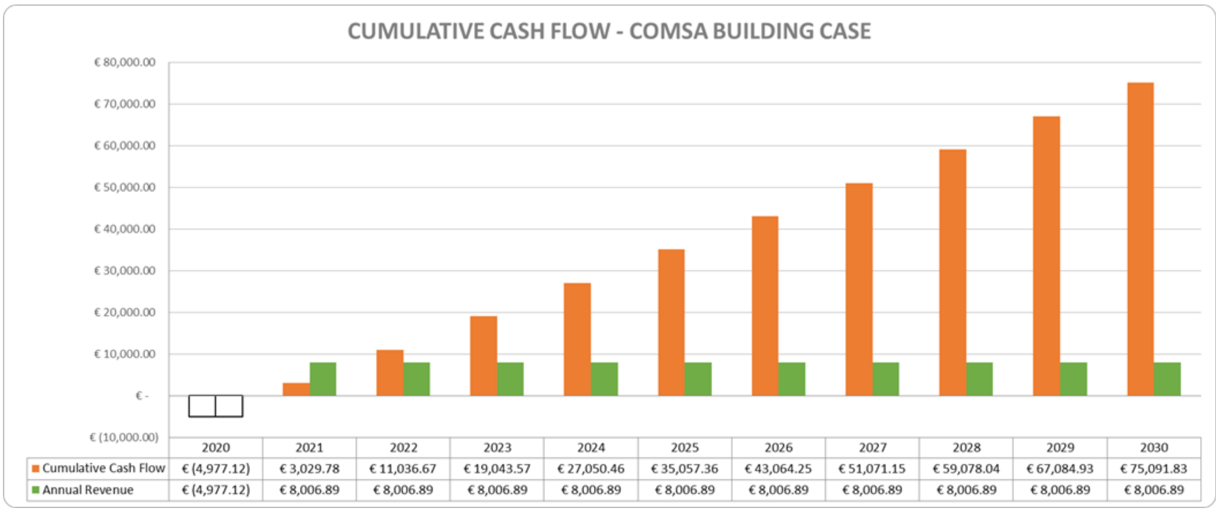

Figure 3.55: Case 3 - Cumulative Cash Flow graph, Second-life battery (SLB). Source: Author (2020)

In Case 3, the Figure 3.55, the amount of € 4977.12 in the first year, corresponds to the initial investment considering the second-life battery, inverters and also the licenses (ADSM, ReDR and WSM) included in the solution. The integration of the Time-of-Use (ToU) led to yearly savings included in the analysis. A cash flow analysis is done and represents how this initial investment is returned through the 10-year time period.

3.7 Revenues Model - Comparison between scenarios

3.7.1 New battery (NB) scenario results

NEW BATTERY ECONOMIC ANALYSIS RESULTS	CASE 1 - ToU	CASE 2 - All Licenses	CASE 3 - All Licenses+ToU
Economic indicators No discount rate			
Discount Rate - %	0%	0%	0%
Net Present Value (NPV) - €	€ 15,696.16	€ 26,021.00	€ 65,067.16
Internal Rate Return (IRR) - %	21%	32%	74%
Payback Period (PP) - years	6.10	4.94	3.34
Benefit Cost Ratio (BCR)	1.44	2.41	6.46
Average yearly revenue - €	€ 2,659.41	€ 3,684.00	€ 7,513.41

Figure 3.56: New battery (NB) economic analysis results. Source: Author (2020)

1. All cases have positive NPV and yearly revenues. The Case 1 - ToU not using any licenses only ToU will have a yearly revenue of 2659.41 €/year approximately in the study period, not applying a discount rate. The Internal Rate of Return (IRR) is 21% and the payback period will be 6.10 years keeping a positive Benefit-Cost ratio (BCR) of 1.44. The Time-of-Use (ToU) net yearly savings are 3829.41 €/year.

2. Case 2 - All Licenses also will have annual revenues of 3684 EUR/year but without the ToU savings this case is not so profitable as Case 3 - All Licenses + ToU. Case 2 - All Licenses has a better payback period of 4.94 years rather than the Case 1 - ToU. Also, this case has a higher Benefit-Cost ratio (BCR) of 2.41 and an a greater Internal Rate of Return (IRR) of 32% rather than Case 1 - ToU.

3. The most profitable case is the Case 3 - All Licenses + ToU with annual revenues of 7513.41 €/year. The Internal Rate of Return (IRR) increased until 74% which is the best rate from three cases. The payback period is about 3.34 years and the Benefit-Cost ratio (BCR) will be 6.46. Compared with the Case 2 - All Licenses, there is a revenue of 2.03 times higher by applying the ToU with the licenses.

4. To apply Case 2 - All Licenses or Case 3 - All Licenses + ToU, it is better to wait until the end of 2020 or the beginning of the 2021, when the Spanish energy legislation be fully defined in terms of potential DSO and FCR revenue streams depending on the building.

From the results, it is visible that the parameters in the business model will have to shift to make the model more profitable. A sensitivity analysis for the new battery (NB) scenario is calculated in order to show the variations between battery prices through a specific time period.

The cost of the battery has a significant impact on the initial investment and will therefore impact the NPV of the project. Current battery cost can be estimated to be 550€/kWh for lithium-ion batteries. Figure C.10 in the Appendix C, shows the cost variation data in a period for the most profitable case. This price is expected to drop over the coming years due to the battery depreciation and also the faster growth battery market.

Sensitivity Analysis - New Battery Price - Zero Crossings NPV = 0	CASE 1 - ToU	CASE 2 - All Licenses	CASE 3 - All Licenses+ToU
Sensitivity Analysis - Battery Price - No discount rate			
Battery Price (€) for COMSA Building	€ 1,899.58	€ 2,631.43	€ 5,366.72
Battery Price (€/kWh)	€ 135.68	€ 187.96	€ 383.34

Figure 3.57: Sensitivity Analysis zero crossings - New battery (NB). Source: Author (2020)

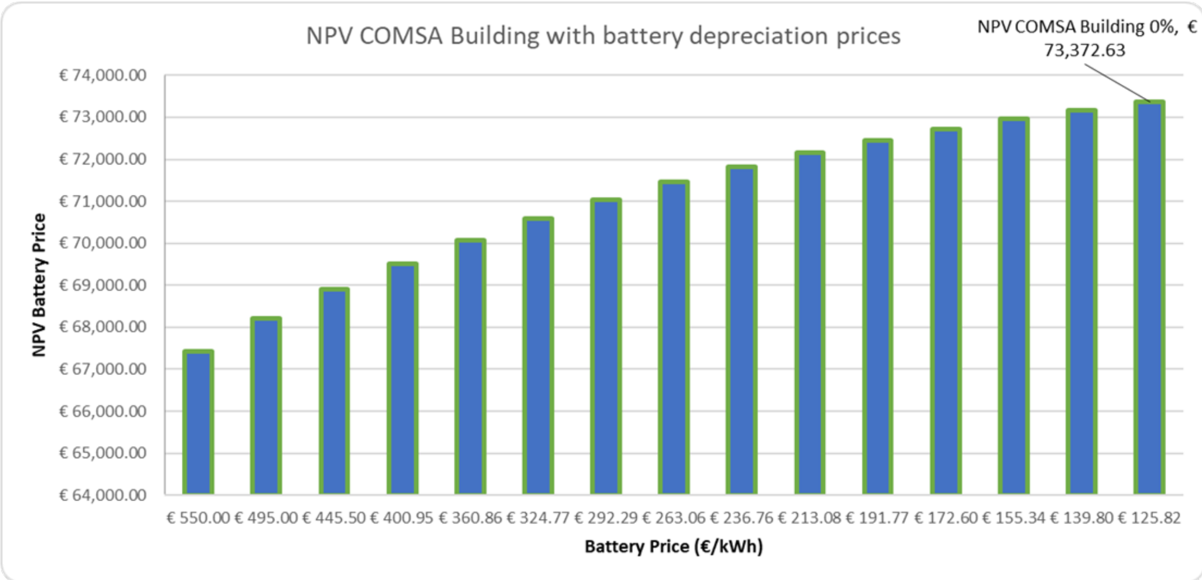

Figure 3.58: NPV comparison - New battery (NB) price. Source: Author (2020)

Regarding the most profitable analysis, Case 3 - All Licenses + ToU, in order to start with an NPV equals to zero in the project, with zero earnings neither losses, the price of the new battery implemented (14 kWh) should be 383.34 €/kWh, about 166.66 € more cheaper than is already in the battery market nowadays (550 €/kWh).

Figure 3.58 shows how the new battery prices will decrease during the time period while a positive NPV with a 0% discount rate, will rise year by year regarding the cases studied for the scenario. This shows that a positive NPV can be expected in the near future while the prices are plummeting from the actual price reference of 550 €/kWh.

3.7.2 Second-life battery (SLB) scenario results

SECOND-LIFE BATTERY ECONOMIC ANALYSIS RESULTS	CASE 1 - ToU	CASE 2 - All Licenses	CASE 3 - All Licenses+ToU
Economic indicators No discount rate			
Discount Rate - %	0%	0%	0%
Net Present Value (NPV) - €	€ 25,720.83	€ 35,723.00	€ 75,091.83
Internal Rate Return (IRR) - %	54%	72%	161%
Payback Period (PP) - years	3.84	3.38	2.62
Benefit Cost Ratio (BCR)	4.43	6.23	15.09
Average yearly revenue - €	€ 3,152.89	€ 4,146.00	€ 8,006.89

Figure 3.59: Second-life battery (SLB) economic analysis results. Source: Author (2020)

1. All cases have positive NPV and yearly revenues. The Case 1 - ToU not using any licenses only ToU will have a yearly revenue of 3152.89 €/year approximately in the study period, not applying a discount rate. The Internal Rate of Return (IRR) is 54% and the payback period will be 3.84 years keeping a positive Benefit-Cost ratio (BCR) of 4.43. The Time-of-Use (ToU) net yearly savings are 3860.89 €/year.

2. Case 2 - All Licenses also will have annual revenues of 4146 EUR/year but without the ToU savings this case is not so profitable as Case 3 - All Licenses + ToU. Case 2 - All Licenses has a better payback period of 3.38 years rather than the Case 1 - ToU. Also, this case has a higher Benefit-Cost ratio (BCR) of 6.23 and an a greater Internal Rate of Return (IRR) of 72% rather than Case 1 - ToU.

3. The most profitable case is the Case 3 - All Licenses + ToU with annual revenues of 8006.89 €/year. The Internal Rate of Return (IRR) increased until 161% which is the best rate from the three cases. The payback period is about 2.62 years which is the lowest of the cases and the Benefit-Cost ratio (BCR) will be 15.09, the highest. Compared with the Case 2 - All Licenses, there is a revenue of 1.86 times higher by applying the ToU with the licenses.

4. To apply Case 2 - All Licenses or Case 3 - All Licenses + ToU, it is better to wait until the end of 2020 or the beginning of the 2021, when the Spanish energy legislation be fully defined in terms of potential DSO and FCR revenue streams depending on the building.

From the results, it is visible that the parameters in the business model will have to shift to make the model more profitable. A sensitivity analysis for the second-life battery (SLB) scenario is calculate in order to show the variations between battery prices through an specific time period.

The cost of the battery has a significant impact on the initial investment and will therefore impact the NPV of the project. Current battery cost can be estimated to be 275 €/kWh for lithium-ion batteries. Figure C.11 in the Appendix C, shows the cost variation data in a period for the most profitable case (Case 3 - All Licenses + ToU). It is expected that the cost will drop over the coming years due to the battery depreciation and also the faster growth battery market and stationary storage applications.

Sensitivity Analysis - SL Battery Price - Zero Crossings NPV = 0	CASE 1 - ToU	CASE 2 - All Licenses	CASE 3 - All Licenses+ToU
Sensitivity Analysis - Battery Price - No discount rate			
Battery Price (€) for COMSA Building	€ 2,815.08	€ 3,701.79	€ 7,149.01
Battery Price (€/kWh)	€ 251.35	€ 330.52	€ 638.30

Figure 3.60: Sensitivity Analysis zero crossings - Second-life battery (SLB). Source: Author (2020)

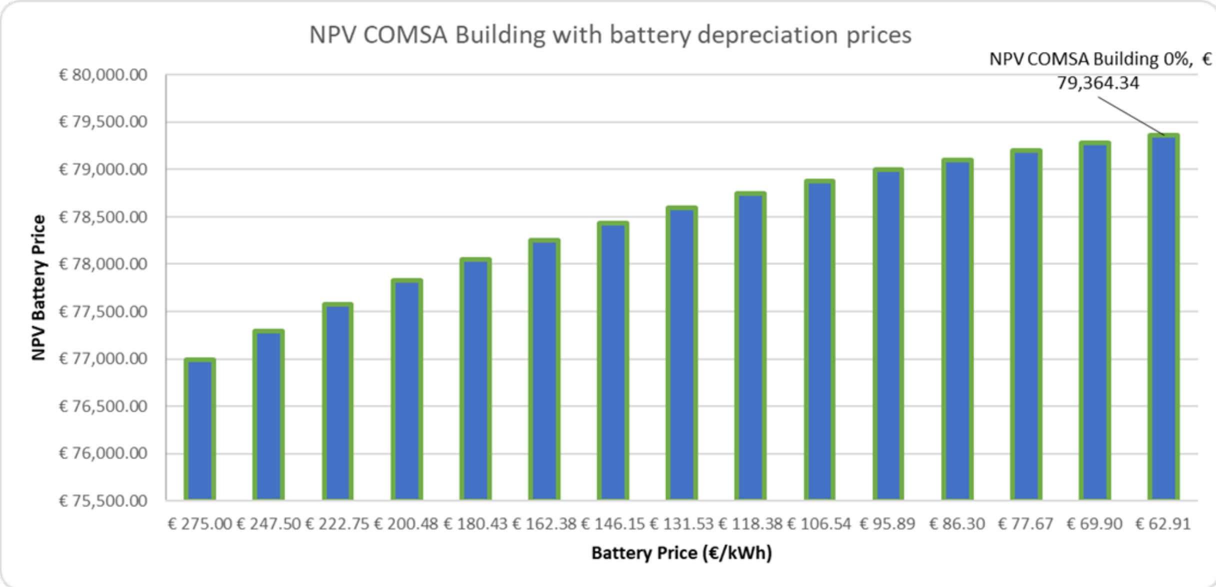

Figure 3.61: NPV comparison - Second-life battery (SLB)) price. Source: Author (2020)

Regarding the most profitable analysis, Case 3 - AEC + Licenses + ToU, in order to start with an NPV equals to zero in the project, with zero earnings neither losses, the battery price should increase to 638.30 €/kWh, more than is already in the second-life battery market nowadays. This shows that a positive NPV can be expected using as a starting price reference of 275 €/kWh, as stated for this scenario.

Figure 3.61 shows how the new battery prices will decrease during the time period while a positive NPV with a 0% discount rate, will rise year by year regarding the cases studied for the scenario. This shows that a positive NPV can be expected in the near future while the prices are plummeting from the actual price reference of 275 €/kWh.

In summary, after evaluating both scenarios with a new battery (NB) and a second-life battery (SLB), the implementation of a second-life battery in the installation with the software operational license apps and a Time-of-Use (ToU) scheme will give around a 6.56 % more in annual earnings than using a new battery in this project, which means around € 493.50 more in savings per year comparing both scenarios.

A reduced initial investment due to the second-life battery prices in market, will carry out more advantages in future projects, in terms of a faster payback period, a positive NPV, and a better benefit cost ratio (BCR). The deployment of this study in other buildings with higher energy demand will give some benefits to consider for the building owners and users.

Chapter 4

Energy Management System (EMS) and implementation barriers

4.1 General context

Energy Management Systems (EMS) are computer-based automated systems that monitor and control all energy related systems from mechanical and electrical equipment in buildings. Building energy management systems (BEMS) are commonly used to automate all services and functions within the building, which include energy management tasks. These building energy management systems connect building components with a central computer to enable the control of different variables and parameters within the building enabling possible ways to achieve energy monitoring, savings, and developing the smart-green building concept.

In addition, EMS are essential part of tertiary buildings which are associated with high costs, and considered a key success factor of businesses and services produced from the building or facility. Typically, EMS implement basic automation functionalities for these assets which can be adjusted from the central supervisory software, for example: definition of on/off schedules, instant on/off commands and regulation of indoor temperature based on Proportional-Integrative-Derivative techniques. Also, other more efficiency-oriented functionalities are sometimes included like free-cooling and night-cooling for HVAC and automatic regulation of artificial lighting to leverage natural lighting, among others.

Energy Management Systems (EMS) in tertiary buildings encompass a significant number of components organized in a multi-layer architecture, as it can be seen in the Figure D.1, the software embodying the logic of control of the energy-related assets is distributed across different hardware units (controllers and central computer) and it has been integrated in a tailor-made project.

The vision of the wider integration DERs is also a prerequisite for efficient use of energy at the consumer level through intelligent demand response. In order to develop a proper demand response program, real time access to control information related to the status of transmission and distribution network is essential. An increased level of collaboration, integration and interoperability among the array of technologies and disciplines is thus required, opening up new frontiers of integration of information and communication technology (ICT) with the energy infrastructure.

Achieving a demand-responsive smart-grid depends on the capacity of the business stakeholders to collaborate effectively, in order to give rise to a new generation of innovative, reliable, and secure smart-grid services. In an environment of increased collaboration, four strategic challenges at the intersection between ICT and energy infrastructures are vital:

* **Interoperability:** – For ensuring convergence of network (ICT) and transmission (grid) protocols for enhanced cooperation and communication.

* **Reliability and security:** – For trusted provision of services and enhanced resilience taking into account new barriers such as cyber-security and local security.

* **Decentralized and self-organizing architecture:** – For enhanced flexibility in grid control and management, and for increased resilience through self-healing.

* **Innovative business models:** – For increased participation by stakeholders (e.g., users, telecommunication operators, utilities, DSO, etc.) – to release investments required for a thorough infrastructure upgrade. This was discussed in the Chapter 3, section 3.3.

In the Section 4.2, the interoperability concept will be developed at making the operation of the system as simple as possible in terms of controls and communication, with use of intelligent communication and control devices. In this way, the users get feedback on their energy consumption. Thus, users can monitor their energy consumption and make decisions, whether to change their energy behavior. In addition, in the section 4.3, the local security related to EMS and Smart Grids will be explained focusing in the building sector and reviewing the potential risks to this type of technologies.

4.2 Interoperability

The Internet of Energy (IoE) mentioned in the Section 2.11 is a new concept derived from the Internet of Things (IoT), and emphasizes on enabling technologies, protocols and application issues related to the energy sector. The IoT is enabled by the latest developments in smart sensors, communication technologies, and internet protocols. The basic premise is to have smart sensors collaborating directly without human involvement to deliver a new class of applications.

According to M. Guizani et al [13], in the upcoming years, the IoT is expected to bridge diverse technologies to enable new applications by connecting physical objects together in support of intelligent decision making. This project provides a horizontal overview of the IoT as a summary of the most relevant protocols and application issues to enable application developers to understand on how the different protocols fit together to deliver desired functionalities without having to go through the standards specifications.

Interoperability is the ability of two or more devices to exchange information and work together in a system. This is achieved using published objects and data definitions, standard commands and protocols. As communication and information technologies emerge in power systems, smart devices/systems need to leverage realistic and scalable field deployment. The interdisciplinary structure of the smart grid concept requires heterogeneous devices with different capabilities to cooperate together to achieve global and local control objectives through real-time information handling and data interoperability of the cyber-physical component.

Utilities and independent system operators seek the most proper way to reach required information easily and securely for various domains including bulk generation, non-bulk generation, transmission, distribution, customer, markets, operations, service providers and foundation support systems. In the end, the smart grid interoperability needs to use compatible data exchange formats for a fully integrated framework.

4.2.1 Optimization strategies for Building Energy Management Systems (BEMS)

As it was stated in the Section 1.1, the DRIvE relies on integrating building energy management system (BEMS), multi-agent system (MAS) optimisation, model predictive control (MPC) and computational intelligence (CI) based forecasting to unlock the demand response potential. Existing Computational Intelligence-based forecasting algorithms are extended by coupling advanced clustering techniques and physics based simulation. The DRIvE model predictive control (MPC) is based on day-ahead forecasting of load every 15 minutes, generation and flexibility enabling the actuation of controlled devices at the most suitable time, thereby maximizing the Demand Response (DR) potential of the building case study at COMSA Corporación.

In these terms, physical characteristics of a building and its Heating Ventilation and Air Conditioning (HVAC) components are extracted and fed into a series of energy balance equations. The balance equations are used for prediction of the future evolution of cooling/heating dynamics. An alternative is to use a data-driven model (e.g. Artificial Neural Networks (ANN), Fuzzy Logic (FL), or other elements of AI) to Model Predictive Control by simply fitting a modeling to the cooling/heating data regardless of the particular physical structure of the building.

With these predictive approaches, the fluctuations ranges within energy prices, load profiles and input profiles from renewable energy sources can be handled in an effective way. In addition, the performance of an MPC-based energy system crucially depends on the accuracy of the load forecasts, response/execution time of the Model Predictive Control algorithm, uncertainty that may be acceptable in the domain of application. Figure 4.1 shows a simplified process and data-flow for a MPC that is applied in the COMSA Building.

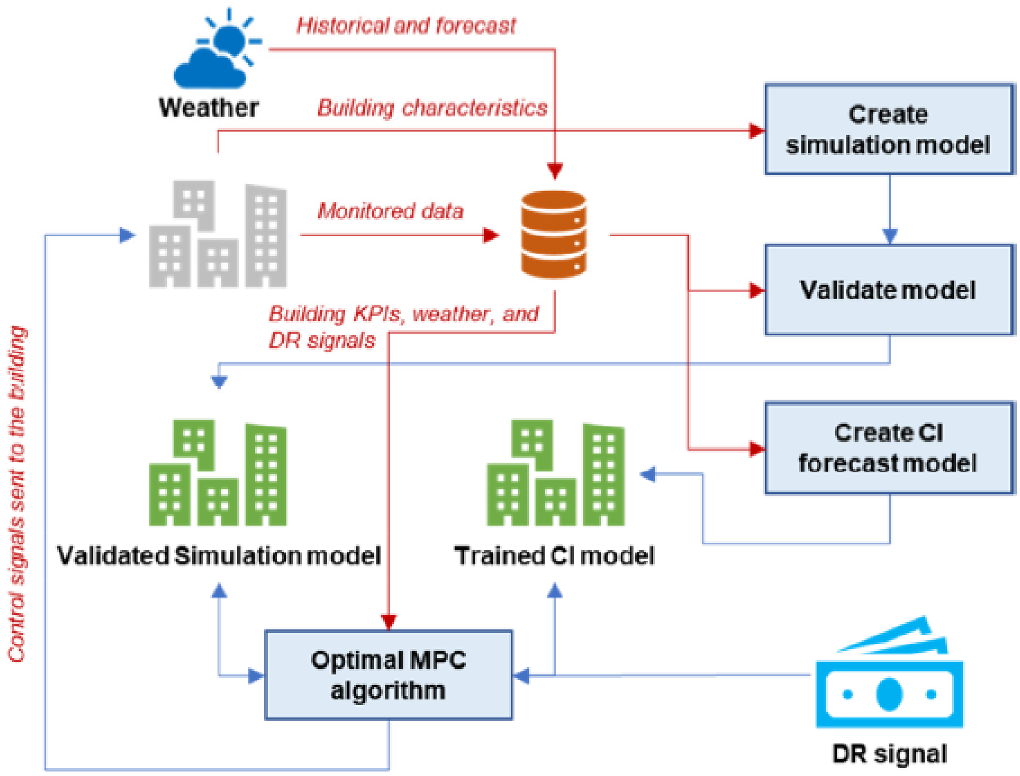

Figure 4.1: Simplified process and data-flow diagram for Model Prediction Control. Source: DRIvE H2020 (2018)

Consequently, the DRIvE H2020 project [10] is an example to address the building and district energy management by a distributed optimization where the energy network is modeled as a cooperation network that is distributed among different interacting agents. The alternating direction method of multipliers (ADMM) is the adopted as a central tool for optimization. In DRIvE, the ADMM optimization algorithm will be extended in order to:

* Participate in a transparent way to multiple Demand Response (DR) schemes
* Support the management of flexibility for Low-Voltage and Medium-Voltage assets (e.g. Virtual Power Plants (VPP), Energy Storage Systems (ESS), Combined Heat & Power (CHP), etc.)
* Provide new ancillary services (such as Congestion Management and power quality) to Distribution System Operators (DSOs) during the plan and validate phase

* Integrate home heating as an active load through the Model Predictive Control (MPC) module

* Interface with the real-time management components that intervene in the operate phase

Furthermore, the multi-agent algorithmic framework could be coupled with the Blockchain technology that will allow for peer-to-peer (P2P) payment transactions among participants. Several energy utility companies have taken interest in exploring the potential benefits of distributed ledger technologies (DLT), as an enabling technology for low-carbon transition and sustainability. This topic is not developed in this Master thesis but it is important to mention it for future technology considerations.

4.3 Local security

4.3.1 Industrial Network Protocols

According to Knapp et al [33], there are many highly specialized protocols used for industrial automation and control, most of which are designed for efficiency and reliability to support the economic and operational requirements of large industrial control system (ICS) architectures. Industrial protocols are real-time communications protocols, developed to interconnect the systems, interfaces, and instruments that make up an industrial control system.

Communication protocols provide the means to exchange data electronically and can be viewed as electronic languages. Just as there are many different human languages, there are many communication protocols, often developed to meet different types of requirements. They are also usually defined in layers although usually some of the layers can be combined in a particular standard. These layers consist of:

* Information models and profiles, which identify the types of data and their abstract formats, with a focus on the business purpose of the data. For instance, an information model can identify the data elements of 'phase voltage', 'energy price', and 'customer name'.

* Application layer protocols, which define the message structures (header, body, cybersecurity parts), services, and translation of the abstract data formats into 'bits and bytes'.

* Transport layer protocols, which provide the mechanisms for navigating through networks, such as across the Internet or within a local area network. The most common protocols used are the Internet Protocol (IP) which identifies the address of systems and devices, and the Transport Control Protocol (TCP) which ensures that even long messages that have been cut into pieces (e.g. for efficiency and for sharing the media) are correctly reassembled at the far end. Another common protocol is Ethernet, used primarily on local area networks.

* Media-specific protocols, which are tailored to manage the different characteristics of various media, such as fiber optic cables, microwave systems, WiFi, Bluetooth, etc.

More specifically, in the DR schemes the aggregators should be able to remotely access appliances or pre-determined loads, specified by the end-consumer, and be able to conduct load controls to extract a specified DR capacity. In addition to this, reasonable graphical user interfaces (GUI) must be made available to end-consumers by aggregators in order to communicate DR signals and allow for some level of end-consumer customization.

Advances in ICT/AMI have allowed the development of home energy management systems (HEMS) and building energy management systems (BEMS), which support interactive environments that allow effective control of consumer loads and enable effective communication abilities. AMI is defined as an infrastructure that measure, monitor, collect, and analyze data of energy parameters and the associated quality figures. This system can communicate with meters based on a coordinated schedule and with central distributed controllers. In some literature, these is an expectation for an AMI to activate two-way communication among several players in smart grids such as consumers, aggregators, retailers, and utilities to enable advanced intelligent functions within AMI.

4.3.2 Modbus

In the manufacturer webstite [34], Modbus is an application layer messaging protocol that allows efficient communications between interconnected assets based on a 'request/reply' methodology. Extremely simple devices, such as sensors or motors, use Modbus to communicate with more complex computers, which can read measurements and perform analysis and control.

To support a communication protocol on a simple device requires that the message generation, transmission, and receipt all require very little processing overhead. This same quality also makes Modbus suitable for use by PLCs and remote terminal units (RTUs) to communicate supervisory data to an ICS system. Modbus operates independently of underlying network protocols residing at Layer 3, allowing it to be easily adapted to both serial and routable network architectures.

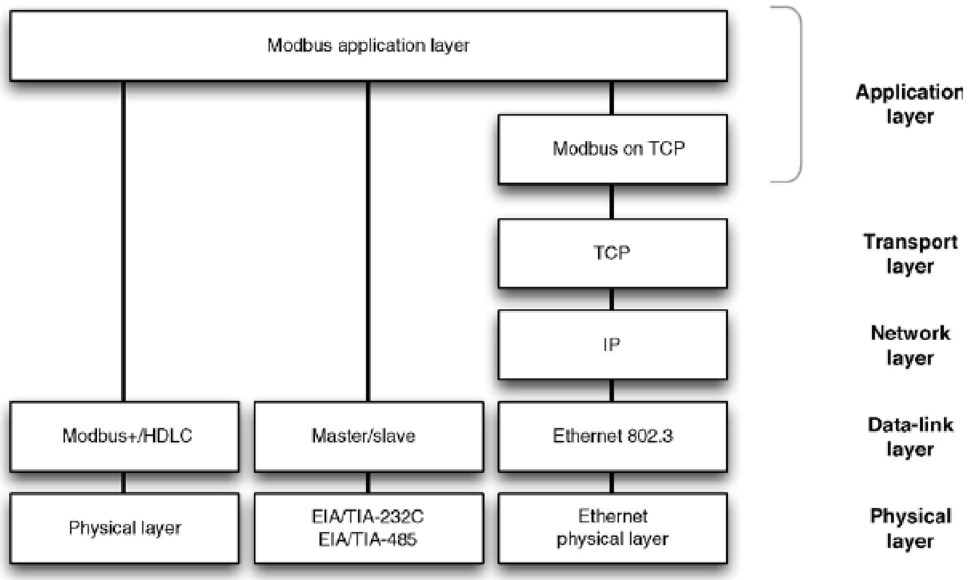

Figure 4.2: Modbus alignment with OSI 7-Layer model. Source: Modbus.org (2019)

Modbus TCP is a communication standard for measurement and control systems. Devices from different manufacturers can exchange data with each other via Modbus TCP that stands for Transmission Control Protocol and defines the way in which data is exchanged between the individual network components. TCP is part of the Internet protocol family, the basis of the Internet, and is therefore also called TCP/IP. Modbus TCP/IP communicates via Ethernet [34].

Modbus can also be transported over Ethernet using TCP in two forms. The basic form takes the original Modbus RTU ADU and applies a Modbus Application Protocol (MBAP) header to create a new frame. That is passed down through the remaining layers of the communication stack adding appropriate headers before being placed on the Ethernet network.

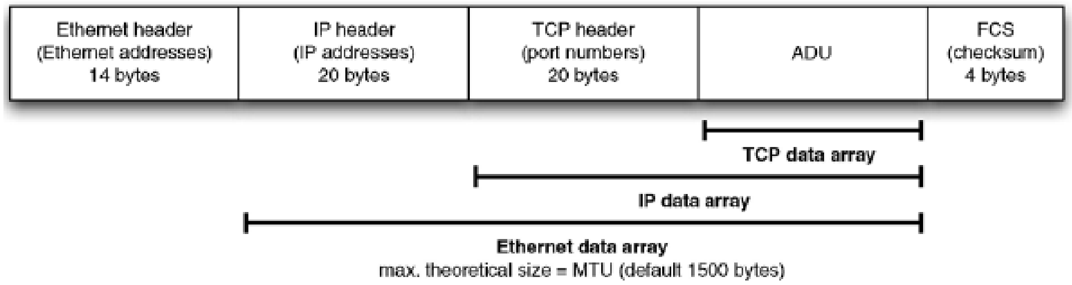

Figure 4.3: Modbus ADU. Source: Modbus.org (2019)

This form of protocol is very common with older, legacy devices that contain a Modbus RTU serial interface and are connected to a 'device server', which places this information on an industrial network and is received by a similar 'device server' converting it back to serial RTU form.

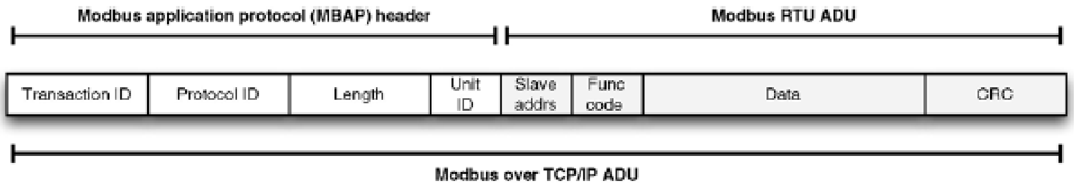

Figure 4.4: Modbus frame. Source: Modbus.org (2019)

Modbus TCP is the more common form and uses TCP as a transport over IP to issue commands and messages over modern routable networks. Modbus/TCP removes the legacy address and error checking. Modbus is used in multiple master-slave applications to monitor and program devices; to communicate between intelligent devices and sensors and instruments; to monitor field devices using PCs and HMIs.

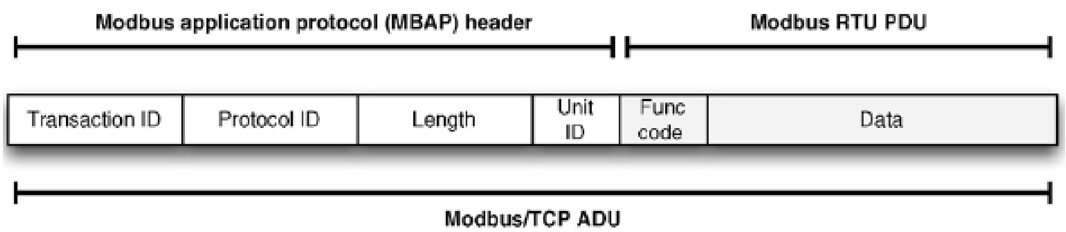

Figure 4.5: Modbus TCP. Source: Modbus.org (2019)

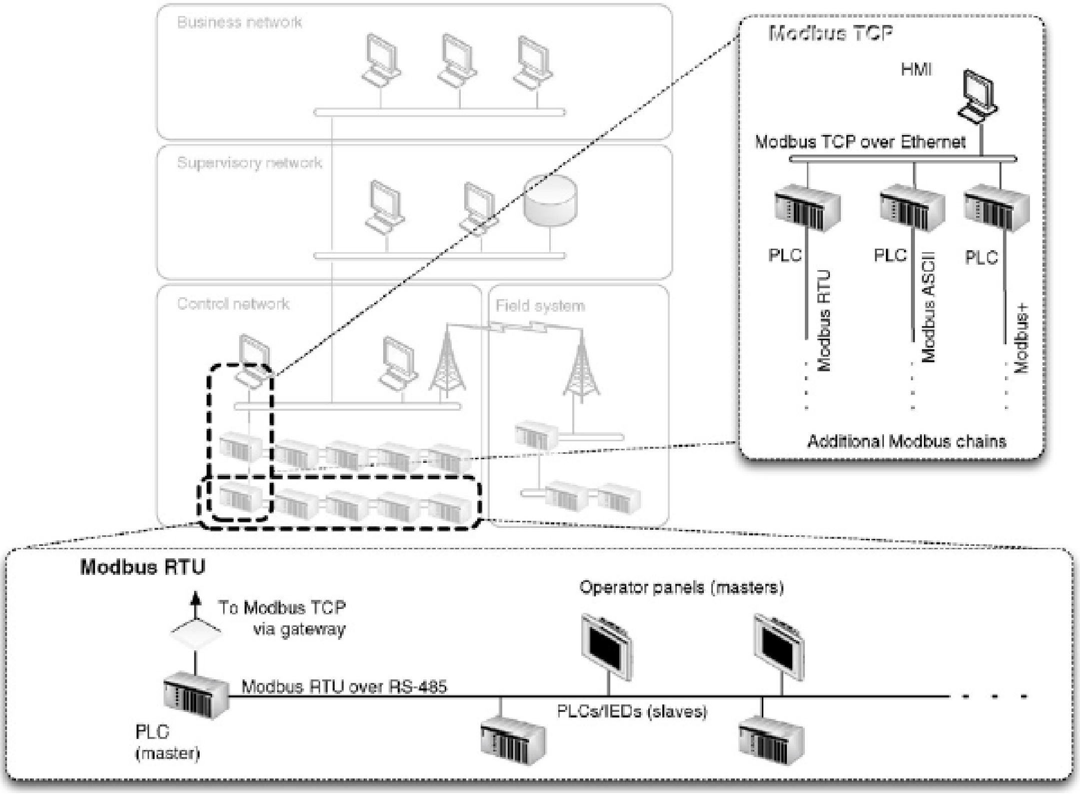

Figure 4.6: Modbus ICS. Source: Modbus.org (2019)

Modbus is also an ideal protocol for RTU applications where wireless communication is required. For this reason, it is used in other applications like building, infrastructure, transportation and energy applications also make use of its benefits. Modbus TCP/IP has become ubiquitous because of its openness, simplicity, low-cost development, and minimum hardware required to support it. There are several hundred Modbus TCP/IP devices available in the market and it is used to exchange information between devices, monitor, and program them. It is also used to manage distributed I/Os, being the preferred protocol by the manufacturers of this type of devices.

4.3.3 Open Charge Point Protocol (OCPP)

The ability of the software and hardware systems to interchange information is a key factor for the success of the electric vehicle industry. In this master thesis, the implementation of electric vehicles is not contemplated but a potential deployment of the business case including EVs can be possible, so it is important to emphasizes the communication protocols that can work with EVs. Standards have been developed and are in use to ensure base level interoperability of the front-end communication and signaling processes for smart charging between electric vehicles and charge stations. Electric charging stations have become a new target for attackers, which poses a risk to manufacturers and users.

According to Venkata P. [36], open standards and a shared infrastructure for EV charging are key in finding a satisfactory density of charging stations that also allow EVs to seamlessly operate across service areas or even countries. However, this procedure requires the coordination of a number of services, including: Metering and payment for energy, communication between the EV battery management system and the charge point (CP), communication between the CP and a central management system (CS), and communication between the CS and energy suppliers and the power grid.

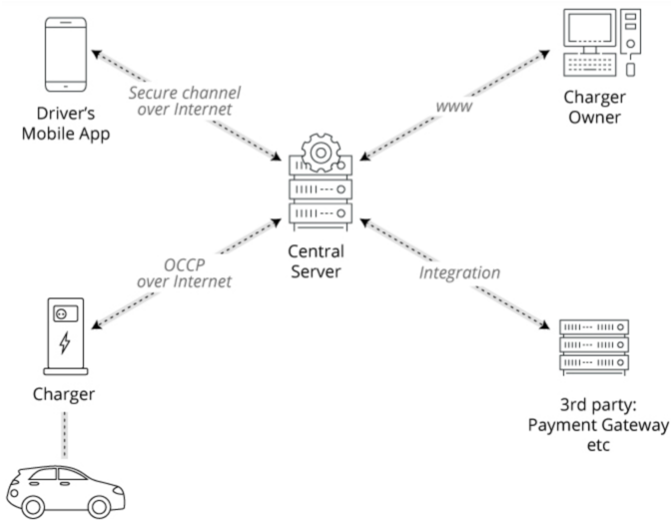

Figure 4.7: OCPP Diagram. Source: OCPP (2020)

These infrastructures, composed of mobile devices, autonomous entities and heterogeneous cyber-physical systems, require the standardization of protocols and the implementation of two primary interfaces, one for electricity and another for control related to status, authorization, metering, and billing. Concretely, the OCPP protocol is mainly concerned with reservations and management of charging processes with restricted security considerations, principally limited to ensuring that charging is performed only when authorized by a billing system.

One of the ways to ensure the security of these devices is by using secure communications that allow us to prevent incidents, such as enabled insecure services that could allow brute force attacks or code injection (HTTP, SOAP, among others). To do so, the Open Charge Alliance (OCA) [35], a group of European industries, have developed an open source common back-end protocol, called Open Charge Point Protocol (OCPP), for charging stations to reduce and secure overall investment costs. The OCPP intends to enable grid services based on smart charging. The Open Charge Alliance (OCA) enlist the current protocol types:

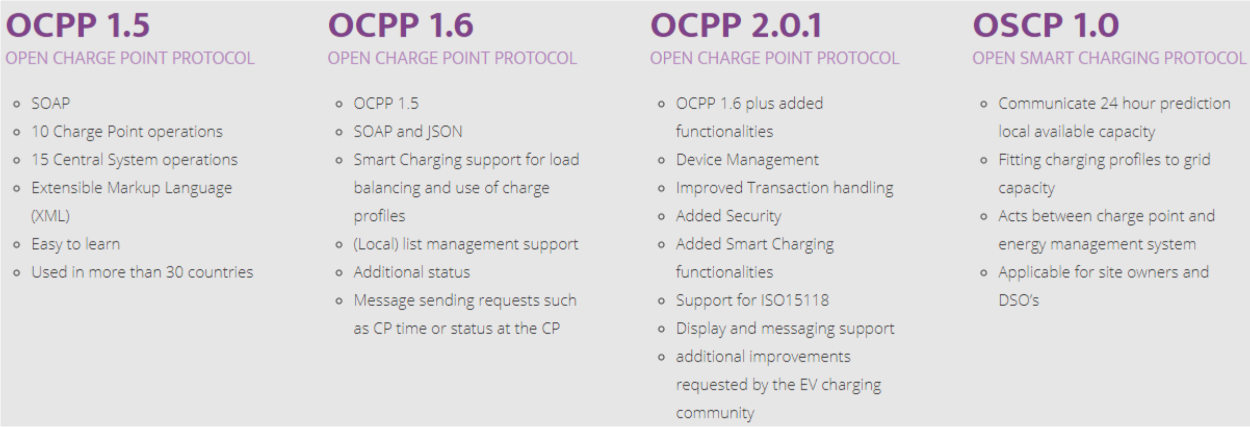

Figure 4.8: OCPP types. Source: Open Charge Alliance (OCA) (2020)

The local security at electric vehicle charging stations could cause problems for users, stations or central systems. It is therefore important to know how to identify, through security analysis, the possible attack vectors in communications using this type of protocol, which can be classified into different types:

* Physical aspects (hardware) regarding the charging stations, such as the physical breakage of the station.

* Aspects related to information technology (TCP/IP), both linked to the charging station and the backend system. Here we can find protocols that are not secure, such as HTTP, or other services that could be used, such as the mobile telephone, where during the data exchange the communication could be tapped and said information obtained.

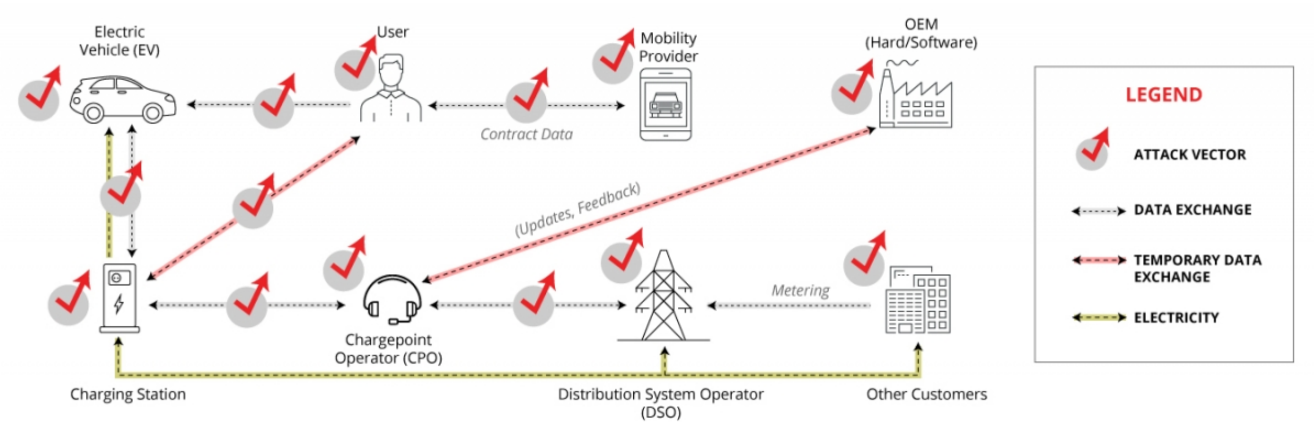

Figure 4.9: Attack Vectors in Charging Stations. Source: OCPP (2020)

The communications used between the charge point and the central station are secure so that there are no possible attack vectors creating a possible vulnerability. Therefore, the following improvements are recommended:

* Expand the OCPP protocol with digital signatures for greater security between charge points and central systems.

* Digital signatures add the possibility to verify the integrity of the entire electric vehicle infrastructure chain. Thus, when using digital signatures created from the charge points there will be no problems in the size of the chain.

* Using the public key of the corresponding charge point, we can verify the integrity of the digital signature.

* Using PKI (Public Key Infrastructure) with the use of digital signatures and certificates, although this will require more effort by the operator of the charge points.

The OCPP protocols, used in communications between charging stations and electric cars, allow a standardisation of communications that facilitates control in information exchange. These protocols should include improvements in its protection mechanisms in aspects such as the use of digital signatures, the use of PKI systems or in the process of fortifying its communications to deal with future cybersecurity challenges.

4.4 Supply Chain Risk Management (SCRM)

The lack of a cybersecurity strategy can threaten any business or breakthrough. A growing number of major companies have had to temporarily shut down their activity as a result of undetected malware attacks. Far from being isolated cases, such incidents are now quite common for smaller companies in every sector. So vast is the territory used by hackers that the World Economic Forum has ranked cybercrime as one of the top five global risks.

The unfolding and evolving risk landscape is fast moving and unpredictable, which is likely to leave some energy system players blind to emerging threats and less prepared if they continue to rely on passive normal system to provide energy security. New risks such as cybersecurity challenges to operation systems can overwhelm the unprepared where existing response strategies are not necessarily useful. Cyber and digital disruption exercises are essential to identify specific vulnerabilities and better understand where the organization, company or user needs to improve its overall cyber-risk management framework.

Integrated risk management and the search for dynamic resilience capabilities, explained in the section 2.7, show how prepared is a company, organization or user against malicious attackers or cyberthreats and also mention how the energy market players are contemplating a broader landscape of systemic and new risks to be anticipated such as increasing price volatility of energy, cybersecurity, vulnerability of the energy infrastructure and extreme weather events that could affect the energy supply goals.

The implementation of smart grids as a new technological development in a particular project, carry with it several concerns that must be enlisted to address particular risks, barriers and issues that confront the forward progress, adoption, and acceptance of this technology in the field of security.

1. **Stakeholder Engagement:**

   At the early stages of smart grid implementations, stakeholder's negative perceptions can derail even the most beneficial project, especially when the proponents fail to pay close attention to the educational aspects. Advocates need to be able explain and clearly identify the benefits of each component of the smart grid to the customers that are the potential key to service success.

2. **Security:**

   As a ke part of smart grids, the prominence of information technology may introduce new cyber-security vulnerabilities. Mitigating security risks is among the most important research and development smart grid activity. On this section, this important barrier must be understood in detail.

3. **High initial costs:**

   High unsustainable costs of pilot programs can act as obstacles to acceptance and adoption of smart grids and IoT technologies in the energy sector.

4. **Fear of obsolesce:**

   As many technology users (computers, smart phones, etc.) are painfully aware, the adoption of new tools can open the door to new and additional costs for the consumer. This fear can be addressed through the development of interoperability standards and backward compatibility of technologies.

5. **Privacy:**

   Insufficient oversight of how data are used increases the risk of potential consumer privacy violations. This concern needs to be addressed appropriately to gain consumer acceptance and trust.

Chapter 5

Conclusions

Tertiary buildings are a key source of energy flexibility due to their high energy demand and their possibilities for decentralized generation of energy from renewable sources. The impact of the solution proposed in this project, is optimizing the energy (flexibility) exchange within the COMSA building which leads to a more stable and efficient energy usage, so it stays reliable even when the decentralized renewable energy applications grow in future. The COMSA building pilot can grow towards a maximal level of sustainability and interoperability with the implementation of second-life batteries into its energy infrastructure. Moreover, optimized control using operational licenses and adequate ICT-IoT devices will also allow the comparison of energy use for different buildings and enables bench marking which will lead to an increased efficiency of the existing energy infrastructure.

COMSA Corporación as an implementer of this energy solution can increasingly produce and consume, some or all, its own energy produced as demonstrated in the Chapter 3, Subsection 3.5.1 about Time-of-Use (ToU) scheme, either instantaneously or in a deferred manner through a decentralized stationary energy storage, behind the connection point with the grid (i.e. the meter) and with this, have some extra revenues regarding the feed-in-tariff schemes. Moreover, the potential scalability of the solution regarding the Spanish energy framework could bring to COMSA several business opportunities within the tertiary building sector in the next years after analyzing the local energy market in EU.

The current cost difference between second-life batteries and new batteries is a very attractive proposition and will play a significant role in increasing the usage of second-life EV batteries in the next 10 years. These batteries will generate significant value and will bring down the cost for stationary energy storage applications. The EV batteries at EOL can be reused for the next 8-10 years in residential and tertiary buildings. Therefore, this project analyzed the two potential scenarios for the COMSA building pilot, (new and second-life battery), in which the most profitable scenario was the implementation of a second-life battery because of its initial CAPEX (lower battery price), and the possibility to couple this battery with the current energy and communication infrastructure that led the battery to operate without any faults.

A reduced initial investment due to the second-life battery prices in market, around 50% less, will carry out more advantages in future projects, in terms of a faster payback period, a positive NPV, and a better benefit cost ratio (BCR). The deployment of this business case study in other buildings with higher energy demand and similar surface(a minimum of 2000 m^2)

will give some benefits to consider for the building owners and users. A second-life battery can perfectly operate with some DR licenses apps (ADSM, WSM, ReDR) and also integrate other energy schemes like the Time-of-Use (ToU), increasing the energy savings, value of the building assets and annual monetary earnings around a 6.56 % rather than using a new battery as it was discussed in the results.

After the LCOE analysis calculations is demonstrated that using a second-life battery storage system plus a BIPV installation, the LCOE value will be around 33.05 €/MWh, a value that is lower than the average benchmarked value of 38.40 €/MWh in the current year 2020 for a typical energy storage + PV system project of this size. It is expected for the year 2021, the LCOE auction value will decrease making these projects more profitable, so this means that the implementation of a second-life battery in COMSA building will bring techno-economical benefits during the study period of the analysis.

Interoperability integrates technologies like EVs, HVACs, stationary energy storage (new and second-life batteries, water heaters, etc), customer devices (including automation and human interface) and AMI information models that could be deployed in the grid-interactive efficient buildings (GEBs), so it is necessary to integrate a more agile and adaptive response framework with a greater emphasis on resilience and rapid recovery in order to successfully develop interoperability standards. Moreover, there is a need for the energy industry to convey the benefits of interoperability to the final customers and empower them by seeking and obtaining additional benefits from their assets as the DR schemes pretend with 'prosumers' figure. The role of the customer is becoming more important, with the grid becoming more decentralized with intelligence embedded along the grid edge.

Chapter 6

Environmental Impact

According to the *"Circular Economy Action Plan"* written by the European Commission[24], a comparison using natural gas fuel or fossil-fuels for peak electrical power generation, around a 56% reduction in CO2 emissions is possible when an EV battery is re-purposed to store off-peak clean electricity to serve peak demand. The magnitude of CO2 mitigation associated with a second-life battery is similar to switch from using a conventional vehicle to an electric vehicle, meaning that the benefits of vehicle electrification could be doubled by extending the life of EV batteries, and better using off-peak low-cost clean electricity.

One of the main drivers for this project is the environmental feasibility of re-using electric vehicle (EV) batteries at their automotive end-of-life into stationary applications so, the life of a lithium ion (Li-ion) EV battery is extended to incorporate the re-purposing and re-use in grid storage for a utility application. In the battery recycling process, energy for the extraction, processing, manufacturing and delivery of lithium-ion batteries is known by the research community as embodied energy so, CO2 emissions from the production of lithium-ion batteries are a concern. At the same time, re-purposing lithium-ion batteries could help to avoid CO2 emissions associated with the extraction and transportation of raw materials in the recycling process but also in other stationary storage applications in buildings.

As stated in the Chapter 3, in a second-life application a specialized company re-purposes the battery cells for a new use without completely dismantling them, often in combination with a new set of power electronics, software, and housing structure. The re-purposing process consist of a (limited level of) disassembly, testing for degradation and failure, state of health (SoH), the energy consumption to perform a complete charge/discharge cycle for each module is considered and finally the re-packaging. Moreover, dismantling of the cells within a vehicle battery pack is neither technically nor economically feasible, therefore it is expected that packs will be re-purposed at the pack or module level. In the end, a new packaging guarantees the safety conditions in the second-use applications.

Whereas recycling focuses on the value of the battery's metal content, second-life applications focus on the value of re-purposing a partially used battery. As noted above, when a battery capacity is between 90% to 20% of its rated capacity, it can be used as second-life battery. By staying on top of the changes and designing strategies that develop within this circular economy, participants across the value chain can ensure the commercial and environmental sustainability of EV batteries.

Additionally, a calculation about the amount of reduced tCO2 eq./MWh regarding the implementation of a battery energy storage system (BESS) plus a BIPV installation in the COMSA building is made. In terms of CO2 emissions reduction, the Red Eléctrica de España (REE) shows a factor of 0.11 tCO2 eq./MWh at 27/10/2020 from the Spanish national generation system in the Figure 6.1:

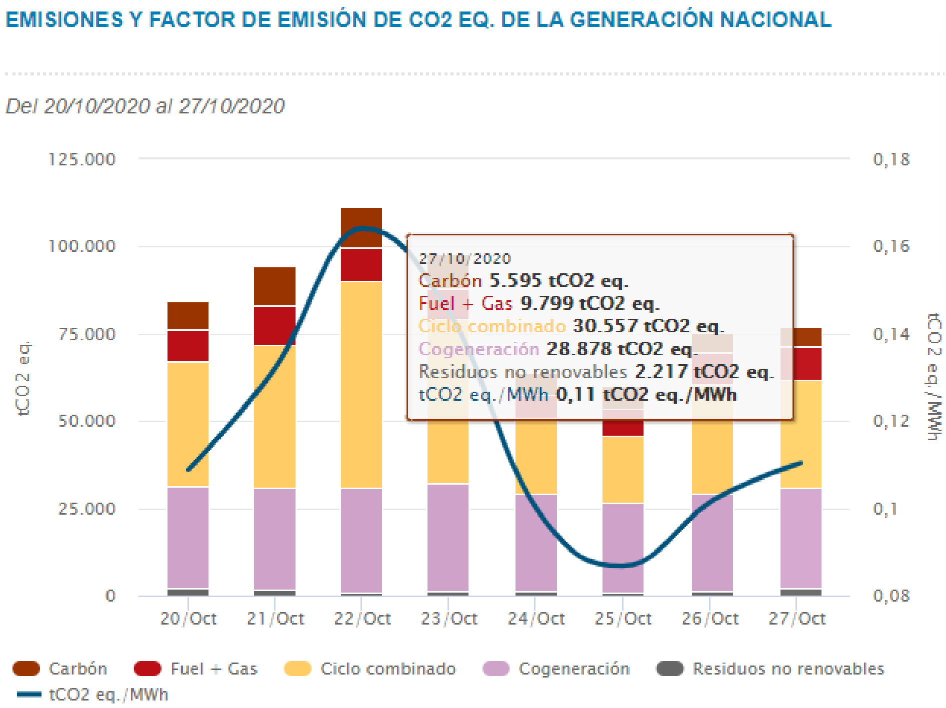

Figure 6.1: Equivalent CO2 emissions tonnes per MWh from Spanish national generation system - 27/10/2020. Source: REE (2020)

COMSA Building - Environmental Impact		
Building area	2600	m2
Energy consumption	360000	kWh/year
Annual Energy Savings	36959.43	kWh/year
Energy savings	10.27%	%
tCO2 eq./MWh from Red Eléctrica España (REE)	0.11	tCO2 eq./MWh
tCO2 emissions produced	39.6	tCO2eq/year
tCO2 emissions reduced	4.07	tCO2eq/year
Consumption per surface in building	138.46	kWh/m2
Energy Savings per surface in building	14.22	kWh/m2

Figure 6.2: Environmental Impact, equivalent CO2 emissions tonnes per MWh at COMSA Building. Source: Author (2020)

In this analysis, the Figure 6.2 shows that with annual energy savings of 36959.43 kWh/year produced by the application of a ToU scheme (see Chapter 3, Section 3.5.1) will represent a 10.27% from the total energy consumption of the COMSA building. The amount of equivalent CO2 tonnes per year due to the implementation of the proposed solution will reduce around 4.07 tCO2 eq./year from the 39.6 tCO2 eq./year of the total consumption. It is clearly seen an environmental impact regarding the project implementation of this case study.

Chapter 7

Budget

The budget for the development of this master thesis is detailed in this chapter. The budget is divided in three branches (Tools and Devices, Software and Human Resources) and the costs are calculated for the time frame of the project (7 months) in the current year.

1. **Tools and Devices Budget:**

   This budget considers the tools and devices used and are amortized in a period of 4 years and they are shown in Table 7.1:

   Table 7.1: Tools and Devices Budget:

Item	Unit Price	Unit	Amortized Cost
Laptop HP	€ 800	1	€ 114.28
Wireless Mouse Logitech	€ 15	1	€ 2.14
Total			**€ 116.42**

2. **Software Budget:**

   This budget considers the softwares used and are amortized in a period of 4 years and they are shown in Table 7.2:

   Table 7.2: Software Budget:

Item	Unit Price	Unit	Amortized Cost
MS Office 365 License	€ 100	1	€ 14.28
McAfee Antivirus	€ 40	1	€ 5.72
Matlab + Simulink License	€ 400	1	€ 57.14
Total			**€ 77.14**

3. **Human Resources Budget:**

   For the Human Resources budget, it is considered the number of hours dedicated for the academic case study design, programming in Matlab and MS Excel also the writing of the document from scratch. In the Table 7.3 all the data for this budget is enlisted:

Table 7.3: Human Resources Budget:

Activity	**Price per hour**	**Hours**	**Total**
Academic case study design	9 €/h	250	€ 2250
Programming	9 €/h	150	€ 1350
Document Writing	9 €/h	250	€ 2250
Total			**€ 5850**

4. **Total Budget:**

   Finally in the Table 7.4, all the budgets are calculated with a VAT and the final budget for the development of the project is:

Table 7.4: Total Budget:

Budget	**Total**
Tool and Devices Budget	€ 116.42
Software Budget	€ 77.14
Human Resources Budget	€ 5850
Total without VAT	€ 6043.56
VAT (21%)	€ 1269.15
Total Budget	**€ 7312.71**

Appendices

Appendix A

Business Model Canvas and Market analysis

A.1 BESS with second-life batteries - Business Model Canvas (BMC)

SWOT Analysis	Internal Factors	
	Strengths	**Weaknesses**
	Second-life battery technologies as ESS in buildings	Not experienced partners to develop this technology
	Advanced ICT and battery costs plummeted (second-life batteries)	Low capacity of energy flexibility by prosumers
	Diversification of the energy mix and mitigate risks	Low customer awareness of dynamic electricity price
	Using EVs to provide fast response and high power capacities	Existing V2G infrastructure is very limited
External Factors		
Opportunities	**Attack (S-O) Strategies**	**Reinforce (O-W) Strategies**
Provide flexible capacity to integration of renewable energy resources and make profit	Cost reduction strategies and packages of control system and DER equipment	Aggregation of consumers by DR programs and energy solutions accesibility
Forecasting mechanisms by integrating end-consumer technology and loads	Easy, user-friendly and cutting-edge control systems	Software support for forecast and data analysis
Increase customer awareness about energy consumption and solutions (second-life batteries)	Tailor-made maintenance and energy consulting services	Marketing strategies to improve awareness of energy solutions
Increase the Technology Readiness Levels (TRLs) of the business unit	Take advantage of lower costs of technologies and deploy fast in the market before competitors	Tailormade contracts and payment schemes for customers
Offer peak load services to system operators to maintain grid reliability	Apply a better congestion management	Incentives from regulators, TSOs /DSOs
Threats	**Develop (S-T) Strategies**	**Avoid (W-T) Strategies**
Regulation and framework barriers creating uncertain business environments	Regulation changes that allow access to the balancing markets	Create technology awareness and provide updates about situation via webinar and workshops
Lack of smart meter communication standards can minimize potential for economies of scale	Energy consulting and service (training) regarding consumer behaviour	Maintain customers updated about the energy and technology market
End-consumers concerns of their electrical consumption data to external market participants	Increase the social acceptance of the idea via good marketing strategies	Provide periodic data performance reports to customers
Slow ROI and payback period	Increase the number of customers, partnerships and maximize profit	Add BESS and V2G infrastructure to increase the revenues from balancing markets

Figure A.1: SWOT analysis. Source: Author (2020)

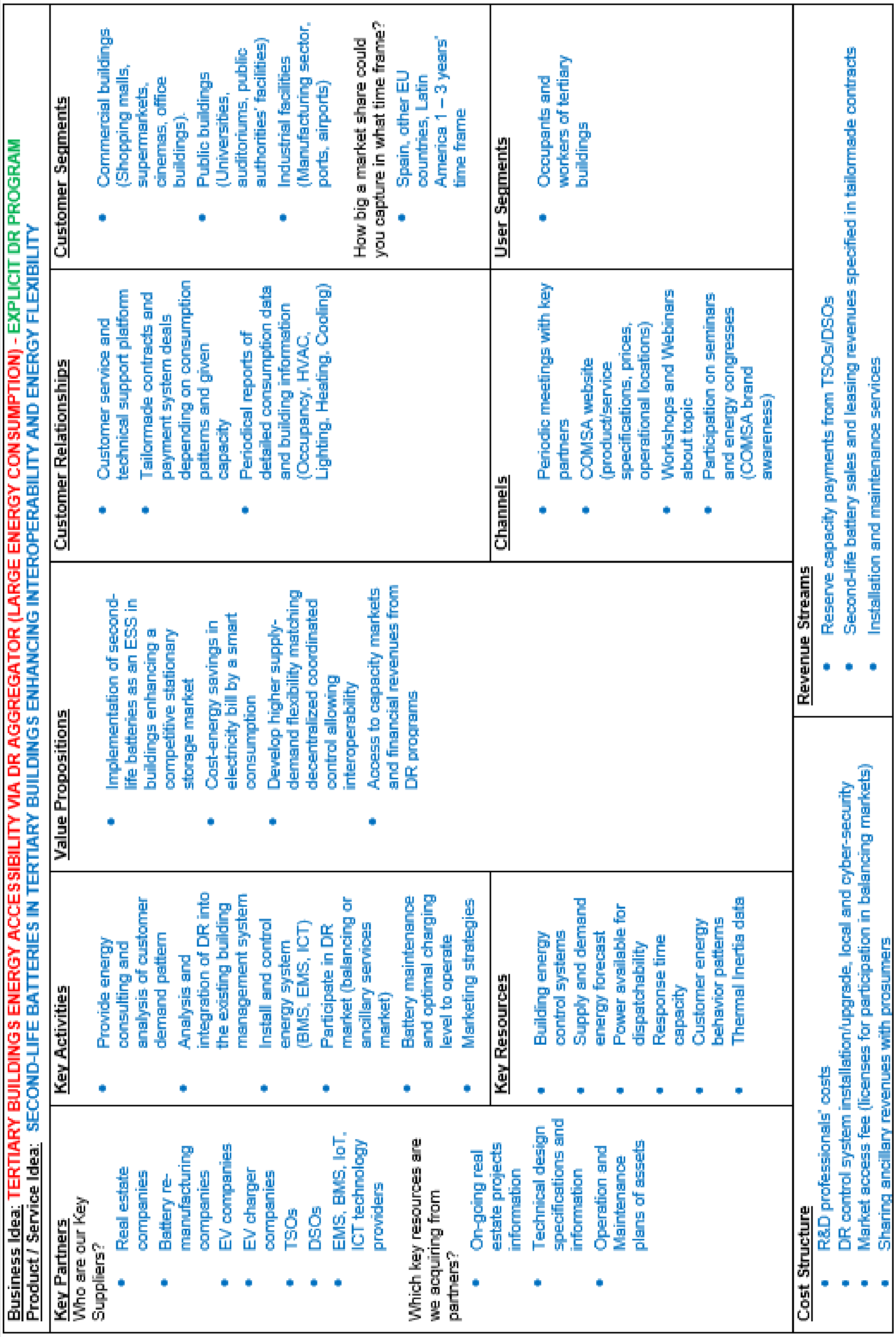

Figure A.2: Business Model Canvas (BMC) - Explicit DR via an Aggregator, large energy consumption including EVs. Source: Author (2020)

A.2 Balancing Market Services

BALANCING MARKETS SERVICES							
Type	**Description**	**Timeframe**	**Assets used**	**Users of the service**	**Market based or Regulated tariff?**	**Pricing method**	**Process overview**
Frequency Containment Reserves (FCR)	'FCR' means the active power reserves available to contain system frequency after the occurrence of an imbalance. TSOs and DSOs are obligated to cooperate in order to facilitate and enable the delivery of aFRR by units located in the distribution systems.	10-30 seconds	Generators, Load, pump storage and batteries	TSO	Regulated tariff: In ES and IT, generators connected to grid obligated to meet an amount of capacity for TSO requirements	Only reservation is paid. Short and fast activations lead to payments cancelled out.	*1. Prequalification:* FCR provider submits formal application to TSO and meet requirements. *2. Bidding/Selection:* Self-dispatch or unit-based dispatch. *3. Delivery:* FCR activated for defined timeperiod when deviation persists. *4. Settlement:* EU bases on a target approach, TSO-BSP settlement on Marginal Price. *5. Monitoring:* Ex-post checks and real-time monitoring
Automatic Frequency Restoration Reserve (aFRR)	This service is a centralised automatic function intended to replace FCR and restore the frequency to the target frequency – (50 Hz). aFRR 'can be activated by an automatic control device'.	Activation time: preparation period (Noe energy delivered) and ramping period	Generators, Storage Demand Response (DR)	TSO	Market based	Regulated price (FR, DK), Pay as bid (DE, IT, Central EU), Marginal pricing (ES, PT, NL and RO)	*1. Prequalification:* aFRR provider submits formal application to TSO and meet requirements. *2. Bidding/Selection:* aFRR balancing product bids to the TSO. *3. Activation:* aFRR is automatic. Setpoints signals sent to BSP depending on aFRR demand. *4. Selection:* Bid selection and then merit order lists managed by optimisation algorithm. *5. Settlement:* Marginal Price (SE, RO, GR, ES, PT), Regulated Pricing (FR, PO, SR), Pay as bid (Central EU, Nordics) TSO-DSO and TSO-BSPs settlement.
Manual Frequency Restoration Reserve (mFRR)	A manual change in the operation set-points of the reserve (mainly by re-scheduling), in order to restore system frequency to the set point value frequency and, for a synchronous area consisting of more than one load-frequency control area, to restore power balance to the scheduled value.	10 minutes (cross-border exchange), maximum of 12.5 minutes	Generators, pump storage, batteries	TSO	Market based	Pay as bid in Central EU and Marginal prices in others	*1. Prequalification:* TSO develops a prequalification process, formal application to TSO. *2. Bidding:* two types: 'Scheduled only' (scheduled activation) and 'Direct' (scheduled and at anytime during 15 minutes after scheduled activation. *3. Activation:* mFRR follows merit orders from lowest to highest marginal production costs. *4. Settlement:* Pay as bid and Marginal Price (Nordics and Iberian peninsula). TSO-DSO and TSO-BSPs settlement *5. Monitoring:* Real-time monitoring (DE, RO, SE), ex-post check (FR, NL, A), hybrid (ES, NO, GR)
Replacement reserves (RR)	The RR process replaces the activated FRR and/or complements the FRR activation by activation of RR. The replacement reserve process is activated in the disturbed LFC area. Activation is semi-automatic or manual.	Full activation: 30 minutes, Ramping from 0 to 30 minutes	Load	TSO	Market based	Marginal pricing (ES, RO, FR), Pay as bid (UK, CH, HU)	*1. Prequalification:* TSO develops a prequalification process, formal application to TSO. *2. Bidding:* TSO receives offers from BSPs (dispatching model, integrating scheduling bids) *3. Selection:* Algorithm that performs clearing of consumers curve vs supply curve. *4. Activation:* by TSO via manual and scheduled approaches. *5. Settlement:* TSO-TSO and TSO-BSPs settlement *6. Monitoring:* Ex-post checks and a combination of ex-post and real time monitoring.
Fast frequency reserves (FFR)	FFR is defined as any type of rapid active power increase or decrease by generation or load, in a timeframe of less than 2 seconds, to correct supply-demand imbalances and assist with managing frequency.	Full activation 49.6 Hz, 2 seconds. Duration 30 seconds (minimum time), maximum 15 minutes	Synchronous condensers, batteries, DR	TSO	Market based	Pay as bid (NO) and Marginal Price	*1. Prequalification:* Depends on provider (Demand Response, Power Plan, Hydro power plant) tested and provision of FR *2. Bidding / Selection:* *4. Activation:* aFRR at 49.6 Hz. *5. Settlement:* TSO-TSO and TSO-BSPs settlement
Ramp control	Ramp control or ramping margin is a new service that is intended to ensure system stability by responding to variations in demand, variable weather forecast errors and plant outages.	Up to 8-hour ramping period with 8 hours of maintaining level of production.	Dispatchable assets	TSO	Interim tariff proposal, Market-wide tariff	Availability payment	*1. Prequalification:* Product unit has to pass system service test proving its capabilities. *2. Bidding / Selection:* *4. Activation:* Dispatched. *5. Settlement:* TSO-TSO and TSO-BSPs settlement. Market-wide 'availability' tariff plus costs and regulated rate, depends on performance.
BRP portofolio balancing	BRP has the obligation to balance his own position. This volume of energy could be produced by generation units in the BPR's portfolio but could also be imported or bought on the market. By balancing his own position, the BRP contributes to the balance of the electricity system.	0-2 hours ahead of operation interval	Generators, Storage Demand Response (DR)	BRP	Market based	-	BRP- Service Provider Settlement

Figure A.3: Balancing Market Services in Europe. Source: Author (2020)

Appendix B

Battery Sizing Model

B.1 COMSA Corporación office building site - Sizing Model

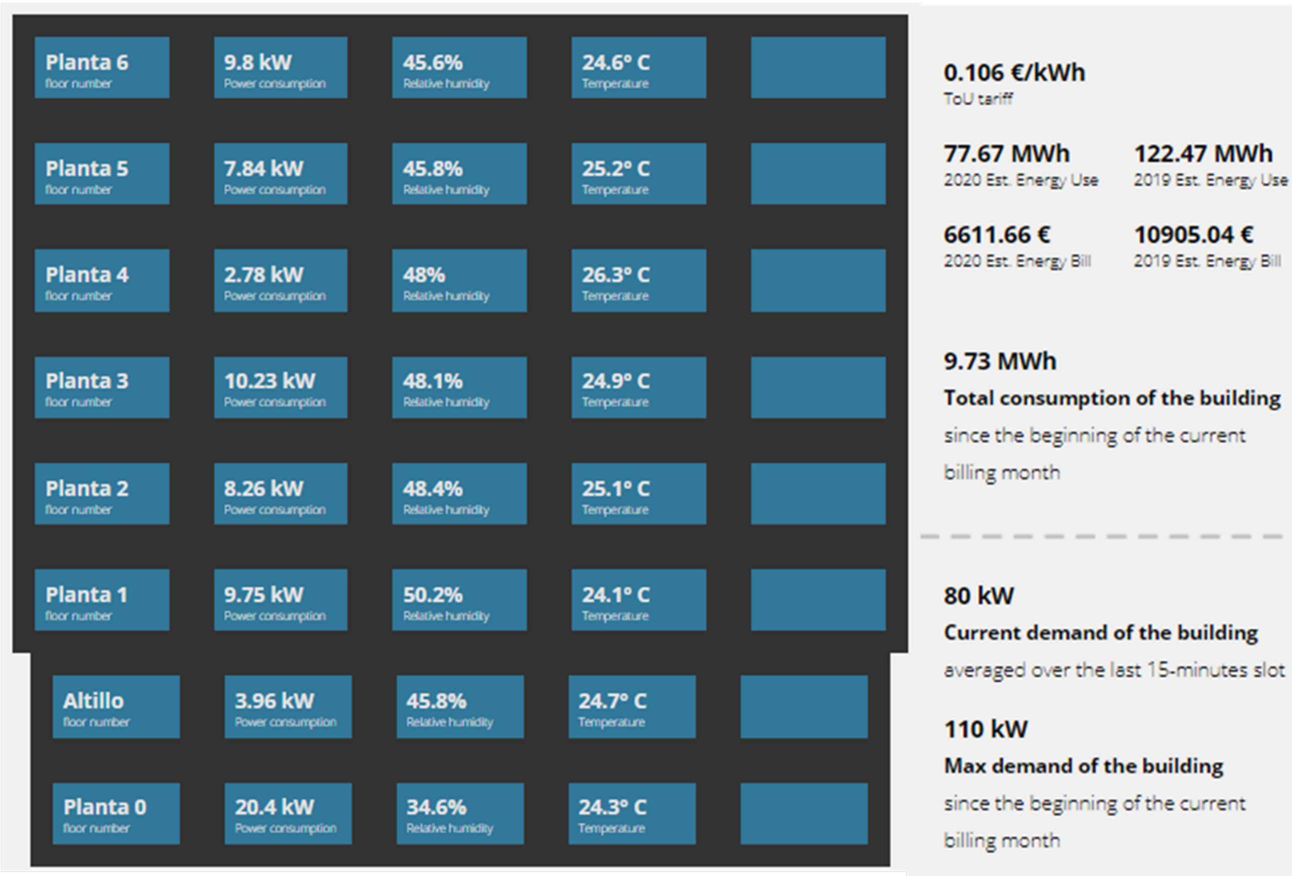

Figure B.1: COMSA office building data consumption per floor. Source: COMSA Corporación - iLECO server (2020)

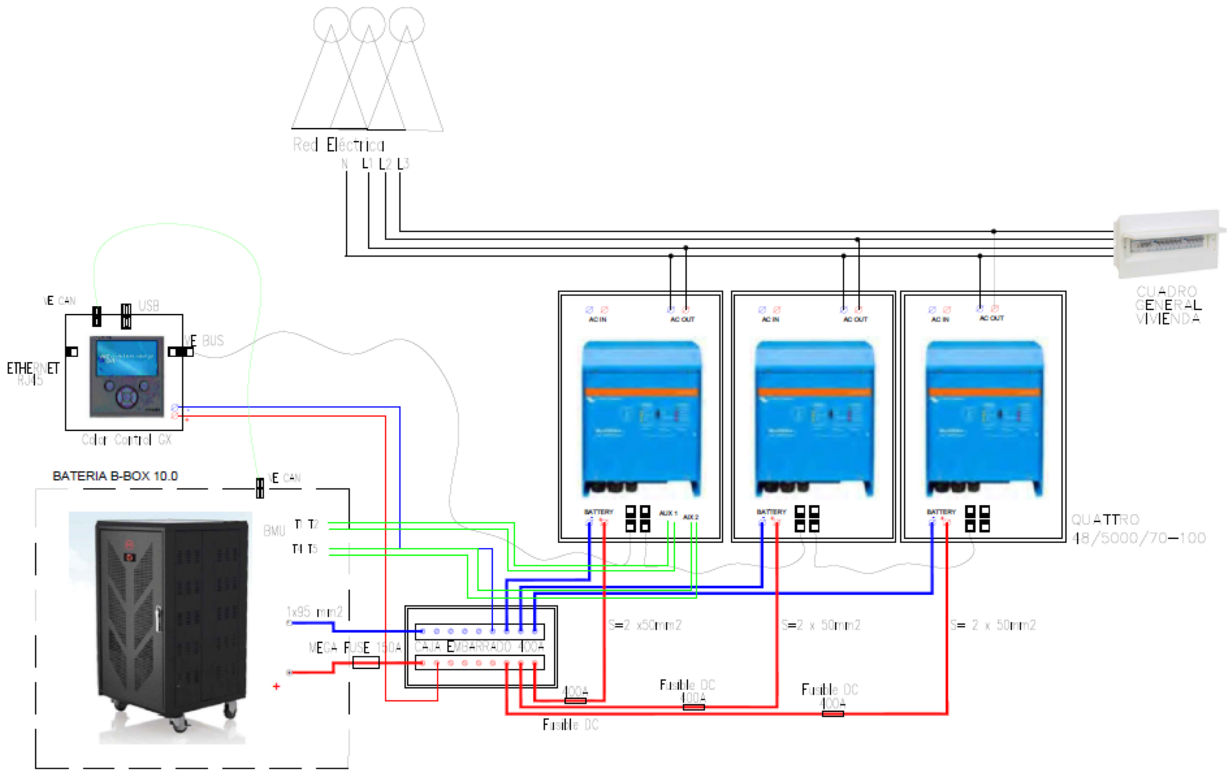

Figure B.2: System configuration at COMSA building. Source: COMSA (2020)

	Battery-Box L 3.5	Battery-Box L 7.0	Battery-Box L 10.5	Battery-Box L 14.0
Battery module	B-Plus L 3.5 (3.5 kWh) 1 module	2 modules	3 modules	4 modules
Usable Energy [1]	3.5 kWh	7.0 kWh	10.5 kWh	14.0 kWh
Max Output Power	3.0 kW	6.0 kW	9.0 kW	10.0 kW
Peak Output Power	5.0 kW, 10 s	10.0 kW, 10 s	15.0 kW, 10 s	15.0 kW, 10 s
Round-Trip Efficiency	≥95.3 % [1]			
Nominal Voltage	51.2 V			
Operating Voltage Range	40~59.2 V			
Communication	RS485 / CAN			
Dimensions (W/H/D)	620 x 475 x 320 mm	620 x 711 x 320 mm	620 x 947x 320 mm	620 x 1183 x 320 mm
Weight	65 kg	108 kg	151 kg	194 kg
Enclosure Protection Rating	IP55			
Warranty	10 years			
Operating temperature [2]	-10 ℃ to +50℃			
Certification & Safety Standard	UN 38.3/ UL1642, is currently being certified: TUV(IEC62619) / CE / RCM / VDE2510 / Sicherheitsleitfaden			
Scalability	Max. 3 systems in parallel / 42 kWh			
Compatible Inverters	SMA / GOODWE / Victron / Sungrow / Selectronic, more brands to be announced			
Application	ON Grid / ON Grid + Backup (Refer to BYD Minimum Configuration List)			

[1] Test conditions: 100% DOD, 0.2C charge & discharge at + 25 ℃
[2] -10 ℃ to 10 ℃ will be derating

Figure B.3: BYD Battery Box L 14.0. Source: BYD Battery Box (2020)

MultiPlus 12 voltios 24 voltios 48 voltios	C 12/800/35 C 24/800/16	C 12/1200/50 C 24/1200/25	C 12/1600/70 C 24/1600/40	C 12/2000/80 C 24/2000/50	12/3000/120 24/3000/70 48/3000/35	24/5000/120 48/5000/70
PowerControl	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**
PowerAssist	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**
Conmutador de transferencia (A)	**16**	**16**	**16**	**30**	**16 ó 50**	**100**
Funcionamiento en paralelo y en trifásico	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**	**Sí**
INVERSOR						
Rango de tensión de entrada (V CC)	9,5 – 17 V 19 – 33 V 38 – 66 V					
Salida	Tensión de salida: 230 VAC ± 2% Frecuencia: 50 Hz ± 0,1% (1)					
Potencia cont. de salida a 25 °C (VA) (3)	800	1200	1600	2000	3000	5000
Potencia cont. de salida a 25 °C (W)	700	1000	1300	1600	2500	4500
Potencia cont. de salida a 40 °C (W)	650	900	1200	1450	2200	4000
Pico de potencia (W)	1600	2400	3000	4000	6000	10.000
Eficacia máxima (%)	92 / 94	93 / 94	93 / 94	93 / 94	93 / 94 / 95	94 / 95
Consumo en vacío (W)	8 / 10	8 / 10	8 / 10	9 / 11	15 / 15 / 16	25 / 25
Consumo en vacío en modo de ahorro (W)	5 / 8	5 / 8	5 / 8	7 / 9	10 / 10 / 12	20 / 20
Consumo en vacío en modo de búsqueda (W)	2 / 3	2 / 3	2 / 3	3 / 4	4 / 5 / 5	5 / 6
CARGADOR						
Entrada CA	Rango de tensión de entrada: 187-265 V CA Frecuencia de entrada: 45 – 65 Hz Factor de potencia: 1					
Tensión de carga de 'absorción' (V CC)	14,4 / 28,8 / 57,6					
Tensión de carga de flotación (V CC)	13,8 / 27,6 / 55,2					
Modo de almacenamiento (V CC)	13,2 / 26,4 / 52,8					
Corriente de carga batería casa (A) (4)	35 / 16	50 / 25	70 / 40	80 / 50	120 / 70 / 35	120 / 70
Corriente de carga batería de arranque (A)	4 (solo modelos de 12 y 24V)					
Sensor de temperatura de la batería	sí					
GENERAL						
Salida auxiliar (A) (5)	n. d.	n. d.	n. d.	n. d.	Sí (16A)	Sí (25A)
Relé programable (6)	Sí					
Protección (2)	a - g					
Puerto de comunicacion VE.Bus	Para funcionamiento paralelo y trifásico, supervición remota e integración del sistema					
Puerto com. de uso general (7)	n. d.	n. d.	n. d.	n. d.	Sí (8)	Sí
Remote on-off	Sí					
Características comunes	Temperatura de funcionamiento: -20 a + 50ºC (refrigerado por aire) Humedad (sin condensación) : máx. 95%					
CARCASA						
Características comunes	Material y color: aluminio (azul RAL 5012) Categoría de protección: IP 21					
Conexiones de la batería	cables de batería de 1,5 metros			Pernos M8	Cuatro pernos M8 (2 conexiones positivas y 2 negativas)	
Conexión 230 V CA	Conector G-ST18i			Abrazadera de resorte	Bornes de tornillo de 13 mm.² (6 AWG)	
Peso (kg)	10	10	10	12	18	30
Dimensiones (al x an x p en mm.)	375x214x110			520x255x125	362x258x218	444x328x240

Figure B.4: Inverter Victron MultiPlus-II. Source: Victron (2020)

B.2 Time-of-Use (ToU)

Time-of-Use (ToU) COMSA Building							
	Stored energy produced by PV system			Rate Schedule			Period Savings
Months	PV generated energy (kWh)	PV stored energy battery (kWh)	PV surplus energy (kWh)	P3 - Off-Peak (€/kWh)	P2 - Mid-Peak (€/kWh)	P1 - Peak (€/kWh)	Savings (€)
January	2435.34	420	2015.34	€ 0.07664	€ 0.10131	€ 0.10787	€ 249.58
February	2546.71	420	2126.71	€ 0.07664	€ 0.10131	€ 0.10787	€ 261.60
March	3298.83	420	2878.83	€ 0.07664	€ 0.10131	€ 0.10787	€ 342.73
April	3339.44	420	2919.44	€ 0.07664	€ 0.10131	€ 0.10787	€ 347.11
May	3697.90	420	3277.90	€ 0.07664	€ 0.10131	€ 0.10787	€ 385.78
June	3701.45	420	3281.45	€ 0.07664	€ 0.10131	€ 0.10787	€ 386.16
July	3798.12	420	3378.12	€ 0.07664	€ 0.10131	€ 0.10787	€ 396.59
August	3658.82	420	3238.82	€ 0.07664	€ 0.10131	€ 0.10787	€ 381.56
September	3146.54	420	2726.54	€ 0.07664	€ 0.10131	€ 0.10787	€ 326.30
October	2766.54	420	2346.54	€ 0.07664	€ 0.10131	€ 0.10787	€ 285.31
November	2262.69	420	1842.69	€ 0.07664	€ 0.10131	€ 0.10787	€ 230.96
December	2307.05	420	1887.05	€ 0.07664	€ 0.10131	€ 0.10787	€ 235.74
Yearly PV energy production (kWh)	36959.43	5040.00	31919.43	Time-of-Use (ToU)			€ 3,829.41
Building Demand/year (kWh)	360000			Annual Energy Cost (AEC)			€ 36,360.00

Figure B.5: COMSA PV installation - ToU savings using new battery. Source: Author (2020)

Stored energy produced by PV system				Rate Schedule			Period Savings
Months	PV generated energy (kWh)	PV stored energy battery (kWh)	PV surplus energy (kWh)	P3 - Off-Peak (€/kWh)	P2 - Mid-Peak (€/kWh)	P1 - Peak (€/kWh)	Savings (€)
January	2435.34	336	2099.34	€ 0.07664	€ 0.10131	€ 0.10787	€ 252.21
February	2546.71	336	2210.71	€ 0.07664	€ 0.10131	€ 0.10787	€ 264.22
March	3298.83	336	2962.83	€ 0.07664	€ 0.10131	€ 0.10787	€ 345.35
April	3339.44	336	3003.44	€ 0.07664	€ 0.10131	€ 0.10787	€ 349.73
May	3697.90	336	3361.90	€ 0.07664	€ 0.10131	€ 0.10787	€ 388.40
June	3701.45	336	3365.45	€ 0.07664	€ 0.10131	€ 0.10787	€ 388.78
July	3798.12	336	3462.12	€ 0.07664	€ 0.10131	€ 0.10787	€ 399.21
August	3658.82	336	3322.82	€ 0.07664	€ 0.10131	€ 0.10787	€ 384.18
September	3146.54	336	2810.54	€ 0.07664	€ 0.10131	€ 0.10787	€ 328.92
October	2766.54	336	2430.54	€ 0.07664	€ 0.10131	€ 0.10787	€ 287.93
November	2262.69	336	1926.69	€ 0.07664	€ 0.10131	€ 0.10787	€ 233.58
December	2307.05	336	1971.05	€ 0.07664	€ 0.10131	€ 0.10787	€ 238.37
Yearly PV energy production (kWh)	36959.43	4032.00	32927.43	Time-of-Use (ToU)			€ 3,860.89
Building Demand/year (kWh)	360000			Annual Energy Cost (AEC)			€ 36,360.00

Figure B.6: COMSA PV installation - ToU savings using second-life battery (SLB). Source: Author (2020)

Appendix C

Techno-Economic Model

C.1 Data and calculations - Excel Model

CELL COLOR CODE
Catalog Data
Input Data
Results

Figure C.1: Cell Color Code. Source: Author (2020)

CALCULATION OF ENERGY STORAGE CAPACITY FOR A LARGE BUILDING		
Battery Catalog Specifications		
Initial Parameters	Values	Units
Type of Battery	NEW BATTERY	
Brand	BYD	
Model	B-Plus L 14.0 (14 kWh)	
Battery Type	LiFePO4	
Nominal Voltage	51.2	V (max)
Specific Energy	1891	Wh/kg
Weight	194	kg
Ampere hours	7165.12	Ah
Charge & Dicharge Duration (0.2C)	5	hours
Current	1433.02	A
Maximum Discharge Pulse Current	10	seconds
State of Health (SoH) - %	100%	%
State of Charge (SoC) - %	100%	%
Depth of Discharge (DoD) - %	0%	%
Battery Lifetime (@ 0.2C) - Warranty	10	years
Battery Cycles	1	cycles/day
Battery Cycles	30	cycles/month
Battery Cycles	364.7	cycles/year
Battery Unit - Max Size Power	10	kW
Max Output Power	10	kW
Peak Output Power	15	kW
Scalability, systems in parallel	42	kWh
Price of battery (€/kWh) - 2020	€ 550.00	€/kWh
Battery charging costs (€/month)	€ 10.00	€/month

Figure C.2: Initial battery catalog parameters. Source: Author (2020)

Battery Power Sizing		
nº of modules per battery	4	packs/battery
Usable energy size per battery module	3.5	kWh
Battery Unit - Max Usable Size Energy	14	kWh
(SoH) - % of battery size used	100%	%
Available battery size for COMSA	14	kWh storage
Price of battery (€/kWh) depends on type selected at the beginning	€550.00	€/kWh
One Building-Battery Demand Design		
Model	Values	Units
nº of batteries in power shelf	1	batteries/shelf
nº of power shelves in cabinet	1	shelves/cabinet
nº of cabinets per column	1	cabinet/column
nº of columns per row	1	columns/row
nº of rows per floor	1	rows/floors
nº of active floors (high occupancy)	7	floors/building

Figure C.3: Initial battery sizing parameters. Source: Author (2020)

CALCULATION OF ENERGY STORAGE TO ENERGY CONSUMPTION RATIOS FOR LARGE BUILDING, ASSUMING LI-ION BATTERY		
Input Values		
nº of active floors (high occupancy)	7	active floors
Average occupancy per floor	38	occupants
Total occupancy of building	270	occupants
Average energy price (EUR/kWh)	0.101	€/kWh
Contracted Power (3 periods)	150	kW/month
Energy Use: COMSA Building	30000	AVG kWh/month
	30	AVG MWh/month
	360000	kWh/year
	360	MWh/year
	€ 36,360.00	AVG €/year

Figure C.4: Initial COMSA building parameters. Source: Author (2020)

C.2 System Costs - Excel Model

Total System Costs - Initial Investment Year 1		
	COMSA Building	
nº of buildings	1	# buildings
nº of floors (apartments) per building	7	floors/building
nº of batteries used	1	# batteries
Available battery size for COMSA	14	kWh
Price of battery (€/kWh)	€ 550.00	€/kWh
Battery costs (CAPEX)	€ 7,700.00	€
Inverter costs (CAPEX)	€ 3,180.00	€
Licenses costs (OPEX)	€ 600.00	€/year
Battery depreciation costs (OPEX)	€ 770.00	€/year
Battery + Inverters maintenance costs (OPEX)	€ 400.00	€/year
Total investment in CAPEX and OPEX		
Total investment CAPEX	€ 10,880.00	€
Total investment OPEX	€ 1,770.00	€
Total investment in Y1		
Total investment in Y1	€ 12,650.00	€

Figure C.5: Initial investment - New battery case. Source: Author (2020)

BATTERY + INVERTERS		
Price of battery (€/kWh) - 2020	€ 550.00	€/kWh
Battery capacity (kWh) - BYD L 14.0	14	kWh
Battery charging costs (€/month)	€ 10.00	€/month
Total price of battery (€)	€ 7,700.00	€
Price of inverter (€) - Victron Energy 2020	€ 1,060.00	€
Number of inverters	3	nº inverters
Total price of inverters (€)	€ 3,180.00	€

Figure C.6: New battery + inverters costs. Source: Author (2020)

Total System Costs - Initial Investment Year 1		
	COMSA Building	
nº of buildings	1	# buildings
nº of floors (apartments) per building	7	floors/building
nº of batteries used	1	# batteries
Available battery size for COMSA	11.2	kWh
Price of battery (€/kWh)	€ 275.00	€/kWh
Battery costs (CAPEX)	€ 3,080.00	€
Inverter costs (CAPEX)	€ 3,180.00	€
Licenses costs (OPEX)	€ 600.00	€/year
Battery depreciation costs (OPEX)	€ 308.00	€/year
Battery + Inverters maintenance costs (OPEX)	€ 400.00	€/year
Total investment in CAPEX and OPEX		
Total investment CAPEX	€ 6,260.00	€
Total investment OPEX	€ 1,308.00	€
Total investment in Y1		
Total investment in Y1	€ 7,568.00	€

Figure C.7: Initial investment - Second-life battery case. Source: Author (2020)

BATTERY + INVERTERS		
Price of battery (€/kWh) - 2020	€ 275.00	€/kWh
Battery capacity (kWh) - BYD L 14.0	11.2	kWh
Battery charging costs (€/month)	€ 10.00	€/month
Total price of battery (€)	€ 3,080.00	€
Price of inverter (€) - Victron Energy 2020	€ 1,060.00	€
Number of inverters	3	nº inverters
Total price of inverters (€)	€ 3,180.00	€

Figure C.8: Second-life battery + inverters costs. Source: Author (2020)

SOFTWARE AND LICENSES						
ADSM Automatic Demand Side Management	€200.00	€	24	h/year	10.0%	Savings %
ReDR Reward for Demand Response	€200.00	€	10	h/year	5.0%	Savings %
WSM Wholesale electric market trading	€200.00	€	10	h/year	10.0%	Savings %
Total price of Licenses (€/year)	€ 600.00	€/year			15.0%	Total savings %

Figure C.9: Software licenses costs. Source: Author (2020)

C.3 Sensitivity Analysis

COMSA Building				
Battery Price (€/kWh)	2020	2021-2030		0%
€ 550.00	€ (7,700.00)	€ 7,513.41		€ 67,434.15
€ 495.00	€ (6,930.00)	€ 7,513.41		€ 68,204.15
€ 445.50	€ (6,237.00)	€ 7,513.41		€ 68,897.15
€ 400.95	€ (5,613.30)	€ 7,513.41		€ 69,520.85
€ 360.86	€ (5,051.97)	€ 7,513.41		€ 70,082.18
€ 324.77	€ (4,546.77)	€ 7,513.41		€ 70,587.37
€ 292.29	€ (4,092.10)	€ 7,513.41		€ 71,042.05
€ 263.06	€ (3,682.89)	€ 7,513.41		€ 71,451.26
€ 236.76	€ (3,314.60)	€ 7,513.41		€ 71,819.55
€ 213.08	€ (2,983.14)	€ 7,513.41		€ 72,151.01
€ 191.77	€ (2,684.82)	€ 7,513.41		€ 72,449.32
€ 172.60	€ (2,416.34)	€ 7,513.41		€ 72,717.80
€ 155.34	€ (2,174.71)	€ 7,513.41		€ 72,959.44
€ 139.80	€ (1,957.24)	€ 7,513.41		€ 73,176.91
€ 125.82	€ (1,761.51)	€ 7,513.41		€ 73,372.63

Figure C.10: Sensitivity analysis data - New battery (NB) price - (Case 3 - All Licenses + ToU). Source: Author (2020)

COMSA Building				
Battery Price (€/kWh)	2020	2021-2030		0%
€ 275.00	€ (3,080.00)	€ 8,006.89		€ 76,988.94
€ 247.50	€ (2,772.00)	€ 8,006.89		€ 77,296.94
€ 222.75	€ (2,494.80)	€ 8,006.89		€ 77,574.14
€ 200.48	€ (2,245.32)	€ 8,006.89		€ 77,823.62
€ 180.43	€ (2,020.79)	€ 8,006.89		€ 78,048.16
€ 162.38	€ (1,818.71)	€ 8,006.89		€ 78,250.23
€ 146.15	€ (1,636.84)	€ 8,006.89		€ 78,432.11
€ 131.53	€ (1,473.15)	€ 8,006.89		€ 78,595.79
€ 118.38	€ (1,325.84)	€ 8,006.89		€ 78,743.10
€ 106.54	€ (1,193.26)	€ 8,006.89		€ 78,875.69
€ 95.89	€ (1,073.93)	€ 8,006.89		€ 78,995.01
€ 86.30	€ (966.54)	€ 8,006.89		€ 79,102.41
€ 77.67	€ (869.88)	€ 8,006.89		€ 79,199.06
€ 69.90	€ (782.89)	€ 8,006.89		€ 79,286.05
€ 62.91	€ (704.61)	€ 8,006.89		€ 79,364.34

Figure C.11: Sensitivity analysis data - Second-life battery (SLB) price - (Case 3 - All Licenses + ToU). Source: Author (2020)

Appendix D

Energy Management System (EMS)

D.1 EMS and Energy Infrastructure in COMSA Corporación building

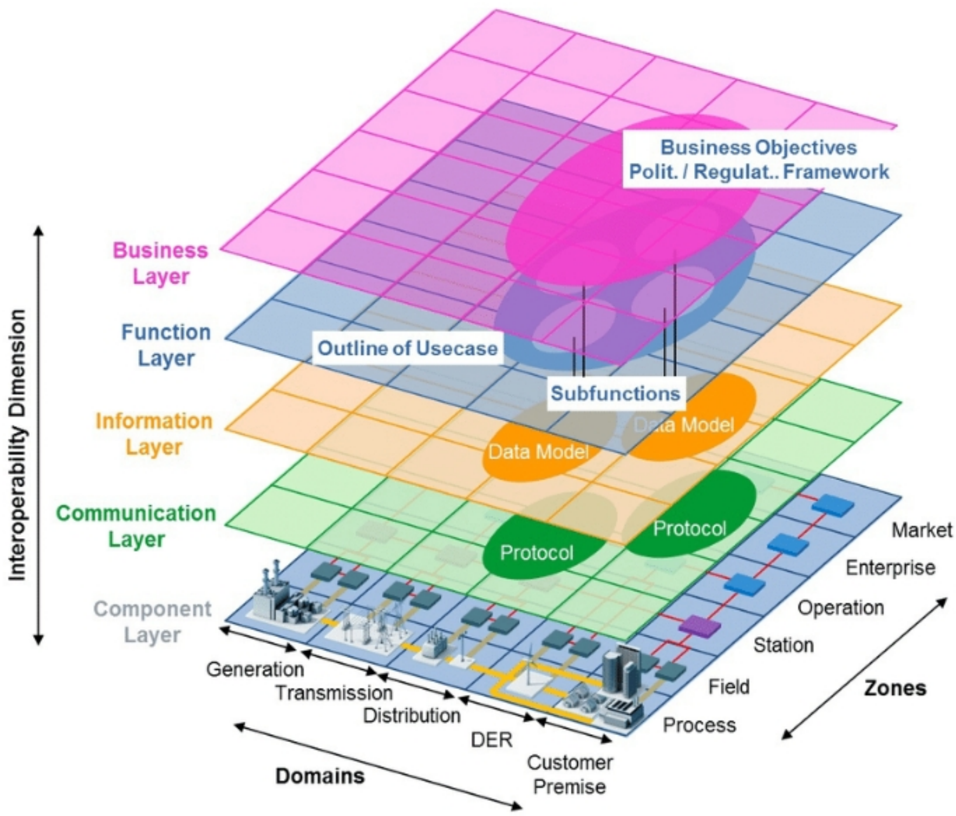

Figure D.1: Smart grid architecture model (SGAM) with interoperability layers. Source: The Smart Grid Architecture Model – SGAM (2017)

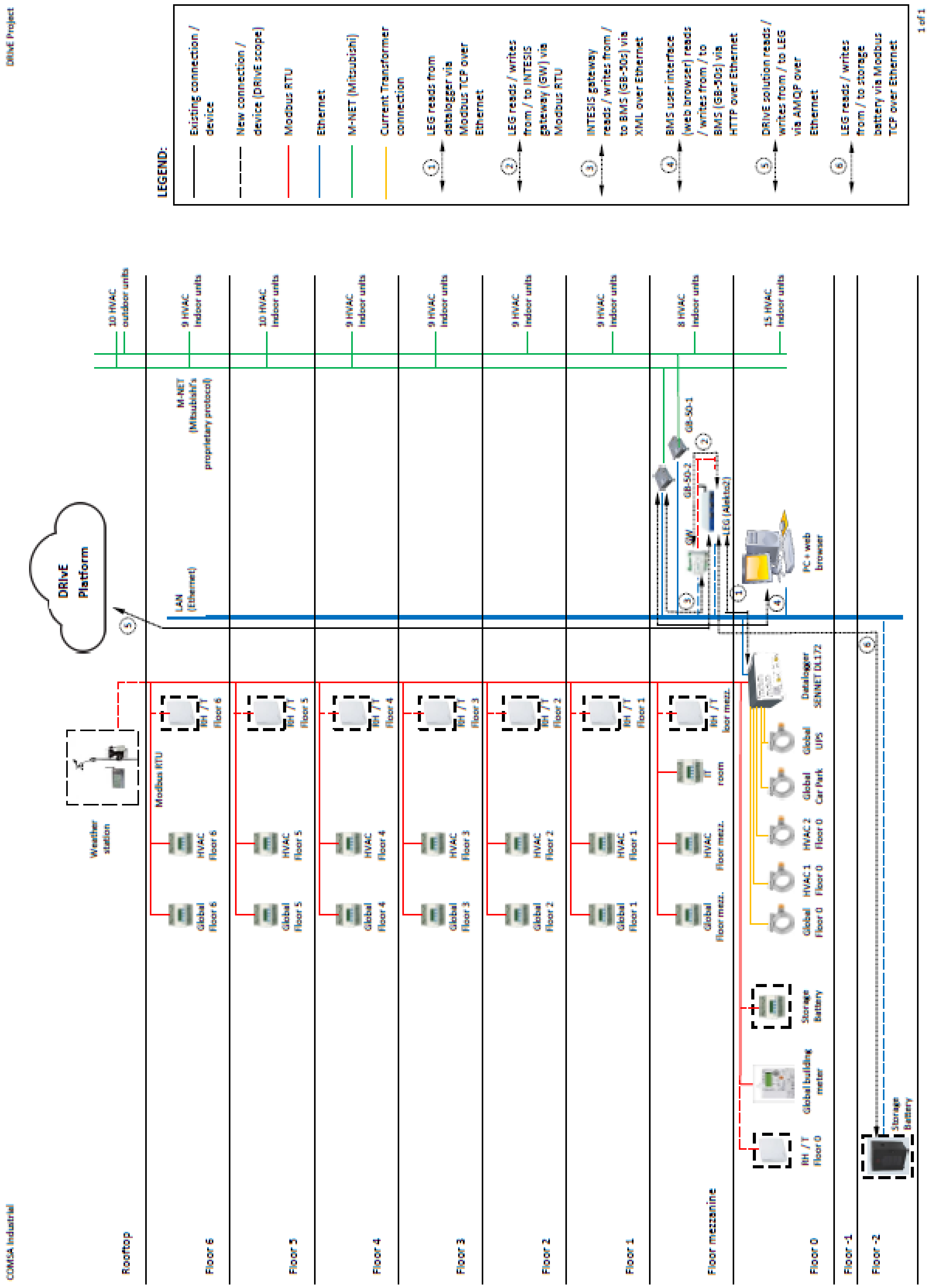

Figure D.2: COMSA Corporación grid architecture. Source: COMSA Corporación (2019)

Appendix E

Matlab Modelling

E.1 Matlab codes

Listing E.1: **Battery_ COMSA.m**

```
clc
clear
syms T;
time = 0.1:0.1:10;
time = time';
c = 0.8;
k = 1.2;
n=0.953; %Round-trip battery efficiency
I=1433; %Current (A)
Emin=40; %Minimum Voltage (V)
Emax=59.2; %Maximum Voltage (V)
Vnom=51.2; %Nominal Voltage (V)
Ed=1891.55; %Energy density (Wh/kg)
Q=7165.12; %Q is the maximum capacity of the battery (Ah)

H=Q/I %Theoretical discharge time(h)

%t1=H*(Q/I*H)^k %Theoretical time t


Qnom=(I^k)*H %Peukert's Law


%Cp Battery capacity discharged at 1Ah
%I Real discharging current (A)
%t Real discharging time (h)
%k Peukert constant



%Resistance equation
R=Vnom*((1-n)/((1-c)*Qnom))
```

```
%'A' value
A=Emax-Emin

%'B' value
B=3/Q

%Polarization Voltage (V)
K=(Emax-Vnom+A*(exp(-B*I*H)-1)*(Q-Qnom))/Qnom

%E0 Constant Battery Voltage
E0=Emax+K+R*I-A



%Modelling discharge equation battery
E=E0-K*(Q/Q*I*H)-(R*I)+(A*exp(-B*I*H))
%E Charging/Discharging Voltage (V)
%E0 Maximum Battery Voltage (V)
%Emin Polarization Voltage (V)
%Q Maximum capacity of the battery (Ah)
%I*T Instant state of charge (Ah)



% vector initialization
current = zeros(length(time),1);
E=zeros(length(time),1); %exponential
E1 = zeros(length(time),1); %lineal
E2 = zeros(length(time),1); %lineal
q1f = zeros(length(time),1);
q1b = zeros(length(time),1);
q1c = zeros(length(time),1);
q1d = zeros(length(time),1);
q1e = zeros(length(time),1);


for i=1:length(time)
 t=time(i);
 current(i) = 10-3*t;
end



%figure (1)
total = 7165.12; %total energy capacity Ah
total2 = total;
total3 = 0;
total4 = 0;

%Battery Capacity
q1a = total-I*(1-exp(-k.*time))./k+c*I*(1-exp(-k.*time))./k-c*I*time;

for i=1:length(time)
 t=time(i);
if q1a(i)<=0
 q1a(i)=0;
```

```
else
 q1a(i)=q1a(i);
end
end


 %Discharge Voltage at Different Discharge Time
for i=1:length(time)
 t=time(i);
 current(i) = 10-3*t;
 %Edischarge(i)=E0+K*(q1a(i)/q1a(i)*current(i)*t)+(R*current(i))-(A*exp(-B*cu
 E1(i)=Emin+(Emax-Emin)*q1a(i)/Q; %lineal
end

 %Charge Voltage at Different Charging Time
for i=1:length(time)
 t=time(i);
 current(i) = 10-3*t;
 %Echarge(i)=E0-K*(q1a(i)/q1a(i)*current(i)*t)-(R*current(i))+(A*exp(-B*curren
 E2(i)=Emin-(Emax-Emin)*q1a(i)/Q; %lineal
end


for i=1:length(time)
 t=time(i);
 q1b(i)=total+int(((c-1)*exp(-k.*(t-T))-c)*(current(i)),T,0,t);%one step
 q1c(i)=total+int(((c-1)*exp(-k.*T)-c)*(current(i)),T,0,t);%I(t-T)

 % term1 = int(((c-1)*exp(-k.*t)-c)*(20),T,0,t-0.1);
 % term2 = int(((c-1)*exp(-k.*t)-c)*(20),T,t-0.1,t);

 increment = int(((c-1)*exp(-k.*(t-T))-c)*(current(i)),T,t-0.1,t);
 total = total + double(increment);
 q1d(i) = total; % this one does not obtain the correct answer

 increment = int(((c-1)*exp(-k.*T)-c)*(current(i)),T,t-0.1,t);
 total2 = total2 + double(increment);
 q1e(i) = total2;

 increment2 = int(((c-1)*exp(-k.*T)-c)*(current(i)),T,t-0.1,t);
 total3 = total - double(increment2);
 q2e(i)=total3;

 %increment3 = int(((c-1)*exp(-k.*T)-c)*(I),T,t-0.1,t);
 %total4 = total - double(increment3);
 %q2f(i)=total4;
end

 q2f = total+I*(1-exp(-k.*time))./k-c*I*(1-exp(-k.*time))./k+c*I*time;

 I1=total*k./((1-exp(-k.*time))*(1-c)+k*c*time) %Discharge Current

 I2=-(total*k./((1-exp(-k.*time))*(1-c)+k*c*time)) %Charge Current

 %I2=(-k*total+total*(1-c)*k*c*(1-exp(-k*time)))/(1-exp(-k*time)+c*(k*time-1+e
```

```
figure(1)
plot(time,q1a,'b');
title('Battery Capacity at Different Discharge Time')
xlabel('Time (hour)');
ylabel('Battery Capacity (Ah)');
legend('Capacity q1a')

figure(2)
 plot(time,E1,'b');
 title('Battery Internal Discharge Voltage at Different Discharge Time')
 xlabel('Discharge Time (hours)');
 ylabel('Battery Internal Discharge Voltage (V)');
 legend('Voltage V')


 figure(3)
plot(time,q2f,'r');
title('Battery Capacity at Different Charge Time')
xlabel('Time (hour)');
ylabel('Battery Capacity (Ah)');
legend('q2f(charging process with 1433 A)')

figure(4)
plot(time,E2,'r');
title('Battery Internal Charge Voltage at Different Charging Time')
xlabel('Charging Time (hours)');
ylabel('Battery Internal Charge Voltage (V)');
legend('Voltage V')

%figure(5)
 %plot(time,Echarge,'r');
 %title('Battery Internal Charge Voltage at Different Charge Time')
 %xlabel('Discharge Time (hours)');
 %ylabel('Battery Internal Discharge Voltage (V)');
 %legend('Voltage V')

%figure(6)
%plot(time,current,'g--')
%title('Step Current over three separate time periods')
%xlabel('Time (hour)');
%ylabel('Current (A)');
%legend('current')


%figure(7)
%plot(time,q1b,'g--');
%title('Battery Capacity at Different Discharge Time')
%xlabel('Discharge Time (hour)');
%ylabel('Battery Capacity (Ah)');
%legend('q1b (one-step with I(T))')

%figure(8)
%plot(time,q1c,'r-.');
```

```
%title('Battery Capacity at Different Discharge Time')
%xlabel('Discharge Time (hour)');
%ylabel('Battery Capacity (Ah)');
%legend('q1c (one-step with I(t-T))')

%figure(9)
%plot(time,q1d,'m--');
%title('Battery Capacity at Different Discharge Time')
%xlabel('Discharge Time (hour)');
%ylabel('Battery Capacity (Ah)');
%legend('q1d (increment with I(T))')


%figure(10)
%plot(time,q2e,'g');
%title('Battery Capacity at Different Charge Time')
%xlabel('charge Time (hour)');
%ylabel('Battery Capacity (Ah)');
%legend('q2e(charging process with different current)')



figure(11)
plot(time,I1,'g');
title('Battery Discharge Current vs Discharging Time')
xlabel('Discharging Time (hours)');
ylabel('Battery Discharge Current (A)');
legend('Current I')

figure(12)
plot(time,I2,'g');
title('Battery Charging Current vs Charging Time')
xlabel('Charging Time (hours)');
ylabel('Battery Charge Current (A)');
legend('Current I')
```

Listing E.2: **Battery_ Modelling.m**

```
% The aim of this program is to study how curtailed generation and non
% supplied power are affected if the PVinstalled, Pconvmax and
% Ebatmax are modify


% Loading the data and setting parameters
load dataCOMSA.mat
% Col 1 - Actual measure time, every 15 min
% Col 2 - Actual PV power/PV power installed
% Col 3 - Actual load/Peak load power (HVAC) of COMSA Building
% Col 4 - Actual State of Charge SoC (%) for one day


minuts = 31774; %data per year, 31774 data measures

incT = 0.025; % 1 hour time increments
Ppeak = 100; % Peak demand (kW)
cost_PV = 1500; % EUR/kW cost panel
cost_convbat = 300; % EUR/kW cost battery converter
cost_bat = 550; % EUR/kWh cost battery (depends if it's new battery or
%second-life battery)

% Define variables to be optimized
%[PVinstalled BATconverter BATenergy SoC]
x(2)= 22; % PVinstalled kW according to previous study at COMSA (22)
x(3)= 7.2; % Pconvmax kW according to previous study at COMSA (7.2)
x(4)= 14; % Ebatmax kWh according to previous study at COMSA
x(5)= 1; %SoC

% Analysing one year of data
Ebatmax=x(4);
Ebatmin=x(4)*0.2; % 20% max discharge
Pbatmax=x(3);
SoC=x(5);

time= dataCOMSA([1:minuts],1)*x(1); % time
genPV= dataCOMSA([1:minuts],2)*x(2); % W PV available
totalgen = genPV; % total generation
dload = dataCOMSA([1:minuts],3)*Ppeak/10; % W demand in
tmax = length(dload)*incT;

SoC= dataCOMSA([1:minuts],4)-dload; % percentage

Eini = Ebatmin + (Ebatmax-Ebatmin)*0.5; %initial energy in the battery
Ebat(1) = Eini;

for ii = 1:1:length(genPV)
    difference = totalgen(ii) - dload(ii);

    if ii == 1
        % If it is generated more than needed
        if difference >= 0
            % If energy can be saved, store it in the battery
            if Eini + difference*incT <= Ebatmax
```

```
                Pconv(ii) = difference;
            else
                Pconv(ii) = (Ebatmax - Eini)*incT;
            end
            % Accomplish the converter restriccion
            if Pconv(ii) > Pbatmax
                Pconv(ii) = Pbatmax;
                r = r + 1;
            end
        % If it is needed more than generated
        else
            % Energy can be drawn from the battery until the low limit is
            % reached
            if Eini + difference*incT >= Ebatmin
                Pconv(ii) = difference;
            else
                Pconv(ii) = -(Eini-Ebatmin)*incT;
            end
            % Accomplish the converter restriccion
            if Pconv(ii) < -Pbatmax
                Pconv(ii) = -Pbatmax;
                r = r + 1;
            end
        end
        % Battery Balance
        Ebat(ii) = Eini + Pconv(ii)*incT;

    else

        if difference >= 0
            if Ebat(ii-1) + difference*incT <= Ebatmax
                Pconv(ii) = difference;
            else
                Pconv(ii) = (Ebatmax - Ebat(ii-1))*incT;
            end
            if Pconv(ii) > Pbatmax
                Pconv(ii) = Pbatmax;
            end
        else
            if Ebat(ii-1) + difference*incT >= Ebatmin
                Pconv(ii) = difference;
            else
                Pconv(ii) = -(Ebat(ii-1)-Ebatmin)*incT;
            end
            if Pconv(ii) < -Pbatmax
                Pconv(ii) = -Pbatmax;
            end
        end
        Ebat(ii) = Ebat(ii-1) + Pconv(ii)*incT;
    end

end

% Analyzing and showing results
%[PVinstalledBATconverterBATenergy]
cost = x(2)*cost_PV+ x(3)*cost_convbat + x(4)*cost_bat;
```

```
Enetot=sum(dload);
lifetime=10; %years
lcoe= cost/(1e-6*lifetime*(8760/length(Ebat))*Enetot); % EUR/MWh lifetime

% Deviation between available generation and load, positive->curtailment,
%negative->load non supplied
Ptotal= (genPV - Pconv' -dload);
etotcg= sum(max(0,Ptotal)); %Total curtailed generation
etotns= sum(max(0,-Ptotal)); %Total demand non-supplied

display(['Ppeak = ' num2str(Ppeak) 'kW (Power Peak Demand)'])
display(['PPV = ' num2str(x(2)) ' kWp (Power BIPV installation)'])
display(['Pbatmax = ' num2str(x(3)) ' kW (Battery converter power)'])
display(['Ebatmax = ' num2str(x(4)) ' kWh (Battery Capacity)'])
display(['Curtailed generation = ' num2str(etotcg) ' kWh'])
%display(['Non supplied demand = ' num2str(etotns*1e-3) ' kW'])
display(['Total cost = ' num2str(cost*1e-3) ' k (Installation costs)'])
display(['LCOE (MWh) = ' num2str(lcoe*1e-3) '  /MWh'])
display(['LCOE (kWh) = ' num2str(lcoe*1e-6) '  /kWh'])


% Graphics
figure(1)
plot(dload(23302:23392))
%hold on
%plot(SoC(23302:23392))
title('HVAC 4th floor demand in one day : 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
%yyaxis right
%ylabel('State of Charge (SoC) - %')
legend('Demand')


figure(2)
plot(dload(22931:23528))
title('HVAC 4th floor demand in one week : 27/01/2020 - 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
legend('Demand')


figure(3)
plot(dload(20629:23258))
title('HVAC 4th floor demand in one month : 01/01/2020 - 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
legend('Demand')

figure(4)
%plot(genPV(1:8760))
%hold on
plot(dload(1:31774))
title('HVAC 4th floor demand in one year: 01/05/2019 - 01/05/2020')
xlabel('Time (every 15 min)')
```

```
ylabel('Power␣(kW)')
legend('Demand')


figure(5);
plot(Pconv);
title('Battery␣Converter␣Power')
xlabel('Time␣(h)')
ylabel('Power␣(kW)')

%figure(6)
%plot(Ebat)
%title('Stored Energy from PV generation')
%xlabel('Time (h)')
%ylabel('Energy (kWh)')


figure(6)
plot(genPV(1:minuts))
hold on
plot(dload(1:minuts))
title('PV␣Power␣Generation␣and␣Annual␣Energy␣Demand')
xlabel('Time␣(h)')
ylabel('Power␣(kW)')
legend('PV␣Power', 'Demand')

figure(11)
plot(Ebat(23302:23392))
title('Stored␣energy␣in␣one␣day␣:␣31/01/2020')
xlabel('Time␣(h)')
ylabel('Energy␣(kWh)')

figure(8)
plot(Ebat(22931:23528))
title('Stored␣energy␣in␣one␣week␣:␣27/01/2020␣-␣31/01/2020')
xlabel('Time␣(h)')
ylabel('Energy␣(kWh)')

figure(9)
plot(Ebat(20629:23258))
title('Stored␣energy␣in␣one␣month␣:␣01/01/2020␣-␣31/01/2020')
xlabel('Time␣(h)')
ylabel('Energy␣(kWh)')

figure(10)
plot(Ebat(1:minuts))
title('Stored␣energy␣in␣one␣year␣:␣01/05/2019␣-␣01/05/2020')
xlabel('Time␣(h)')
ylabel('Energy␣(kWh)')

%figure(8);
%plot(Pconv(22931:23528));
%title('Converter Power in one week')
%xlabel('Time (h)')
%ylabel('Power (kW)')
```

```
%figure(10)
%plot(genPV(1:462))
%hold on
%plot(dload(22931:23528)) %168, una semana son 462 datos
%title('Power Generation and HVAC 4th floor demand in one week')
%xlabel('Time (h)')
%ylabel('Power (kW)')
%legend('PV Power', 'Demand')

%figure(10)
%plot(genPV(1:8760))
%hold on
%plot(dload(1:31774)) %168 un da son 90 datos
%title('Power Generation and HVAC Demand in one year')
%xlabel('Time (h)')
%ylabel('Power (kW)')
%legend('PV Power', 'Demand')
```

Listing E.3: **Battery_ Modelling_ Building.m**

```
% The aim of this program is to study how curtailed generation and non
% supplied power are affected if the PVinstalled, Pconvmax and
% Ebatmax are modify


% Loading the data and setting parameters
load dataCOMSA.mat
% Col 1 - Actual measure time, every 15 min
% Col 2 - Actual PV power/PV power installed
% Col 3 - Actual load/Peak load power (HVAC) of COMSA Building
% Col 4 - Actual State of Charge SoC (%) for one day


minutes = 31774; %data per year, 31774 data measures, 31182 Building

incT = 0.025; % 1 hour time increments
Ppeak = 110; % Peak demand (kW)
cost_PV = 1300; % EUR/kW cost panel
cost_convbat = 300; % EUR/kW cost battery converter
cost_bat = 550; % EUR/kWh cost battery (depends if it's new battery or
%second-life battery)

% Define variables to be optimized
%[PVinstalled BATconverter BATenergy SoC]
x(2)= 22; % PVinstalled kW according to previous study at COMSA (22)
x(3)= 0; % Pconvmax kW according to previous study at COMSA (7.2)
x(4)= 0; % Ebatmax kWh according to previous study at COMSA
x(5)= 1; %SoC

% Analysing one year of data
Ebatmax=x(4);
Ebatmin=x(4)*0.2; % 20% max discharge
Pbatmax=x(3);
SoC=x(5);

time= dataCOMSA([1:minutes],1)*x(1); % time
genPV= dataCOMSA([1:minutes],2)*x(2); % W PV available
totalgen = genPV; % total generation
dload = dataCOMSA([1:minutes],4)*Ppeak/1000; % W demand in
tmax = length(dload)*incT;

SoC= dataCOMSA([1:minutes],4)-dload; % percentage

Eini = Ebatmin + (Ebatmax-Ebatmin)*0.5; %initial energy in the battery
Ebat(1) = Eini;

for ii = 1:1:length(genPV)
    difference = totalgen(ii) - dload(ii);

    if ii == 1
        % If it is generated more than needed
        if difference >= 0
            % If energy can be saved, store it in the battery
            if Eini + difference*incT <= Ebatmax
```

```
                Pconv(ii) = difference;
            else
                Pconv(ii) = (Ebatmax - Eini)*incT;
            end
            % Accomplish the converter restriccion
            if Pconv(ii) > Pbatmax
                Pconv(ii) = Pbatmax;
                r = r + 1;
            end
        % If it is needed more than generated
        else
            % Energy can be drawn from the battery until the low limit is
            % reached
            if Eini + difference*incT >= Ebatmin
                Pconv(ii) = difference;
            else
                Pconv(ii) = -(Eini-Ebatmin)*incT;
            end
            % Accomplish the converter restriccion
            if Pconv(ii) < -Pbatmax
                Pconv(ii) = -Pbatmax;
                r = r + 1;
            end
        end
        % Battery Balance
        Ebat(ii) = Eini + Pconv(ii)*incT;

    else

        if difference >= 0
            if Ebat(ii-1) + difference*incT <= Ebatmax
                Pconv(ii) = difference;
            else
                Pconv(ii) = (Ebatmax - Ebat(ii-1))*incT;
            end
            if Pconv(ii) > Pbatmax
                Pconv(ii) = Pbatmax;
            end
        else
            if Ebat(ii-1) + difference*incT >= Ebatmin
                Pconv(ii) = difference;
            else
                Pconv(ii) = -(Ebat(ii-1)-Ebatmin)*incT;
            end
            if Pconv(ii) < -Pbatmax
                Pconv(ii) = -Pbatmax;
            end
        end
        Ebat(ii) = Ebat(ii-1) + Pconv(ii)*incT;
    end

end

% Analyzing and showing results
%[PVinstalledBATconverterBATenergy]
cost = x(2)*cost_PV+ x(3)*cost_convbat + x(4)*cost_bat;
```

```
Enetot=sum(dload);
lifetime=10; %years
lcoe= cost/(1e-6*lifetime*(8760/length(Ebat))*Enetot); % EUR/MWh lifetime

% Deviation between available generation and load, positive->curtailment,
%negative->load non supplied
Ptotal= (genPV - Pconv' -dload);
etotcg= sum(max(0,Ptotal)); %Total curtailed generation
etotns= sum(max(0,-Ptotal)); %Total demand non-supplied

display(['Ppeak = ' num2str(Ppeak) 'kW (Power Peak Demand)'])
display(['PPV = ' num2str(x(2)) ' kWp (Power BIPV installation)'])
display(['Pbatmax = ' num2str(x(3)) ' kW (Battery converter power)'])
display(['Ebatmax = ' num2str(x(4)) ' kWh (Battery Capacity)'])
%display(['Curtailed generation = ' num2str(etotcg) ' kWh'])
%display(['Non supplied demand = ' num2str(etotns*1e-3) ' kW'])
display(['Total cost = ' num2str(cost*1e-3) ' k (Installation costs)'])
display(['LCOE (MWh) = ' num2str(lcoe*1e-3) '  /MWh'])
display(['LCOE (kWh) = ' num2str(lcoe*1e-6) '  /kWh'])


% Graphics
figure(1)
plot(dload(23404:23496))
%hold on
%plot(SoC(23404:23496))
title('COMSA Building load demand in one day : 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
%yyaxis right
%ylabel('State of Charge (SoC) - %')
legend('Demand')


figure(2)
plot(dload(23029:23496))
title('COMSA Building load demand in one week : 27/01/2020 - 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
legend('Demand')


figure(3)
plot(dload(20598:23496))
title('COMSA Building load demand in one month : 01/01/2020 - 31/01/2020')
xlabel('Time (every 15 min)')
ylabel('Power (kW)')
legend('Demand')

figure(4)
%plot(genPV(1:8760))
%hold on
plot(dload(1:31182))
title('COMSA Building Load demand in one year: 01/05/2019 - 01/05/2020')
xlabel('Time (every 15 min)')
```

```
ylabel('Power (kW)')
legend('Demand')


figure(5);
plot(Pconv(1:31182));
title('Battery Converter Power')
xlabel('Time (h)')
ylabel('Power (kW)')

%figure(6)
%plot(Ebat)
%title('Stored Energy from PV generation')
%xlabel('Time (h)')
%ylabel('Energy (kWh)')


figure(6)
plot(genPV(1:minuts))
hold on
plot(dload(1:minuts))
title('PV Power Generation and Annual Energy Demand')
xlabel('Time (h)')
ylabel('Power (kW)')
legend('PV Power', 'Demand')

figure(11)
plot(Ebat(23404:23496))
title('Stored energy in one day : 31/01/2020')
xlabel('Time (h)')
ylabel('Energy (kWh)')

figure(8)
plot(Ebat(23029:23496))
title('Stored energy in one week : 27/01/2020 - 31/01/2020')
xlabel('Time (h)')
ylabel('Energy (kWh)')

figure(9)
plot(Ebat(20598:23496))
title('Stored energy in one month : 01/01/2020 - 31/01/2020')
xlabel('Time (h)')
ylabel('Energy (kWh)')

figure(10)
plot(Ebat(1:minuts))
title('Stored energy in one year : 01/05/2019 - 01/05/2020')
xlabel('Time (h)')
ylabel('Energy (kWh)')

%figure(8);
%plot(Pconv(22931:23528));
%title('Converter Power in one week')
%xlabel('Time (h)')
%ylabel('Power (kW)')
```

```
%figure(10)
%plot(genPV(1:462))
%hold on
%plot(dload(22931:23528)) %168, una semana son 462 datos
%title('Power Generation and HVAC 4th floor demand in one week')
%xlabel('Time (h)')
%ylabel('Power (kW)')
%legend('PV Power', 'Demand')

%figure(10)
%plot(genPV(1:8760))
%hold on
%plot(dload(1:31774)) %168 un d a son 90 datos
%title('Power Generation and HVAC Demand in one year')
%xlabel('Time (h)')
%ylabel('Power (kW)')
%legend('PV Power', 'Demand')
```

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