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Energy Engineering

June 2017

Final Degree Project

Energy Engineering

Impact of energy storage systems in distribution grids with high renewable energy penetration

Memory, Budget and Attachments

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Call: June 2017

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Resum

El present marc del sistema elèctric de potencia realça la introducció gradual de fonts d'energies renovables per requisits mediambientals. Dins d'aquest escenari, micro-generadors renovables són progressivament estesos en xarxes de distribució de baixa tensió (LV), actuant com proveïdors d'energia per autoconsum en esquemes elèctrics residencials i industrials.

La generació distribuïda mitjançant micro-generadors renovables en xarxes de baixa tensió ocasiona alteracions significatives en els paràmetres elèctrics a causa de la injecció d'energia superàvit durant períodes de baixa demanda elèctrica. Com a resultat de pertorbar el balanç energètic de la xarxa elèctrica es genera sobre-voltatge, el flux de càrrega és alterat i la corrent augmenta.

Per permetre la contínua implementació de micro-generadors en xarxes de baixa tensió, tal com panels fotovoltaics i turbines eòliques, s'han de desenvolupar tècniques de mitigació per regular les pertorbacions generades. Per tant, l'objectiu del present treball tracta d'emfatitzar l'avaluació de sistemes d'emmagatzematge d'energia com a eina de mitigació.

D'acord amb les premisses establertes, el present estudi analitza l'efectivitat de bateries centralitzades en xarxes de distribució de baixa tensió amb alta penetració de micro-generadors renovables i la seva influencia sobre fases desequilibrades i pèrdues d'energia mitjançant simulació. Aleshores, s'ha creat una eina de simulació específica, automatitzant tot el procediment a través d'un algoritme implementat en MATLAB® i MATPOWER.

Amb la finalitat d'adquirir resultats apropiats en el procés de simulació, s'ha dissenyat un model específic que recrea una xarxa de baixa tensió residencial amb la inclusió de micro-generadors i un sistema d'emmagatzematge centralitzat basat en dades reals. A més, s'estudien diferents escenaris modificant els paràmetres variables del model, a fi d'aproximar el cas d'estudi a condicions reals (comportament mitjà i millor/pitjor dels casos).

Per últim, els resultats de les simulacions son avaluats per determinar l'efectivitat i viabilitat de l'eina de mitigació proposada. Per això, es valoren els trets positius i negatius d'acord amb els avantatges tecnològics i la viabilitat econòmica de la tecnologia emprada.

Per concloure, a part dels apartats inclosos en l'anàlisi del present estudi, altres complements rellevants són destacats en els annexos del projecte. Aquests inclouen l'impacte mediambiental del treball, el estudi econòmic, mètodes de càlcul utilitzats, descripcions dels programes involucrats i totes les dades empleades per crear el model i dur a terme les simulacions.

Resumen

El presente marco del sistema eléctrico de potencia realza la introducción gradual de fuentes de energías renovables por requisitos medioambientales. Dentro de este escenario, micro-generadores renovables son progresivamente extendidos en redes de distribución de baja tensión (LV), actuando como proveedores de energía para autoconsumo en esquemas eléctricos residenciales e industriales.

La generación distribuida mediante micro-generadores renovables en redes de baja tensión ocasiona alteraciones significativas en los parámetros eléctricos a causa de inyección de energía superávit durante periodos de baja demanda eléctrica. Como resultado de perturbar el balance energético de la red eléctrica se genera sobre-voltaje, el flujo de carga es alterado y la corriente aumenta.

Para permitir la continua implementación de micro-generadores en redes de baja tensión, tal como paneles fotovoltaicos y turbinas eólicas, se deben desarrollar técnicas de mitigación para regular las perturbaciones generadas. Por lo tanto, el objetivo del presente trabajo trata de enfatizar la evaluación de sistemas de almacenamiento de energía como herramientas de mitigación.

De acuerdo con las premisas establecidas, el presente estudio analiza la efectividad de baterías centralizadas en redes de distribución de baja tensión con alta penetración de micro-generadores renovables y su influencia sobre fases desequilibradas e pérdidas de energía mediante simulación. Por consiguiente, se ha creado una herramienta de simulación específica, automatizando todo el procedimiento a través de un algoritmo implementado en MATLAB® y MATPOWER.

Con el fin de adquirir resultados apropiados en el proceso de simulación, se ha diseñado un modelo específico que recrea una red de baja tensión residencial con la inclusión de micro-generadores y sistema de almacenamiento centralizado basado en datos reales. Además, se estudian diferentes escenarios modificando los parámetros variables del modelo, a fin de aproximar el caso de estudio a condiciones reales (comportamiento promedio y mejor/peor de los casos).

Por último, los resultados de las simulaciones son evaluados para determinar la efectividad e viabilidad de la herramienta de mitigación propuesta. Para ello, se valoran todos los rasgos positivos e negativos de acuerdo con las ventajas tecnológicas y la viabilidad económica de la tecnología empleada.

Para concluir, a parte de los apartados incluidos en el análisis del presente estudio, otros complementos relevantes son destacadas en los anexos del proyecto. Éstos incluyen el impacto medio-ambiental del trabajo, el estudio económico, métodos de cálculo utilizados, descripciones de los programas involucrados y todos los datos usados para crear el modelo e llevar a cabo las simulaciones.

Abstract

The present framework of the electric power system enhances the gradual introduction of renewable energy sources because of environmental requirements. Within this setting, renewable micro-generators are progressively spreading in low voltage (LV) distribution grids acting as self-consumption energy supply for residential and industrial electric schemes.

Distributed generation through renewable micro-generators in LV networks causes significant alterations in the electric parameters due to surplus injected energy in off-peak load demand hours. As a result of disturbing the power balance of the electric grid, over-voltage appears, power flow is upset and current increases.

To permit further implementation of renewable micro-generators in LV grids, such as PV panels and wind turbines, mitigation techniques must be developed to regulate the inflicted alterations. Hence, the objective of the present work enhances the evaluation of energy storage systems to work as mitigation tools.

According to the settled premises, the present study analyzes the effectiveness of centralized batteries on the electric parameters of LV distribution grids with many renewable micro-generator modules, and their influence on unbalanced phases and energy losses, all through simulations. Therefore, a specific simulation tool has been created, automating the entire procedure through an algorithm that functions in the MATLAB® and MATPOWER working environment.

In order to acquire appropriate and valid result outcomes during the simulation process, a specific model that recreates a realistic residential LV distribution grid with included micro-generators and centralized energy storage system has been established based on real data. Furthermore, different possible scenarios modifying variable parameters of the model are discussed in order to approximate the case study to real conditions (average behavior and best/worst case scenarios).

Ultimately the outcomes of the simulation process are evaluated in order to determine the effectiveness and viability of the proposed mitigation tool. Therefore, all positive and negative traits are appraised according to technological vantages and economic viability of the technology.

To conclude, apart from the sections included in the analysis of the present study, additional relevant working areas are also featured within the appendices of the project. These include environmental impact, economic study, computation methods, tool descriptions and utilized data.

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Preface

Origin of the project

The progressive growth of renewable energy resources in the electric power system is a given reality. Because of environmental causes, the total implementation of these technologies is unavoidable to foment a sustainable development.

The usage of renewable micro-generators in LV distribution grids is spreading apace because of the necessity of non-contaminating energy generators and their benefits for self-sufficient energy supply in residential and industrial environments. The gradual insertion of these systems in LV networks cause important struggles altering the electric parameters of the grid. Hence, mitigation techniques must be developed in order to allow further implementation of distributed generation. For the time being, possible mitigation tools have been assessed on theoretical basis, but none proven to work on real implementation.

Within the research approaches of the CITCEA-UPC (research center for technological innovation in static converters and drives of the Polytechnic University of Catalonia), the analysis of possible regulation implements for the integration of renewable energy sources in the electric network is one of the main objectives. Therefore, current studies involve the appraisal of energy storage systems to face growth of micro-generators in LV distribution grids, according to actual and future energy requirements.

Under the proposed premises, the present work has been labored analyzing the possible impact of energy storage systems in LV distribution grids with high renewable energy penetration throughout simulations of a propound model.

Motivation

Hitherto, energy storage systems have always been contemplated as energy management devices, shifting the time lapse between generation and demand. Notwithstanding, batteries have much more capabilities within the electric power system that are not exploited yet. Therefore, the analysis of these technologies for the purpose of electric parameter mitigation supposes a great challenge.

From a more generic environmental point of view, given the necessity of transition from fossil fuels to renewable energy sources to stop the negative impact caused by climate change, the analysis of energy storage systems in LV grids to allow implementation of renewable micro-generators encourages the development of a sustainable future.

Introduction

Objectives of the project

The objective of the present work is the evaluation of the effectiveness of centralized energy storage systems to mitigate altered electric parameters in LV distribution grids because of high renewable energy penetration. According to this, generated over-voltage by renewable micro-generators in the LV network is intended to be regulated, complying legal voltage variation boundaries as far as reaching optimal working conditions.

In order to bring into being the objective of the study, two additional targets are needful for the realization of the present work. First, a simulation tool must be developed, designing a specific algorithm for the purpose of automating the analysis of the subject according to the requisites of the problem. Secondly, the establishment of a realistic model that recreates a residential LV distribution grid is needed to perform the simulation of the study.

Scope of the project

With the purpose of achieving the objective of study, several tasks have been carried out along the scope of the project:

- Research on the current status of distribution grids.
- Study of the most relevant problems caused by renewable micro-generators in LV grids.
- Election of the proposed mitigation technique: centralized energy storage system.
- Creation of a simulation tool working in MATLAB® and MATPOWER environment.
- Establishment of a realistic model recreating a residential LV grid with renewable micro-generators and centralized energy storage system.
- Review of different scenarios for the purpose of the study.
- Simulation of the subject within specific time intervals.
- Evaluation of the outcomes of the assay to appraise effectiveness and viability of batteries.
- Environmental and economic analysis of the project.

Chapter 1

State of the art

In this chapter the current state of the art regarding the electric power system, renewable energy penetration and energy storage systems will be presented. First, the actual generic traits of the electric grid are treated to perceive the base framework of the project. Secondly the introduction of renewable energy sources is discussed, evaluating the current insertion status of the generators in electric power systems, distributed generation, possible future growth and smart grids as necessary measurement. By last, energy storage systems are analyzed, treating the existing typologies, possible use in electric grids and actual stage of implementation.

1.1 Electric power system

The electric power system or grid is the interconnected network responsible for generating, transmitting and delivering electric energy to the final consumer, always complying the law of energy conservation. The network is composed of different systems that work simultaneously enabling the energy transformation and transportation: power generators, electrical substations, transmission lines and distribution grid.

1.1.1 Structure

The structure of the electric power system is conditioned by the geographical distribution of the power generators and final consumers, that are usually not located at the same space. Therefore, in order to allow electric access to the community, an extended electrical grid is required to enable the energy transmission and the connection between both terminals:

Within the general scheme of the grid it is possible to identify the main constituents that permit the operations of the electric power system:

- **Generator**: Any system that transforms energy from primary sources into electricity. Traditionally generators, especially those based on thermal technologies (fossil fuels and nuclear), were concentrated in large scale far from population, imposing the existing grid scheme. Nevertheless, the introduction of new renewable energy sources is slowly evolving the outline into distributed generation.

- **Transmission lines**: High voltage lines (36 KV - 400 KV) that transport electricity from the generation points to power substations near consumption areas in order to reduce energy losses. Usually these lines work in alternating current (AC), even though technological advance is introducing new direct current (DC) lines for certain applications.

- **Distribution lines**: Medium (1 KV - 36 KV) and low voltage (0 KV - 1 KV) lines that transmit electricity from power substations to the loads (final consumer).

- **Substation**: System that either transforms the state of electricity (adapting the voltage, frequency and phases through transformers) or distributes/connects different lines (interconnecting transmission systems). They are required at every level of the grid to adapt the physical circumstances of the electric energy to each stage, assuring the stability and security of the system.

- **Load**: Any device that consumes electric energy. Depending on the load type, consumer voltage and phase value at the end of distribution lines can vary.

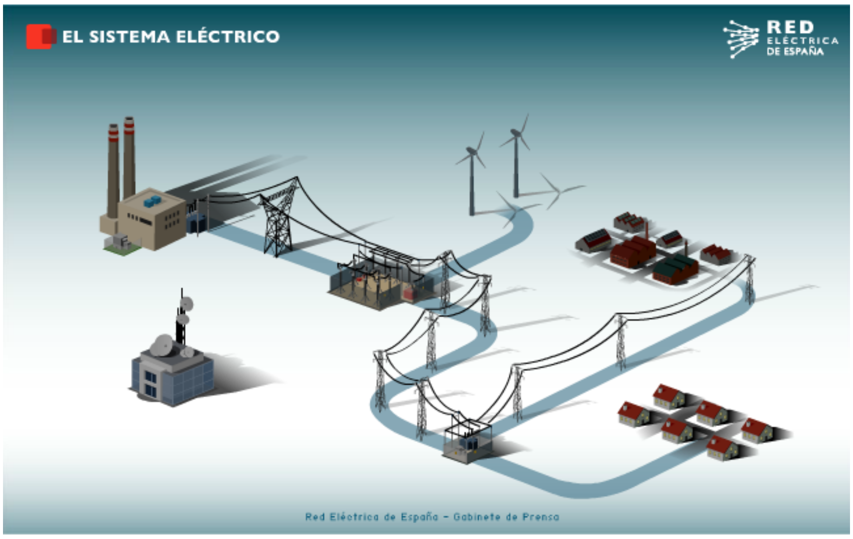


Figure 1.1: General scheme of the electric power system. Extracted from [1]

The elements that compose the electric grid (in traditional operation) work unidirectionally, from generation to consumption. Following this criteria, the structure of the electric power system is determined by the frame of the transmission and distribution lines, that are arranged depending on their corresponding transportation stage. The transmission lines in high voltage present a mesh structure interconnecting all points of the grid, which ensures great operational flexibility. Distribution lines in medium voltage are usually looped, providing the required reliability to the system, and low voltage lines are radial, simplifying possible modifications. So, in the present configuration, the main structure of the electric grid gets simpler, but at the same time less infallible with the progress from energy generation to the final consumption.

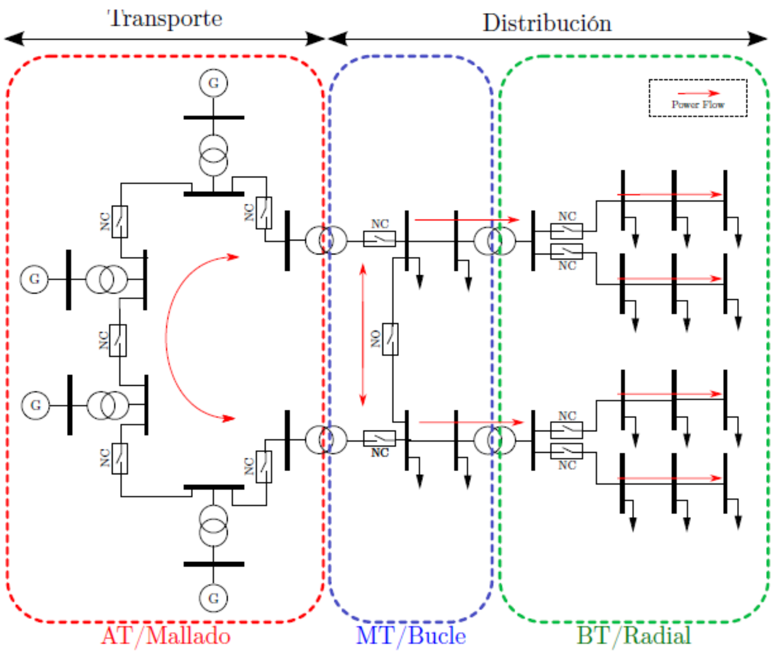


Figure 1.2: Structure of the electric grid. Extracted from [2]

1.1.2 Electric parameters

The electric power system is governed by physical parameters that condition and characterize the behavior of the grid. These can be classified in two typologies, according to the physical structure of the network and the operation of the system.

First, electric parameters that condition the scheme of electric lines include resistance, inductance, capacitance and conductance. These features determine the electricity transmission through the wires, in accordance with inner and external agents that alter the electromagnetic conduct of the energy flow. Hence, the electric power system must be dimensioned in accordance with the previous features in order to allow proper functionality.

Secondly, electric traits that affect the operation of the power network comprehend power, voltage, current, frequency and waveform. These characteristics influence the performance of electric system, settle different levels in the grid and determine power quality of the treated energy.

All presented electric parameters define the electric power system and must be handled according to specific values in order to secure the adequate operation of the grid. Because of this, legislative regulations bound the electric features to concrete value ranges that must be fulfilled.

Within the purpose of the present study, the proposed electric features determine the conditions of the realized analysis. The exact definitions of all presented parameters of the electric grid are depicted in **Appendix C**.

1.1.3 Power balancing

The aim to achieve a balanced power flow is one of the biggest challenges in the operation of electric grids, fulfilling the principle of conservation of energy. Therefore, it is required that the consumed energy at the loads equals the generated electricity at each time step.

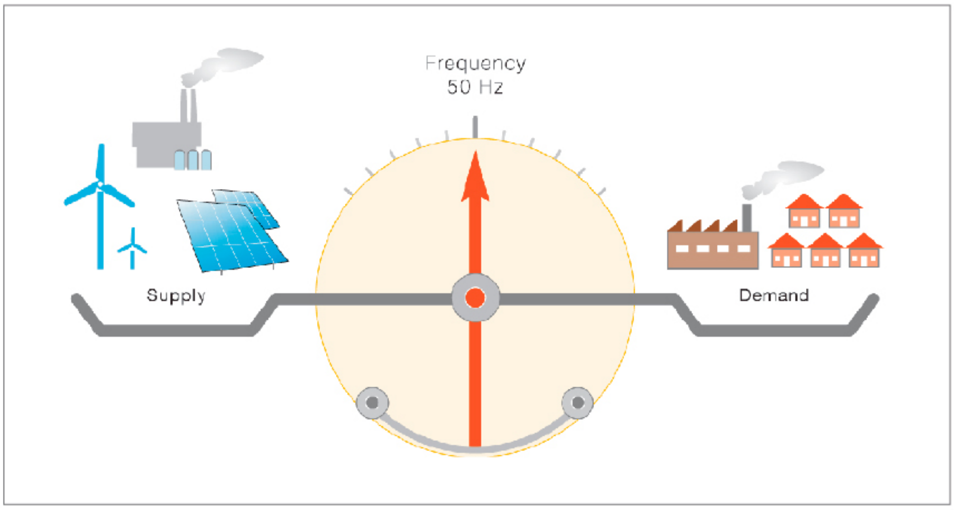


Figure 1.3: Power balancing in the electric grid. Extracted from [3]

Ideally, if this conditions are met, the electric power system presents great stability. Unfortunately, it is very tough to perfectly balance the produced/consumed energy due to the impossibility of exactly foreseeing the demand. Hence, the uneven load balancing causes disturbances on the grid parameters, altering the voltage and frequency values. Technological development, such as the progress in machine learning algorithms, is currently treating this dare trying to diminish the possible load discrepancies.

1.2 Renewable energy penetration

Renewable energies (RE) play an essential role within the electric power system, being the most significant solution to face a sustainable technological development. Up to date, their implementation increases continuously in all levels of the electric system, entailing a big challenge for the stable operation of the grid. For this reason, one of the major dares relies in adapting the electric grid to permit the insertion of new renewable energy generators.

1.2.1 Renewable energies

In the context of electric power systems, renewable energies are power generators, that transform electricity from renewable resources (opposite to traditional generators based on fossil fuels or nuclear energy), that can show up in form of sunlight, wind, water flows, tides, waves and geothermal heat. The great advantage of using renewable sources relies on the trait that they do not harm the environment, avoiding any pollution or physical damaging, what in the present circumstances is one of the main measurements against climate change.

In the current state of the worldwide power sector, renewable energies already represent a significant share of 23,7 %, which is composed of all different types of existing renewable resources.

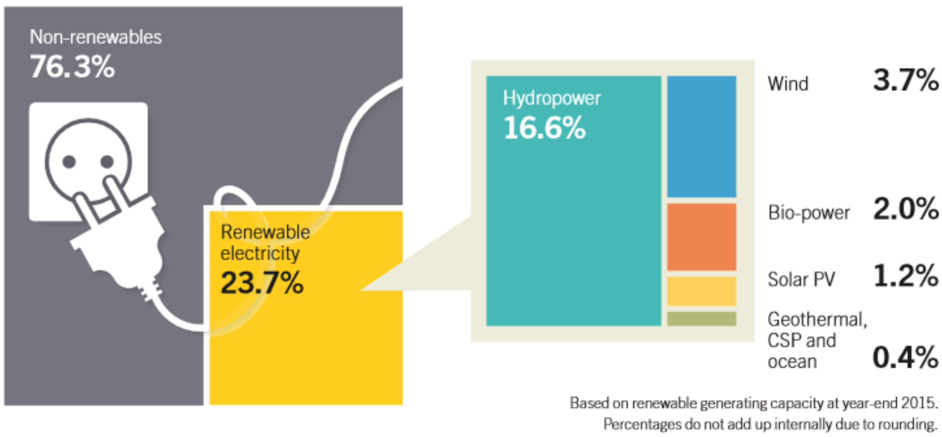


Figure 1.4: Worldwide renewable energy share by 2015. Extracted from [4]

Within the mix of renewable energies, the most competitive and advanced technologies that already show a great implication on a global scale are staged by hydro power, wind mills and solar PV. Nevertheless, there are other technologies that feature big potential and are in the process of spreading: geothermal power, concentrated solar power and ocean power.

In terms of power share, the actual installed capacity of renewable energies is already immense, reaching 1849 GW globally. The biggest section of the mix is present in UE-28, BRICS (Brazil, Russia, China, India and South Africa) and the US.

TECHNOLOGY	Global	EU-28	BRICS[1]	China	United States	Germany	Japan	India	Italy	Spain
	GW			GW						
Bio-power	106	36	31	10.3	16.7	7.1	4.8	5.6	4.1	1
Geothermal power	13.2	1	0.1	~0	3.6	~0	0.5	0	0.9	0
Hydropower	1,064	126	484	296	80	5.6	22	47	18	17
Ocean power	0.5	0.3	~0	~0	0	0	0	0	0	~0
Solar PV	227	95	50	44	26	40	34	5.2	18.9	5.4
Concentrating solar thermal power (CSP)	4.8	2.3	0.4	~0	1.7	~0	0	0.2	~0	2.3
Wind power	433	142	180	145	74	45	3	25	9	23
Total renewable power capacity including hydropower	**1,849**	**402**	**746**	**496**	**202**	**97**	**65**	**83**	**51**	**49**
Total renewable power capacity (not including hydropower)	**785**	**276**	**262**	**199**	**122**	**92**	**43**	**36**	**33**	**32**
Per capita capacity (kilowatts per inhabitant, not including hydropower)	0.1	0.5	0.1	0.1	0.4	1.1	0.3	0.03	0.5	0.7

Figure 1.5: Worldwide renewable energy capacity by 2015. Extracted from [4]

From a point of view of total installed power, countries with a big population such as the US and China show undoubtedly the biggest capacity of renewable energies. Nevertheless, considering the relative installed power, some European countries as Germany and Spain present a very big share of renewable resources, what supposes a greater impact on the actual electric power system due to a higher penetration of renewable energies.

1.2.2 Distributed generation

The structure of the electric power systems is conditioned by the traditional power flow hierarchy, going unidirectional from very big concentrated energy generators towards the final consumer. This shape has been held during the past century with few changes, supporting the use of fossil fuels during the second industrial revolution. However, this structure does not fit the current needs of power transmission because of the continuous transition from centralized to decentralized power generation, which changes the entire perception of power transportation.

The new frame of decentralized electricity sources leads to the concept of distributed generation (DG), where energy generators work dispersed on local basis at all voltage levels, permitting great flexibility. Even if the existence of DG is partially due to the required improvement of the grid because of its advantages, the main reason of its appearance is explained through the present requirements and insertions of new technologies. Hence, one of the main drivers that forces the appearance of DG are renewable energy sources (in addition to batteries and responsive loads).

Energy generators based on renewable resources do not exist at very large scale (with the exception of big hydroelectric power plants), usually varying between 20 W and 100 MW [21]. An important amount of the RE power capacity emerges from self-consumption installations at residential and industrial level that contribute to the electric grid, turning the power flow from top-down (generators to consumers) to bottom-up. Additionally, in some cases, generators based on solar, wind or tidal resources, can be very inefficient when concentrated at the same spot because of the irregular weather conditions. For this reason, up to date renewable energy generators only exist in form of DG.

Based on the treat that RE sources foster distributed generation, it is important to analyze how this feature affects the electric power system. The traditional unidirectional structure of the electric grid will change to an interconnected web where energy flows in all directions:

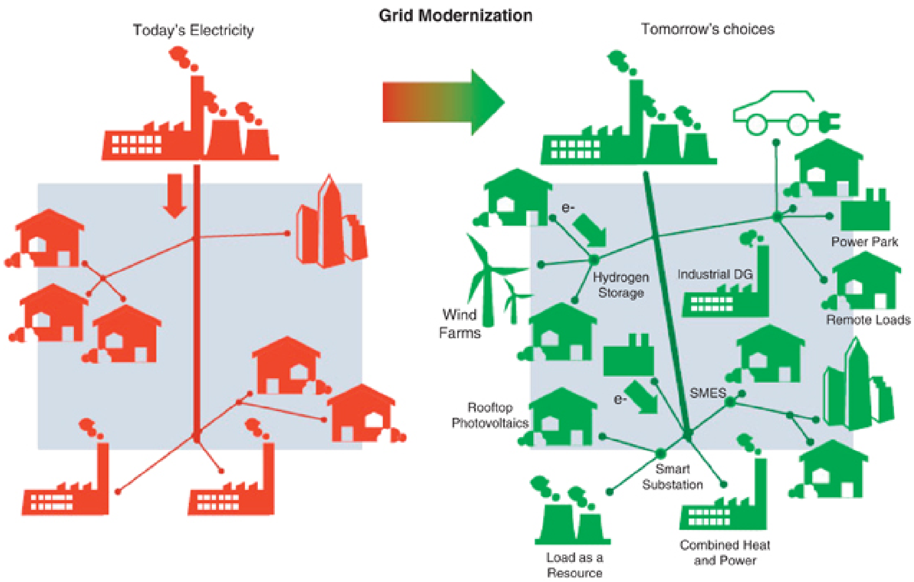


Figure 1.6: Evolution of the electric grid with distributed generation. Extracted from [5]

The change within the electric power system due to DG (distributed energy sources, bidirectional power flow and mesh structure) in addition to the unpredictable energy penetration of RE in the grid (unstable weather conditions) will result in the emergence of some great technical struggles that must be considered [22]:

- **Over voltage**: The increase of RE sources in the electric grid causes voltage variations due to unpredictable changes of injected energy (weather constrained). This phenomena usually shows up as a voltage rise effect, limiting the renewable energy capacity of the grid unless measurements are taken to balance the fluctuations.
- **Power quality**: Both voltage variations and harmonic distortion within the network result in depletion of the power quality. Therefore, DG can suppose a large inconvenient when it's not appropriately designed causing breaches in the quality standards.
- **Protection**: Requirements to protect the entire electric grid harden with the implementation of DG, especially considering bidirectional power flows (most of the actual equipment

is not supposed to handle changing energy flows). If not considered properly, actual protections designed for unidirectional current flow might either be activated wrongly or fail.

- **Stability**: With the growing penetration of RE sources, stability becomes a considerable issue affecting the network security.

1.2.3 Growth of renewable energy penetration

The appearance of new renewable energy generators is a potential challenge in order to handle the electric power system due to distributed generation. Hence, in order to evaluate the magnitude of the problem, it is important to know the actual penetration of RE in the electric grid and its possible growth in the near future.

The global development and growth of renewable energy resources is evaluated statistically on an annual basis by REN21 (worldwide renewable energy network). The last data has proved that in between 2014 and 2015 there has been an outrageous growth in new installed power of RE (surpassing the variations of all previous years), with a global increase of **9** %, which represents a total of **147 GW** [4].

On a long term scale, RE resources have been constantly growing during the last 25 years reaching the actual global 20 % share. The average annual gain of RE by technology within the power sector from 1990 to 2014 has been as following:

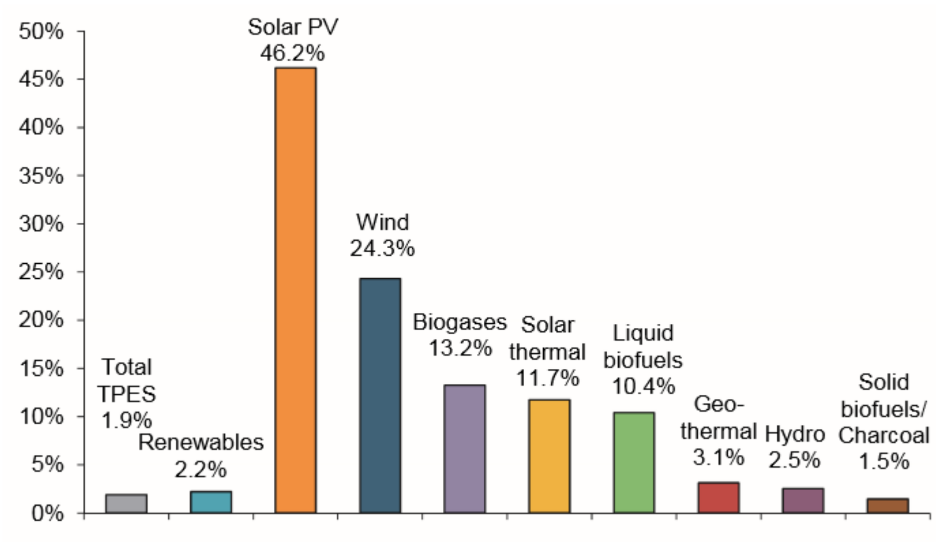


Figure 1.7: Average annual global growth of renewable energies from 1990 to 2014. Extracted from [6]

So, being aware of the current tendencies of RE gain in the electric power system, it is possible to asses its future development based on the actual knowledge. Being aware of the global needs to challenge climate change, the approval of the COP21 by 195 countries (limiting the increase of global warming) objectifies the undeniable tendency that renewable energies will grow during the next decades, albeit the rate is yet unsettled. Moreover, during the last years, growth of RE has already exceeded the gain of all fossil fuels together, entailing that the future of the electric grid will most likely be governed by these technologies.

1.2.4 Required measurements: Smart Grids

The manifested growth of renewable energies within the electric power system will suppose a great burden to deal with. In order to face such a challenge, important measurements have to be taken in order to adapt the current outdated electric grid to the needs of implementing distributed generation.

> *"We've got to do more than just add extra solar megawatts to our electrical grid. That's because this grid - which is made up of everything from power lines to generators to the meters in your home - still runs on century-old technology. It wastes too much energy, it costs us too much money, and it's too susceptible to outages and blackouts. To offer one analogy, just imagine what transportation was like in this country back in the 1920s and 1930s before the Interstate Highway System was built. It was a tangled maze of poorly maintained back roads that were rarely the fastest or the most efficient way to get from point A to point B. Fortunately, President Eisenhower made an investment that revolutionized the way we travel - an investment that made our lives easier and our economy grows."* - Obama [23]

Hitherto, the electric power system presents the same unchanged structure which has been reliable for the traditional energy generation scheme. As with any other system, the advance of new technologies and needs forces the electric grid to be further developed. The necessity of implementing RE depicts the moment where there is no other choice than evolving the grid in order to face this new challenge. Therefore, the required measurement in order to allow sustainable implementation of distributed generation is the introduction of smart grids [24].

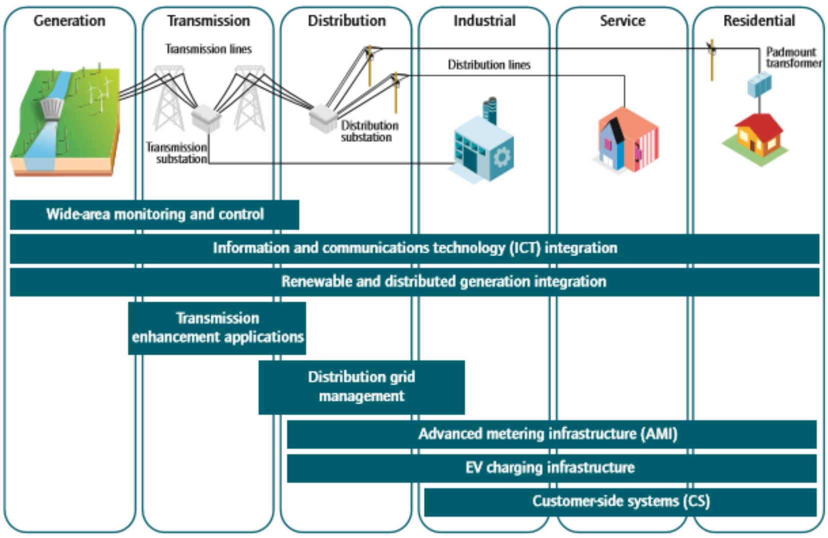


Figure 1.8: Technology areas involved in smart grids. Extracted from [7]

Smart grids cover the entire concept of efficient, reliable and sustainable electricity transport taking advantage of new technologies in order to monitor all connected agents controlling the energy flow and adapting the generation/consumption. Moreover, smart grids are not only about implementing communication tools to operate the grid, but also changing outdated physical technologies, introducing new systems to improve the network (such as energy storage, superconductors, controlled converters and electric vehicle charging stations) and extending the distribution framework, guaranteeing bidirectional energy flow with greater reliability and stability.

The implementation of smart grids in the electric power system is present at all levels of the grid, combining different technologies to create a "smart" operational environment. Apart from all the targets that smart grids intend to face, the two most representative ones to challenge distributed generation is to set new technologies capable of lowering the negative impact of renewable energy sources on the electric power system and adapting the changeable energy flow to the load peaks.

1.3 Energy storage in electric power systems

The challenge of managing the introduction of renewable energies in the electric power system has to be faced with smart grids, wherein one of the most important components is the use of energy storage systems. Their potential and benefit to the electric grid is immense, although up to date most energy storage technologies are still under development and not ready to be applied efficiently on power systems.

1.3.1 Definition: energy storage system

An energy storage system is any device capable of maintaining energy over a period of time (interval varies upon technology) after being charged, and then releasing it (they do not generate on their own). These storage systems can be used in different energy forms (electrical potential, chemical energy, heat, compression, kinetic energy, potential energy and radiation), and often the stored energy does not coincide with the loaded and released energy type. This can be very advantageous when the primary energy is very hard to store, such as electricity. Hence, in electric power systems, energy storage always works with different forms of energy.

Storage systems have a lot of benefits for different areas within the electric grid, although all of them present significant losses. Nowadays there exist several technologies for energy storage applications in electric power systems with different characteristics [25]:

- **Pumped hydro power**: Water is pumped from lower to higher points in order to take advantage of potential energy. Pumped hydro power is currently the most advanced and used energy storage system in electric grids to store big amounts of energy.
- **Compressed air energy storage** (CAES): Air is compressed within big closed spaces (usually caves), and then released to generate electricity with gas turbines. Equal to hydro power, it is used in large scale applications.
- **Flywheel**: Electricity is stored in form of kinetic energy on a rotating mass (usually in vacuum to reduce losses), which can be released with an inverted motor/generator. Great use when big amounts of energy are needed in short time.
- **Chemical batteries**: Electricity is stored in form of chemical energy. There exist a lot of different types of chemical batteries depending on the used materials, with distinct capacities and efficiency. They are utilized in a big range of applications, varying from very small to medium size.
- **Flow batteries/Fuel cells**: Energy storage is based on chemical energy, but different to chemical batteries, they have the advantage that the electrolyte is rechargeable as long as energy is provided. This technology is used in small and mid-scale systems.
- **Supercapacitors**: Energy is stored as electric potential in big electrical condensers. Similar to flywheels, they are good in short term discharge and often used together with chemical batteries in order to improve individual disadvantages.

- **Superconducting magnetic storage** (SMES): Energy is stored in super conductor coils through magnetic field. They are used for short time energy supplies, but are still under development as they also consume a lot of energy to maintain operating condition (refrigerating the system to allow superconductivity).
- **Thermal energy storage**: Uses generated heat, storing it through different materials (i.e. thermal oil and molten salts) in isolated tanks. These systems are mostly used in concentrated solar power plants.

All energy storage systems are driven by two parameters that decide the different areas where the technologies can be applied: discharge time and energy capacity.

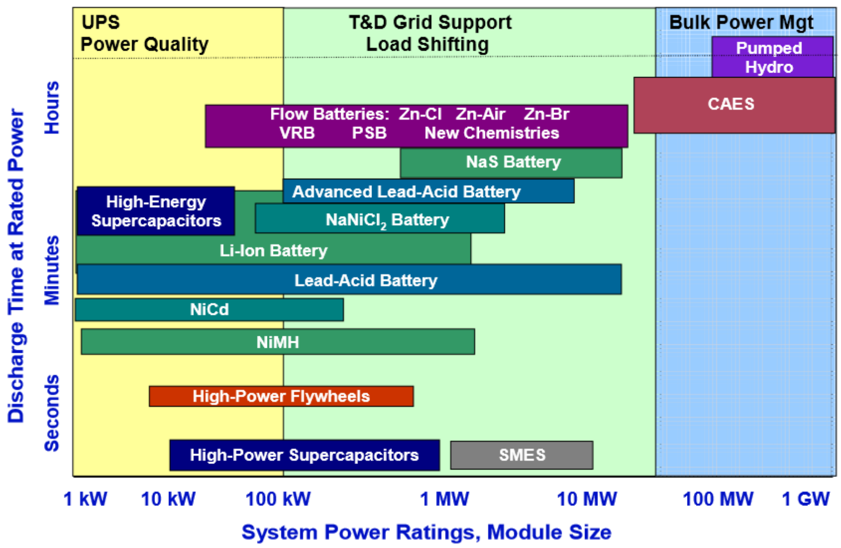


Figure 1.9: Power rating vs discharge time of energy storage technologies. Extracted from [8]

Following this criteria, it is possible to define the avail of different batteries/accumulators inside the various levels of the electric grid.

1.3.2 Benefits of energy storage systems in electric grids

Energy storage systems, within the new concept of smart electrical grids, have the potential to strongly contribute to the electric power system. Independently of the scale of application, it is possible to identify two main benefits of batteries when handling distributed generation because of renewable energies.

Energy flow management, in order to adapt energy production to the consumption. This appliance is crucial when handling renewable energy sources as it is not possible to determine when to produce electric energy (bound to external weather conditions). The problem relies in the fact that generation has to be adapted to daily load shapes of consumers following the first principle of energy conservation. Hence, potential generation intervals of renewable energy sources rarely flap totally with consumption periods. Therefore, in order not to loose great amount of energy, storage systems are required to take profit of the entire generation capacity, adapting the power flow to the load.

Energy quality improvement, ensuring that the stability and quality of the electricity is maintained within the electric grid. The introduction of distributed generation in the electric power system creates several hassles that affect power quality. The most noticeable of these effects is the voltage raise caused due to the injection of electricity proceeding from renewable energies to the grid. This happens because of the variability of production, which depends on external agents. In big electric power plants this phenomena appears as a result of breaching the law of energy conservation when generation does not correspond to the required demand. Nevertheless, at this scale the effect is not that perceptible because of the restrictions that big power plants are subject to. On the contrary, voltage raise is very significant at low distribution level, where renewable energy sources are handled with the purpose of self-consumption. In this subjects, energy that is left over during off-peak hours (energy that is not self consumed) is usually injected to the grid (raising the voltage level). Thereupon, energy storage systems have the capability of storing unexpected energy injections in the electric grid (reducing the generation/load deviations) in order to cut voltage variations.

Knowing the main benefits of energy storage systems on the electric grid, it is possible to evaluate the aptitude of different technologies to be applied in several fields of energy management and quality improvement:

Application	Description	CAES	Pumped Hydro	Flywheels	Lead-Acid	NaS	Li-ion	Flow Batteries
Off-to-on peak intermittent shifting and firming	Charge at the site of off peak renewable and/ or intermittent energy sources; discharge energy into the grid during on peak periods	◐	◐	○	●	●	●	●
On-peak intermittent energy smoothing and shaping	Charge/discharge seconds to minutes to smooth intermittent generation and/or charge/discharge minutes to hours to shape energy profile	○	◐	◐	●	●	●	●
Ancillary service provision	Provide ancillary service capacity in day ahead markets and respond to ISO signaling in real time	◐	◐	◐	◐	◐	◐	◐
Black start provision	Unit sits fully charged, discharging when black start capability is required	◐	◐	○	●	●	●	●
Transmission infrastructure	Use an energy storage device to defer upgrades in transmission	○	○	○	●	●	●	●
Distribution infrastructure	Use an energy storage device to defer upgrades in distribution	○	○	○	●	●	●	●
Transportable distribution-level outage mitigation	Use a transportable storage unit to provide supplemental power to end users during outages due to short term distribution overload situations	○	○	○	◐	●	●	●
Peak load shifting downstream of distribution system	Charge device during off peak downstream of the distribution system (below secondary transformer); discharge during 2-4 hour daily peek	○	○	○	●	●	●	●
Intermittent distributed generation integration	Charge/Discharge device to balance local energy use with generation. Sited between the distributed and generation and distribution grid to defer otherwise necessary distribution infrastructure upgrades	○	○	○	●	◐	◐	◐
End-user time-of-use rate optimization	Charge device when retail TOU prices are low and discharge when prices are high	◐	◐	○	◐	◐	◐	◐
Uninterruptible power supply	End user deploys energy storage to improve power quality and /or provide back up power during outages	○	○	◐	●	●	●	●
Micro grid formation	Energy storage is deployed in conjunction with local generation to separate from the grid, creating an islanded micro-grid	○	○	○	●	●	●	●

Definite suitability for application ● ; Possible use for application ◐ ; Unsuitable for application ○

Figure 1.10: Application of energy storage technologies to benefit the electric grid. Extracted from [9]

1.3.3 Current development of grid energy storage

The current state of energy storage systems applied to the electric grid is not very advanced and bounded to further development. This is because existent storage technologies are still very expensive and need to be improved in order to adapt to large scale production. However, considering their great potential and necessity within the introduction of renewable energies, there are already numerous projects worldwide, and more importantly, big expectations of future implementation.

Up to date there are 1267 finished projects of grid storage systems worldwide, summing up a total of 171,05 GW. Although this value only represents an approximate 10 % of total installed renewable energy capacity (around 2,5 % of total global laid power), it tends to grow continuously over time:

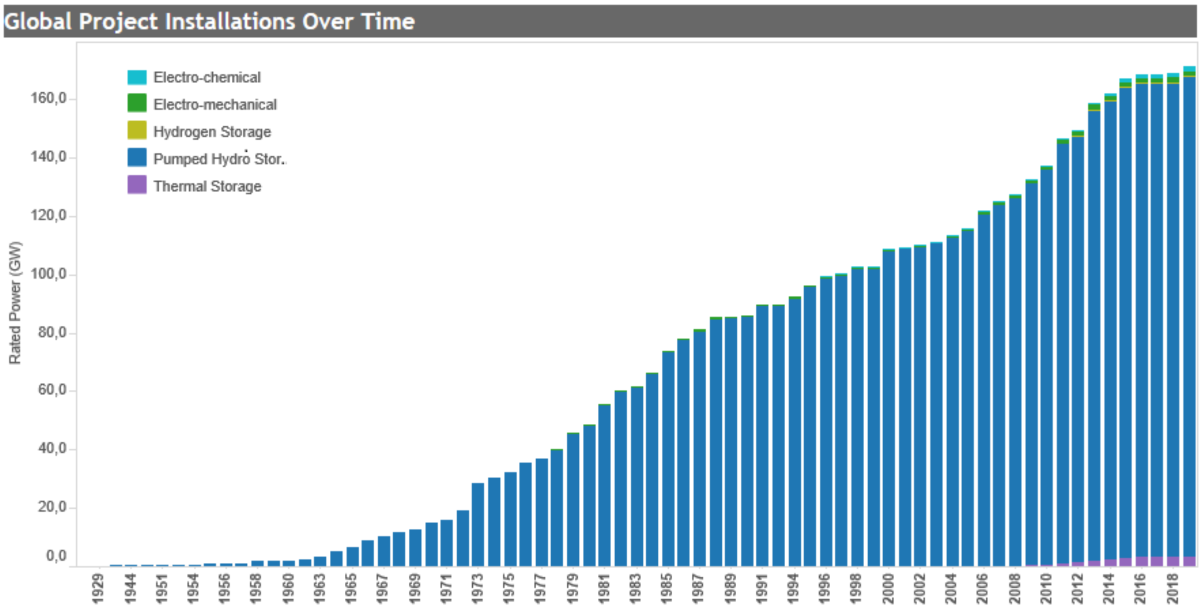


Figure 1.11: Evolution of global grid energy storage projects over time. Extracted from [10]

Most of the existing installations are represented by pumped hydro storage as it is the most developed and viable technology applied on large scale energy production from renewable sources. Furthermore, the majority of projects are devoted to energy management of big renewable power plants in order to optimize their viability balancing the energy generation and demand.

Within the present framework, energy storage systems are not introduced yet as electric parameter mitigation tools in real scenarios. This is because up to now, distributed generation in LV grids has not supposed immediate necessity of introducing regulation methods to secure power quality. Nevertheless, assuming the foreseen growth of renewable energy sources, trait that conditions the further introduction of renewable micro-generators in the LV network, batteries are being evaluated to allow this progress.

According to recent studies [26], there are two types of energy storage systems that have great potential for he electric parameter mitigation purpose in LV grids: Li-ion chemical batteries and Fuel cell flow batteries. This is because both present similar traits that correspond to great functionality in small-scale applications, modularity, proper discharge rate over prolonged time intervals and easy installation. Li-ion batteries are selected over other chemical storage systems because of their high efficiency and current development. Comparing the two proposed technologies, both present different advantages and disadvantages, such as efficiency, discharge depth and energy density. Up to now, the election between both must be further studied and depends on concrete applications.

Chapter 2

Problem analysis

This chapter treats the purpose of the present work, recognizing the problem that entails the motive of this analysis and evaluating the required treatment to perform the study. Hence, first the concrete problem of the present study is identified: the integration of renewable micro-generators in LV grids, evaluating different caused problems to focus the study on the most significant one and reviewing possible mitigation techniques. The second part concentrates on the elected mitigation tool (batteries), assessing their known influence in the electric grid as mitigation technique, followed by the proposed procedure to realize the analysis of energy storage systems.

2.1 Problem statement

Nowadays the continuous introduction of renewable energies to the electric power system is not only an indispensable requirement for a sustainable development of the energy sector, but a given reality [4]. The implementation of these technologies supposes the appearance of distributed generation, what offers a lot of advantages, but also great challenges within the electric grid. This new concept of energy generation switches from big concentrated power units to distributed small-medium sized generators, taking advantage of the circumstances that flatter renewable sources which are mostly constrained by external causes.

The raise of distributed generation does not only bring into existence a new scheme of fractioned power plants, but also introduces the concept of **micro-generation** (very small sized self-consumption energy generation units). This outline offers big prospects for future implementations of renewable energy sources, allowing users to be energetically self-sufficient while fomenting a sustainable electricity sector (i.e. installing PV panels or micro wind turbines for domestic/industrial usage). As advantageous and needful the appearance of micro-generation is, it also implies a great hassle for the old remained electric power system, which is not prepared to face this new environment.

2.1.1 Renewable energy penetration: micro-generation

Micro-generation, also known as self-consumption, is the arise of small energy generators (based on renewable sources) that are used within the distribution grid by individuals, industries or communities to produce their own electricity and participate in the energy sector, being connected to the grid through power electronics, with the purpose of a more environmental friendly and local energy generation. The majority of micro-grid installations are based on PV technologies as a result of their raise in popularity during the last decades within the self-consumption sector (therefore fairly developed) due to modularity, simple installation and total renewable nature. Nevertheless, there are several technologies on date that are introduced for the purpose of self-consumption energy generation: wind turbines, geothermal heat pumps, fuel cells, micro hydro generation and co-generation.

The functioning of micro-generation is quite simple, all self produced energy is auto-consumed when it is required by the load. If the generated power surpasses the demand, the surplus energy is injected in the grid, on the contrary, lacking energy is demanded from the grid. Following this criteria, generation often differs from load consumption due to the nature of renewable generation systems.

Taking the example of PV installations, generation usually exceeds consumption during midday with maximum radiation hours, whilst it reverses at the beginning and end of the day:

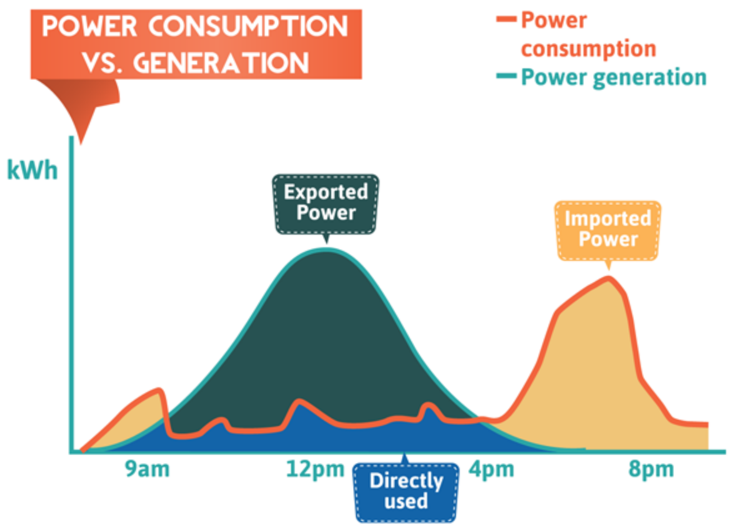


Figure 2.1: Generation vs consumption at PV micro-generation. Extracted from [11]

This behavior supposes a new outline of interaction between consumers and the electric grid, creating the concept of *prosumers* [27]. The idea of injecting/consuming energy from the same point revolutionizes the electric grid, confirming the appearance of DG while empowering the existence of smart grids. Hence, this interaction entails great potential to improve power supply, whilst it also implies the appearance of essential struggles.

The use of micro-generation has two very important benefits within the electric power system. First of all, the more than clear requirement of introducing renewable sources into the global energy mix. But, from a technical point of view, it has also a great advantage: the suppression of joule effect whilst combining generation and consumption at the same place. With this, energy losses of the distribution system decrease, as well as energy quality is more likely to be insured for the consumer.

2.1.2 Impact of distributed generation on LV distribution grids

The gradual and uncoordinated insertion of micro-generation in the electric distribution grid, especially on low voltage (LV) level, causes noticeable negative impact. As they are subject to consumers dominion, although having certain restrictions/regulations which may vary between different countries, it is hardly possible to control the direct impact that emerges with the increase in self-consumption installations. Whereas inhibiting the growth of distributed generation would be controversial against the sustainable and necessary evolution of the electric power system.

In LV electric distribution grids, prosumers create noticeable problems in the operation of the power system due to discrepancy between generation and consumption, particularly when surplus energy is injected in the grid. This struggles appear in form of altered power flows, power quality decrease and voltage variations [13].

- **Altered power flow**: The introduction of micro-generation in low voltage distribution grids increases significantly the present power flow with the injection of surplus energy. Most probably the electric infrastructure is not designed to support this big amounts of energy, wherefore failures within the physical system are likely to occur. Additionally, and even more considerable, is the apparition of **bidirectional power flows** due to the prosumer behavior. The known electric power system was build to manage unidirectional power flow from concentrated energy generators to consumers. Therefore, bidirectional power flows suppose a great problem affecting numerous components of the electric grid, adversely detaching security of the system.

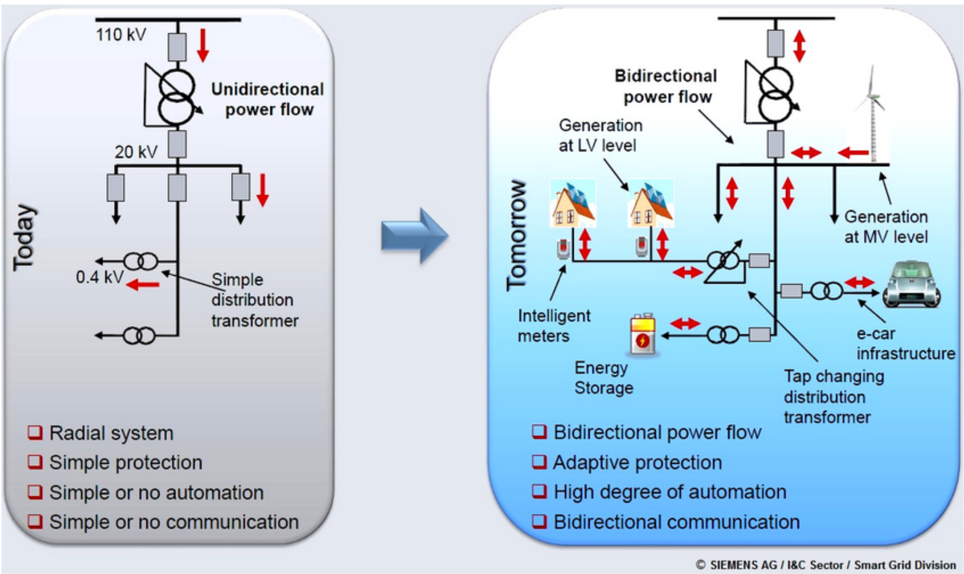


Figure 2.2: Bidirectional power flow due to micro-generation. Extracted from [12]

In order to face the issues caused by altered power flows, it is unavoidable to change several components of the electric grid, although the required measurements are known and achievable.

- **Power quality decrease**: The increase of distributed generation within the distribution system aggravates power quality influencing the harmonics of the power signal. When there are numerous combined renewable micro-generators in the same grid, voltage, current and frequency can be disturbed causing **waveform distortions**:

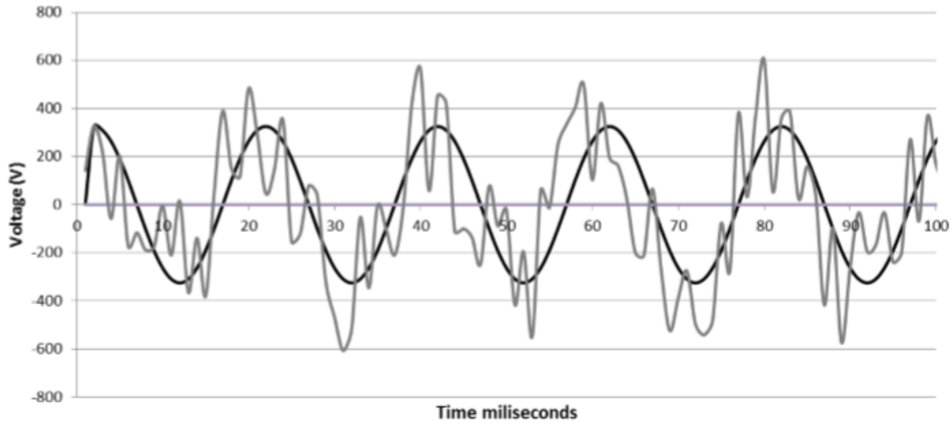


Figure 2.3: Distortion in voltage waveform. Extracted from [13]

This treat is not only a negative influence on the entire electric power system, but also creates big controversial as there exist regulated distortion limits that need to be fulfilled (bounds vary in every country, taking an approximate value of 8 %).

At any rate, even if distributed generation intensifies the decrease of power quality, it is not the main reason for its appearance. Hence, it is important to have this effect in mind, but it does not suppose a game-ending constraint.

- **Voltage variations**: The uncontrolled injection of surplus energy proceeding from renewable micro-generation during low consumption periods unbalances the principle of energy conservation. As a result of this rise in power flow, the electrical parameters are distorted giving place to **over voltage**.

Voltage variations have a very bad effect on the entire electric grid, deteriorating all involved components which are not designed to handle such values. As the uncontrolled injection of leftover energy is a feature that all renewable micro-generators posses, which hardly can be managed, the excess of voltage raise within the LV electric distribution grid is the biggest existing threat of distributed generation.

Numerous studies have proven how injected energy from self-consumption renewable generators raise voltage levels during load peak-off periods according to the following expression [28]:

$$\Delta U = (R \cdot P + X \cdot Q)/V_G \tag{2.1}$$

Where R and X represent the impedance of the electric line (resistance and reactance respectively), P and Q the injected power (active and reactive) and V_G the base voltage of the grid. Therefore, as higher the exchanged power at a given node in the LV distribution is (surplus injected energy from renewable sources that was not foreseen to cover load demand), the more noticeable the voltage increase will be. If the degree of renewable energy penetration in a LV distribution grid increases, overvoltage becomes an essential problem. This behavior is proven in figure 2.4, that shows a study taken in Oahu (Hawaii, US) in 2014, that measured the impact of surplus injected energy from PV panels on the voltage raise.

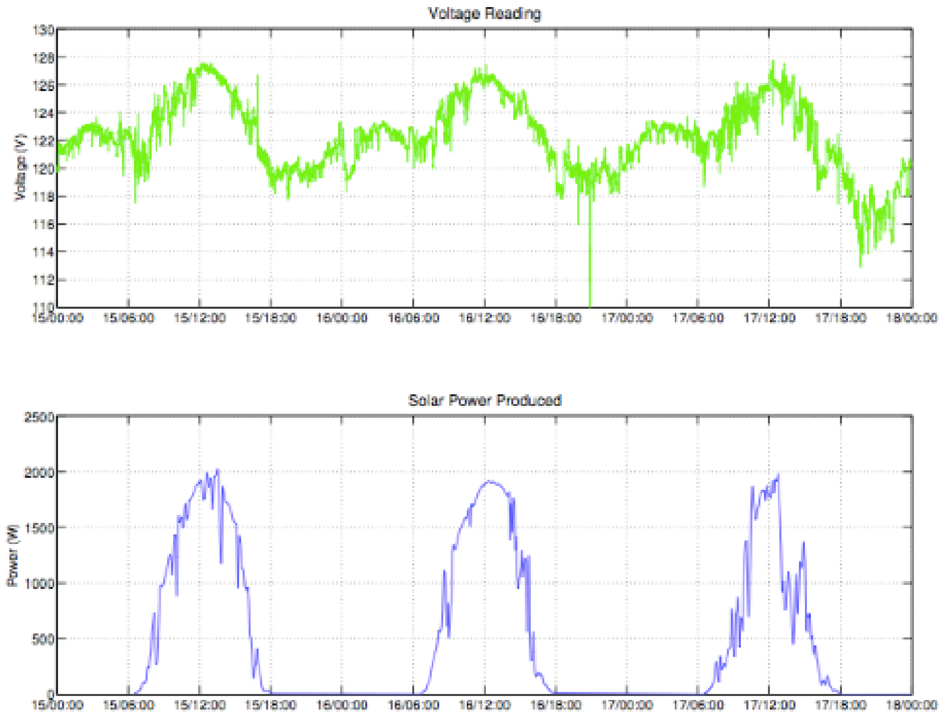


Figure 2.4: Over-voltage results due to PV power injection from an OPQ study realized in Oahu in 2014. Extracted from [14]

Every voltage gain during load off-peak hours (midday) is directly related to the produced energy from the photovoltaic solar panels, what at the same time proves validity of equation 2.1.

Voltage variations within the electric power system are not only very damaging, but also restricted by hard regulations which cannot be broke. According to European standards (EN 61000), voltage variations must be kept in a maximum range of **10** % during at least 95 % of the time period included in an entire week [29]. Furthermore, local Spanish restrictions (RD 1955/2000) impose a top range of **7** % [30].

Out of the numerous existent hassles that the gradual implementation of renewable micro-generator systems cause in LV distribution grids, the most significant one is the appearance of overvoltage. In order to face future development of the electric power system, ensuring the sustainable growth of renewable energies, it is essential to solve the problem. Therefore, **the present work aims to find and prove a viable mitigation technique to reduce overvoltage** within the increasing penetration of RE in low voltage distribution grids achieving the optimal voltage variation range of 3 % [24].

2.1.3 Recognition of possible over-voltage mitigation techniques

Over-voltage is the biggest threat to the operation of electric power systems when handling micro-generation systems in LV electric grids. Hence, several mitigation strategies have been developed in order to analyze possible solutions for the hassle. The main proposals for over-voltage mitigation encompass the possibility of controlling the operation of self-consumption users, changing current infrastructure of the electric grid and adding new technologies [27]:

- **Limitation of renewable energy penetration**: limit the number of connected micro-generators based on renewable sources to prevent aggravation of over-voltage effect.
- **Renewable energy generation curtailment**: restrain micro-generators that are connected to the grid to unlink if voltage raises too much.
- **Reactive power support**: control voltage variations through reactive power management using power electronic components such as inverters and STATCOM systems.
- **New network infrastructures**: replace electric grid infrastructure in order to allow greater power flows while decreasing over-voltage effect.
- **Automatic voltage regulation transformers**: transformers capable of adjusting voltage magnitudes and phase shifts within the distribution grid.
- **Self-consumption methods**: reduction of the load in self-consumption systems.
- **Demand side management**: management of domestic loads, redistributing the consumption strategically in order to soften the demand curve avoiding peaks and drops.
- **Energy storage systems**: Use energy storage devices to keep injected surplus energy during off-peak periods.

All mentioned over-voltage mitigation strategies have an appreciable aim of facing the proposed challenge. Nonetheless, the effectiveness of these techniques varies significantly taking into account their complexity and actual impact. Hence, in order to decide which is the most promising system for the purpose of this work, it is important to analyze possible advantages and disadvantages.

First of all, management of micro-generators applying restrains (such as limitation of renewable energies, generation curtailment and demand side management) is an effective approach to mitigate the over-voltage struggle, but instead of fostering the implementation of renewable energies it stops further development. Secondly, replacing the old electric grid infrastructure does correct voltage variations and also allows growth of distributed generation, but is a very inefficient solution in terms of viability, as it is very cost-effective and infeasible to change the entire distribution system. By last, additional technologies that can be incorporated in the existing LV distribution grid (such as reactive power support, voltage regulation transformers and energy storage systems) are very promising (although still under development), as they have the ability of correcting over-voltage and fomenting renewable energy expansion whilst supposing simple and viable solution due to their modularity.

As the most appropriate measure to face over-voltage appears to be the implementation of additional devices on the grid, there are several possible technologies that encompass this technique and could be further analyzed. In order to select an adequate system (out of the proposed technologies, it has not been proven yet that neither of them works better than the other), the criteria that follows the aim of the present work will be the most outstanding: ensuring the effective and sustainable growth of renewable energy penetration within the electric power system. Therefore, the leading choice is the evaluation of **energy storage systems** to mitigate the over-voltage phenomena, because they do not only settle the problem such as power electronics and regulation transformers, but additionally manage the power flow within the LV grid, storing surplus energy which is then re-injected when consumer loads need it the most (especially during the night). So, implementing energy storage systems might not only mitigate the existing problem, but also take most benefit out of renewable micro-generation.

2.2 Problem treatment

Over-voltage has been identified as the most significant problem that needs to be treated in order to allow further implementation of renewable energy micro-generators in LV grids. The most promising mitigation technology selected in order to face the given challenge are energy storage systems due to their potential capacity of treating the hassle whilst taking benefit out of renewable sources. Now, the next step consists in determining the workspace for the proposed analysis, identifying the treats of the besought mitigation technique and evaluating the procedure that should be followed in order to prove the effectiveness of batteries through simulation.

2.2.1 Analysis of energy storage systems in LV distribution grids

Energy storage systems are slowly penetrating in the global electric power system whilst their technology matures, as can be seen in figure 1.11. Nevertheless, most of these installations are designed to act as energy management systems to regulate generation/demand relation for renewable power plants. Therefore, the effectiveness of batteries in real applications as over-voltage mitigation devices is yet unknown. However, several studies have already analyzed the potential of energy storage devices in LV distribution grids to reduce voltage variations.

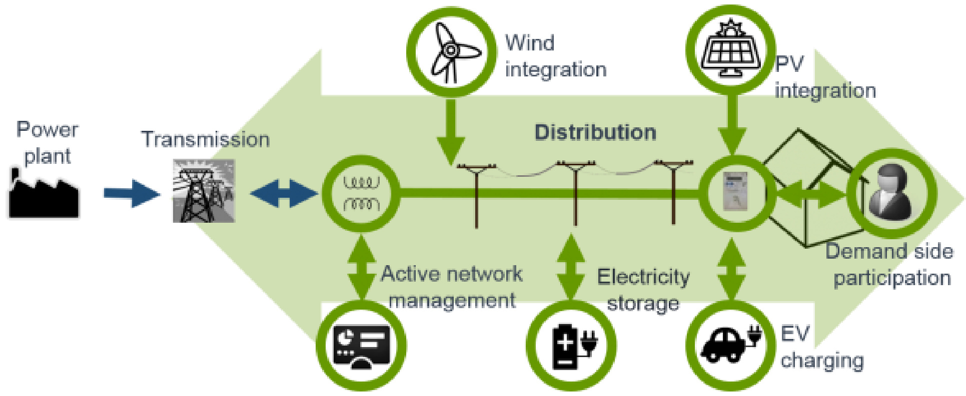
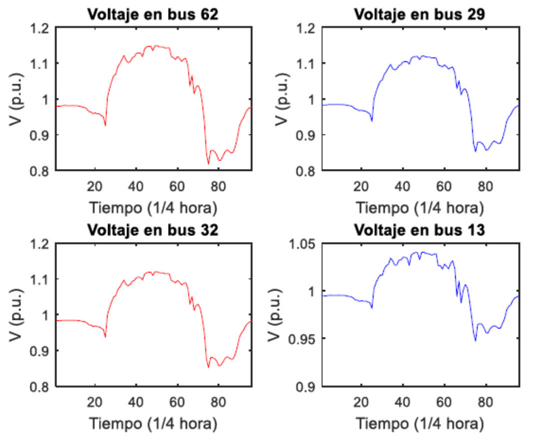


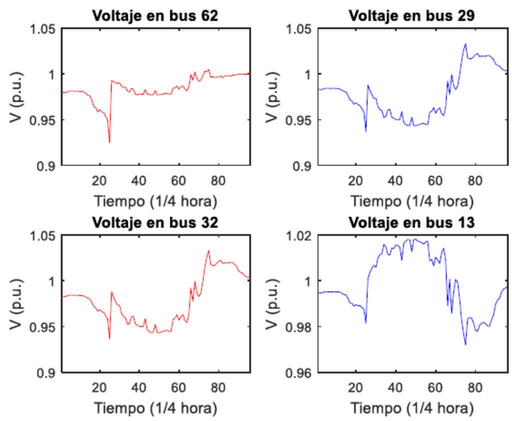
Figure 2.5: Energy storage systems in micro-generation LV grids. Extracted from [15]

According to a research project realized through simulations about the effectiveness of different energy storage systems (centralized on critical nodes and decentralized on the loads) in residential LV distribution grids with high PV penetration from the Technical University of Denmark [28], these technologies have been proven to be very beneficial within the purpose of mitigating voltage variations. Additionally, their impact improves even more if combined with reactive power support technologies. Hence, it is possible to confirm that energy storage systems do have the potential to work as over-voltage mitigation agents. From here on, the objective is to analyze in more detail the impact of energy storage systems on the distribution grid with high renewable energy penetration.

The present project is based on a previous work [16] that studied the impact of energy storage systems on a residential LV grid through simulation, comparing the performance of centralized and decentralized energy storage systems to instantaneously mitigate over-voltage at different renewable energy penetration rates (33 %, 66 % and 100 %). The analysis worked out properly, proving the effectiveness of a generic energy storage device that reduced voltage variations in a proposed model. Furthermore, the study showed that centralized batteries suppose a better solution in small residential grids. Results of the mitigation capacity of the implemented energy storage systems in the model are shown in figure 2.6, where it can be observed how voltage variations diminish with the use of centralized batteries:



(a) Voltage behavior at furthest points of the modeled grid with 100 % renewable energy penetration and no batteries



(b) Voltage behavior at furthest points of the modeled grid with 100 % renewable energy penetration and centralized batteries

Figure 2.6: Impact of centralized batteries as over-voltage mitigation technique according to the results obtained within the model of the previous project (study on which the present work is based on). Extracted from [16]

Relying on the obtained data from the previous project (centralized batteries are more suitable than decentralized systems) in addition to the purpose of providing a modular solution that can be applied from the point of view of the grid operator (without interfering in consumer loads which would harden the growth of RE) in order to create a self-contained system applicable to any LV grid, the content of this work will only focus on the implementation of **centralized energy storage systems**.

So, starting from the results of the base project [16], the objectives of the current analysis will enhance new topics widening the assessment in order to get data from a more realistic simulation approach (evaluating the effect of batteries on several traits of the grid) to model the impact of centralized energy storage systems in a residential LV distribution grid. The proposed subjects will enhance the following features:

- Inclusion of **energy losses** within the model for the grid and energy storage system.
- Simulate **three-phase distribution lines** considering the effect of unbalanced loads.
- Account **continuous impact** of storage systems within a time period of several days (instead of momentary effect).
- Consider evolution of long term **gradual penetration of renewable energy micro-generators** in LV grids (in lieu of fixed scenarios).

2.2.2 Method of assay: power flow analysis

The impact of centralized energy storage systems on LV distribution grids with high renewable energy penetration - in form of micro-generators, is going to be evaluated throughout the simulation of a proposed model that represents a residential distribution grid. In order to simulate the approximation of a real scenario, energy flow must be computed within a given time period (with several iterations) to obtain data about voltage, current, power (active/reactive) and phase shift to evaluate the effect of the besought mitigation system (centralized batteries). Therefore, it is required to perform a **power flow analysis** on the model using different cases.

The power flow analysis or load-flow study is a steady state numerical assay of the energy flow within an interconnected electric system. The studied framework is composed of buses (nodes that can represent both generators and loads) and lines that connect them. In this way, by assigning known electrical parameters to the buses and lines, power flow analysis can be solved in order to simulate the operation of the system. The settlement of the load-flow study works out the voltage and phase angle value at each bus in addition to the power flow (active/reactive) at each line. Given that load flow analysis is usually performed at AC (alternating current) power grids, computations are made in p.u. (per unit) following a one-line diagram scheme.

Before starting the computations to solve the power flow analysis, first the problem needs to be formulated. Therefore, all buses must be classified according to their typology in order to assign known and unknown variables:

- **PQ Bus**: Nodes that are only composed of loads. Active (P) and reactive (Q) power of the consumption is known, whilst voltage (V) and voltage angle (θ) are unknown.
- **PV Bus**: Nodes that include at least one generator. Active power (P) and voltage (V) of the generation is known, whereas reactive power (Q) and voltage angle (θ) are unknown.
- **Slack Bus**: Reference bus that balances active and reactive power of the system, injecting or absorbing energy when required. Hence, slack bus can either be placed according to the grid morphology (usually at energy substations) or at a randomly chosen PV bus when the scheme does not highlight a specific grid connection point where power can be freely shifted. So, voltage (V) and voltage angle (θ) are known, while active (P) and reactive (Q) power is unknown.

Next, line parameters between buses must be defined. This can be done following a π model, determining line admittance [2]:

$$Y = G + jB \tag{2.2}$$

Y represents the admittance, G the conductance and B the susceptance, where admittance is directly proportional to the impedance of the line:

$$Y = \frac{1}{Z} = \frac{1}{R + jX} \tag{2.3}$$

Where Z stands for the impedance, R for the resistance and X for the reactance in the line. The model used to compute the admittance of branches is as following:

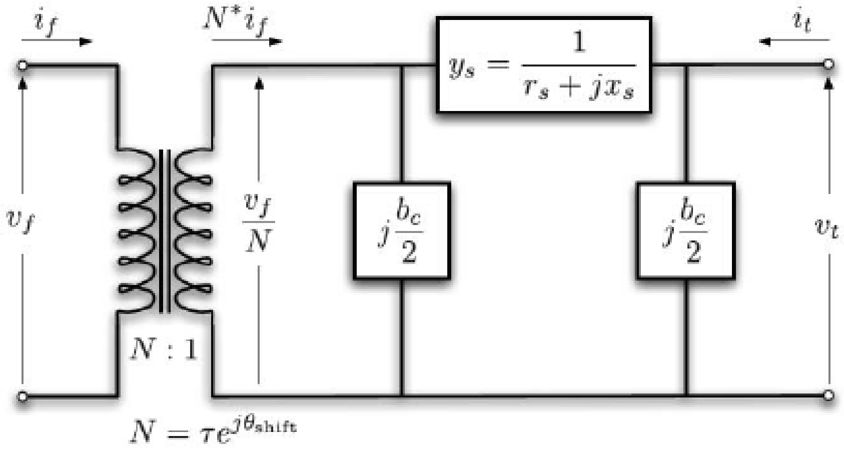


Figure 2.7: Branch model. Extracted from [17]

From here on, the admittance matrix that represents all branches of the analyzed system can be build:

$$Y = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{12} & \cdots & \underline{Y}_{1n} \\ \underline{Y}_{21} & \underline{Y}_{22} & & \vdots \\ \vdots & & \ddots & \underline{Y}_{(n-1)n} \\ \underline{Y}_{n1} & \cdots & \underline{Y}_{n(n-1)} & \underline{Y}_{nn} \end{bmatrix} \tag{2.4}$$

Once all required parameters are defined, it is possible to solve the load-flow analysis using power balance equations for active and reactive power [2]:

$$P_i = v_i \sum_{j=1}^{n} v_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{2.5}$$

$$Q_i = v_i \sum_{j=1}^{n} v_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \tag{2.6}$$

This generic formulation can be applied to any electric power system if it is defined correctly. Although there is an important inconvenient, which is that the power flow analysis is computed using a non-linear system (impedance depends on the square of applied voltages). Hence, when studying big electric networks, it is often not possible to find an exact solution. So, in order to realize the load-flow analysis with the purpose of the present work, it is necessary to apply numerical iterative simulations to obtain the required results. There are several different methods that work out well in order to find a proper solution for big grids, of which the most known is the **Newton-Raphson** method, that will also be the one used along this project. The resolution procedure of the Newton-Raphson method is explained in more detail in **Appendix D**.

All power flow analysis resolution methods are focused on single phase schemes, simplifying electric lines into one-line diagrams. But, in order to fulfill the approach of simulating the impact of energy storage systems realistically, branches between buses will have to be considered as triphasic lines in order to bring the model closer to a real LV distribution grid. Therefore, in order to ease computations, all three phases will be considered independently during the resolution of the power flow analysis, merging parameters with previous and post data treatment.

Chapter 3

Methodology

This chapter evaluates the methodology used to perform the present work. Therefore, first the proposed procedure to accomplish the analysis will be presented, that includes the creation of a model, the simulation process and evaluation of the results. Secondly, the designed simulation tool, defined by a purposely created algorithm to solve the analysis, is presented including the employed software and the structure of the program.

3.1 Procedure

The procedure that is followed in the methodology of the present work - after recognizing and evaluating the problem that entails the purpose of the analysis of centralized batteries in LV distribution grids with high renewable micro-generator penetration, is composed of three main stages: creating a model that depicts a realistic case scenario, simulating the established model using an adequate algorithm (simulation tool) and finally assessing the obtained results evaluating the possible impact.

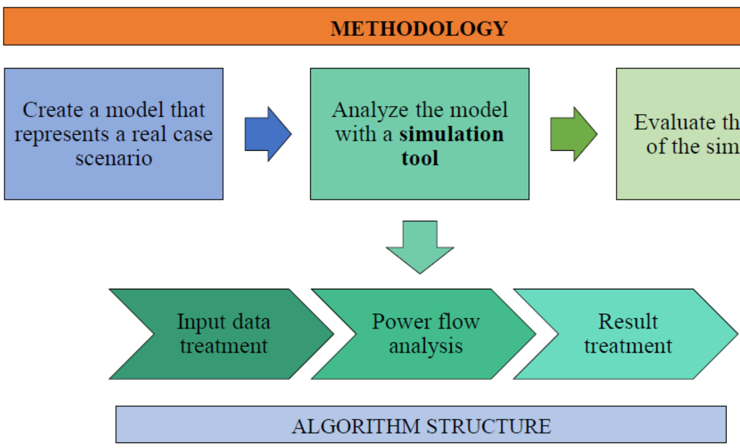


Figure 3.1: Proposed methodology to solve the present analysis

In order to carry out the procedure, a generic simulation tool (algorithm) will be created with the purpose of analyzing the present work, including required characteristics that haven't been evaluated in previous studies (such as energy losses or unbalanced loads), that can later on be applied to the created model within the given methodology.

3.1.1 Model establishment

The first step within the procedure of analyzing the impact of energy storage systems is the recreation of a model that will represent a real case scenario of a LV distribution grid. To do so, it is necessary to define the virtual grid as close as possible to reality using appropriate data and precision. First, the base structure of the grid needs to be modeled with constant parameters that depict the infrastructure of the proposed electric power system, including loads, generators, lines and substations. Once the base basic scheme is shaped, variable data can be assigned to the distribution grid according to different cases that quantify consumption, energy generation, load balancing on phases and battery capacity.

Constant parameters

- **Grid structure**: The first step consists in establishing the characteristics of the LV electric grid that is going to be analyzed. This will be done according to data taken from an existing residential distribution grid, parameterizing the main components.
  - *Buses*: Nodes of the system that are represented by domiciles, generators, batteries and substations. The number of involved buses must be sized and determined, assigning the adequate type according to their nature: PQ, PV and Slack.
  - *Lines*: Lines that connect all buses must be determined, adding required data about electrical parameters (type of branch, impedance, inductance, capacitance, voltage and distance).
- **Substation sizing**: Electric transformer where the case object (LV distribution gird) is connected to the main grid, which must be dimensioned according to the size of the model and the energy needs.
- **Generator dimensioning**: Renewable micro-generators involved in the model should be designed realistically in accordance to the different consumption needs of the houses, in order to be added to the existing loads, with a range from 0 to 100 % renewable energy penetration.

Variable parameters

- **Energy data**: Information about the amount of energy that flows in the proposed electric power system must be defined for different scenarios.
  - *Load data*: Energy consumption of the loads that will vary constantly over the day as a function of the customer profile and load curve.

  - *Generator data*: Energy production from renewable micro-generators installed at the domiciles, which depends on the external weather conditions (several cases can be considered for different climatic terms).

- **Load distribution**: Ideally loads are distributed totally balanced among the three phases of the distribution lines. As this does not always apply in real scenarios, it is advantageous to include possible balancing deviations in the analysis to foresee result variations.
- **Renewable energy penetration**: Continuous increase of renewable energy sources within the modeled electric system must be considered in order to review the impact of energy storage system along the real future expected development of the technologies. Hence, different micro-generator penetration values must be taken into account from 0 to 100 %.
- **Battery design**: The analysis of the work has to consider the implementation of different energy storage systems regarding their typology and energy capacity. Therefore, the dimensioning of the studied batteries will vary.

3.1.2 Simulation of the model

The simulation of the designed model is going to be performed through power flow analysis, applying the Newton-Raphson numerical method (steady-state evaluation of the system). In order to asses the simulation over a certain period of time, the process will need to be done iteratively according to the established terms. To do so, all initial data from the model will be adapted to the conditions of the load-flow analysis environment with previous data treatment. While realizing the simulations, two treats are necessary to be considered:

- **Sampling time**: Number of performed iterations (power flow analysis) within a total time span. This variable is crucial in order to obtain an adequate solution, being it essential to find an appropriate sampling time that is big enough to allow a good-working simulation ambience, but at the same time small enough to provide detailed results.
- **Simulation time**: Total time span that will be considered for each simulation. This characteristic of the analysis is also very important because of the nature of the problem - evaluate the operational impact of batteries in the electric grid. Therefore, it is a good option to observe how energy storage systems are able to mitigate over-voltage issues on concrete time periods (i.e. a proposed day with good, average and bad scenario conditions), but also how their effectiveness evolves within the work environment during several days (e.g. an entire week).

Once all parameters are settled, simulations of the model can be done using the purposely created simulation tool/algorithm that is explained in section 3.2.2.

3.1.3 Evaluation of the results

The last step of the procedure consists in the evaluation of the obtained results from the simulations. Hence, in order to take advantage of the proposed study properly, the following treats will be emphasized during this part of the analysis:

- **Case scenarios**: There will be a vast number of possible cases that can be analyzed that surge from the combination of different variable parameters (defined in section 3.1.1). In order to select the appropriate scenarios to foment the purpose of the work, the chosen cases will be based on statistically average parameters and worst-case scenarios to highlight the effectiveness of the proposed solution.
- **Result representation**: Similarly to the case scenarios, there are many different obtained results (e.g. voltages, currents, power flows, phase shifts) at numerous points of the grid. Therefore, the most relevant data of the outcomes that is directly related to the problem will be prioritized.
- **Indicators**: Results are going to be quantified in several indicators (e.g. voltage variations and energy losses), in order to ease comparison between different outcomes.

To sum up the evaluation of the results, the obtained outcomes will serve as pointers to justify a reasonable epitome regarding the state of the art of current technologies and possible development according to existing knowledge.

3.2 Simulation tool

The simulation of the proposed model will be done using a specific algorithm created for the purpose of this work. The model is going to be executed on generic mathematical softwares that empower the resolution of load-flow analysis, employing the proposed algorithm to adapt the given data to the required characteristics of the problem.

3.2.1 Software

The simulation process is going to be performed using **MATLAB®** [31] as main environment. MATLAB® is a high advanced numerical computation program developed by MathWorks that is based on its own programming language. It does not only allow the resolution and graphical representation of any kind of mathematical/numerical task, but also enables the creation of algorithms to solve complex problems. Hence, taking into account its great graphical capabilities, it is the optimal working space to develop the simulation tool for the present work.

The realization of the simulation is bounded to several steps including previous and post data treatment that are executed by the implemented algorithm working in MATLAB®. However, the load-flow analysis itself will be carried out by an additional software - **MATPOWER** [32]. This tool is designed to solve power flow studies making use of the Newton-Raphson numerical method. The exact functionality of the MATPOWER software is specified in **Appendix E**.

3.2.2 Algorithm structure

The foreseen analysis of a LV distribution grid with numerous buses, renewable micro-grid generators and storage systems, realized over a period of time that requires a noticeable amount of samples involves an enormous number of data that must be handled. Therefore, the creation of an algorithm that automatizes the entire procedure is very advantageous.

Making use of the powerful MATLAB® working environment and using MATPOWER to ease the resolution of the load-flow analysis, a specific simulation tool has been created, permitting the user to carry out infinite simulations for different scenarios without redoing the entire previous and post data treatment. The created tool is based on a user interface (modifiable MATLAB® function) where the simulation properties can be chosen, and once executed follow the structure of the implemented algorithm. The proposed methodology is divided in three main sections: previous data treatment to provide the selected simulation configuration (information taken from set up databases), power flow analysis utilizing the MATPOWER package and result treatment (computing needful indicators and depicting the outcomes graphically).

The generic structure of the created algorithm that is implemented along this work is shown in figure 3.2.

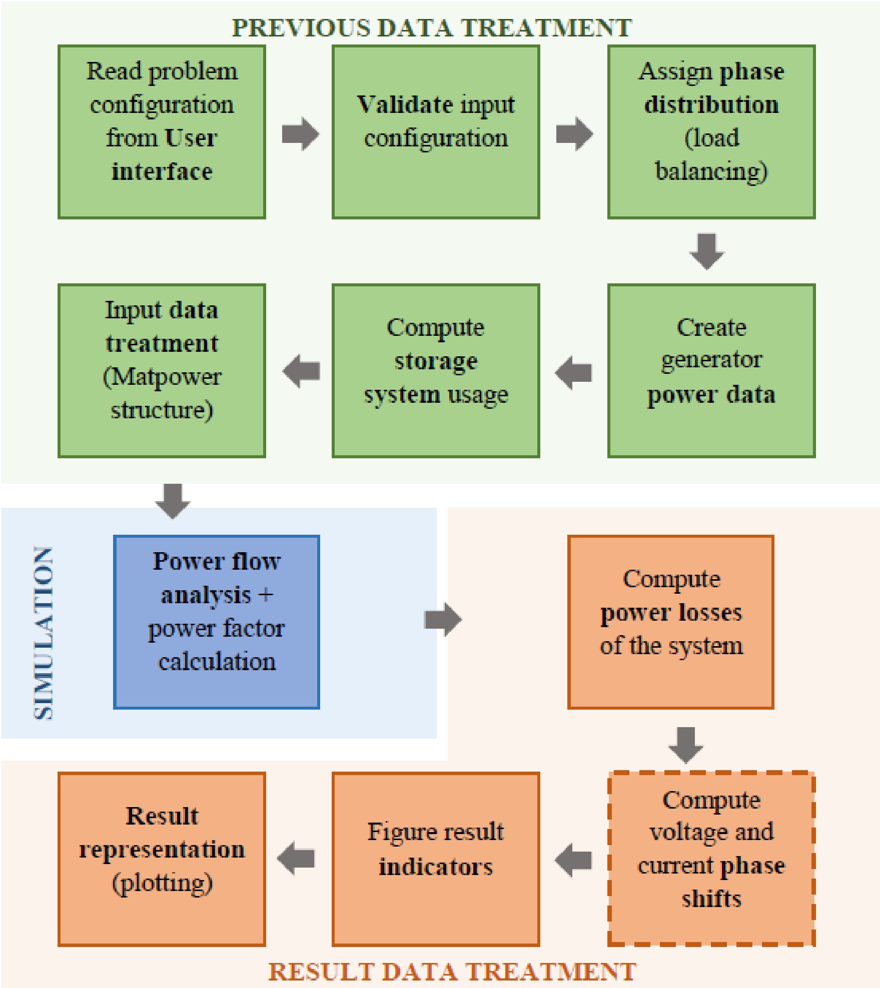


Figure 3.2: Structure of the created algorithm to perform the simulation

Each element that appears in the scheme represents an entire block of the procedure that is implemented as an independent MATLAB® function. Hence, all data involved in the simulation is processed step by step following the order of the given course.

From here one, knowing the general scheme of the simulation tool, detailed characteristics of all involved blocks are going to be presented in the following sections.

Input data processing

This first part of the algorithm is focused on the previous data modeling in order to prepare all required parameters for the simulation. Hence, it comprehends the evaluation introduced configuration in the user-interface, reading and adapting all required data from the model according to the selected scenario and preparing parameter input structures for the MATPOWER load-flow resolution.

- **User interface**

  The user interface allows to choose the simulation configuration confining the possible variable parameters. This can be done modifying the proposed data in assigned variables within a MATLAB® function. After selecting the proper arrangement and running the simulation tool, the remaining procedure works automatically. The parameters that can be changed in order to define the configuration are shown in figure 3.3.

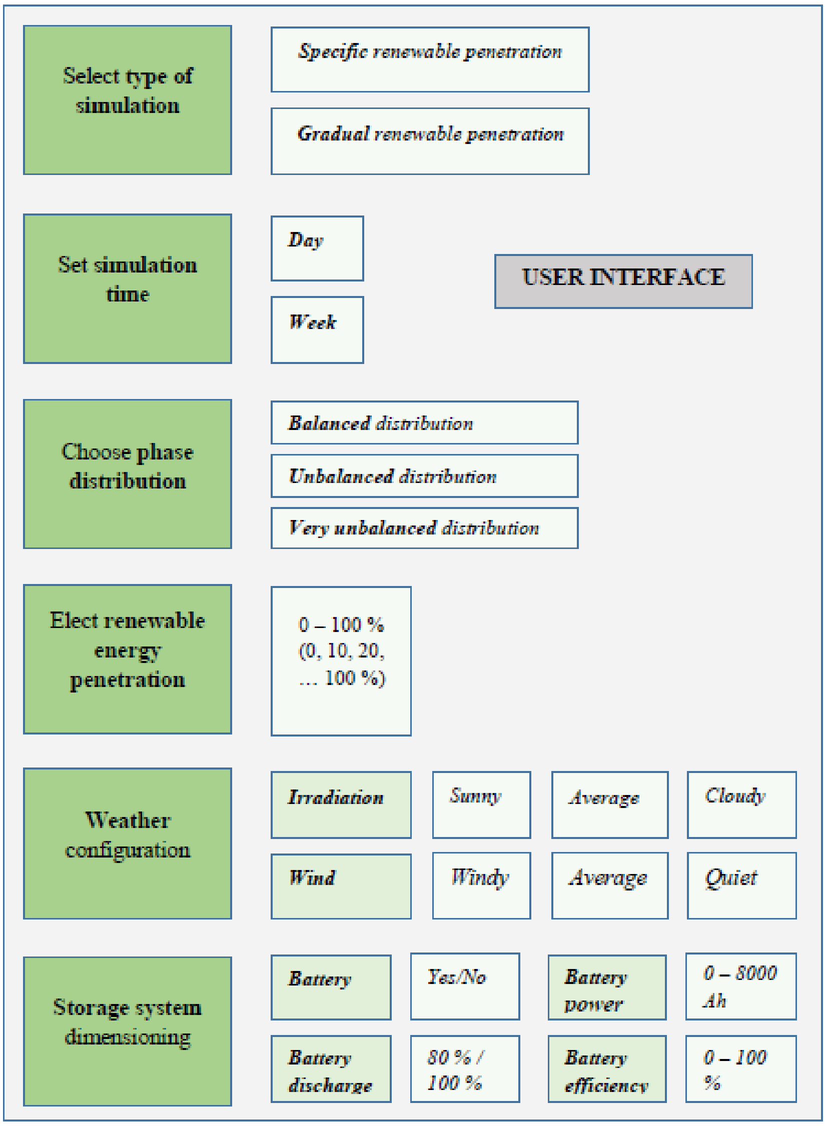


Figure 3.3: Structure of the user interface of the created simulation tool

The variable options that can be modified within the user interface include:

- Simulation type: It is possible to choose in between to main configurations, either analyzing the impact of energy storage systems on a specific renewable energy penetration factor (evaluating direct voltage mitigation), or assessing the continuous introduction of these energy sources in LV grids from 0 to 100 % penetration (reviewing the gradual impact).

  – Simulation time: Simulation can be performed during a single day to observe the instantaneous mitigation effectiveness of batteries on over-voltage, or for an entire week, in order to assess the discharge rate over longer a period of time (a week is chosen as it is long enough to represent all statistical weather conditions, but at the same time short enough to not overstep simulation data size).
  – Phase distribution: Phase distribution can be selected in order to simulate different possible load balance scenarios. Ideally consumption points are equally distributed over all three phases of the electric line, but unfortunately this is not always the case. Hence, to consider worst case scenarios, the possibility of less balanced phase distributions are included in the algorithm.
  – Renewable energy penetration: In case the first simulation type is selected (specific renewable energy penetration), penetration rate can be chosen in between eleven different values - 0 %, 10 %, 20 %, 30 %, 40 %, 50 %, 60 %, 70 %, 80 %, 90 % and 100 %. The actual relation between existing micro-generators and renewable energy penetration is going to be defined along the formulated model.
  – Weather conditions: these variables directly influence the amount of produced energy from the renewable micro-generators. Being PV panels and wind mills the most usual and appropriate technologies for 100 % renewable self-consumption systems, wind and sun irradiations will be considered within the weather conditions. For both cases, good, average and bad scenarios can be selected.
  – Energy storage system: In order to determine the energy storage system that will be considered during the simulation, several aspects play an important role. First of all, whether there shall be batteries or not during the analysis. In case there will be a storage system included, battery discharge coefficient, capacity and efficiency will have to be chosen within the given value ranges. On the contrary, the parameters defined in this variables will not affect the progression of the simulation.

  The MATLAB® code that represents the real user interface is added in **Appendix F**.

- **Validation of input configuration**

  This component of the process validates the selected parameters from the input configuration of the user interface. If any of the introduced values is not within the possible boundaries, the entire simulation is stopped in order to avoid possible errors. Otherwise, if all data is correct, the parameter units are adapted to the working conditions (e.g. power from kW to MW).

- **Phase distribution allocation**

  The phase distribution (order in which loads are connected to the three phases) is created in this module according to the selected option. The numerical patterns that simulate the proposed behavior of connected loads can either recreate balanced, unbalanced or very unbalanced phase distribution (see section 4.2.2). Taking use of this allocations, it is possible to evaluate the impact of energy storage systems in cases with perfect balanced grids, but also in scenarios with overloaded phases.

- **Generator data creation**

  Along this part, the produced power from all involved micro-generators is computed according to the renewable energy penetration rate and the selected weather conditions. Hence, using irradiation and wind curves, energy can be obtained combining this information with the nominal power of every installation. Generator data is going to be calculated for every time step over the entire simulation period.

$$\textbf{PV systems:} \qquad P_{G_k} = (S_k \cdot Irr) \cdot PV_{eff} \tag{3.1}$$

  P_{G_k} represents the generated PV power of system k, S_k the surface of installation k, Irr the sun irradiation (W/m^2) and PV_{eff} the efficiency of the solar panels. Notice that PV installations only produce active power.

$$\textbf{Wind turbines:} \qquad \begin{aligned} \text{[Power (W)/Wind speed (m/s) curve]} &\vdash P_{G_i} \\ \text{[Power (W)/Wind speed (m/s) curve]/10} &\vdash Q_{G_i} \end{aligned} \tag{3.2}$$

  Active (P_{Gk}) and reactive (Q_{Gk}) power generated by the wind mills is determined through the Power/Wind-speed curve (proportioned by the turbine manufacturer) knowing the wind speed values for every time step of the simulation. Reactive power cannot be obtained precisely, hence it is estimated as $Q_{G_i} \approx 10\% P_{G_i}$.

- **Storage system usage**

  In this section, supposing energy storage systems are included in the simulation in accordance with the initial input configuration, battery operations for every time step (charge, steady-state and discharge) are computed. Therefore it is important to mention that the included energy storage system can only be at one operational mode at every time step (e.g. it is not possible to charge and discharge simultaneously).

  Generic operation possibilities are determined according to the following statements:

$$P_{G_i} > P_{D_i} \rightarrow \text{Battery charged} \tag{3.3}$$

$$P_{G_i} = P_{D_i} \rightarrow \text{Battery unchanged} \tag{3.4}$$

$$P_{G_i} < P_{D_i} \rightarrow \text{Battery discharged} \tag{3.5}$$

  Where P_{G_i} stands for the total generated power of the system and P_{D_i} for the total consumed energy, both at time step i. This basic rules apply in all scenarios, which are extended with more advanced features in the proposed model (energy storage control scheme) in section 4.1.4, and are always conditioned by the charge status (maximum/minimum possible charge/discharge capacity).

- **Input data treatment**

  The last step before proceeding to the load-flow analysis consists in reading all required information and adapting the parameters to the input structure of the MATPOWER tool.

  First of all, load profiles from all involved buses are adapted to the samplings that will be utilized during the analysis. Next, produced/consumed power parameters from generators and loads are adjusted to the phase distribution determined previously. By last, all required information is structured according to the three MATPOWER input schemes (branches, buses and generators) in matrix form. Therefore, already existing outlines that include the constant parameters of the model are modified with the inclusion of the corresponding variable inputs for loads and generators (branch parameters are fixed permanently as the generic structure of the grid does not change).

Power flow analysis simulation

The power flow analysis is performed running the MATPOWER tool with all parameters from the previous data treatment. Additionally, within the power flow simulation, an extra tool (MATLAB® function) computes the instantaneous power factor at the critical nodes.

- **Load-flow study**

  The entire load-flow analysis is based on an iterative process, applying the steady state Newton-Raphson numerical method for every time step in order to obtain a dynamic evaluation within a defined time period considering all iterations together. Therefore, the simulation is programmed as a loop function within the MATPOWER environment, enabling daily and weekly system analysis with the given time intervals. During the execution of the algorithm, temporary obtained results from each iteration are assigned to constant variables for the post data treatment.

- **Power factor computation**

  The power factor is computed at critical nodes of the system in order to asses better the operational behavior of the grid. In order to do so, in between every iteration, the power results (active and reactive) obtained at the furthest ends of the branches (near to buses) are used to calculate the power factor through an additional function. The computations for the power factor are based on the main power properties manifested in the following equations:

  $$S_{k,i} = P_{k,i} + jQ_{k,i} \tag{3.6}$$

  $$PF_{k,i} = \frac{P_{k,i}}{S_{k,i}} \tag{3.7}$$

  Where $P_{k,i}$ represents active power, $Q_{k,i}$ reactive power, $S_{k,i}$ complex power (combination of active/reactive) and $PF_{k,i}$ the power factor, all four at point k and time instant i.

  Notice that the obtainment of the power factor at critical points of the grid serves as additional information to prove the adequate functioning of the proposed electric power system within the simulation process. However resulting power factor data is not used to uphold the evaluation of the present study, as it does not immediately affect the mitigation of over-voltage, and is therefore treated according to other technological systems.

Result treatment

The last part of the algorithm scheme consists in the post data treatment, using the obtained results from the power flow simulation to compute and graphically represent the final outcomes.

- **Power losses calculation**

  The power losses comprehend all vanished energy through the joule effect in the electric distribution lines and energy storage efficiency. This treat is very useful in order to asses how batteries could alter power losses, both positively or negatively, depending on the concerned simulation scenario.

  The applied methodology to obtain instantaneous power losses data from the entire system along the the simulation samples is done based on the energy conservation principle for the lines, and the global efficiency of all involved components of the energy storage installation for the batteries.

  - Grid power losses

    In order to compute the power losses in the electric grid due to the joule effect, all instantaneous consumed power at the loads is subtracted from the produced power at the generators, being the difference the power losses of the grid system. Hence, in the case an energy storage system is included in the simulation scenario, the consumed and injected energy from charge and discharge operations of the battery are also included in the power balance equation.

$$P_{GridLosses_i} = P_{G_i} - P_{C_i} = [P_{Gen_i} + P_{Bat_{discharge,i}}] - [P_{Cons_i} + P_{Bat_{charge,i}}] \quad (3.8)$$

    Where P_{G_i} represents the total injected power into the grid at instant i emerging from the addition of all involved micro-generators P_{Gen_i} and battery discharge operation $P_{Bat_{discharge,i}}$, whilst P_{C_i} stands for the entire consumed energy within the grid at time step i, composed of all loads that consume power P_{Cons_i} altogether with the battery charge operation $P_{Bat_{charge,i}}$.

  - Battery power losses

    The power losses that occur within the implemented storage system itself (supposing there will be batteries in the simulation, on the contrary this section is not going to be included in the procedure) surge from the efficiency losses o the entire installation.

$$P_{BatteryLosses_i} = P_{Bat_{charge,i}} - [P_{Bat_{charge,i}} \cdot \eta_{Global}] \quad (3.9)$$

$$\eta_{Global} = \eta_{Battery} \cdot \eta_{Inverter} \cdot \eta_{Wires} \tag{3.10}$$

$P_{Bat_{charge,i}}$ depicts the battery charge power at instant i and η_{Global} the global efficiency of the energy storage system, which is compound of the specific battery losses ($\eta_{Battery}$), the bidirectional inverter losses ($\eta_{Inverter}$) and the cable losses that are included in the installation (η_{Wires}). Therefore, the battery discharge power can be theoretically defined as the battery power losses subtraction to the battery charge power.

$$P_{Bat_{discharge}} = P_{Bat_{charge}} - P_{BatteryLosses} \tag{3.11}$$

Notice that charge and discharge operations can never occur at the same time, so the equation 3.16 expresses a generic battery characteristic, not an instantaneous energy balance.

- **Phase shift variance computation***

  Phase shift variations are computed for both - voltage and current, in order to proof how the stability of the LV distribution grid gets affected due to the high penetration of renewable energy sources. Voltage and current angles for each phase are obtained during the power flow analysis at the critical nodes (previously chosen) of the analyzed system. Using this data, it is possible to compute phase shift variations in between all three phases. Ideally, when totally equilibrated, phase shift variations remain at 120 º between all phases (L1-L2 / L2-L3 / L3-L1).

  *Note that this process step is only applied for the specific renewable penetration analysis configuration (not the gradual renewable penetration configuration). This is due to the nature of the contributed value of information, which in this case supports the concrete operational evaluation of the grid, while not being indispensable for the assessment of the generic impact of renewable sources on the grid in a possible long term insertion.

  Similarly to power factor, phase shift variances computations attend the need to check correct functionality of the electric grid within the simulation process. Hence, voltage and current phase shifts are not included in the assessment of the impact of energy storage systems in LV grids through the simulations in the present work.

- **Indicator settling**

  Once all required data from the simulation process is computed, indicators that size the outcome of the analysis can be defined. The specific indicators vary depending on the chosen initial configuration of the problem (i.e. assessment of a specific renewable energy penetration or gradual insertion of micro-generators), although cover similar subjects. The obtained final traits from the simulation that are going to be used for the result evaluation are as follows:

  – Maximum instantaneous power losses (kW) of every phase in the system amongst all time steps. This indicator serves in order to compare possible momentary power losses in between different scenarios.

  - Total energy losses (%) of the entire LV grid model. This term provides information about the global efficiency of the system, what is a crucial characteristic to compare different mitigation solutions.
  - Maximum instantaneous active power (kW) at any point of the proposed LV grid. This feature depicts the maximum possible active power flow within the electric scheme because of load demand and energy generation.
  - Maximum instantaneous reactive power (kvar) at any point of the proposed LV grid. This trait depicts the maximum possible reactive power flow within the electric scheme because of load demand and energy generation (for those generators that produce reactive power).
  - Maximum instantaneous voltage (V) of the system at one of the three phases. This parameter serves to evaluate the over-voltage problem, identifying impact of renewable energy sourced on the grid, whilst evaluating if the proposed solution (centralized energy storage system) is capable of maintaining this value within the maximum permitted range.
  - Minimum instantaneous voltage (V) of the system at one of the three phases. This term supports the analysis of the simulation, seeing how voltage is affected by renewable energy sources and batteries on the other extreme.
  - Maximum voltage variations ΔV (%) with respect to the base voltage of the system during the entire simulation process. With this, the mitigation capability of the proposed energy storage systems can be reviewed over the entire simulation time period.
  - Maximum current variations ΔI to denote the impact of renewable energy penetration sources on the power flow of the grid. Hence, current variations can be a very relevant issue whilst appraising the impact of these technologies.

- **Result representation**

  Finally, after obtaining all numerical parameters for the ending of the simulation process, the results have to be represented appropriately in graphics. Therefore, in order to improve comprehension of the presented data, some features are included in the plotting procedure:

  - Scaling of the plots in order to facilitate comparison between different outcomes. This procedure is done automatically depending on the maximum and minimum values of the simulation for the represented parameters.
  - Color arrangement to clearly differentiate between the three phases of the grid for all given values.
  - Allowed limits range added to voltage plots (according to official legislations), in order to ease the identification of allowed and non-allowed voltage variations in the undertaken simulation.

Chapter 4

Case of study

This chapter presents the created model that depicts a residential LV grid with renewable micro-generators and centralized energy storage system for the purpose of the analysis and simulation of the study. The first part is going to handle the characteristic parameters of the model, such as simulation environment, the base structure of the grid, buses, lines, loads, micro-generators and batteries. The second section will introduce different possible scenarios regarding weather conditions, load distribution on phases and renewable energy penetration, which are going to allow the assessment of different cases evaluating the impact of energy storage systems on the existing problem.

4.1 Model

The proposed model for the aim of this work enhances the dimensioning of a residential LV distribution grid composed of the physical structure of the electric power system, load demand curves from the consumers, distributed renewable micro-generators and a centralized modular energy storage system. The scheme of the grid is based on an existing LV network, load information is obtained simulating real data scenarios with a specific software and the micro-generators/batteries are purposely set up according to the requirements of the analysis.

4.1.1 Model environment

The model for the proposed analysis is going to be located in **Barcelona**, according to the base project of the present work [16]. Hence, all variables regarding energy generation (bound to weather conditions) are set up at the besought location.

In relation to the time dates that are considered for the simulation of the model, **April** has been elected in order to evaluate an average case scenario (neither low nor high renewable energy production), also following the methodology of the base project.

The specific simulation time period is divided in two options (as specified in section 3.1.2), in order to assess different properties of the analyzed problem. First choice includes evaluation of a single **day** to obtain information about direct impact of energy storage systems on LV distribution grids, and secondly, a time span that covers an entire **week** is taken to review the operational evolution of batteries within the network in order to dimension the proposed installation.

The considered time steps of the simulation are subject to several aspects that need to be taken into account. First of all (following the statement in section 3.1.2), processing time of the simulation and precision are two indispensable requirement for the proper performance of the analysis. Therefore, a very small time step, considering that load-flow analysis has to be solved independently for every time iteration, should not be too small in order to allow reasonable simulation length (e.g. time sampling based on minutes is too little). On the other hand, a very big time step will not allow a precise evaluation of the parameters from the proposed problem (e.g. hour based sampling). Thus, aiming for the proposed criteria whilst accounting the fact that exact weather condition data (as specified in section 4.2.1) for the studied environment is only available for every quarter hour, the most reasonable time step that complies all requisites is determined as every **15 minutes**.

4.1.2 Proposed grid

The structure of the proposed grid model of the analysis is dimensioned according to a feeder that illustrates a residential semi-urban LV distribution grid utilized in a previous analysis of electric vehicle charging [33] (originally provided by the Flemish distribution system operators). The grid consists of a three phase line that connects a LV residential section to the MV (medium voltage) distribution grid, with a total of 62 distributed loads with single-phase grid connection. The assessed grid is linked to the main distribution network through a single 630 kVA transformer that represents the slack bus, from where electric lines are spread in radial shape, creating two nodes that connect several branches. The entire electric wire has a total length of 2815 m, divided in the different existing branches with variable length steps according to the morphology of the net (exact dimensions of the grid branches are depicted in **Appendix H**).

The characteristics of the elected LV grid model regarding line properties and electric parameters are given in table 4.1.

LV GRID MODEL PARAMETERS	
Branches	**61**
Cable type	Al-4 x 150 mm^2
$Vnom_{ln}$	230 V
Imax	315 A
Z	(0.206 + 0.078i) Ω/km
Buses	**62**
Distance	10-125 m
Transformer	**1**
Z trafo	(0.004 + 0.02i) Ω
Distance	1000 m
Nodes	**2**

Table 4.1: Parameters of the proposed LV distribution grid model

The given values are handled as constant parameters for the entire simulation process, creating the foundation of the model. Since the three phases of the line are evaluated independently during the load-flow analysis, voltage of the system is considered neutral-to-phase, wherein the entire simulation will take 230 V as the nominal base voltage reference.

The main grid scheme is provided in figure 4.1, showing the load distribution and critical nodes. Notice that the phase connection of the consumers is not specified in the outline as load distribution is one of the variables that can change pursuant to the selected simulation scenario (more details in section 4.2.2).

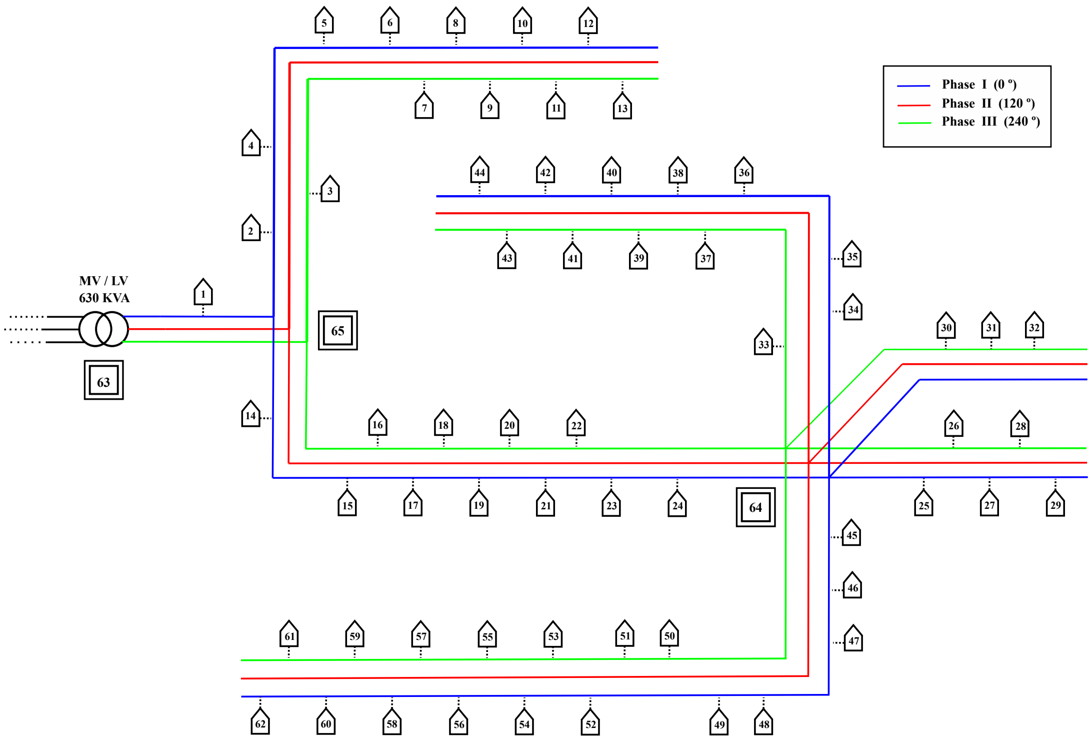


Figure 4.1: Basic structure of the LV distribution grid model

From here on, in order to perform the analysis with the proposed software, data of the electric properties of the grid must be expressed in p.u. Therefore, it is necessary to settle the base parameters along the network specifications (the computation process of the p.u. values using the base parameters is specified in **Appendix G**).

V base	0,23 KV
S base	0,001 MVA
Z base	52,9 Ω

Table 4.2: Base electric parameters

Using this values, the required parameters of the branches (line resistance and reactance in p.u.) for the simulation can be computed knowing the dimensions of the lines.

$$z = r + jx = \frac{Z}{Z_{base}} \tag{4.1}$$

$$Z = \underline{Z} \cdot L \tag{4.2}$$

Where $\underline{Z}$ is the known line impedance specified in table 4.1, L the distance of the considered branch, Z the total impedance of the section, Z_{base} the base impedance determined in table 4.2 and z the global impedance in p.u. containing the required parameters r (resistance) and x (reactance).

The values of all necessary parameters for the MATPOWER power flow simulation regarding every branch of the model are attached in **Appendix I**.

4.1.3 Consumers

The daily power demand curves of the consumers at the buses of the LV distribution grid are recreated with the Load Profile Generator (LPG) software [34]. This tool uses real data bases of existing households to simulate the behavior of different types of consumers generating the corresponding load curves over a specified time range (more details about the functionality of the software are available in **Appendix J**).

With the purpose to simulate a real case scenario with different kinds of consumers, twelve distinct predefined households of the LPG have been selected and assigned to the 62 buses of the LV grid model (according to the consumer types of the base project [16]) in order to recreate a diversified residential area.

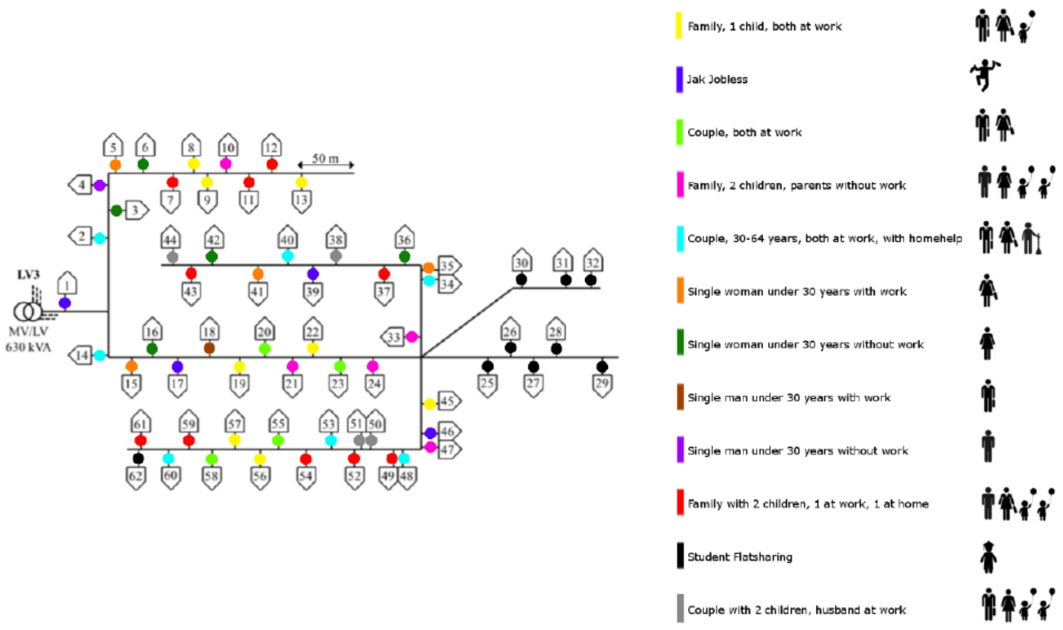


Figure 4.2: Present consumer profiles in the proposed LV grid model. Extracted from [16]

The distribution of the different consumer households is randomly assigned along the 62 buses of the grid model, with the exception of one section of the network that includes buses 25-32, which is only devoted to students representing a student residence. For the rest of the loads, the number of each represented consumer typology is defined according to a proposed average population model for a residential semi-urban area.

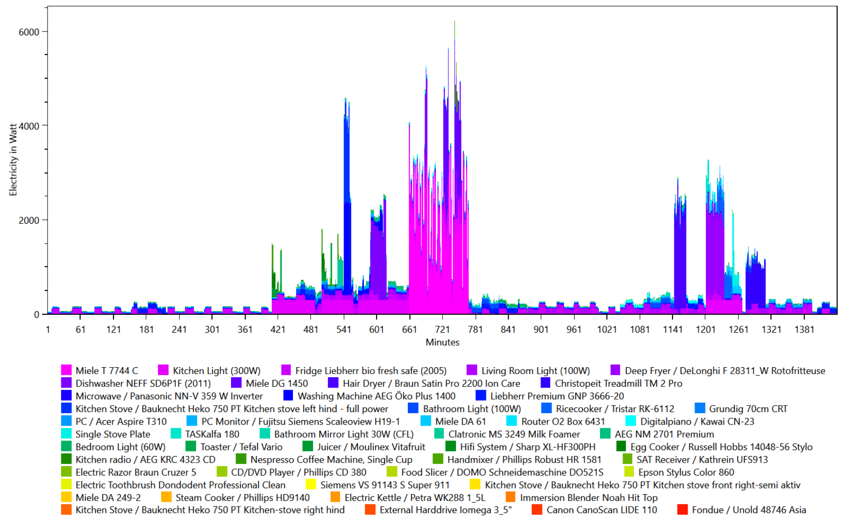
Types of inhabitants	TYPE	# Of houses
Couple, 30 - 64 years, both at work, with homehelp	A	7
Student Flatsharing (Sutend residence)	B	9
Family, 1 child, both at work	C	8
Couple, both at work	D	4
Family with 2 children, 1 at work, 1 at home	E	10
Couple with 2 children, husband at work	F	4
Single man under 30 years with work	G	1
Single woman under 30 years with work	H	4
Family, 2 children, parents without work	I	5
Single man under 30 years without work	J	1
Single woman under 30 years without work	K	5
Jak Jobless	L	4

Table 4.3: Consumer types according to load profile

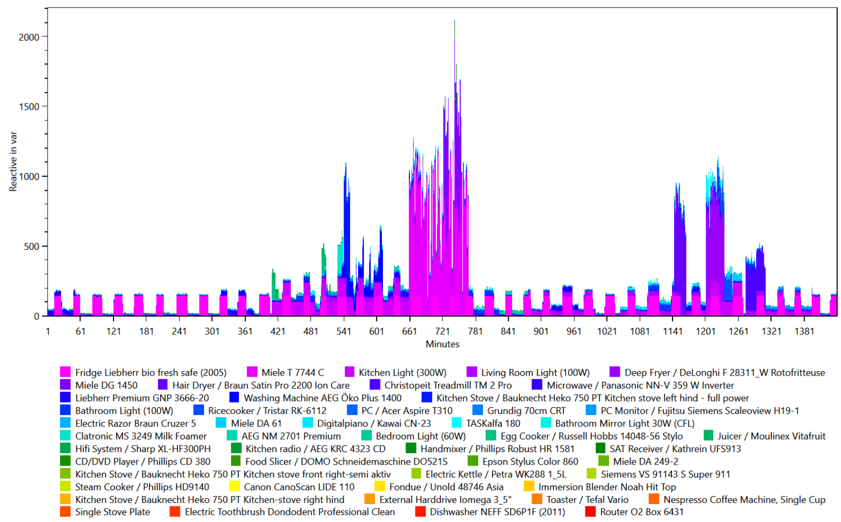
Starting from the selected load typologies of the grid, demand curves for each can be acquired simulating the behavior of the different cases with the LPG algorithm, which uses real data from specific charges in order to obtain the power consumption of the households. In order to adapt the conditions of the selected models to the proposed analysis, households are adjusted by changing the predetermined location to Spain and defining an average consumption behavior for the loads. Additionally, the simulated time range to create the load curves has been adapted assigning the time period to one entire day in mid April. When evaluating a whole week during the simulation process of the work, load curves are supposed to maintain uniform over all included days, hence the obtainment of demand data for a single day is going to be sufficient.

The simulations with the LPG tool provide load demand curves for both, active and reactive power. The resulting values of the consumption are given for every minute within the selected time period (one day) providing a data array for each different load of 1440 values. Hence, post data treatment is required to adapt the sampling time of the LPG to the proposed step size of the analysis (15 minutes) within the created algorithm as depicted in section 3.3.2, downsizing the number of parameters to 96.

The obtained load curves from the LPG are represented as shown in figure 4.3, which depicts one of the chosen household profiles (couple between 30 and 64 years, both at work, with home-help).



(a) Active power load



(b) Reactive power load

Figure 4.3: Consumer load profile: Couple 30-64, both at work, with home-help

The entire set of obtained demand curves for all chosen household models is attached in **Appendix K**.

For the implementation of load information in the simulation process, all data regarding the energy demand must be introduced in the MATPOWER bus input structure matrix (added in **APPENDIX M**). Note that actual values of the demand is added during the previous data treatment of the simulation tool, and is therefore not included in the generic bus input structure.

4.1.4 Renewable micro-generators

The analysis of the proposed problem consists in the incorporation of distributed generation within the LV grid model in order to asses the impact of renewable sources. Hence, numerous renewable micro-generators are designed covering each bus, which will then be implemented in the simulations according to the renewable energy penetration criteria defined in section 4.2.3.

The main part of the elected auto-consumption installations are based on the actual most used and advanced renewable micro-generator technology: PV panels. Additionally, in order to widen the energy mix in the studied LV grid according to the future evolution of micro-generator technologies, several micro wind turbines have also been introduced in the model.

The proposed micro-generators are distributed and dimensioned for every single household (all 62 load buses), in order to simulate the renewable energy generation up to 100 % renewable penetration. The remaining required energy that is consumed in the gird is provided from the slack bus (trafo) that connects the LV grid model to the main MV distribution network acting as an unlimited energy source.

The allocation of the renewable energy generators is realized according to a possible real case scenario. Therefore, all individual households are more likely to install PV panels, whereas the student residence section (buses 25-32) takes advantage of wind turbines to cover the entire student urbanization.

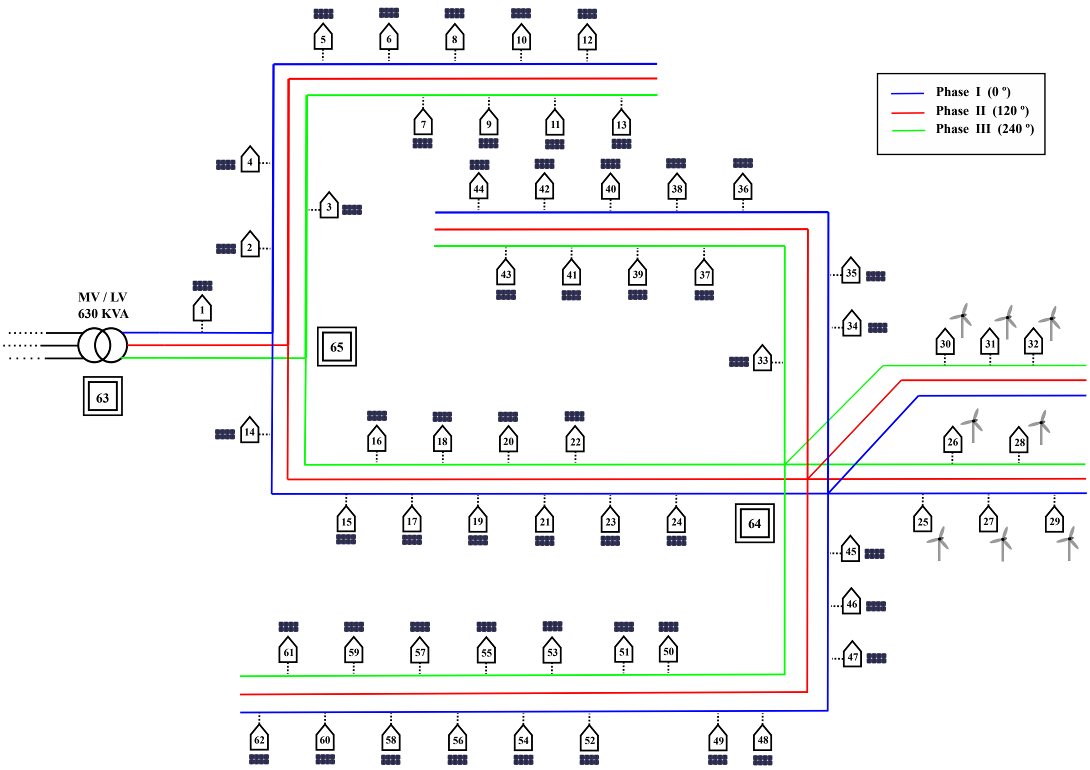


Figure 4.4: Structure of the LV distribution grid model with included renewable micro-generators

From here on, knowing the distribution of the renewable micro-generators, the installations are dimensioned according to the energy requirements of each load (PV panels are sized for every consumer type, whilst wind turbines only for student households).

PV panels

The proposed PV panels are dimensioned according to the energy demand of the consumer loads (only active power), the characteristics of the present energy resource in Barcelona and the specifications of the installation (efficiency).

First, daily energy demand for every load model can be obtained from the demand curves generated by the LPG. Therefore, mean consumed power of the load is calculated using the data from the load profile simulation given for every minute of the day.

$$P_{average_h} = \frac{\sum_{i=0}^{1440} P_{h_i}}{1440} \quad (W) \tag{4.3}$$

Where P_{h_i} is the instantaneous active power consumed for household type h and time instant i. Next, once the average power is known, total daily consumed energy can be computed.

$$E_{consumed_k} = P_{average_h} \cdot 24h \quad (Wh/day) \tag{4.4}$$

After establishing the consumed energy for each load, the contributed energy from sun irradiation must be determined (to further dimension the PV panels). Annual information about daily direct sun irradiation in Barcelona is obtained from the Spanish sun irradiation Atlas [35], that features monthly average values. In order to size the installations appropriately, an average annual energy criteria is chosen to figure the optimal energy generation for the entire year (instead of over or under dimensioning the micro-generators for specific periods of the year). Hence, from the monthly irradiation data, the average parameter is extracted and used along the dimensioning of the PV panels.

By last, the efficiency of the entire installation has to be calculated in order to know the required PV panels. Therefore, several parameters are included in the efficiency computation using the specific equation for energy losses in PV systems [36].

$$K_T = PV_{eff} \cdot [1 - (K_B + K_C + K_R + K_X)][1 - \frac{K_A D_{out}}{P_{D_{max}}}] \tag{4.5}$$

Where K_T represents the global efficiency of the PV panel installation, computed with the given parameters: solar panel efficiency (PV_{eff}), battery operation losses (K_B), AC/DC inverter losses (K_C), DC/AC regulator losses (K_R), additional losses due to joule effect (K_X), battery discharge losses (K_A), autonomy days of the installation (D_{out}) and maximum battery discharge rate ($P_{D_{max}}$).

As decentralized energy storage systems are not considered for the purpose of this study, all losses and parameters related to batteries can be neglected. Hence the global efficiency is obtained considering PV efficiency (18 % for standard developed monocrystalline panels), converter losses (10 % for both inverter and regulator as standardized values according to [36]) and cable losses (10 %). Hence, the total efficiency of the PV micro-generators is **12.6** % as stated in equation 4.6.

Direct sun irradiation in Barcelona	
Month	Direct sun irradiation ($[kWh \cdot m^2]/day$)
January	1.36
February	2.09
March	2.80
April	3.85
May	4.17
June	4.73
July	5.25
August	3.90
September	3.09
October	2.05
November	1.43
December	1.20
Average	3.00

Table 4.4: Monthly average daily direct sun irradiation in Barcelona

$$K_T = PV_{eff} \cdot [1 - (K_C + K_R + K_X)] = 0.18 \cdot [1 - (0.1 + 0.1 + 0.1)] = 0.126 \qquad (4.6)$$

Once all required parameters are known, PV panel surface for each household can be computed according to equation 4.7.

$$PV_{surface_k} = \frac{E_{consumed_k}}{Irr_{average} \cdot K_T} = \frac{E_{consumed_k}}{3(kWh \cdot m^2)/day \cdot 12.6\%} \qquad (4.7)$$

The obtained results are then round up/down in order to have integer number of sized PV panel square meters for every load type. All acquired installation surfaces are presented in table 4.5.

Wind turbines

The wind turbines that are introduced to cover the auto-consumption of the student residence within the LV grid model cannot be dimensioned equally to the PV panels because they do not present the same modularity on this small size (only specific wind generator sizes are available), and energy production highly depends on the power/wind-speed ratio of the selected turbine. Therefore, the deciding criteria to dimension the wind mills is the average wind speed of the area, from where on the size of the turbine can be chosen according to the power-wind ratio in order to optimize energy production (either one big or several smaller wind turbines can be installed to cover the demand of the section).

The average wind speed in the selected location of Barcelona is fairly small, approaching a value of approximately 4 m/s (further specified in section 4.2.1). Almost all micro wind turbines with a nominal power of 3 kW or above do not work properly under this poor circumstances, hence

Total consumed energy	Wh/day	kWh/day	PV Surface (m2)	Real PV Surface (m2)
Family, 1 child, both at work	5326,22	5,33	14,09	14
Jak Jobless	3194,09	3,19	8,45	8
Couple, both at work	6138,77	6,14	16,24	16
Family, 2 children, parents without work	15940,34	15,94	42,17	42
Couple, 30 - 64 years, both at work, with homehelp	16420,68	16,42	43,44	43
Single woman under 30 years with work	4600,76	4,60	12,17	12
Single woman under 30 years without work	5309,92	5,31	14,05	14
Single man under 30 years without work	6334,87	6,33	16,76	17
Single man under 30 years with work	3394,12	3,39	8,98	9
Family with 2 children, 1 at work, 1 at home	14880,34	14,88	39,37	40
Student Flatsharing	8969,79	8,97	23,73	24
Couple with 2 children, husband at work	13033,12	13,03	34,48	35

Table 4.5: PV panel dimensioning

the best solution is the implementation of very small turbines placed at each student household to take advantage from the given wind resource.

The best suited wind turbine model which is proposed for the analysis enhances a 2 kW turbine with the following characteristics:

Wind turbine specifications	
Nominal power (at 9 m/s)	2 kW
Average power (at 4 m/s)	0.4 kW
Minimum wind velocity	3 m/s
Maximum wind velocity	35 m/s
Rotation velocity	400 rpm
Number of blades	3
Height	8 m

Table 4.6: Characteristics of the selected wind turbine

Although the power rate at average wind speed is not high, the turbine does cover very low velocities, with start-up speed around 2 m/s and minimum generation speed at 3 m/s. Further information about specific properties from the turbine data sheet and the power/wind-speed curve plot are attached in **Appendix L**.

After defining all renewable micro-generators of the proposes LV grid model, nominal power rate for all generators can be determined. Wind turbines are settled at their nominal generation capacity and PV panels are evaluated at standardized sun irradiation (1000 $W \cdot m^2$) including the global efficiency according to equation 4.8.

$$P_{PV_{nom,k}} = PV_{surface_k} \cdot Irr_{standard} \cdot K_T \tag{4.8}$$

With the obtained nominal power scales of the micro-generators for all households, total nominal power is established according to the total number of every load type. The results are presented in table 4.7.

Types of inhabitants	Nominal PV power	Nominal Wind Power	Total power
Couple, 30 - 64 years, both at work, with homehelp	5,5 kW	–	38,5 kW
Student Flatsharing (Sutend residence)	3 KW (1 student)	2 kW	19 kW
Family, 1 child, both at work	2 kW	–	16 kW
Couple, both at work	2 kW	–	8 kW
Family with 2 children, 1 at work, 1 at home	5 kW	–	50 kW
Couple with 2 children, husband at work	4,5 kW	–	18 kW
Single man under 30 years with work	1 kW	–	1 kW
Single woman under 30 years with work	1,5 kW	–	6 kW
Family, 2 children, parents without work	5 kW	–	25 kW
Single man under 30 years without work	2 kW	–	2 kW
Single woman under 30 years without work	2 kW	–	10 kW
Jak Jobless	1 kW	–	4 kW

Table 4.7: Micro-generator nominal power according to load type

4.1.5 Batteries

The battery system is not dimensioned specifically in order to evaluate different scenarios within the simulation process. Nevertheless, certain boundaries are set up in order to recreate a possible realistic case study, being able to choose within the options presented in section 3.2.2.

The energy storage system can either be defined throughout a Li-Ion chemical battery or Fuel Cell flow battery (the two technologies with most potential for LV grid appliances concerning overvoltage mitigation). Therefore, depending on the considered technology, properties of the energy storage system can vary:

- **Li-Ion chemical battery** has a very high efficiency rate (90 % for the most developed models [26]). The present discharge limit is approximately of 80 % of the battery capacity, hence the storage system cannot be fully unloaded.
- **Fuell cell flow battery** has a much lower efficiency (60 % when using alkaline electrolyte at low temperatures in small size systems under 200 kW). Even so, it does not incorporate a discharge limit, which is a great advantage.

The two energy storage systems are very promising for the given application, presenting different capabilities and disadvantages (specified in section 1.3). In order to appreciate the direct impact within the simulation, both options are incorporated in the LV grid model.

The energy capacity of the elected storage system can be chosen within a proposed range, which is defined according to the total load consumption of the grid. The daily energy demand is computed summing up all consumer curves of the Load Profile Generator (LPG) simulations of the households, resulting in 634.56 kWh/day (taking data from tables 4.3 and 4.5). This value can be adapted into battery capacity using the base voltage of the system (230 V neutral-to-phase) as conversion parameter, obtaining 2759 Ah. In obedience to this result, with the purpose of analyzing the mitigation ability of energy storage systems in LV grids over a prolonged time lapse, the possible battery capacity range is defined from 0 Ah up to 8000 Ah (the equivalent to almost 3 days energy consumption of the entire system) in order to cover all possible outcomes of the simulation.

Ultimately, in order to determine the global efficiency of the energy storage system, some conditions must be added to the elected battery performance. These include the efficiency of the bi-directional inverter/converter of 98 % in both directions [37], and the additional energy losses of the installation due to the joule effect that comprises an approximate value of 5 %. Therefore the global performance rate of the storage system is computed as:

$$\eta_{T_{bat}} = \eta_{bat} \cdot 0.91238 \tag{4.9}$$

Where η_{bat} represents the specific variable battery efficiency, and 91.238 % the efficiency of the additional conditions of the system.

The present batteries in the LV grid model are reflected as a centralized energy storage system. In order to take most advantage of the mitigation capacity of the installation for the proposed problems in the study, the storage system is located at the critical node that interlaces all branches of the grid, being the central point of the model.

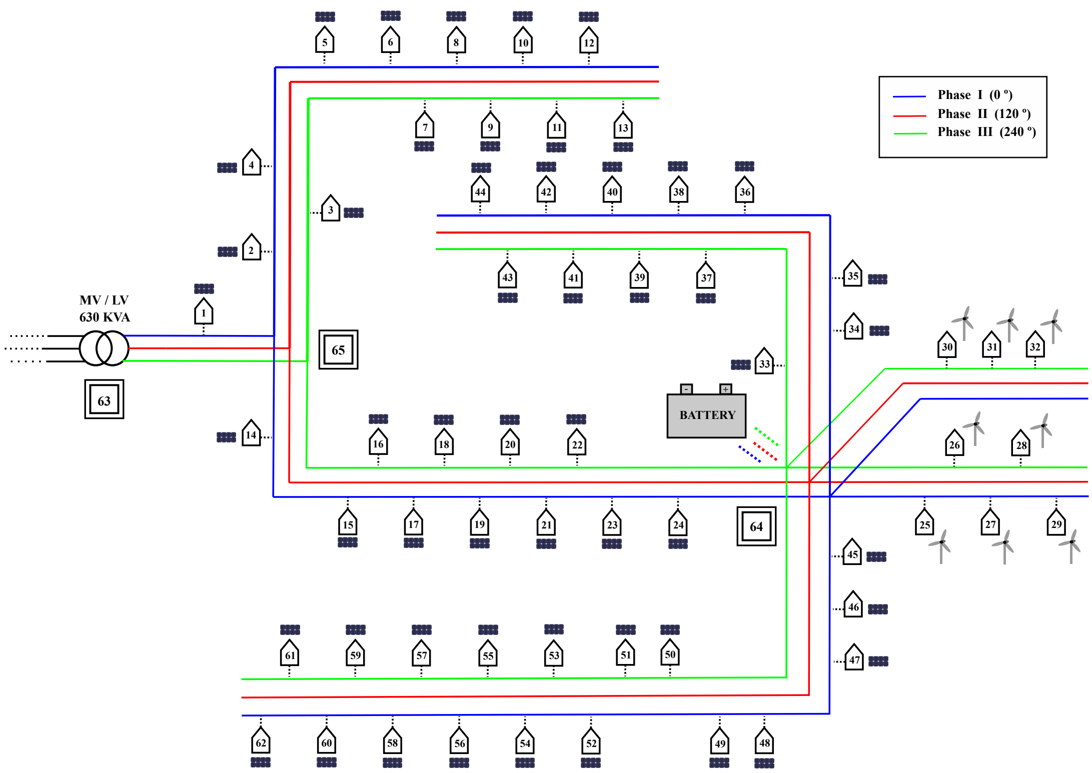


Figure 4.5: Structure of the LV distribution grid model with included renewable micro-generators and centralized energy storage system

After determining all physical details of the proposed energy storage system, operational behavior must also be considered. This trait is essential for the simulation of the grid, setting up a specific algorithm that recreates the charge and discharge stages of the batteries within the physical boundaries. Therefore, according to the instantaneous energy balance stage of the grid, the storage system can either be fully charged (with enough free storage capacity), partially charged (loading until maximum battery capacity), maintain invariable, partially discharged (injecting until minimum battery capacity) or fully discharged (with enough saved capacity).

Apart from the basic operations of the energy storage system, a very advantageous feature can be added to the algorithm: a phase shift control method. Currently electric power inverters are developed with included load balancing control for the lines, managing the amount of injected energy to each phase. Therefore, in order to grasp the full possible potential of energy storage systems in LV grids, a phase shift control algorithm is appended to the operational scheme of the batteries. This control system determines the amount of energy that is injected/extracted from each phase to balance possible deviations, although under the strict rule of the global energy balance of all three phases for generic operational conditions (energy storage system cannot be in more than one operational state at a time, see section 3.2.2).

Together with the transformer that connects the model to the medium voltage (MV) distribution grid, the energy storage system foments the only connection point of the three phases of the system during the simulation, hence all computations within the battery operation algorithm must be done for all time steps providing information about each single phase for the subsequent load-flow analysis, in accordance with the global energy storage operation of all phases. Additionally, energy storage system efficiency is also considered in every step of the proposed process, forcing that the amount of discharged energy from the battery is correspondingly higher to the actual injected energy pursuant to the present losses.

According to all the formulated premises, the energy storage operation algorithm is designed as described in figure 4.6, using the following variables:

- $\mathbf{PB_{Xi}}$ Power balancing at the analyzed phase X and time step i. The same variable is used along the scheme to assign values for all three phases (replacing the X by the corresponding phase, 1, 2 or 3).
- $\mathbf{P'B_{Xi}}$ Charged/discharged power by the battery matching PB_{Xi}, although can be set to 0 according to load balance conditions.
- $\mathbf{PG_{Xi}}$ Generated power at the analyzed phase X and time step i.
- $\mathbf{PD_{Xi}}$ Consumed power at the analyzed phase X and time step i.
- $\mathbf{PB_i}$ Global energy balancing of the entire system (all three phases) at time step i.
- $\mathbf{Bat_i}$ Battery status at time step i.
- $\mathbf{BatG_{Xi}}$ Battery discharge energy (generated) at the analyzed phase X and time step i. The same variable is used along the scheme to assign values for all three phases (replacing the X by the corresponding phase, 1, 2 or 3).

- $\mathbf{BatD_{Xi}}$ Battery charge energy (demanded) at the analyzed phase X and time step i. The same variable is used along the scheme to assign values for all three phases (replacing the X by the corresponding phase, 1, 2 or 3).
- $\mathbf{Bat_{max}}$ Maximum battery capacity.
- $\mathbf{Bat_{min}}$ Minimum battery capacity.

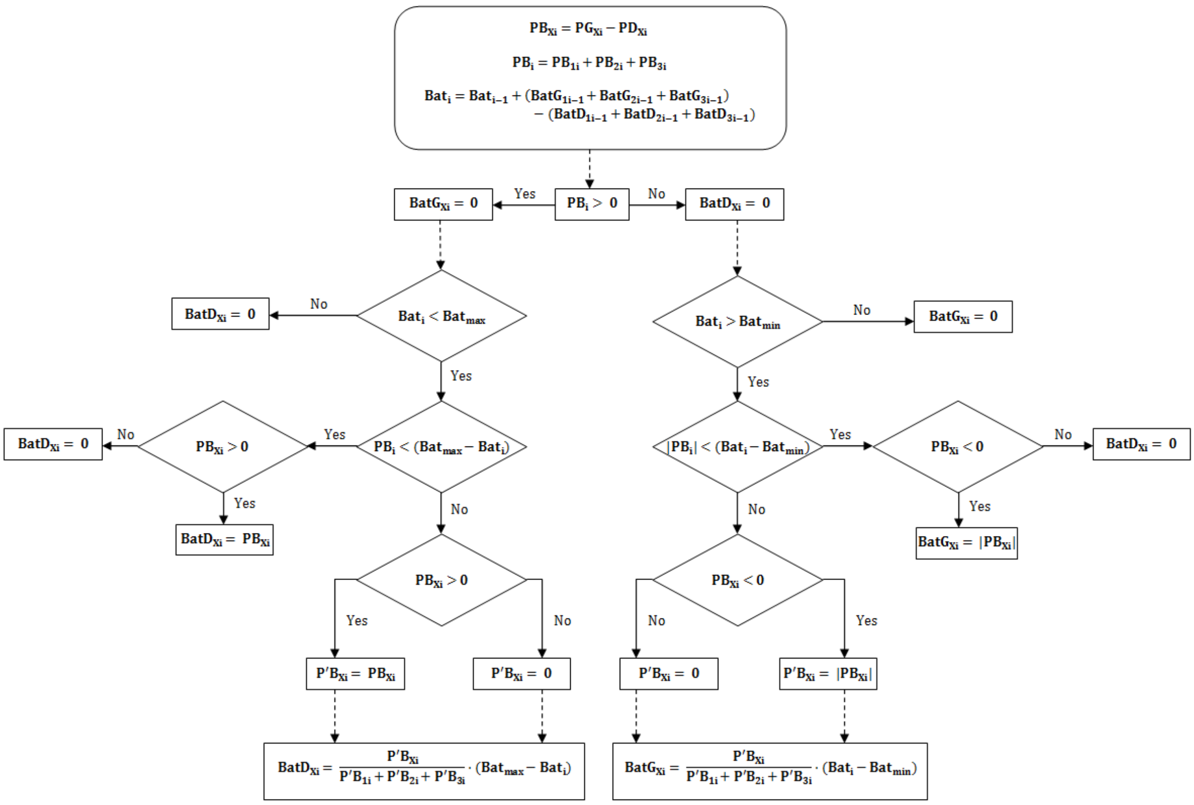


Figure 4.6: Structure of the battery operation algorithm

The entire operational algorithm scheme of the energy storage system depicts one of the process steps (MATLAB® function) of the created simulation tool specified in section 3.2.2.

For the introduction of generation data in the simulation process, all micro-generator energy production values and battery discharge rates must be introduced in the MATPOWER generator input structure matrix (added in **APPENDIX N**). Notice that concrete generation data for each bus and time step is added during the previous data treatment of the simulation tool according to the elected initial configuration, so is not included in the generic generator input structure.

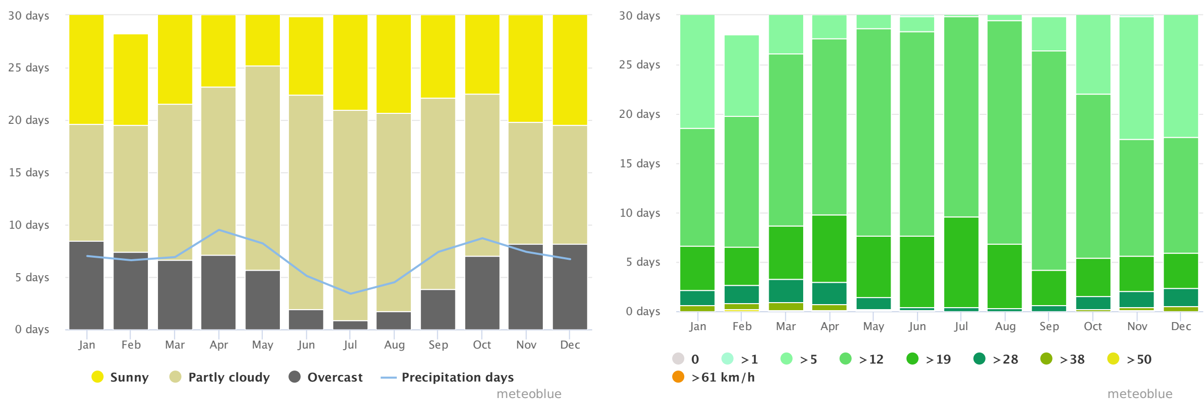
4.2 Scenarios

The proposed scenarios for the simulation of the LV grid model cover the variable parameters of the analysis that set up different case studies. These variables include distinct weather conditions during the elected time period and location, several possible load distribution patterns and gradual renewable energy penetration. The combination of different proposed options allows the assessment of additional parameters that can be affected due to energy storage systems such as load phase shift and energy losses, simulation over prolonged periods of time with changing variables and evaluation of the future evolution of renewable micro-generators in LV grids.

4.2.1 Weather conditions

The weather conditions that affect the energy production through renewable micro-generators are sun irradiation and wind speed. Both are resources that constantly vary over time. Therefore, the integration of different weather scenarios is crucial to create a realistic model. These cases include clear sky, little cloudy and very cloudy for sun irradiation, and high, average and slow wind conditions for wind speed. All information to determine the parameters is taken from real measured data over large time periods from specific tools for the selected location, providing values for different occurrences, such as average behavior.

For the simulation of the present study, evaluated time period can either be of a single day or an entire week. Hence, according to the first option, any possible combination of sun and wind parameters can be elected. On the other hand, for the assessment of an entire week, a specific weather evolution forecast is recreated using real statistical data of the location according to mean meteorological demeanor from Meteoblue (meteorologic service based at the University of Basel, Switzerland).



(a) Sun irradiation behavior **(b)** Wind speed behavior

Figure 4.7: Monthly weather statistics in Barcelona. Extracted from [18]

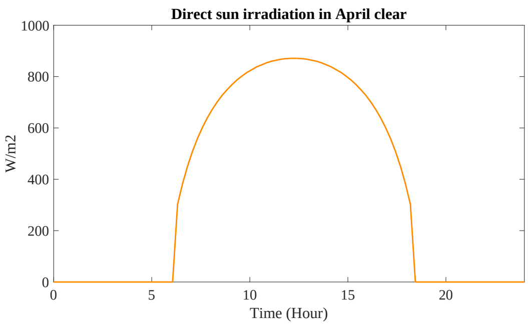
According to these meteorological statistics, concretely focusing on the month of April, sun irradiation presents on average 6.8 clear sky days (22.67 %), 16.1 slightly clouded days (54.67 %) and 7.1 very cloudy days (23.67 %). For wind speed data, presupposing that all wind velocities over 19 km/h (5.27 m/s) are considered fast, and all values under 12 km/h (3.3 m/s) are accounted slow, Barcelona presents 2.4 days of quiet wind (8 %), 17.9 days of average wind (59 %) and 9.8 days of fast wind (30 %). Transposing this real statistical data to a single week, a weather forecast scenario can be determined for the simulation of the study, combining the different options randomly.

Weather forecast for weekly analysis		
Week	Sun irradiation	Wind velocity
Day 1	Partly cloudy	Average
Day 2	Partly cloudy	Slow
Day 3	Cloudy	Average
Day 4	Partly cloudy	Fast
Day 5	Partly cloudy	Fast
Day 6	Clear	Average
Day 7	Cloudy	Quiet

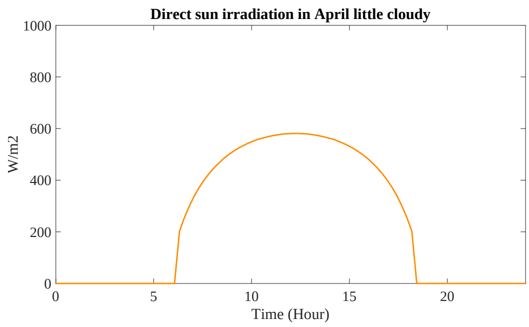
Table 4.8: Weekly weather forecast according to statistical meteorological data from Barcelona

Knowing the weather behavior of the case of study, next weather parameters are defined.

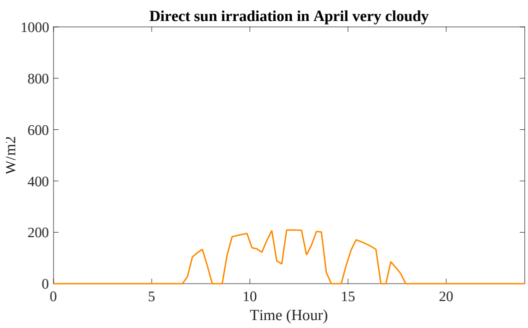
Sun irradiation



(a) Sun irradiation on a clear sky day



(b) Sun irradiation on a partly cloudy day

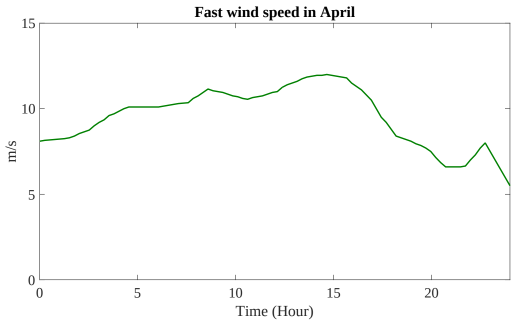


(c) Sun irradiation on a very cloudy day

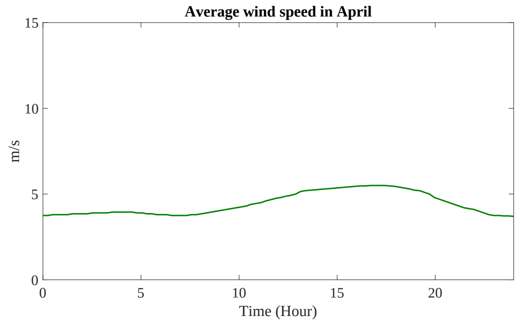
Figure 4.8: Average daily sun irradiation during April in Barcelona

Sun irradiation data that is represented in figure 4.8 is obtained using the Photovoltaic Geographical Information System (PVGIS) from the Institute for Energy and Transport of the European Commission [38]. This tool is able to provide average sun irradiation data for any chosen location and month on a given inclination and orientation, with a sampling time of 15 minutes over an entire day. Although the software gives data for global, direct and diffuse irradiation for different axis systems (fixed and 2 axis tracking) on the selected conditions, only direct irradiation can be seized and is determined on a fixed plane according to the given microgenerators in the model. Exact sun irradiation data for daily clear-sky, partly-cloudy and very cloudy conditions is attached in **Appendix O**.

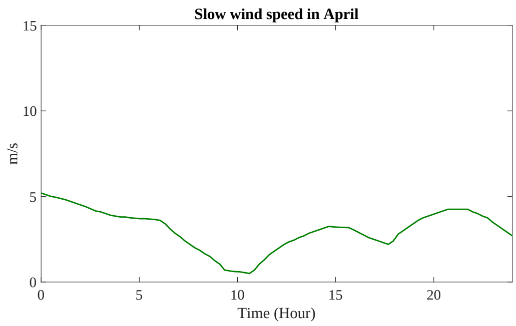
Wind speed



(a) Wind velocity profile on a fast day



(b) Wind velocity profile on an average day



(c) Wind velocity profile on a quiet day

Figure 4.9: Daily wind velocity during April in Barcelona at 8 m height

Wind speed data from the curves of figure 4.9 is gathered through the Windographer software developed by AWS Truepower [39]. The application is able to manage big data files containing hourly based wind information of several years, computing all characteristics of the proposed configuration such as average wind speed, Weibull curve, wind frequency rose and wind speed at specific height. Data can be obtained for any geographical position using the MERRA-2 data downloader that acquires meteorological data bases from NASA. The files used for the present work cover wind measurements for the location of Barcelona during the past 36 years, which are adapted to the height of 8 m from the ground (altitude of the wind turbines). The average wind speed of the model is determined according to the mean wind profile computed by the tool, whereas fast and low wind speed condition curves are defined according to sample days occurred during April 2016, showing possible good and bad scenarios. All exact data from the proposed wind speed plots are given in **Appendix P**.

Additionally, for the purpose of dimensioning the wind turbines for the LV grid model (section 4.1.4), it is valuable to determine global average wind speed velocity of the location. The resource varies significantly along the duration of the year, thus bounded to the fact that wind turbine generation is not linearly proportional to wind speed (production usually increases exponentially with higher velocities due to the nature of the technology), not only monthly mean velocity, but minimum average wind speed should be accounted.

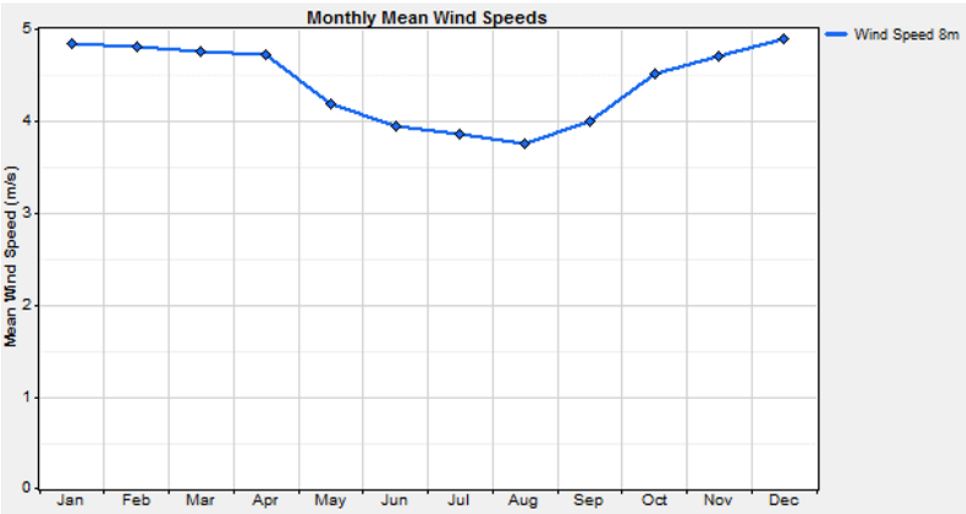


Figure 4.10: Monthly mean wind velocities in Barcelona at 8 m height obtained with Windographer

In agreement with the monthly average wind velocities from figure 4.10, it is possible to affirm that the lower mean wind speed has a value of approximately 4 m/s, which has been used to model the present wind turbine micro-generators.

Unlike PV panel energy generation, wind mill production does not only depend on the wind speed resource, but also on the power/wind-speed ratio curve of the selected wind turbine. Hence, it is possible to know forehand the total produced energy by every single 2 kW windmill for the three scenarios (as there is only one type of wind generator), according to the data provided in Appendix P and Appendix L. As can be noticed in table 4.9, wind turbine generation indeed grows exponentially with rising wind velocity.

Wind turbine energy generation	
Weather scenario	Energy production
Fast wind	27.03 kWh/day
Average wind	10.17 kWh/day
Slow wind	5.47 kWh/day

Table 4.9: Daily wind turbine energy production according to wind weather conditions

4.2.2 Phase distribution

Phase distribution of the loads is an important property of the LV grid model. Ideally consumption points are always distributed uniformly over the three phases of the electric lines, creating an equilibrated power flow. However, in real applications with numerous loads (especially when they are not inserted simultaneously in the grid), it is not always possible to know the actual phase distribution of the consumers, which might not be balanced. Hence, in order to foresee possible scenarios with distinct phase distributions, three different patterns are proposed to allocate the loads of the model according to the configuration of the analysis.

$$Balanced = \mathbf{1}, \mathbf{2}, \mathbf{3}, 1, 2, 3, ..., 1, 2, 3 \tag{4.10}$$

$$Unbalanced = \mathbf{1}, \mathbf{2}, \mathbf{3}, \mathbf{2}, 1, 2, 3, 2..., 1, 2, 3, 2 \tag{4.11}$$

$$\text{Very unbalanced} = \mathbf{1}, \mathbf{2}, \mathbf{1}, \mathbf{3}, \mathbf{1}, \mathbf{2}, 1, 2, 1, 3, 1, 2, ..., 1, 2, 1, 3, 1, 2 \tag{4.12}$$

According to the presented phase distributions, balanced load placements define the best-case scenario, Unbalanced loads the average allocation and very unbalanced worst-case scenario.

Unequal phase distribution has the potential of aggravating the over-voltage problem significantly when renewable micro-generators are casually concentrated on specific phases. Therefore, it is not only convenient to evaluate direct impact of energy storage systems on over-voltage issues, but also on unbalanced load distribution on the lines, taking advantage of the incorporated phase control system in the operational process of the batteries (see section 4.1.3).

4.2.3 Renewable energy penetration

The renewable energy penetration rate defines the amount of inserted renewable micro-generators in the LV grid model, ranging from 0 to 100 %. Within the simulation process, either a concrete renewable energy penetration can be chosen in order to evaluate all electric parameters in the grid under these circumstances, or gradual renewable energy insertion can be analyzed, where the load-flow study is reiteratively performed for every possible renewable energy penetration (see section 3.3.2), assessing the development of future maximum over-voltage and energy losses hassles.

The assignment of different possible renewable energy penetration rates to the households (i.e. which are most likely to install first renewable micro-generators for self-consumption) is realized according to possible money resources of the consumers (a family with both parents working is more presumable to install such energy systems than a jobless alone living person) and probable grants (public buildings such as the student residence have high chances of receiving subsidies). So, the elected allocation of the renewable energy penetration to the different consumer types, in accordance with the depicted criteria, is shown in figure 4.10.

Types of inhabitants	Penetration
Couple, 30 - 64 years, both at work, with homehelp	10%
Student flatsharing (Sutend residence)	20%
Family, 1 child, both at work	30%
Couple, both at work	40%
Family with 2 children, 1 at work, 1 at home	50%
Couple with 2 children, husband at work	60%
Single man under 30 years with work	70%
Single woman under 30 years with work	70%
Family, 2 children, parents without work	80%
Single man under 30 years without work	90%
Single woman under 30 years without work	90%
Jak Jobless	100%

Table 4.10: Successive renewable energy penetration according to consumer profiles

The simulation process bound under a specific energy penetration rate (whether it is singularly for a concrete scenario or repeatedly for the renewable energy evolution with different values) works implementing micro-generators to all loads that are covered within the renewable penetration rate. For example, if the analyzed system has 20 % renewable penetration, the consumer profiles A (couple 30 - 64, both at work, with home-help) and B (Student flatsharing) will present renewable micro-generators dimensioned according to their consumption needs in their respective buses, whilst all other existing households remain unchanged. This feature generates a non-linear renewable energy source implementation rate, which does not grow proportionally with time, but depends on consumer resources and public grants. Hence, the proposed energy penetration evolution for the model is approximated to the future realistic micro-generator expansion in LV grids.

Chapter 5

Result analysis

This chapter depicts the results of the realized simulations during the study, evidencing the impact of energy storage systems in LV distribution grids with high renewable energy penetration. The section is divided in different parts which identify the existing problem, manifest the impact of the proposed solution (centralized battery) on the grid, describe the required dimensions of the system and evinces future development. Hence, first the problems generated by renewable micro-generators in LV grids regarding over-voltage and power flow alterations are evaluated, followed by the mitigation capacity of energy storage systems for that specific features. Secondly, additional traits of the proposed energy storage system are assessed, which include the effectiveness to ease unbalanced phase distribution and how the batteries influence energy losses. Next, the actual dimensions of the energy storage system that are required for the proposed LV grid model are analyzed. Ultimately, the effectiveness of batteries within the gradual renewable energy insertion in LV distribution grids is assessed.

5.1 Effect of renewable micro-generators on the LV grid model

The presence of renewable micro-generators in LV distribution grids has noticeable controversial effects that disturb electric parameters. Therefore, according to the recognized problems in section 1.2.2, power flow alterations, current increase and over-voltage are assessed comparing the LV grid model with 0 % renewable penetration and 100 % renewable penetrations.

Scenario	
Constant parameters	Variable parameters

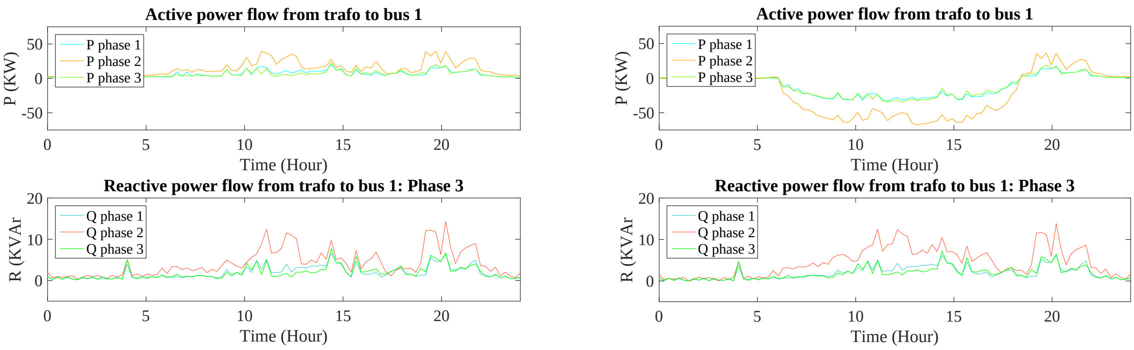
Daily analysis
Average **unbalanced** phase distribution
Best-case weather conditions (high energy production)
  Clear day
  High wind velocity
No energy storage system
	Renewable energy penetration
	  0 % Renewable penetration
	  100 % Renewable penetration

Evaluated parameters are assessed at the most representative and critical points of the grid:

power flow at the transformer connecting the grid to the MV distribution network, current at node 64 (main intersection point) and over-voltage at bus 62 (furthest point of the grid).

Power flow

Active and reactive power flow curves for all three phases are depicted at the transformer of the LV grid model.



(a) No renewable penetration **(b)** 100 % renewable penetration

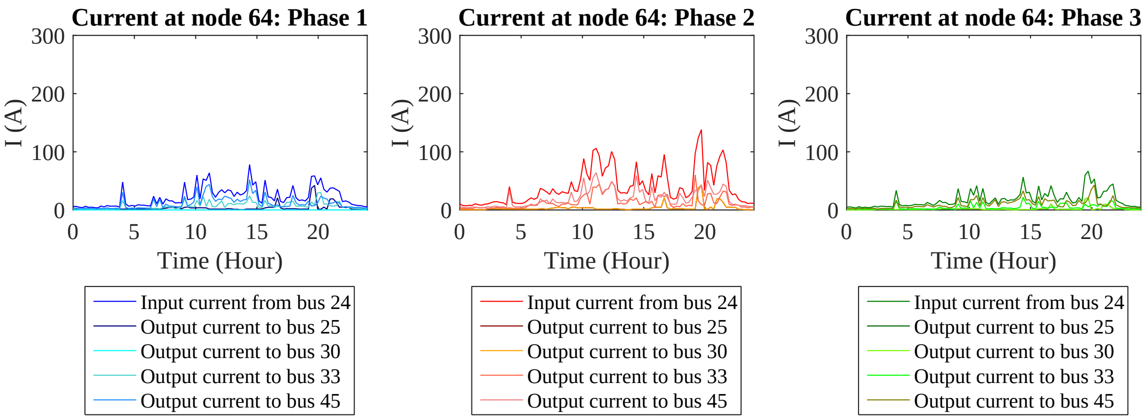
Figure 5.1: Active and reactive power flow from trafo to the LV grid

Active power flow is strongly altered by the introduction of 100 % renewable micro-generators in the system. It does not only increase significantly, but also reverse flow direction, injecting great amount of energy back to the MV distribution network (surplus produced energy by the generators). This phenomena occurs during day time hours because most present micro-generators are based on PV technology, hence only work with sun irradiation. Reactive power flow is vaguely affected by the introduction of renewable sources. This is because PV panels do not produce reactive power and the contribution of the small share of wind turbines does not provoke any changes.

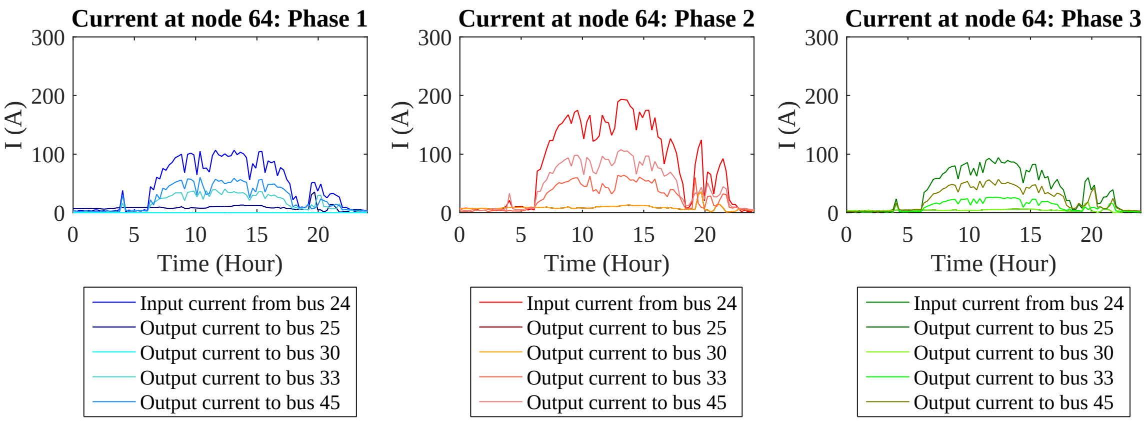
Current

Simulation results of input and output currents of the intersecting branches at node 64 for all three phases are represented in figure 5.2. The summation of all input/output currents equal 0, according to Kirchoff's law. Similarly to the power flow, current direction changes identically within the branches according to the amount of injected surplus energy (although the plots only represent absolute values).

As can be observed in the obtained outcomes from the simulation, current raises noticeable within all three phases due to the integration of renewable micro-generators, almost doubling the maximum current value. Additionally, the trait that phases are slightly unbalanced worsens the impact of renewable energy sources on the current, as it increases significantly more in the unbalanced section (phase 2).



(a) No renewable penetration



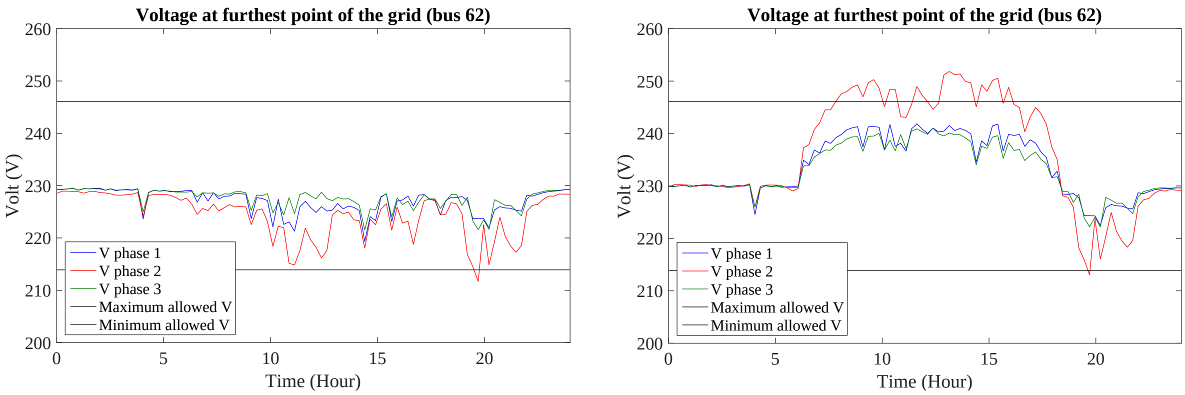
(b) 100 % renewable penetration

Figure 5.2: Current at node 64 (critical point of the grid)

Overvoltage

Impact of renewable energy sources on the voltage variations is determined in the results of the simulations along figure 5.3. The measured point is located at the furthest bus of the system (bus 62) to highlight the most critical outcome.

The results clearly evidence the appearance of the over-voltage problem imposed by the high penetration of renewable energy sources in the LV grid. The first sample with no micro-generators presents no voltage increase at any time step of the simulation, only reflecting the awaited voltage drop due to line resistivity. On the other hand, with to 100 % renewable energy penetration, big amount of generated surplus energy is injected during daytime in the grid (according to figure 5.1) which causes a great voltage raise. Hence, the system does not only destabilize, but furthermore voltage surpasses Spanish permitted legislative limits of 7 % voltage variations (according to [30]) over prolonged periods of time.



(a) No renewable penetration **(b)** 100 % renewable penetration

Figure 5.3: Voltage at bus 62 (furthest point of the grid)

From all obtained results of the simulations, evaluating the backspin of renewable energy sources on the LV grid model, indicators have been computed to portray maximum and minimum values of the electrical parameters. Notice that the values from the indicators must not necessarily coincide with the represented results of the previous figures, as these only enhance concrete points of the grid, whilst indicators are computed as absolute max/min parameters for the entire LV network model.

Effect of renewable micro-generators on the LV grid model		
Indicator	No renewable penetration	100 % Renewable penetration
Pmax	39.13 kW	68.78 kW
Qmax	13.56 kvar	13.21 kvar
Imax	180.22 A	295.78 A
Vmax	230 V	251,83 V
Vmin	211.67 V	213.06 V
$\Delta Vmax_+$	0 %	9.49 %

Table 5.1: Indicators for the impact of renewable energy sources on the LV grid model

In agreement with the concluded evidence from the resulting plots of the simulation, all electric parameters, with the exception of reactive power, increase significantly due to the penetration of renewable auto-consumption generators. Active power flow such as current are both roughly doubled, while over-voltage passes from non-existent to breaching permitted limit.

5.2 Mitigation capacity of energy storage systems on the LV grid model with renewable energy penetration

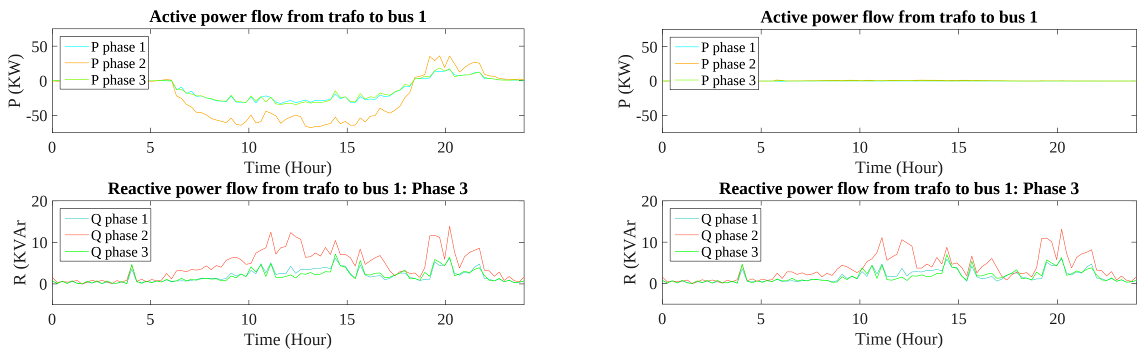
Within the purpose of the present work, centralized energy storage systems are proposed to mitigate the problems generated by high renewable energy penetration on the electric parameters of LV grids (power flow alterations, current raise and over-voltage). Therefore, using an identical scenario as in section 5.1 (only changing the variable parameter), now the LV grid with 100 % renewable micro-generator penetration from the previous analysis is compared to the same network with included centralized energy storage system. To do so, the biggest available battery installation is chosen in order to avoid possible restrictions and uniquely concentrate on the generic mitigation capacity of the technology.

Scenario	
Constant parameters	Variable parameters
Daily analysis	Energy storage system
Average **unbalanced** phase distribution	**No** battery
Best-case weather conditions (high energy production)	**8000 Ah** battery
Clear day	
High wind velocity	
100 % Renewable energy penetration	

Assessed parameters (power flow, current and over-voltage) are again evaluated at the same points of the grid as in section 5.1.

Power flow

Active and reactive power flow curves outcomes for all phases are represented in figure 5.4.



(a) 100 % renewable penetration

(b) 100 % renewable penetration with centralized energy storage system

Figure 5.4: Active and reactive power flow from trafo to the LV grid

Active power flow is heavily influenced by the centralized energy storage system. The entire LV grid model is almost auto-sufficient, cutting the injected and demanded active power flow at the

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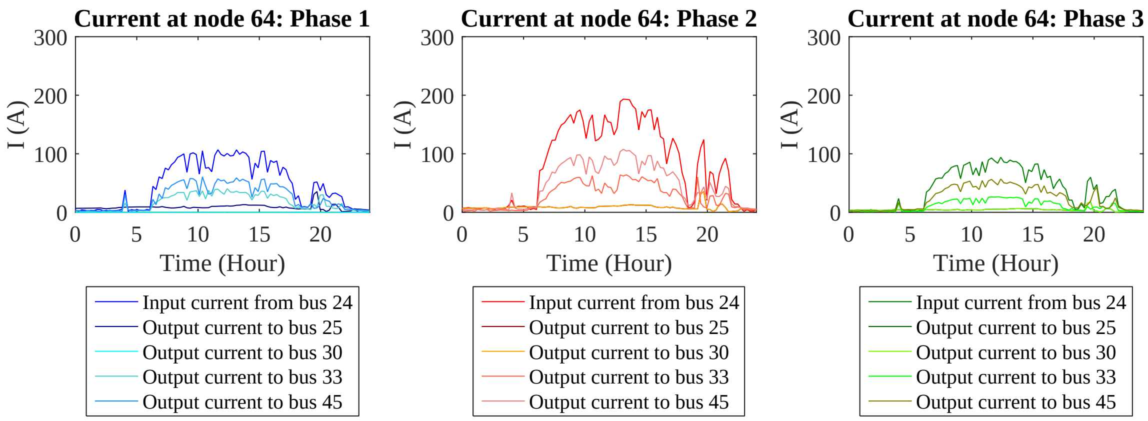
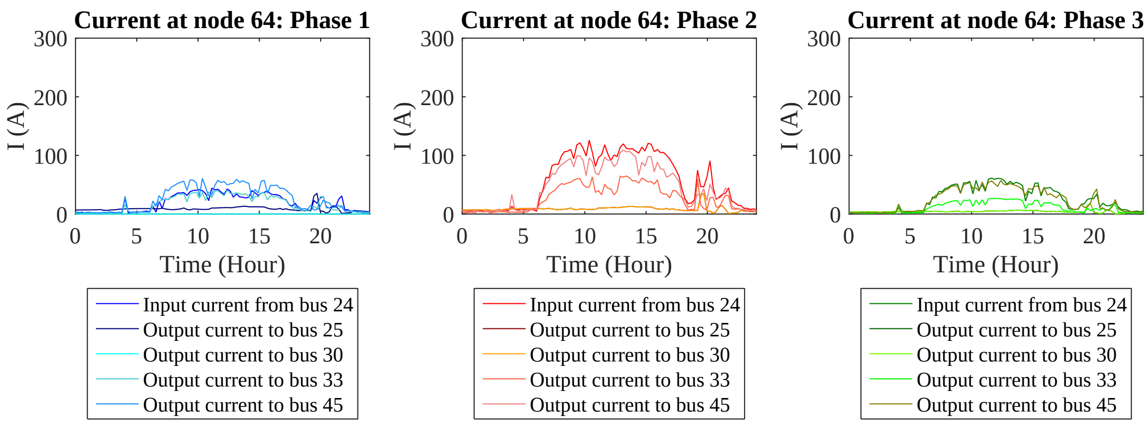
transformer. Hence, the proposed batteries are capable of saving all surplus energy from the renewable micro-generators during day time, and re-injecting the missing power during demand peak hours at night. The actual variations in maximum active power flow cannot be determined from the present figure as it only covers a specific location of the grid, and thereupon must be assessed by means of the maximum power indicator resulting from the simulation outcome specified in table 5.2. Reactive power flow is again totally unaltered as the energy storage system does not affect reactive power, equally to PV generators.

Current

The obtained current results for the present analysis are noticeably affected by the implemented energy storage systems, which achieves to generally reduce current curves within the LV grid model, as displayed in figure 5.5.



(a) 100 % renewable penetration



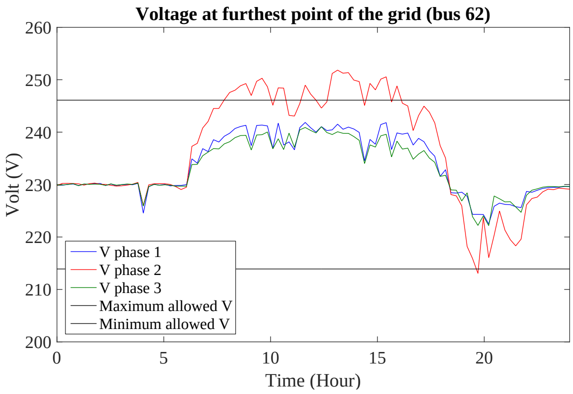
(b) 100 % renewable penetration with centralized energy storage system

Figure 5.5: Current at node 64 (critical point of the grid)

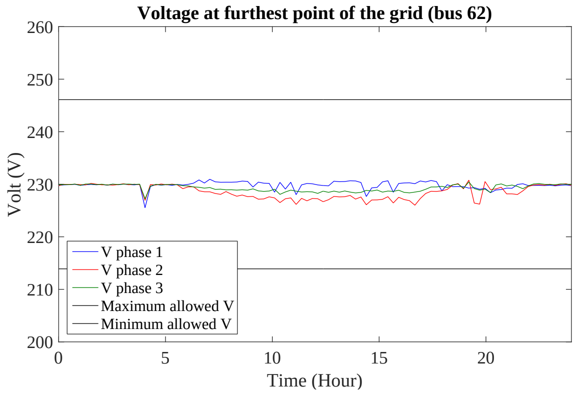
Although maximum current values are reduced, the overall flow tendency is maintained as the renewable energy production during daytime is still present. Nevertheless, the proposed battery system supposes an important relieve to the network according to current parameters.

Overvoltage

The proposed centralized energy storage system functions perfectly as mitigation measurement for the generated over-voltage due to the renewable micro-generators as depicted in figure 5.6.



(a) 100 % renewable penetration



(b) 100 % renewable penetration with centralized energy storage system

Figure 5.6: Voltage at bus 62 (furthest point of the grid)

Voltage variations are completely controlled for all phases of the grid, stabilizing the system and complying the legislative voltage limits of ±7 % [30].

The computed indicators from the simulation outcomes that demonstrate the exact effect of energy storage systems on the electric parameters of the LV distribution grid model with high renewable energy penetration are presented in table 5.2.

Effect of energy storage systems on the LV grid model with 100 % renewable energy penetration		
Indicator	100 % Renewable penetration	100 % Renewable penetration with energy storage system
Pmax	68.78 kW	28.62 kW
Qmax	13.21 kvar	13.04 kvar
Imax	295.78 A	125.81A
Vmax	251.83 V	232.59 V
Vmin	213.06 V	221.89 V
$\Delta V max_+$	9.49 %	1.12 %

Table 5.2: Indicators for the impact of energy storage systems on the LV grid model with high renewable energy penetration

The impact of centralized batteries on the maximum/minimum values of the parameters along the considered scenarios is undoubtedly commodious. Both maximum instantaneous power flow and current within the LV grid are cut down more than half of their original values. Furthermore, the initial over-voltage hassle is completely solved, not only complying with the permitted voltage variation limits, but achieving a voltage profile within the ideal variation range of ± 3 % [24].

5.3 Impact of energy storage systems on unbalanced phase shifts of the LV grid model

Load flow distribution can be very unbalanced over the three phases depending on the present phase distribution. In real cases it is often hard to know the exact distribution of consumers, even though balanced load distribution is always approached during the design of the grid. Hence, because of the possible existence of unbalanced loads in LV grids, in addition to the potential mitigation capacity of the energy storage system with included operational phase control model (section 4.1.5), it can be very significant to evaluate how big the impact can be on distorted load distribution on phases. In case phase balancing by means of the energy storage system in combination with the proposed control system of the inverter works, it would append great value to the positive impact of batteries on the grid.

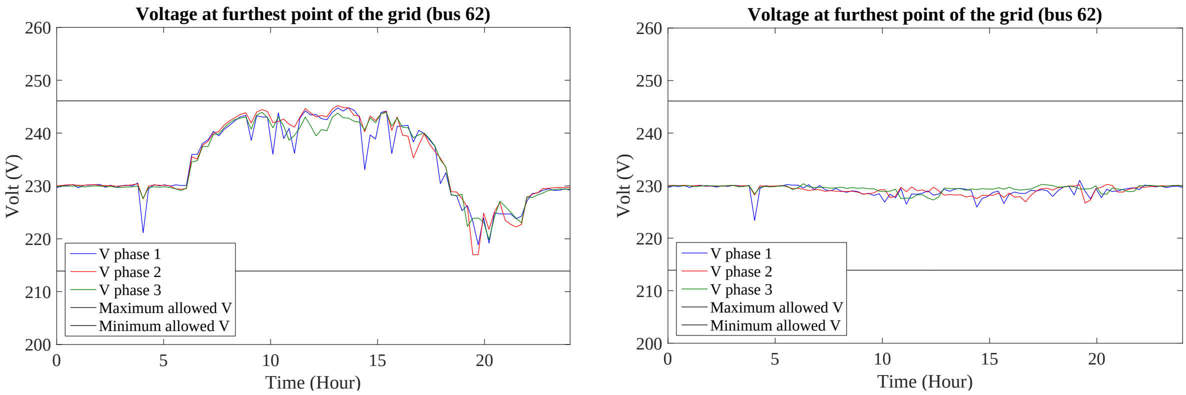
In order to assess the possible effect of energy storage systems on unbalanced load distribution through the simulation, voltage behavior is compared between a LV grid model with 100 % renewable energy penetration, and the same grid with added centralized batteries. These are equally as in section 5.2 considered with no concrete specifications, taking their energy capacity to maximum in order to focus on the proposed analysis of phase distribution. Additionally, the comparison is undertaken for all possible phase distribution patterns (balanced, unbalanced and very unbalanced) to assess the actual mitigation capability.

Scenario	
Constant parameters	Variable parameters
Daily analysis	Centralized energy storage system
Best-case weather conditions (high energy production)	**No** batteries
Clear day	**8000 Ah** batteries
High wind velocity	Load phase distribution
100 % Renewable energy penetration	**Balanced**
	Unbalanced
	Very unbalanced

Notice that for this analysis there are two variable parameters (energy storage system and phase distribution). Within the proposed comparisons, there is always only one changed parameter, hence the LV grid model is compared with and without batteries for each of the three proposed phase distributions. All represented voltage outcomes of the simulations are depicted at the furthest point of the grid (bus 62).

Balanced load distribution

With totally balanced load distribution there are very small differences between the voltage curves of the three phases, affected only by little discrepancies due to different demand and generation curves at the buses. Therefore, the effect of the implemented energy storage system together with the proposed control scheme of the inverter is not noticeable within the result of the simulation in figure 5.7. Batteries do influence over-voltage, but not the gap between voltage at the three phases, as from the start there was not any.



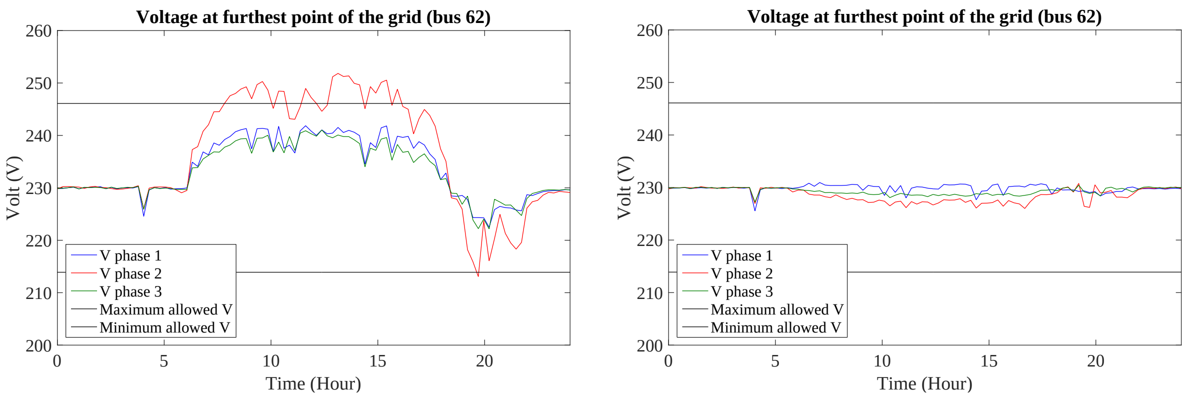
(a) 100 % renewable penetration

(b) 100 % renewable penetration with centralized energy storage system

Figure 5.7: Voltage at bus 62 (furthest point of the grid) with balanced load distribution

Unbalanced load distribution

When assessing the unbalanced load distribution it is possible to recognize how voltage is strongly deviated in phase 2. The centralized energy storage system with the added operational phase control system manages to remake totally balanced conditions within the electric line as shown in figure 5.8. Hence, the proposed mitigation technique is perfectly able to correct concrete load deviations on the phases of the branch.



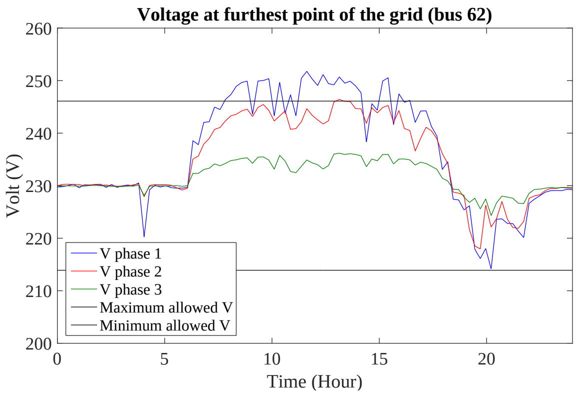
(a) 100 % renewable penetration

(b) 100 % renewable penetration with centralized energy storage system

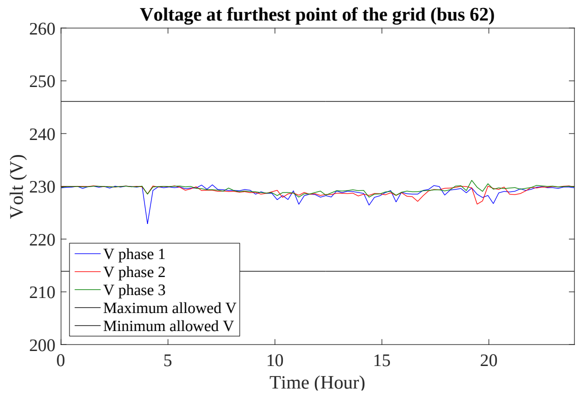
Figure 5.8: Voltage at bus 62 (furthest point of the grid) with unbalanced load distribution

Very unbalanced load distribution

Bounded to the very unbalanced load pattern over the electric line, voltage behavior is entirely distorted with noticeable gaps between all phases. Notice that not only phase shifts are created, but over-voltage also worsens significantly due to the inconvenient phase distribution. Under this worst-case scenario, the energy storage system together with the proposed phase control system is able to completely correct the existing phase deviations, minimizing over-voltage variations and eradicating discrepancies between phases.



(a) 100 % renewable penetration



(b) 100 % renewable penetration with centralized energy storage system

Figure 5.9: Voltage at bus 62 (furthest point of the grid) with very unbalanced load distribution

After figuring graphically the impact of energy storage systems with added operational phase control system on different phase distributions, exact maximum voltage variances between phases are computed for all scenarios.

Effect of energy storage systems on unbalanced phase shifts in the LV grid model with 100 % renewable energy penetration

Indicator	100 % Renewable penetration			100 % Renewable penetration with energy storage system		
	ΔV_{12}	ΔV_{23}	ΔV_{31}	ΔV_{12}	ΔV_{23}	ΔV_{31}
Balanced phase distribution	0.4 V	1.28 V	0.87 V	0.79 V	0.13 V	0.66 V
Unbalanced phase distribution	9.97 V	10.79 V	0.82 V	0.16 V	0.35 V	0.51 V
Very unbalanced phase distribution	5.34 V	10.24 V	15.59 V	0.2 V	1.06 V	0.85 V

Table 5.3: Impact of energy storage systems on unbalanced phase shifts in the LV grid model with high renewable energy penetration

For the balanced phase distribution case, no changes take place with the implementation of batteries, such that voltage gaps are constantly maintained in between 0 V and 1 V. With unbalanced phase distribution, specific deviations are settled from values around 10 V to 0.5 V. Lastly, assessing very unbalanced phase distribution, extended deviations affecting all phases are controlled from maximum variances of almost 16 V down to 1 V. With this indicators it is possible to reaffirm that the combination of centralized energy storage system and the proposed operational phase control scheme is more than capable of correcting the negative effect on electric parameters of unbalanced load distribution.

5.4 Impact of energy storage systems on energy losses of the LV grid model

Energy losses represent one of the most significant issues in every electric power system. The need to minimize possible losses within the grid is directly related to the reduction in operational costs and efficiency of the system. Although all existing components of the electric distribution network present certain performance limits that generate energy leaks, the main share of losses is created by means of the joule effect on the electric lines. Therefore, the introduction of energy storage systems in LV distribution grids suppose significant additional energy losses for the electric power system due to their efficiency rate. For this reason it is essential to evaluate the impact of the proposed centralized energy storage system on the energy losses of the LV grid model, assessing the relation between gain of energy losses due to battery efficiency and decrease of energy losses by means of the improved power-flow.

In order to assess the present analysis, the LV grid model with 100 % renewable energy penetration is compared to the same with included energy storage system. For this concrete simulation, the chosen battery type is essential, because depending on the efficiency of the technology, energy losses can vary significantly. So, to analyze the impact of energy storage systems on power losses of the grid, the two most promising battery technologies for mitigation purposes in LV grids (see section 1.3) - Li-Ion chemical battery and Fuel cell flow battery, are evaluated and compared to the base scenario with no included energy storage system. The specifications of the batteries include 90 % efficiency and 80 % discharge depth to recreate Li-Ion energy storage systems, and 60 % efficiency and 100 % discharge depth for Fuel cell technology (see section 4.1.5).

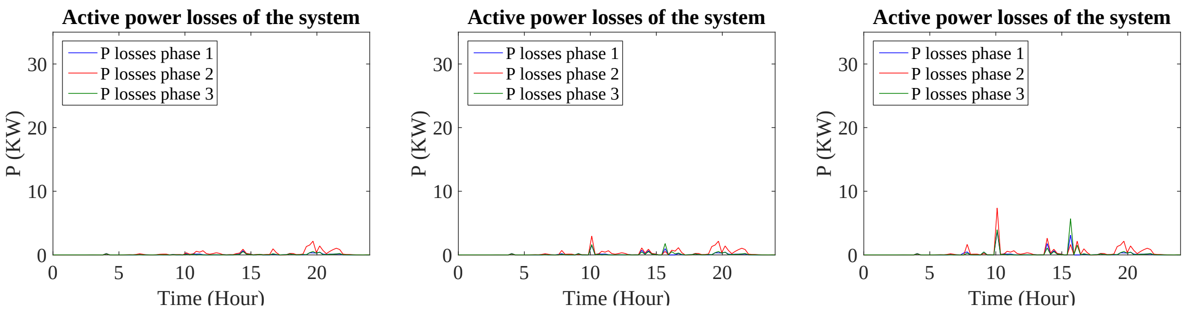
Furthermore, to analyze how energy losses evolve according to micro-generator energy production, considering the relation between gain in energy losses due to battery efficiency and decrease in losses because of improved power flow regarding energy storage mitigation capacity, it is of big interest to simulate different energy production scenarios and evaluate how the stated relation ends up in gain or decline of energy losses.

Scenario	
Constant parameters	Variable parameters
Daily analysis Average **unbalanced** phase distribution **100 %** Renewable energy penetration	Energy storage system **No** battery **Li-ion 8000 Ah** battery **Fuel cell 8000 Ah** battery Micro-generator energy production **Low** (worst-case weather) **Average** (average weather) **High** (best-case weather)

Hence the proposed simulation includes the comparison of the LV grid model incorporating 100 % renewable energy penetration between no batteries, Li-ion batteries and Fuel cell batteries for the three possible energy generation scenarios: very cloudy day + slow wind speed (low micro-generator energy production) / slight cloudy day + average wind speed (average micro-generator production) / clear day + high wind speed (high micro-generator production). Additionally the energy three energy production scenarios given for April (low, average and high) can be extrapolated to other periods of the year, due to the high presence of PV technologies that depend on sun irradiation. Therefore, low energy production does not only represent worst-case weather scenario in April, but average conditions during winter, whilst high energy production shaped as best-case weather scenario during April is equivalent to average conditions in summer.

Low micro-generator energy production

During low micro-generator energy production periods, instantaneous power losses are not significantly altered by the introduction of different energy storage systems as depicted in figure 5.10.



(a) 100 % renewable penetration with no energy storage system **(b)** 100 % renewable penetration with Li-Ion battery **(c)** 100 % renewable penetration with fuel cell battery

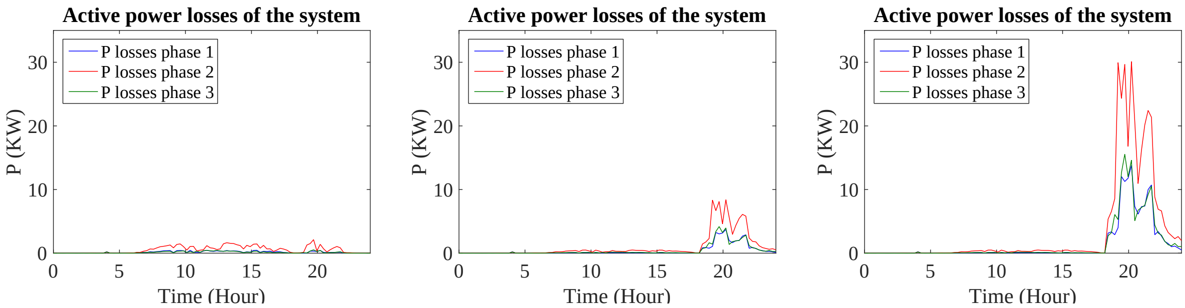
Figure 5.10: Instantaneous power losses of the grid with low micro-generator energy production

Both Li-ion battery and Fuel cell storage system cause a slight increase in energy losses that is roughly noticeable. This is because energy production from renewable micro-generators is low enough to not surpass demand at the loads, hence no surplus energy is injected in th grid and batteries are mostly non-operative, so they don't cause any deviation.

Average micro-generator energy production

In the average energy production scenario there is enough injected surplus energy from the renewable micro-generators, hence the batteries in both cases are operative and produce important alterations in the instantaneous power losses of the grid as can be observed in figure 5.11. The losses occur during load demand peak periods at night when the battery systems are discharged and energy is lost with respect to the initial charged energy. Although Fuel cells have the higher discharge depth, their lower efficiency leads to much greater energy losses in comparison to Li-ion chemical batteries, wherefore are less suitable under this conditions.

Generally seen, according to this energy production scenario, both analyzed battery installations have a negative impact on power losses of the LV distribution grid. With the present circumstances, general power flow in the electric grid is not high enough to cause noticeable energy losses due to the joule effect in the basic scheme (no batteries), although sufficient to activate energy storage systems which aggravate energy losses according to their efficiency.

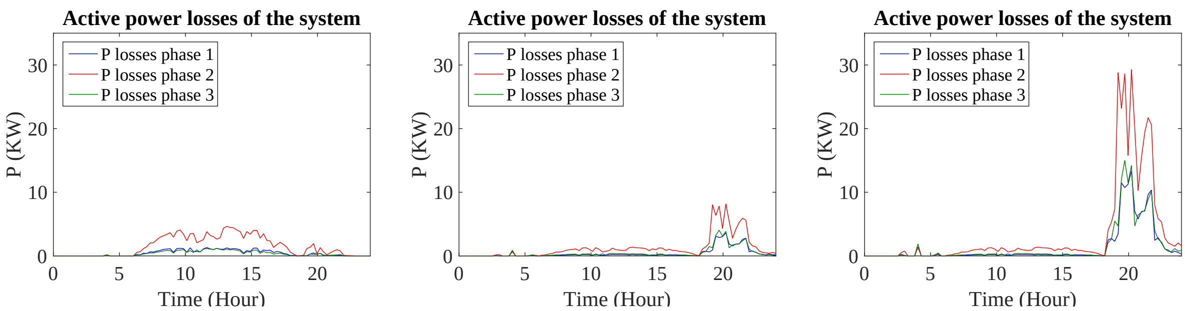


(a) 100 % renewable penetration with no energy storage system **(b)** 100 % renewable penetration with Li-Ion battery **(c)** 100 % renewable penetration with fuel cell battery

Figure 5.11: Instantaneous power losses of the grid with average micro-generator energy production

High micro-generator energy production

Impact of the proposed battery systems on the energy losses of the LV grid model with high renewable micro-generator energy production is exactly the same as for average energy production in the previous scenario, while the losses in the basic case (no batteries) increase noticeably, as can be recognized in figure 5.12. This is because the energy demand of the households, unlike power generation, remains constant. Therefore, discharged energy by the batteries during peak demand periods remain alike, hence energy losses are also unchanged with respect to average energy production. On the other hand, energy losses in the LV grid with no batteries are augmented due to the undeniable increase in power flow as a result of the big renewable micro-generator energy production. The batteries are not affected by that trait as they manage to regulate power flow and over-voltage (according to results from 5.2), and charge operations present no direct influence in energy losses for the LV grid (although stored energy in the modules is less than the charged input energy).



(a) 100 % renewable penetration with no energy storage system **(b)** 100 % renewable penetration with Li-Ion battery **(c)** 100 % renewable penetration with fuel cell battery

Figure 5.12: Instantaneous power losses of the grid with high micro-generator energy production

The general outcome for this last scenario is less clear from the represented parameters. The Fuel cell energy storage system still maintains much higher energy losses than the other two options due to its low efficiency, therefore, according to power losses criteria, this technology is not suitable for any energy generation scenario. On the other hand, no battery and Li-ion battery cases are very similar, even though instantaneous power losses are differently distributed over time, total energy losses cannot be determined accurately to be bigger/smaller in any of both subjects. Hence, the precise outcome is going to be evaluated by means of the obtained indicators in table 5.4. Nevertheless, from the two proposed battery systems, Li-ion technology is definitely more adequate in terms of energy losses.

The resulting indicators that are obtained from the simulation of the scenario include maximum instantaneous power losses and total energy losses. The first parameter represents the maximum lost power according to the plots in figures 5.10, 5.11 and 5.12, which is already perceived visually. The second indicator enhances total energy losses in the LV grid for each phase during the entire day determined in kWh/day, although depicted in form of energy losses in proportion to total energy flow of the grid in %, which will allow to asses exact impact of the batteries on power losses.

Effect of energy storage systems on the power losses of the LV grid model with 100 % renewable energy penetration

Indicator	100 % Renewable penetration		100 % Renewable penetration with Li-Ion battery		100 % Renewable penetration with fuel cell battery	
	Pmax losses	Energy losses	Pmax losses	Energy losses	Pmax losses	Energy losses
Low generation	2.16 kW	1.21 %	2.97 kW	1.76 %	7.38 kW	2.66 %
Average generation	2.12 kW	3.14 %	8.4 kW	6.89 %	30.12 kW	23.15 %
High generation	4.63 kW	8.66 %	8.17 kW	7.99 %	29.27 kW	23.17 %

Table 5.4: Indicators for the impact of energy storage systems on the power losses of the LV grid model with high renewable energy penetration

According to the resultant indicators, within low energy production, batteries have very little effect on energy losses in the LV grid, keeping them under 3 % as already concluded from the plots. The same occurs in average energy production, where power losses substantially increase with included energy storage systems (losses double with Li-ion battery, and augment loosely by 7 for Fuel cells) as expected. For the last analyzed case (high energy generation), battery losses are indeed maintained constant with respect to the average energy production case (almost same quantities of lost energy), whilst the scenario with no included battery shows much bigger energy losses than before, up to the point where they slightly surpass the losses of the grid with incorporated Li-ion batteries. Therefore, the simulation proves that in environments with a lot of injected surplus energy due to renewable micro-generators, Li-ion batteries do not only suppose the most suitable choice out of possible energy storage systems in agreement with power losses, but even manage to ease LV distribution grid energy losses in front of basic grids with no included batteries.

5.5 Assessment of the required energy storage capacity for the LV grid model

Energy storage systems have been proven to have a positive impact on the electric parameters, unbalanced phase distribution and energy losses in LV grids with high renewable energy penetration along the previous sections of the simulation outcomes. Now, it is essential to assess the required size of the energy storage system to enable the convenient effects in the proposed LV network model.

The dimensioning of batteries for the purpose of mitigating emerged problems from renewable micro-generators supposes an important hassle, as it cannot be done in the same manner as for pure energy based applications (conventional energy storage). The purpose of regular energy storage systems is to save produced energy, which is then released when required to cover a certain period of time (the time interval can vary significantly upon the application of the battery, but is usually kept within reasonable limits), whilst batteries for electric parameter mitigation objectives need to work over a much longer time period in worst-case scenarios. Once conventional energy storage systems are fully charged, it does not suppose any inconvenient for the aim of the system. On the contrary, if batteries with the purpose of mitigating over-voltage issues are completely charged and surplus energy keeps being injected into the grid, the entire mitigation system fails. Hence, the dimensions of these energy storage systems are required to be much bigger than conventional batteries, what implies an important economical burden for the implementation of the technologies.

In order to evaluate the actual required size of the centralized energy storage system in the proposed LV grid model, its mitigation capacity and charge operations must be analyzed over a prolonged time range. As the daily analysis performed in the previous simulations does not serve the purpose of this section of the study, a specific weekly analysis model has been created (see section 4.2.1) based on statistically average weather conditions at the selected location.

The proposed energy storage system is going to be evaluated with two different sizes in order to recognize the importance of appropriate dimensioning of the installation. The set up dimensions are elected within the possible battery capacity range (0 Ah - 8000 Ah) of the created simulation tool (see section 4.1.5), that is expressed in equivalent energy demand. Hence, an average sized energy storage system capable of covering an entire day's demand (2759 Ah) of the LV grid model represents the first battery model, and a fairly larger energy storage system that covers almost three days of load demand concurring with the maximum possible charge capacity of the tool (8000 Ah) is elected as second battery model. According to the results from section 5.4, the battery characteristics for both models will concord with the Li-ion chemical battery (although whichever of both proposed battery types is chosen does not affect the outcome of the dimensioning analysis, as the two are capable to mitigate over-voltage).

Apart from comparing different energy storage sizes, it is convenient to appraise how voltage variations evolve during the seven proposed days within the LV grid model with 100 % renewable energy penetration and no included batteries. Thus, the actual impact of the two proposed battery models can be better appreciated.

Scenario	
Constant parameters	Variable parameters
Weekly analysis	Energy storage system
Statistical weather conditions	**No** battery
Average **unbalanced** phase distribution	**Li-ion 2759 Ah** battery
100 % Renewable energy penetration	**Li-ion 8000 Ah** battery

After defining all conditions of the proposed analysis, the first step of the simulation process consists in assessing the weekly evolution of voltage variations within the LV grid model due to the renewable micro-generators (with no included batteries). The resulted outcome is presented in figure 5.13, where it is possible to identify how voltage rises during daytime over the week, with exception of the second and seventh day (low energy generation scenarios due to bad weather conditions).

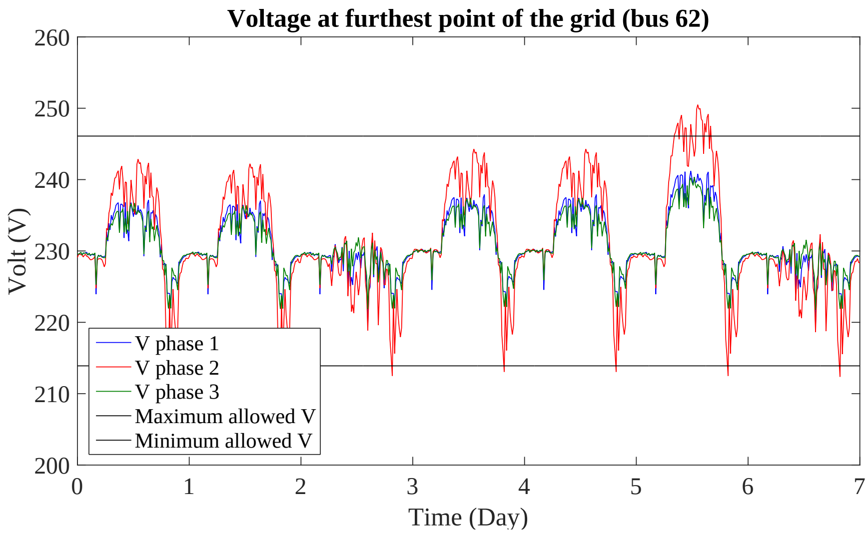
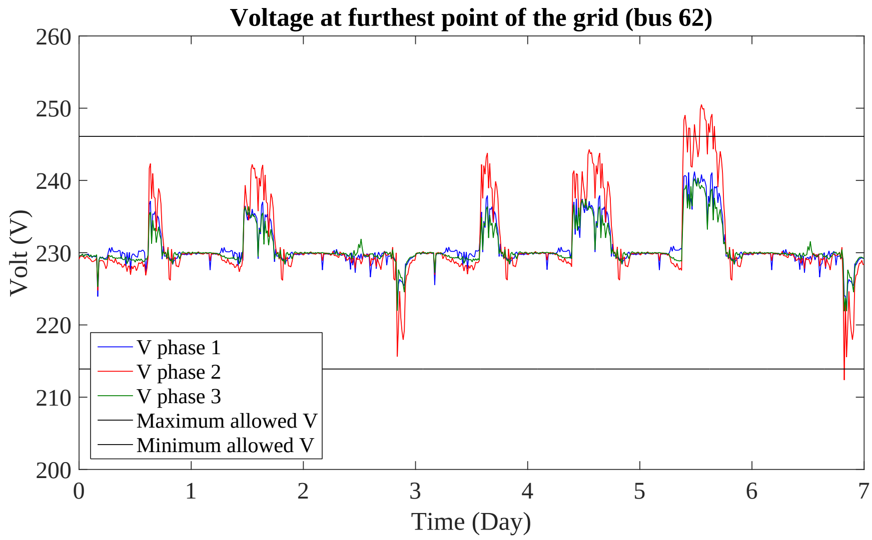


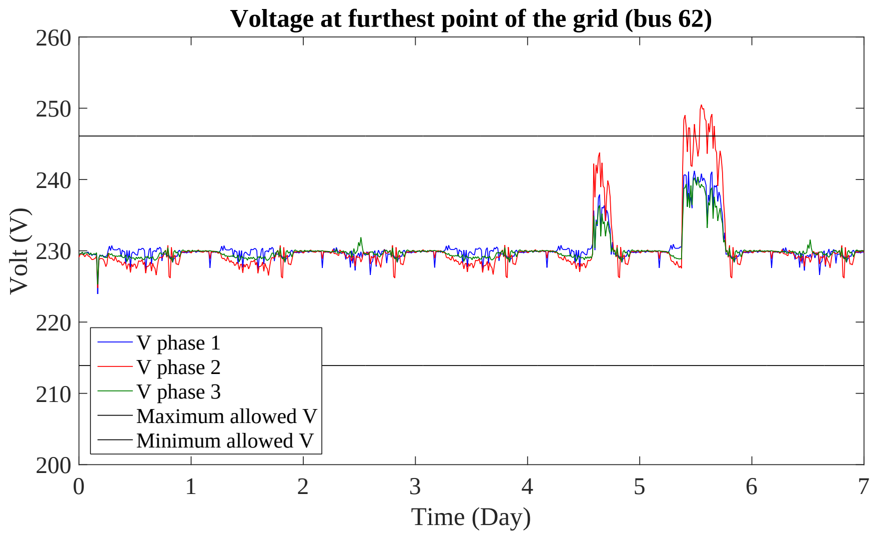
Figure 5.13: Voltage at furthest point of the grid (bus 62) with 100 % renewable energy penetration

According to the figured voltage behavior, which is based on a statistical average weekly scenario, the centralized energy storage system must be able to handle several consecutive days of injected surplus energy. Hence, the accumulation of various average-high energy production periods can be quite troublesome, as the battery system is not able to discharge all gathered excess energy from the renewable micro-generators in time until the point where it is totally loaded.

Now, the two proposed energy storage systems are included in the simulation to assess their effect on over-voltage for the entire week. Outcomes of the analysis are represented in figure 5.14, depicting the voltage behavior with included batteries. The smaller sized energy storage system (2759 Ah) reduces voltage variations significantly, although the over-voltage hassle is far from being solved. The proposed battery capacity is not able to handle voltage variations over the entire proposed time interval as the storage system is rapidly complete charged. The trait is particularly noticeable from days 4 to 6, where the battery gradually looses its effect upon available energy capacity. On the other hand, the bigger sized energy storage system (8000 Ah) does mitigate voltage deviations along the week much better, tearing over-voltage almost completely during the first five days. Nevertheless, after the fifth consecutive day, load capacity of the energy storage system is led up to its limit, equally to the previous smaller battery in the preceding scenario.



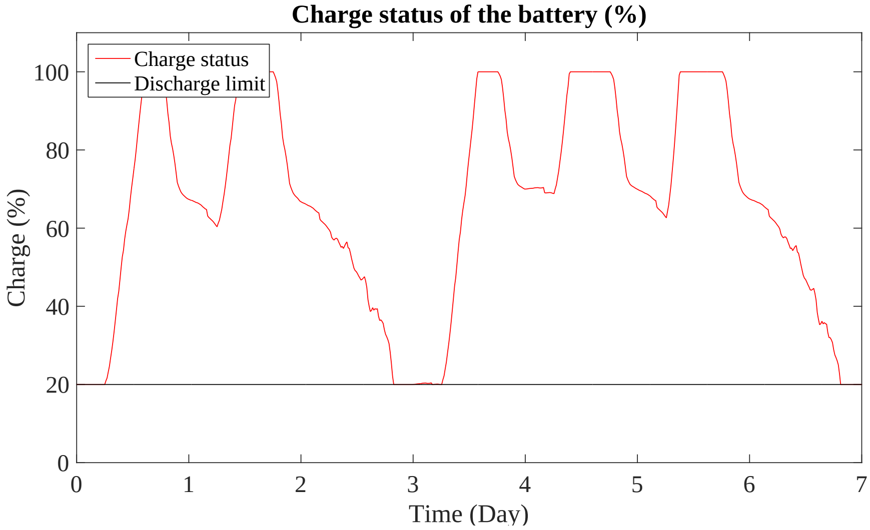
(a) Energy storage system with 2759 Ah capacity



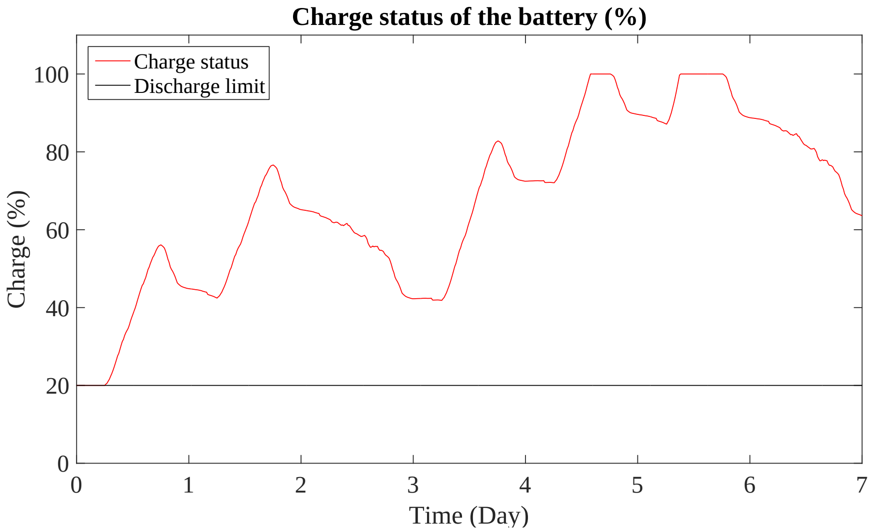
(b) Energy storage system with 8000 Ah capacity

Figure 5.14: Voltage at furthest point of the grid (bus 62) with 100 % renewable energy penetration and energy storage system

The exact charge status evolution of both proposed energy storage systems is portrayed in figure 5.15. This parameters are directly correlated to the voltage variations in the LV grid, since batteries stop operating once they are fully charged, which is why voltage variations reappear.



(a) Energy storage system with 2759 Ah capacity



(b) Energy storage system with 8000 Ah capacity

Figure 5.15: Energy storage system charge operations with 100 % renewable energy penetration

According to this outcomes, battery capacity is essential when dimensioning energy storage systems in LV distribution grids with the aim of regulating electric parameters. Even very big sized batteries (in relation to energy demand in the considered electric power system) for conventional applications may not be sufficient to mitigate over-voltage during a dragged on time interval. Thereupon, the proposed 8000 Ah centralized energy storage system was not able to cover an entire average week within the LV grid model. This feature proves the existing struggle of necessary battery over-dimensioning to secure continuous stable working conditions.

5.6 Evaluation of the development of LV distribution grids with gradual renewable energy penetration

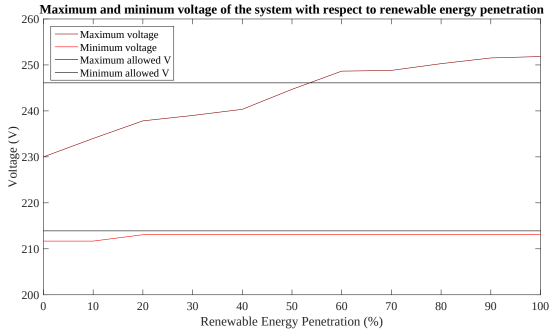
The final part of the present analysis of the impact of energy storage systems on LV distribution grids with high renewable energy penetration enhances the evaluation of batteries from a generic point of view, assessing gradual insertion of micro-generators in LV networks. This section is very important in order to obtain a wider perspective on the existing problems and possible mitigation techniques, because renewable energy penetration does not happen instantaneously, but gradually over a long period of time.

All past simulations have been realized considering worst-case renewable micro-generator presence (100 %) in the LV grid model, what was very advantageous to emphasize concrete struggles of renewable energies and batteries in the electric power system. Although now, it is of bigger interest to perceive the evolution of possible generated problems with gradual insertion of micro-generators, assessing real viable solutions according to the actual needs. In order to do so, the generic configuration of the simulation tool (see section 3.2.2) can be adjusted to gradual renewable energy penetration analysis, which allows to compute maximum/minimum voltage (although minimum voltage is not relevant for the purpose of the present work) and energy losses parameters within a specific scenario for all possible micro-generator penetrations of the model through an iterative process.

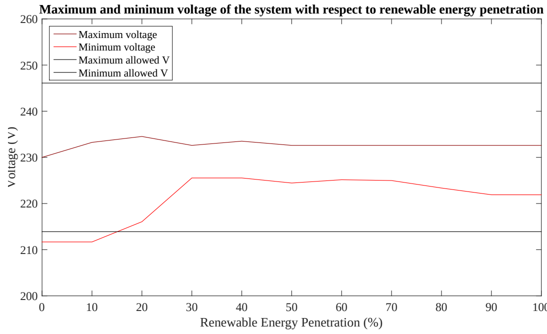
For the analysis, three different cases are proposed to evaluate the future development of LV distribution grids and the possible required interventions to mitigate appearing problems. The first subject of the simulation enhances the basic scheme of the LV grid model with no renewable energy storage system. The second sample considers the direct implementation of the biggest possible battery (8000 Ah Li-ion chemical storage system) to mitigate all obstacles from the beginning. The last case involves a gradual insertion of batteries in the LV grid based on the mitigation needs. Hence, first a smaller battery arrangement (4000 Ah Li-ion storage system) is implemented at 40 % renewable energy penetration, and a second battery structure of the same size is added (summing up a total of 8000 Ah Li-ion storage system) at 70 % renewable energy penetration, making use of the modularity of the technology (batteries can be added to existing energy storage systems increasing energy capacity, without the need of redoing the entire installation).

Scenario	
Constant parameters	Variable parameters
Gradual energy penetration analysis 0 % - 100 % **Daily** analysis Average **unbalanced** phase distribution **Best-case** weather conditions (high energy production) **Clear** day **Fast** wind speed	Energy storage system * **No** battery * **Li-ion 8000 Ah** battery * **Li-ion 4000 Ah** battery (at 40 % penetration) + additional **Li-ion 4000 Ah** battery (at 70 % penetration)

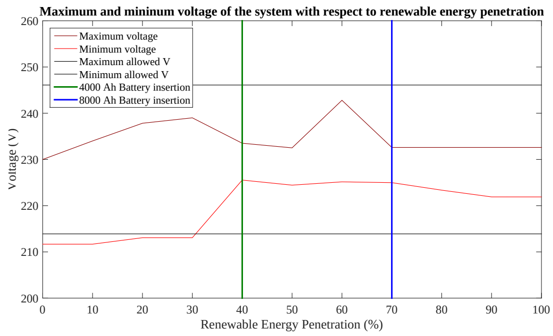
According to the three proposed scenarios, first absolute maximum and minimum voltage values for the LV grid model (at any point of the network and time step) are represented, as depicted in figure 5.16. The presented parameters do not portray voltage variations within the grid, only momentary maximum values (which can happen singularly and do not necessarily show general voltage behavior), wherefore it is not indispensable for the outcome values to be close to nominal voltage (230 V), as long as they are maintained within the legally permitted voltage range (this would mean that in a particular instant of worst-case scenario the electric power system is still able to keep voltage within required boundaries).



(a) No energy storage system.



(b) With energy storage system (8000 Ah)

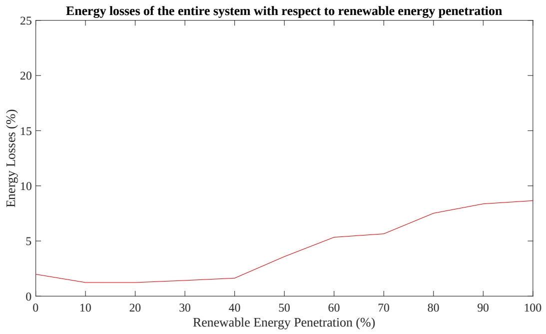


(c) Gradual insertion of energy storage systems (at 40 % renewable penetration: 4000 Ah battery, at 70 % renewable penetration: 8000 Ah)

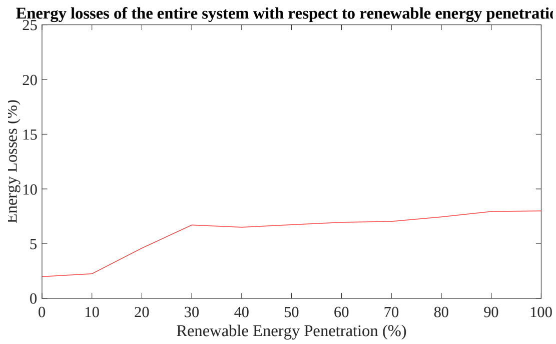
Figure 5.16: Voltage at furthest point of the grid (bus 62) with gradual renewable energy penetration

The first case with no included batteries represents how gradual insertion of renewable energy sources in the LV grid model progressively worsens over-voltage. Hence, in accordance with the proposed energy penetration model (see section 4.2.3), voltage surpasses the permitted limit of + 7 % increase at roughly 55 % micro-generator penetration. Therefore, it is inevitable to take measurements to prevent over-voltage increase due to future insertion of renewable energies in LV networks. The second case that proposes the insertion of an 8000 Ah centralized energy storage system from the beginning, perfectly regulates over-voltage along the entire progression of micro-generator insertion in the network. Additionally, even though it is not enhanced within the purpose of the study, the proposed battery is capable of raising the minimum voltage significantly. By last, the third case that evaluates the proposed configuration simulating the gradual insertion of centralized energy storage modules, results equally effective to mitigate over-voltage. Albeit the obtained voltage range between maximum and minimum values is considerably wider than for the previous case, it still fully complies the existing limitations for over-voltage, and noticeable increases minimum voltage reducing the gap to nominal voltage.

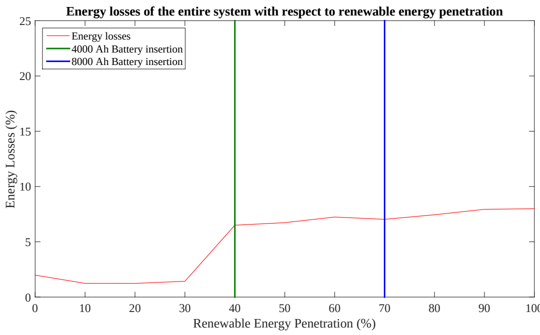
Now, once the impact of the proposed battery configurations on over-voltage is settled, next total energy losses of the LV grid model are assessed to substantiate the viability of the modeled energy storage systems. Results for the evolution of proportional energy losses for the three scenarios are displayed in figure 5.17.



(a) No energy storage system.



(b) With energy storage system (8000 Ah)



(c) Gradual insertion of energy storage systems (at 40 % renewable penetration: 4000 Ah battery, at 70 % renewable penetration: 8000 Ah)

Figure 5.17: Energy losses of the system with gradual renewable energy penetration

The outcomes of the existing energy losses in the system result as expected according to the conclusions from section 5.4. During low energy generation period (small renewable energy penetration) energy losses alterations due to batteries are very slight. For medium micro-generator production (middle renewable penetration) energy losses increase noticeably for both proposed energy storage systems in comparison to the base case. During the last stage of the renewable micro-generator implementation process implying high energy production, losses are again balanced with respect to the basic scenario with (no batteries) up to the point where the introduced energy storage systems determine a slightly more efficient electric power system.

When comparing both proposed energy storage integration models, it is possible to identify that the gradual implementation of batteries in the LV grid model causes less energy losses than the singular implementation at the beginning of the micro-generator penetration process. This trait is quite straight forward, as the later introduction of batteries supposes less power losses during medium generation periods.

Chapter 6

Review of the proposed solution

This chapter handles the general evaluation of the proposed centralized batteries as mitigation system for altered electrical parameters in LV distribution grids with high renewable energy penetration according to the obtained results from the simulations. In order to do so, first the effectiveness of the proposed technology is assessed according to its influence on the electric grid. Secondly, the viability to introduce battery systems in LV networks is discussed, according to present requirements, technological vantages and economic investment.

6.1 Effectiveness

The unavoidable and required raise of renewable micro-generators in LV distribution grids produces substantial alterations in the electric parameters of the grid. Amongst all created hassles, the most direct and problematic one enhances over-voltage during high energy generation hours due to surplus power injection. This phenomena is directly related to a noticeable increase in power flow and current, which have a very negative impact on electric power systems that are not designed for the implementation of distributed micro-generators.

The proposed mitigation method to handle the generated problems enhances the introduction of centralized energy storage systems in LV distribution grids. In accordance with the results from the simulations in chapter 5, the besought battery system is capable of mitigating all interposed issues in the LV grid model, and furthermore, contribute additional convenient features to the electric power system.

Over-voltage

Increased voltage due to distributed renewable micro-generators is the most representative problem of the analysis. The implementation of 100 % renewable self-consumption generators in the households of a LV distribution grid can produce a voltage increase of almost 10 % (see figure 5.3), which is very harmful for the electric power system and breaks legislative boundaries of 7 % voltage variations [30]. The implemented centralized energy storage system handles to narrow over-voltage up to 3 %. Hence, batteries do not only have the capacity of sufficiently mitigating the problem according to legal limits, but manage to set voltage parameters to ideal working conditions [24].

Altered power flow

The power flow within the electric grid is totally disturbed due to the introduction of distributed renewable micro-generation. When injecting produced surplus energy from the micro-generators that are located at the loads, power flow is reversed, opposing the traditional unidirectional energy flow scheme for which the components of the electric power system are not prepared. Additionally, the instantaneous injection of surplus energy increases total active power significantly (almost doubling the initial value, see table 5.1). The proposed centralized energy storage system is not capable of mending bidirectional power flow (micro-generators still produce surplus-energy that is injected to the grid), although it ensures total autonomy for the residential LV distribution grid cutting nearly all energy flow from the main transformer and reduces maximum power flow more than half (see figure 5.2).

Increased current

Current is directly proportional to the power flow of the grid, hence it also changes directions and increases considerably. The existing increment due to big amount of renewable energy sources can be very damaging to the system because all parts of the grid, especially electric lines, have current limitations which must not be surpassed. In agreement with the realized simulations, 100 % present renewable micro-generators in the LV grid cause an increase of 40 % in maximum current (see table 5.1). Under this conditions, the proposed centralized energy storage system reduces current raise significantly, lowering instantaneous current almost 60 % (see table 5.2). Although maximum values are reduced correspondingly, general behavior of current in the LV grid is maintained, depicted as growing flow curve during daytime.

Unbalanced phase distribution

Unbalanced phase distribution is not directly correlated to the implementation of distributed renewable micro-generators in LV grids, but represents a possible generic inconvenient that batteries might handle. Therefore, the control of unbalanced load distribution on the phases is an additional attribute of the proposed battery system. The same centralized energy storage model that was implemented in the previous analysis, together with a phase control algorithm implemented in the inverter that connects the batteries to the grid, achieve to fully equilibrate very unbalanced grid scenarios (see figures 5.7, 5.8 and 5.9). Hence, voltage gaps of more than 15 V between phases can be reduced to nearly 1 V (see table 5.3) taking use of centralized batteries within LV distribution grids.

Energy losses

Energy losses of the electric power system represent an essential feature that must be optimized to raise average efficiency. Considering the LV distribution grid with no added energy storage system, most power losses are based on the joule effect (which influences the electric grid with and without renewable micro-generators). Now, the implementation of batteries implies a very noticeable added energy losses factor due to their own efficiency, that depending on the technology might not be very favorable. Hence, the impact of energy storage systems on power losses is very dependent on the scenario and the chosen technology.

As a general rule, during low energy production periods efficiency of the electric grid is vaguely altered due to batteries, during average generation intervals power losses worsen sufficiently, and for high production phases energy losses are again equated in between both cases, or even slightly lowered (see section 5.4). The same behavior can be expressed in form of renewable micro-generator penetration, where the biggest efficiency struggles appear with mid rated renewable energy implementation. Nevertheless, the deciding factor on how energy losses evolve with the introduction of storage systems, depends on the technology type. In the present simulations, Li-ion chemical batteries with 90 % efficiency and Fuel cell batteries with 60 % efficiency have been compared. The outcomes depicted very big variations, wherein Li-ion batteries perfectly fitted the general rule and even managed to reduce power losses, Fuel cells incremented energy losses heavily, so that the impact was negative on both, average and high power generation periods.

Beyond the results from the simulations of the proposed LV grid model, there is a very important feature that has not been contemplated during the analysis for the sake of energy losses. For the basic case where no batteries are included in the residential LV grid, in a real scenario, energy losses due to the joule effect do not only emerge from the branches of the proper LV grid model, but from the energy losses caused through the entire electric power system (including all transmission lines) when energy is demanded from the transformer during peak load demand. On the other hand, the implementation of storage systems in the network causes the progressive independence of the residential grid, where peak demand is covered by nearby stored energy in the batteries, what removes transportation power losses from the electric transmission system. Hence, it is possible to affirm that under the right circumstances (proper technologies and high energy production by micro-generators), batteries to increase the general efficiency of the electric power system.

6.2 Viability

The viability of implementing centralized energy storage systems in LV distribution grids with high renewable energy penetration is bound to economical restrictions. Even if the proposed technology is perfectly able to handle all existing alterations caused by renewable micro-generators, they must also be feasible in terms of required investment. Nevertheless, the mitigation of caused problems by distributed generation in LV grids is not an uncertain possibility that might or might not be realized. Therefore, economic causes are not the unique decision point in whether possible mitigation techniques are implanted, as they are going to suppose an inevitable requirement.

Energy storage systems present very advantageous features in LV distribution grids that enable the settlement of all negative influences of renewable micro-generators, balance load distribution, adapt energy generation curves to demand, permit self-sufficient energy operation and present easy installation and further adjustments due to their modularity. Hence, from the technological point of view, the implementation of energy storage systems is more than viable within electric networks.

On the other hand, batteries also feature a very significant inconvenient - current energy storage technologies imply a very high price. Under present circumstances, this criteria cannot be disregarded and strictly depends on future development of battery costs, even though they are expected to diminish over time [40]. Therefore, one of the main present approaches is to strengthen economic viability of energy storage systems. In order to do so, three important aspects need to be focused on, elected technology, battery dimensioning and implementation methodology.

There are numerous different battery systems (see section 1.3) that could serve the purpose of electric parameter mitigation in LV grids. All of them enhance distinct advantages and disadvantages regarding their aptitudes (technical and economic). In terms of viability, election criteria must focus on indispensable technical requisites and cost management, instead of covering all possible features. A good example for this statement is the realized energy losses analysis during the simulations of the present work. Although Li-ion batteries show much better efficiency qualities than Fuel cells to handle power losses of the LV grid model, under current circumstances of expensive technologies, this singular trait does not justify the implementation of one system over the other, as there are further characteristics that are relevant and must be accounted to mediate the price, such as battery lifetime and energy density.

The required dimensions for energy storage systems to work as over-voltage mitigation tools in LV distribution grids with high renewable energy penetration have a great influence on the viability criteria. According to the results in section 5.5, batteries that serve as mitigation implements require much bigger size than conventional energy storage systems. Thus, the dimensioning supposes an important aggravation in the viability of energy storage systems in LV networks.

The last relevant subject to the viability of energy storage systems in LV grids is the way how they can be implemented. Batteries have a very useful vantage: modularity, that enables gradual insertion of energy storage modules, expanding power capacity without reforming the entire installation. Therefore, the idea of progressively adding battery components to the centralized energy storage system according to the physical requirements of the grid with high renewable micro-generator penetration, is very convenient to narrow costs. The functionality of gradual battery insertion has been proven along the simulations in section 5.6, where the outcome substantiates that the effect of progressively added battery modules is equally beneficial as single introduction of the total battery capacity at the beginning.

To conclude, it is very difficult to determine actual viability of energy storage systems as electric parameter mitigation tools under the current conditions. According to technological vantages, batteries are more than adequate enough to be implemented in LV distribution grids. On the contrary, high costs of the technology do not foment economic viability in comparison to other possible mitigation techniques [16], although the melange between appropriate battery selection, gradual energy storage insertion and future price decrease supposes promising expectations for nearby viability improvement regarding the required investment. So for now, centralized energy storage viability is bound to elevated expenses, which does not mean the technology is not suitable for the purpose of permitting the expansion of renewable energy sources in LV networks, as they show off essential benefits for the electric power system and great future potential. Especially the combination of centralized batteries with additional mitigation tools such as STATCOMs (see 2.1.3) could suppose great benefits in future energy scenatios. In any case, to deepen more into the concrete evaluation of possible energy storage system viability, further studies must be performed to specifically compare different battery technologies and analyze their implied cost.

Conclusions

Performed tasks

The first stage of the present work involved the analysis of the current status of the electric power system, focusing on renewable energy sources (specifically distributed micro-generators) and energy storage systems (as electric parameter mitigation tools) in LV distribution grids.

The second stage of the work enhances the recognition and discussion of the existing problem created by high renewable energy penetration in LV distribution grids and the proposed solution. Over-voltage due to surplus injected energy of renewable micro-generators supposes the most relevant hassle to the electric power system, which necessarily needs to be regulated, wherefore a centralized energy storage system is proposed as solution.

The third stage treats the employed methodology to perform the analysis of the study. This part includes the design and programming of a specific algorithm that depicts the created simulation tool taking use of MATLAB® and MATPOWER softwares.

The fourth stage manages the creation of the proposed LV grid model for the further analysis through simulations. The model includes constant and variable parameters based on real data to recreate a proper study case.

The fifth stage enhances the simulation of the proposed model, analyzing the impact of energy storage systems on different traits of the electric power system, dimensioning the required battery size and evaluating the evolution of gradual renewable energy penetration.

The sixth and last stage of the work focuses on the review of the outcomes of the present study. Hence, the backspin of the proposed energy storage system is assessed, followed by the evaluation of the technological and economical viability of batteries within the purpose of the analysis.

Conclusions of the realized study

The main objective of the present work was to assess the impact of energy storage systems on LV distribution grids with high renewable energy penetration in order to mitigate caused problems.

The proposed solution of a centralized energy storage system has resulted in being very effective to mitigate electric parameters, and furthermore, has significant benefits on the entire LV network. The vantages of centralized batteries, according to the outcome of the simulations, include:

- Over-voltage mitigation
- Regulation of power-flow alterations
- Reduction of increased current
- Equilibration of unbalanced phase distribution
- Adaption of energy generation to load demand curve
- Self-sufficient energy management in the LV distribution grid
- Modularity for progressive implementation

The viability of the proposed centralized energy storage system depends on the treated subject. In relation to the technological vantage, centralized batteries are totally viable and imply important benefices. On the other hand, in terms of required economic investment, energy storage systems are still too expensive. Nevertheless, the proposed technology has great future potential and represents one of the most relevant available over-voltage mitigation techniques.

Future projects

1. **Improvement of the simulation tool**

   The first project that can be evolved from the present work is the amelioration of the created simulation tool. This directs to the enhancement of a visual interface for the input configuration and result representation. Thereupon, a real graphical user interface that depicts the former code can be created to simplify the selection of the configuration of the analysis. Secondly, a graphical result display, plotting the electric parameters in form of a color map on the represented grid scheme could be of great use when analyzing outcome data.

2. **Analysis of distinct battery technologies**

   The second project that can be developed according to the present study is the specific assessment of different energy storage systems for the purpose of mitigating altered electric parameters in LV distribution grids with high renewable energy penetration. Therefore, comparing concrete traits of different batteries could widen the knowledge about actual viability of the proposed solution.

Acknowledgements

Along the realization of the present project, during the last four months there is people who have played an important role because of their influence, support, dedicated time and presence, and therefore deserve recognition because of their efforts.

First of all I highly appreciate the opportunity that Andreas Sumper gave me in order to handle the present work and be part of the CITCEA-UPC. Without this gesture I wouldn't be under the current circumstance of attributing a small piece to the sustainable development of our future, fomenting the implementation of renewable energy sources.

Secondly, I must thank Francesc Girbau for his guidance and constant availability to solve any problem within the accomplishment of the project.

Facing the entire procedure and the comprehended struggles of the work would not have been possible without the constant motivation and help from my friends that surrounded me, hence I need to thank for all their support until the time being.

The development of my engineering career can be depicted by the doubtless enthusiasm for the establishment of a sustainable future because of the possibilities offered by technology. Therefore I must give special recognition to Raffa, who managed to awake my interest in the topic during my first lessons at school.

By last, I am endlessly grateful to my parents and family, who never stopped believing in my abilities, for their unconditional help and moral support, who did as much as they could to allow all possibilities for my personal growth, and thanks to whom I am here today.

To all who have dedicated part of their lives to encourage me,

Thank you.

Appendix A

Environmental impact

During the entire historical evolution of humankind, the intensified uses of resources from the planet has been accelerating all along. Up to date, the negative human footprint on the environment is more than noticeable because of excessive and bad use of the given prime-materials. Hence, it is essential to mitigate and control the use of available resources for a sustainable development.

Within the scope of the project, the main subject enhances the evaluation of energy storage systems, which can be assessed according to their own environmental effect depending on the used materials, and their possible effect on the electric power system regarding climate change.

A.0.1 RoHS

The European law for environmental impact (2015/863), known as RoHS (Restriction of Hazardous Substances), involves legal boundaries for the used resources in electric and electronic components. This normative restricts the use of Lead, Mercury, Cadmium, Hexavalent Chromium, Polybrominated Biphenyls, Polybrominated Diphenyl Ethers, Bis(2-Elthylhexyl) phthalate, Benzyl butyl phthalate, Dibutyl phthalate and Diisobutyl phthalate.

In relation to the present work, the RoHS law bounds the environmental impact of the proposed energy storage systems, as depending on the technology, several typologies include heavy metals such as Lead that are regulated within the present norm.

A.0.2 Climate change

Climate change is one of the biggest present threats for a sustainable growth of humanity. Therefore it is essential to mitigate the effects of green house gases in the atmosphere. Regarding the energy sector, in accordance with the COP21 agreement, the introduction of renewable energy sources in the electric grid is a doubtless requirement in order to eliminate fossil fuels.

The proposed energy storage system of the present study approaches to enable the introduction of renewable micro-generators in LV distribution grids, fomenting the growth of renewable energies. Hence, batteries as electric parameter mitigation tools in LV networks suppose a very positive environmental impact within the urge of challenging climate change.

Appendix B

Budget

The objective of this section is to define the imputed costs of the project through all included stages of the study. Note that the proposed budget enhances the research of the present work, not the real implementation of the analysis.

B.0.1 Human resources

The costs of human resources, which are depicted in table B.1, enhance all phases of the research project. The first stage includes previous study and research within the state of the art. Second stage covers the creation of the simulation tool through the established algorithm. The third stage treats the simulation process of all evaluated scenarios of the model. Fourth stage depicts the evaluation of the obtained outcome from the simulations. The fifth and last stage incorporates writing the memory. Notice that unitary cost of human resources depend on the required professional profile for the proposed task.

Activity	**Unitary cost** [€/h]	**Units** [h]	**Cost** [€]
Study and research	35	100	3.500,00
Simulation tool design	35	250	8.750,00
Model simulations	35	50	1.750,00
Result assessment	35	50	1.750,00
Project drafting	20	150	3.000,00
Subtotal			18.750,00
VAT (21 %)			3.937,50
Total			**22.687,50**

Table B.1: Budget for human resources

B.0.2 Material resources

Material resources enhance all required tools and softwares for the realization of the research project, as represented in table B.2. Note that the budget does not consider the amortization of the requested resources, which could be reused later on. However, as additional usage of the materials is unknown, full price is accounted in the proposed budget.

Activity	**Unitary cost** [€/u]	**Units** [u]	**Cost** [€]
MATLAB®	2.000,00	1	2.000,00
MATPOWER	0,00	1	0,00
Windographer	934,10	1	934,10
Office 365	63,50	1	63,50
Computer	600,00	1	600,00
Subtotal			3.597,60
VAT (21 %)			755,49
Total			**4.353,10**

Table B.2: Budget for material resources

B.0.3 Total cost of the project

The total cost of the project, as summarized in table B.3, covers all subjects of the present work. These include human resources, material resources and unexpected additional costs due to possible modifications (evaluated in 10 % of the total cost).

Subject	**Cost** [€]
Human resources	22.687,50
Material resources	4.353,10
Unexpected (10 %)	2.704,06
Total (VAT included)	**29.744,66**

Table B.3: Total budged of the project

Appendix C

Electric parameters

The electric grid is determined by physical parameters that condition both, the electric lines and power flux in the system.

First of all, considering the dimensioning of the lines, there are relevant factors that affect the energy transmission and possible losses:

- **Resistance**: The difficulty of electricity to pass through the electric lines, what directly depends on the resistivity of the material ρ, the section of the wire and the temperature.
- **Inductance**: The induced electromagnetic force that affects the electric transmission due to current variations (changes in the created magnetic field) in the grid.
- **Capacitance**: The created electric field in between lines due to the given electric potential (same behavior as a capacitor), affecting the shunt admittance of the wire.
- **Conductance**: Inverse to the leakage resistance, it implies the creation of leakage currents that depend on the atmospheric condition. Generally these currents are very small and unpredictable, which is why conductance is usually neglected.

Secondly, it is possible to identify physical properties of the electric energy that determine the behavior of the grid:

- **Power**: The amount of electric energy that is transferred within time. When handling AC circuits it is possible to differentiate between active power (direct transmission of energy) and reactive power (stored energy released in form of magnetic or electric fields) due to existing phase differences. The combination of both is referred as apparent power, and the relation or ratio between active and apparent power is the power factor, which is a relevant trait in circuit analysis. Ranging from -1 to 1, it is from big interest that the power factor is as high as possible in order to reduce the proportion of reactive power, that is reflected as energy losses in the system.
- **Voltage**: Electromotive force caused due to electric potential (charge) difference in between two points. Voltage, whether in continuous or alternating form (DC or AC), is the

main parameter that defines the different levels of the electric power system (high, medium and low voltage), complying standardized values, which may vary between different countries.

- **Current**: Rate at which the electric charge flows through the conductors. Equally to voltage, it is possible to differentiate between DC and AC current, depending on the nature of the energy source. Current plays a crucial role when considering energy losses in the grid due to the joule effect.
- **Frequency**: Represents the number of oscillations or cycles within time when handling AC systems. Worldwide standardized values are 50 Hz and 60 Hz (oscillations per second), varying from place to place.
- **Waveform**: Shape of the current and voltage oscillations in AC systems, which ideally takes the form of a sine/cosine function, but can differ due to perturbations.

Knowing this properties allows to entirely describe the electric characteristics of a power system. In order to provide stability to any electric grid, it is necessary to ensure the **power quality** of the electric energy itself, which depends on the depletion of voltage and frequency variations, and providing an adequate waveform for AC systems.

Appendix D

Newton-Raphson method

The Newton-Raphson algorithm is an iterative numerical method that solves the power flow analysis. The method works obtaining iterative solutions to the non linear equations of the load-flow problem starting with an initial guess, until achieving a value that is within the permitted error range ϵ, assuming it is possible to solve the analyzed system.

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \tag{D.1}$$

Following this criteria, the result of every iteration is used in order to obtain the guess for the next repetition, taking into account the increment regarding previous outcomes:

$$\Delta P_i = P_i - v_i \sum_{j=1}^{n} v_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{D.2}$$

$$\Delta Q_i = Q_i - v_i \sum_{j=1}^{n} v_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \tag{D.3}$$

Using this system of equations, it is possible to solve the problem linearly with the iterative process starting from an initial guess. This can be represented in matrix form for the entire scheme as following:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = J \begin{bmatrix} \Delta\theta \\ \Delta V/V \end{bmatrix} \tag{D.4}$$

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}^k = \begin{bmatrix} H & N \\ M & L \end{bmatrix}^k \begin{bmatrix} \Delta\theta \\ \Delta V/V \end{bmatrix}^k \tag{D.5}$$

Where J represents the Jacobian matrix, that is composed of H,N,M L sub-matrices. Each of these are composed of the given terms:

- Non-diagonal

$$H_{ij} = v_i v_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \tag{D.6}$$

$$N_{ij} = v_i v_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{D.7}$$

$$M_{ij} = -v_i v_j (G_{ij} cos\theta_{ij} + B_{ij} sin\theta_{ij}) \tag{D.8}$$

$$L_{ij} = v_i v_j (G_{ij} sin\theta_{ij} - B_{ij} cos\theta_{ij}) \tag{D.9}$$

- Diagonal

$$H_{ii} = -Q_i - B_{ii} V_i^2 \tag{D.10}$$

$$N_{ii} = P_i + G_{ii} V_i^2 \tag{D.11}$$

$$M_{ii} = P_i - G_{ii} V_i^2 \tag{D.12}$$

$$L_{ii} = Q_i - B_{ii} V_i^2 \tag{D.13}$$

Once a result is obtained from the linear approximation of the power balance equations, the next guess is obtained according to:

$$\Theta^{k+1} = \Theta^k + \Delta\Theta \tag{D.14}$$

$$V^{k+1} = V^k + \Delta V \tag{D.15}$$

The Newton-Raphson method can be considered successful once the results of linear systems have converged sufficiently, so that the power variation (active/reactive) does not exceed an acceptable error:

$$max(|\Delta P_1^k|, ..., |\Delta P_{n-1}^k|, |\Delta Q_1^k|, ..., |\Delta Q_{nD}^k|) \leq \epsilon \tag{D.16}$$

Appendix E

MATPOWER functionality

MATPOWER is a complementary package of MATLAB® developed by PSERC (Power Systems Engineering Center of the Cornell University) that is dedicated to the resolution of power flow analysis and optimal power flow problems.

Regarding the realization of the power flow analysis, the program is based on the Newton-Raphson method (see **Appendix D**), solving the load-flow problem within 10 iterations. If the result does not converge to an acceptable value within the error margin ϵ after the repetitions, the solution is presented as not possible. In order to realize simulations, numerous input parameters are required in a specific structure to define the evaluated object. The data is introduced in matrix shape, where every array of data represents the information of a concrete element of the grid. From here on, the software environment can easily be changed and adapted to the needs of the analysis.

So, input data is classified in three sections where specific information is required to describe the assessed system [17]:

- **Branches**

  Branches represent the electric lines that connect buses, transformers and phase changers, following the generic π scheme of an electric transmission line. Required data include admittance of the line (resistance, reactance and susceptance), transformer properties and operating status (working/not working).

Branch input data	
F_BUS	Bus where the branch comes from
T_BUS	Bus where the branch goes to
BR_R	Resistance (p.u.)
BR_X	Reactance (p.u.)
BR_B	Susceptance (p.u.)
RATE_A	Long term cut-off power ratio (MVA)
RATE_B	Short term cut-off power ratio (MVA)
RATE_C	Emergency cut-off power ratio (MVA)
TAP	Nominal transformer ratio
SHIFT	Phase shift angle of the transformer
BR_STATUS	Service status of the branch (0/1)
ANGMIN	Minimum allowed shift angle
ANGMAX	Maximum allowed shift angle

Table E.1: Matpower branch input data

- **Buses**

  Buses represent the nodes of the analyzed grid where loads and generators are connected to. MATPOWER uses this section to define the bus typology (PQ,PV and Slack) and subjoin information about the consumed energy of the loads (generators are treated apart). Hence, loads are given as the amount of active and reactive power that is consumed at the buses:

$$S_d = P_d + jQ_d \tag{E.1}$$

  In order to determine all parameters of the buses, information about bus typology, consumed power, shunt elements, voltage traits and load specifications are required.

Bus input data	
BUS_I	Bus number
BUS_TYPE	Bus typology (PQ,PV,Slack)
PD	Real power consumption (MW)
QD	Reactive power consumption (MVAr)
GS	Shunt conductance (MW)
BS	Shunt susceptance (MVAr)
BUS_AREA	Area number
VM	Voltage magnitude (p.u.)
VA	Voltage angle (degrees)
BASE_KV	Base voltage (kV)
ZONE	Loss zone
VMAX	Maximum voltage (p.u.)
VMIN	Minimum voltage (p.u.)

Table E.2: Matpower bus input data

- **Generators**

Generators are represented as buses where energy is injected into the grid, in form of complex power:

$$S_g = P_g + jQ_g \tag{E.2}$$

Elements that are required to define generators include generated power, power features, voltage magnitude and machine status.

Generator input data	
GEN_BUS	Bus number
PG	Generated real power (MW)
QG	Generated reactive power (MVAr)
QMAX	Maximum generated reactive power (MVAr)
QMIN	Minimum generated reactive power (MVAr)
VG	Voltage magnitude (p.u.)
GEN_STATUS	Working status of the generator (on/off)
PMAX	Maximum generated real power (MW)
PMIN	Minimum generated real power (MW)
PC1	Lower power capacity curve (MW)
PC2	Upper power capacity curve (MW)
QC1MIN	Minimum generated reactive power at PC1 (MVAr)
QC1MAX	Maximum generated reactive power at PC1 (MVAr)
QC2MIN	Minimum generated reactive power at PC2 (MVAr)
QC2MAX	Maximum generated reactive power at PC2 (MVAr)
RAMP_AGC	Load following ramp rate (MW/min)

Table E.3: Matpower generator input data

Appendix F

Algorithm user interface (Matlab code)

```
function [Conf,Phasedistribution,Penetration,Sun,Wind,Energylosses,Bat,
BatType,BatPower,BatEff] = UserInterface

%%%% In this section please determine the desired
 configuration of the problem

%% ----------------------------POWER FLOW ANALYSIS----------------------------

%%% Daily analysis: 1 / Weekly analysis: 2

Conf = 1;

%% Phase distribution

% Balanced: 1 / Unbalanced: 2 / Very unbalanced: 3
Phasedistribution = 1;

%% Renewable penetration

% 0%: 0 / 10%: 1 / 20%: 2 / 30%: 3 / 40%: 4 / 50%: 5 / 60%: 6 / 70%: 7 /
  80%: 8 / 90%: 9 / 100%: 10
Penetration = 0;

%% Weather conditions daily analysis

% Sunny: 1 / Average: 2 / Cloudy: 3
Sun = 1;

% Average: 1 / Windy: 2 / Quiet : 3
```

```
Wind = 1;

%% Weather conditions weekly analysis

% Day 1: Average sun / Average wind
% Day 2: Average sun/ Quiet
% Day 3: Cloudy / Average wind
% Day 4: Average sun / Windy
% Day 5: Average sun / Windy
% Day 6: Sunny / Average wind
% Day 7: Cloudy / Quiet

%% Battery configuration

% Are there batteries in the system ... No: 0 // Centralized battery at
 node 64: 1

Bat = 0;

% Type of Battery ... 1: Chemical Battery (80 % Discharge) //
 2: Fuel Cells/Flow battery (100 % Discharge)

BatType = 1;

% Battery power in Ah: Please enter a value between 0 and 8000 Ah

BatPower = 0;

% Battery efficiency: Please enter a value between 0 and 1
% ** All other system efficincies are already included (Bidirectional
 inverter: as converter 98%, as inverter 98% / Cable losses: 5%)

BatEff = 0;

%% ----------------------RENEWABLE PENETRATION ANALYSIS--------------------------

% It is possible to analyze the evolution of energy losses and Voltage
% limits within all renewable penetration ranges. Please note that you
% still have to select a configuration for the system
% (dayly/weekly,phasedistribution,sun,wind,batteries)

% Yes: 1 / No: 0
Energylosses = 0;
```

Appendix G

Electric parameter computations in p.u.

Within the analysis of electric power systems, p.u. notation is frequently used in order to simplify computations. This method consists in determining values fractioned by base parameters, that are consistent for sections of the grid with the same characteristics. Hence, when evaluating grids that include transformers, calculations ease as the p.u. units do not change on either side of the converter, although real parameters are different (base values of the two divisions differ).

So, p.u. systems aim to narrow parameter variances converting actual values into a new reference scheme. Data that can be expressed in p.u. include power, voltage, current, impedance and admittance. After solving treated analysis, parameters can be transformed back to standard units using the base values.

The computation of base parameters for simple lines (single phase) is performed according to the following equations:

$$I_{base} = \frac{S_{base}}{V_{base}} \tag{G.1}$$

$$Z_{base} = \frac{V_{base}^2}{S_{base}} \tag{G.2}$$

$$y_{base} = \frac{1}{Z_{base}} \tag{G.3}$$

Note that power and voltage need to be defined forehand according to proper criteria of the analyzed problem (e.g. assigning parameters to rated values of the system or deciding arbitrarily upon convenience of the computations).

Appendix H

Electric line data of the proposed LV grid model

Element	From	To	Z (Ω/km)	Distance (m)
Transformer	63	1	0,004+0,020i	1000,00
Node	1	65	0,206+0,078i	40,00
Branch	65	2	0,206+0,078i	50,00
Branch	2	3	0,206+0,078i	25,00
Branch	3	4	0,206+0,078i	25,00
Branch	4	5	0,206+0,078i	25,00
Branch	5	6	0,206+0,078i	25,00
Branch	6	7	0,206+0,078i	25,00
Branch	7	8	0,206+0,078i	25,00
Branch	8	9	0,206+0,078i	25,00
Branch	9	10	0,206+0,078i	25,00
Branch	10	11	0,206+0,078i	25,00
Branch	11	12	0,206+0,078i	25,00
Branch	12	13	0,206+0,078i	25,00
Branch	65	14	0,206+0,078i	50,00
Branch	14	15	0,206+0,078i	25,00
Branch	15	16	0,206+0,078i	25,00
Branch	16	17	0,206+0,078i	25,00
Branch	17	18	0,206+0,078i	25,00
Branch	18	19	0,206+0,078i	25,00

Element	From	To	Z (Ω/km)	Distance (m)
Branch	19	20	0,206+0,078i	25,00
Branch	20	21	0,206+0,078i	25,00
Branch	21	22	0,206+0,078i	25,00
Branch	22	23	0,206+0,078i	25,00
Branch	23	24	0,206+0,078i	25,00
Node	24	64	0,206+0,078i	40,00
Branch	64	25	0,206+0,078i	50,00
Branch	25	26	0,206+0,078i	25,00
Branch	26	27	0,206+0,078i	25,00
Branch	27	28	0,206+0,078i	25,00
Branch	28	29	0,206+0,078i	50,00
Branch	64	45	0,206+0,078i	50,00
Branch	45	46	0,206+0,078i	25,00
Branch	46	47	0,206+0,078i	10,00
Branch	47	48	0,206+0,078i	25,00
Branch	48	49	0,206+0,078i	10,00
Branch	49	50	0,206+0,078i	25,00
Branch	50	51	0,206+0,078i	10,00
Branch	51	52	0,206+0,078i	10,00
Branch	52	53	0,206+0,078i	25,00
Branch	53	54	0,206+0,078i	25,00
Branch	54	55	0,206+0,078i	25,00
Branch	55	56	0,206+0,078i	25,00
Branch	56	57	0,206+0,078i	25,00
Branch	57	58	0,206+0,078i	25,00
Branch	58	59	0,206+0,078i	25,00
Branch	59	60	0,206+0,078i	25,00
Branch	60	61	0,206+0,078i	25,00
Branch	61	62	0,206+0,078i	5,00
Branch	64	30	0,206+0,078i	125,00
Branch	30	31	0,206+0,078i	50,00
Branch	31	32	0,206+0,078i	25,00

Element	From	To	Z (Ω/km)	Distance (m)
Branch	64	33	0,206+0,078i	25,00
Branch	33	34	0,206+0,078i	75,00
Branch	34	35	0,206+0,078i	10,00
Branch	35	36	0,206+0,078i	25,00
Branch	36	37	0,206+0,078i	10,00
Branch	37	38	0,206+0,078i	50,00
Branch	38	39	0,206+0,078i	25,00
Branch	39	40	0,206+0,078i	25,00
Branch	40	41	0,206+0,078i	25,00
Branch	41	42	0,206+0,078i	50,00
Branch	42	43	0,206+0,078i	10,00
Branch	43	44	0,206+0,078i	10,00

Table H.1: Branch data

Appendix I

Branch input data for the MATPOWER load-flow simulation

From	To	r	x	b	rate A	rate B	rate C	ratio	angle	status	angmin	angmax
63	1	7,5614E-05	0,00037807	0	0	0	0	0	0	1	-360	360
1	65	0,00015577	5,8979E-05	0	0	0	0	0	0	1	-360	360
65	2	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
2	3	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
3	4	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
4	5	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
5	6	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
6	7	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
7	8	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
8	9	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
9	10	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
10	11	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
11	12	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
12	13	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
65	14	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
14	15	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
15	16	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
16	17	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
17	18	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
18	19	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
19	20	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
20	21	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
21	22	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
22	23	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
23	24	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
24	64	0,00015577	5,8979E-05	0	0	0	0	0	0	1	-360	360
64	25	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
25	26	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
26	27	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
27	28	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
28	29	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
64	45	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
45	46	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
46	47	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
47	48	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
48	49	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
49	50	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
50	51	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
51	52	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
52	53	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360

From	To	r	x	b	rate A	rate B	rate C	ratio	angle	status	angmin	angmax
53	54	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
54	55	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
55	56	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
56	57	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
57	58	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
58	59	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
59	60	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
60	61	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
61	62	1,9471E-05	7,3724E-06	0	0	0	0	0	0	1	-360	360
64	30	0,00048677	0,00018431	0	0	0	0	0	0	1	-360	360
30	31	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
31	32	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
64	33	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
33	34	0,00029206	0,00011059	0	0	0	0	0	0	1	-360	360
34	35	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
35	36	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
36	37	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
37	38	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
38	39	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
39	40	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
40	41	9,7353E-05	3,6862E-05	0	0	0	0	0	0	1	-360	360
41	42	0,00019471	7,3724E-05	0	0	0	0	0	0	1	-360	360
42	43	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360
43	44	3,8941E-05	1,4745E-05	0	0	0	0	0	0	1	-360	360

Table I.1: Branch input data for the MATPOWER simulation procedure

Appendix J

Load Profile Generator (LPG)

The Load Profile Generator (LPG) is a software that recreates demand profiles for electricity, gas, hot water and cold water based on data from real behavior of consumers. The tool is able to simulate the load curve within a determined time range using any sampling time between one minute and one hour.

Regarding functionalities and options that are available in the appliance, households can either be chosen from a numerous list of different predefined models or determined from scratch according to personal preferences. Therefore, location, energy saving policies, connected charges, consumer behavior and external agents such as temperature can be elected.

Once a model is defined, the simulation of the load is realized according to the LPG decision model, where load consumption is bound to the behavior of the consumer, who will perform certain activities that require energy in agreement with is/her needs and desires. Hence, the realized tasks of the subject follow the weight of the possible options, deciding upon the hierarchy of essential needs (such as work and sleep above all) and the previous accumulated activities (e.g. desire to eat, necessity to perform household labors and satisfaction regarding free time activities).

The decision model algorithm of the LPG tool has the following structure:

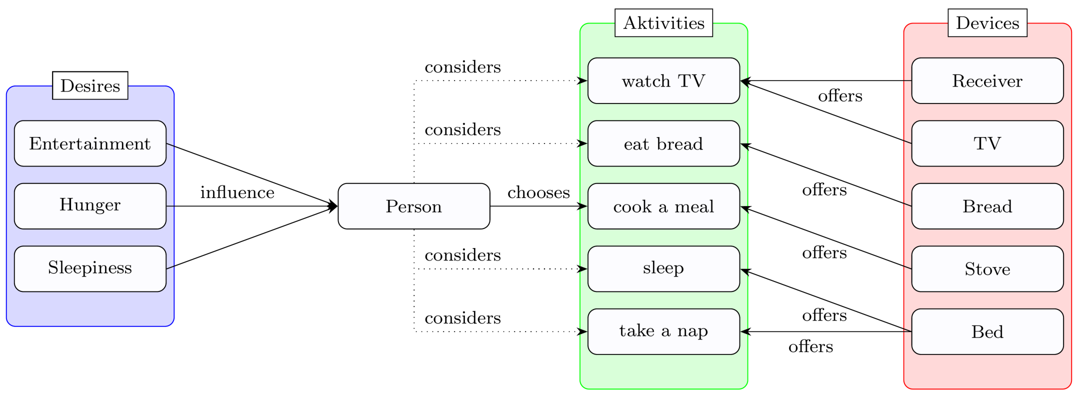
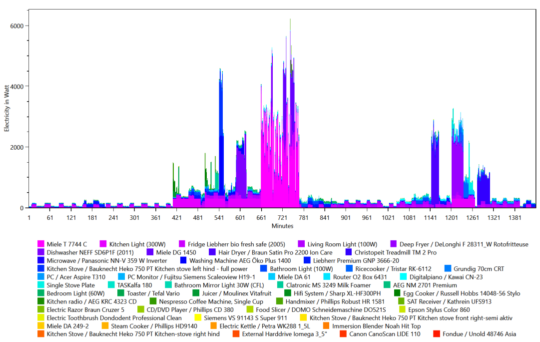


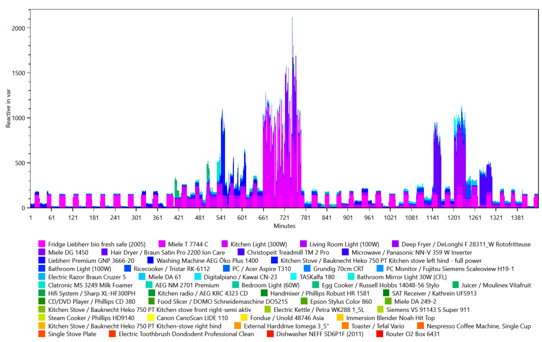
Figure J.1: Load profile generator decision model structure. Extracted from [19]

Appendix K

Load profiles of the consumers of the LV grid model

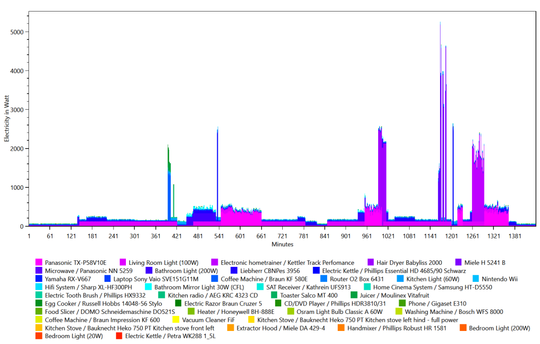


(a) Active power load

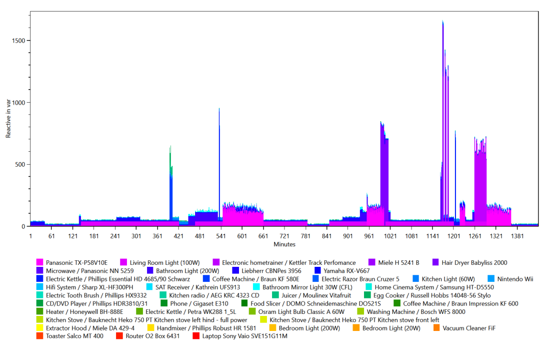


(b) Reactive power load

Figure K.1: Consumer load profile: Couple 30-64, both at work, with home-help

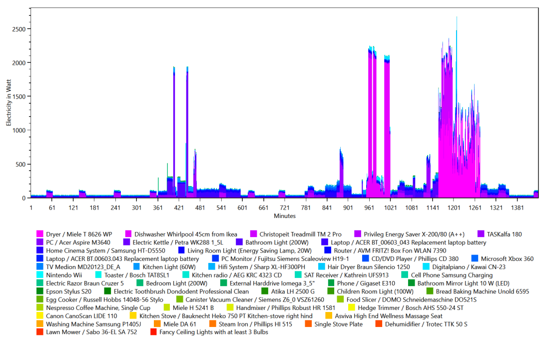


(a) Active power load

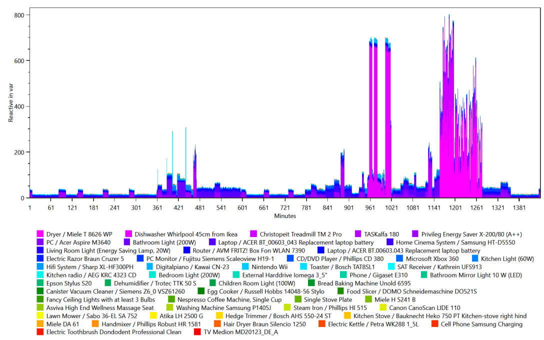


(b) Reactive power load

Figure K.2: Consumer load profile: Student flatsharing

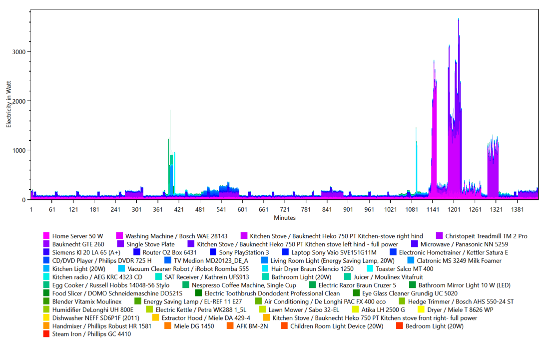


(a) Active power load

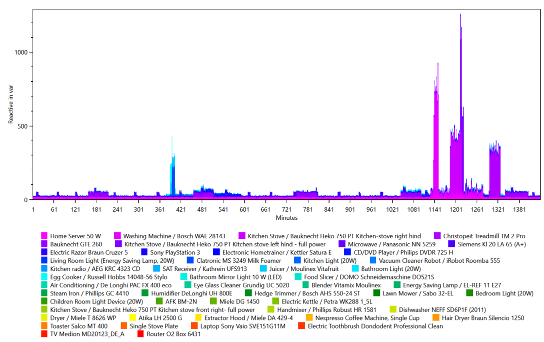


(b) Reactive power load

Figure K.3: Consumer load profile: Family, 1 child, both at work

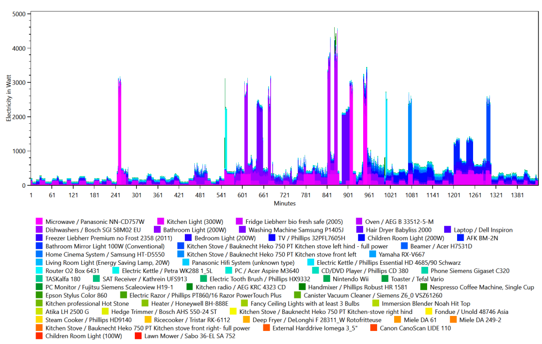


(a) Active power load

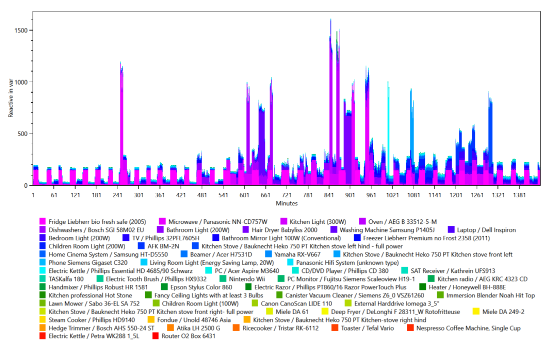


(b) Reactive power load

Figure K.4: Consumer load profile: Couple both at work

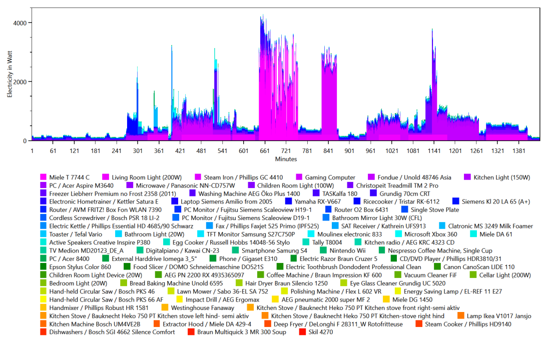


(a) Active power load

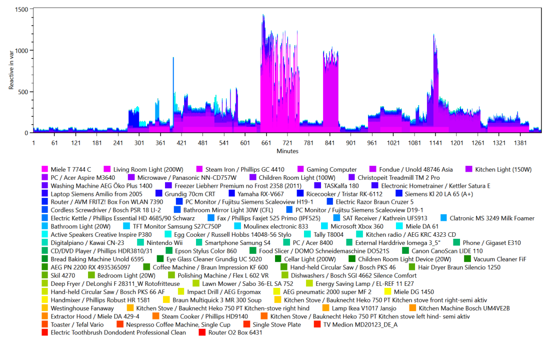


(b) Reactive power load

Figure K.5: Consumer load profile: Family with 2 children, one at work, one at home

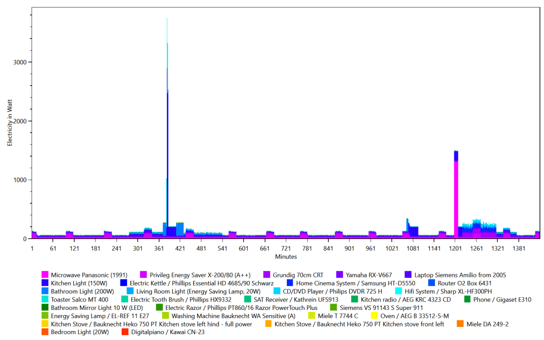


(a) Active power load

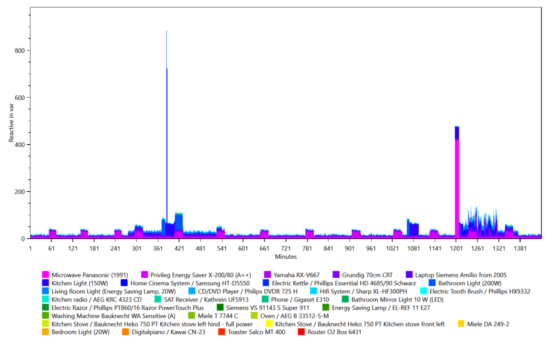


(b) Reactive power load

Figure K.6: Consumer load profile: Couple with 2 children, husband at work

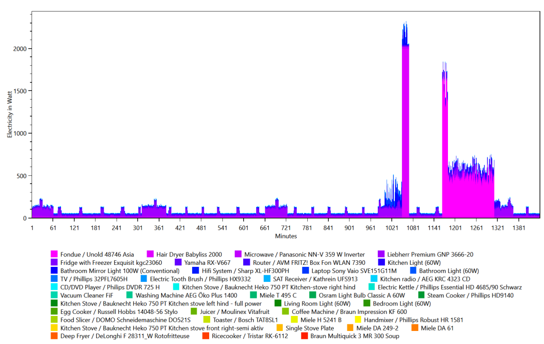


(a) Active power load

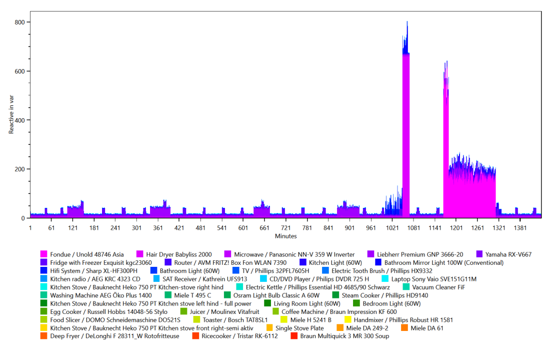


(b) Reactive power load

Figure K.7: Consumer load profile: Single man under 30 years with work

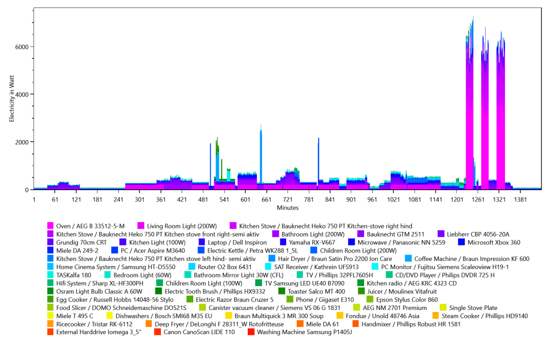


(a) Active power load

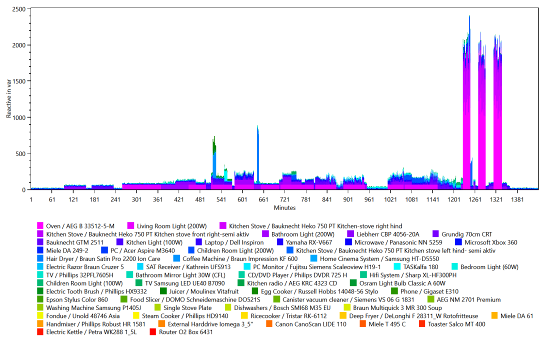


(b) Reactive power load

Figure K.8: Consumer load profile: Single woman under 30 years with work

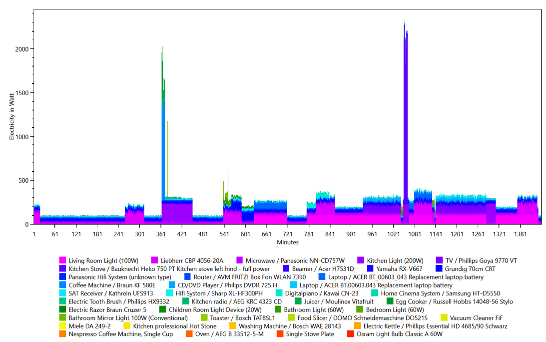


(a) Active power load

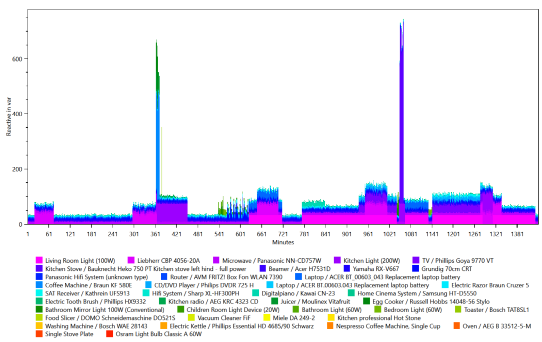


(b) Reactive power load

Figure K.9: Consumer load profile: Family with 2 children, parents without work

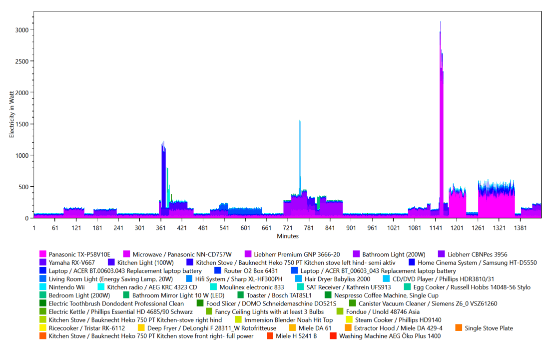


(a) Active power load

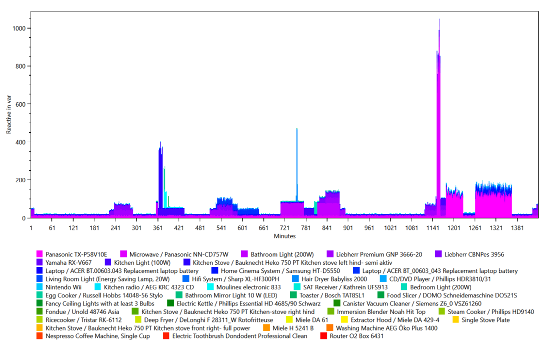


(b) Reactive power load

Figure K.10: Consumer load profile: Single man under 30 without work

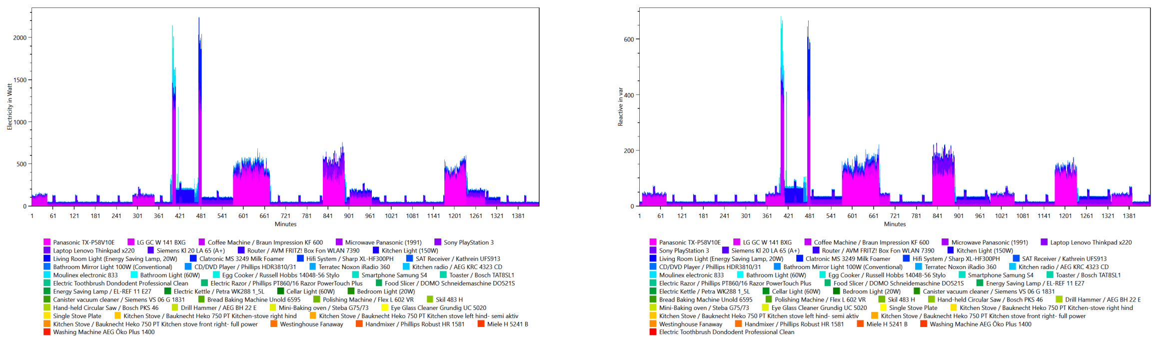


(a) Active power load



(b) Reactive power load

Figure K.11: Consumer load profile: Single woman under 30 without work



(a) Active power load **(b)** Reactive power load

Figure K.12: Consumer load profile: Jack jobless

Appendix L

Specifications of the wind turbine model

The specifications of the selected 2 kW wind turbine modules for the proposed LV grid model are determined it the following figures that are extracted from the manufacturer catalog, Nohana 3000.

Parámetros del Aerogenerador

	500 W	1 Kw	2 Kw
Potencia Nominal	500 W	1 Kw	2 Kw
Voltaje Nominal	24 V	48 V	120 V
Diametro del Aspa	2.5 m	2.7 m	3.2 m
Velocidad del viento Inicial	2 m/s	2 m/s	2 m/s
Velocidad del Viento Nominal	8 m/s	9 m/s	9 m/s
Velocidad del Viento Máxima	35 m/s	35 m/s	35 m/s
Orientación	Mecánica	Mecánica	Mecánica
Velocidad de Rotación	400 r/m	400 r/m	400 r/m
Cantidad de Aspas	3	3	3
Altura Total	8	8	8
Batería recomendada	2 uds de 12V a 200Ah	4 uds de 12V a 200Ah	10 uds de 12V a 200Ah
Inversor Senoidal y Controlador	Controlador e Inversor híbrido	Controlador e Inversor híbrido	Controlador e Inversor híbrido

Figure L.1: Technical specifications of the wind turbine model. Extracted from [20]

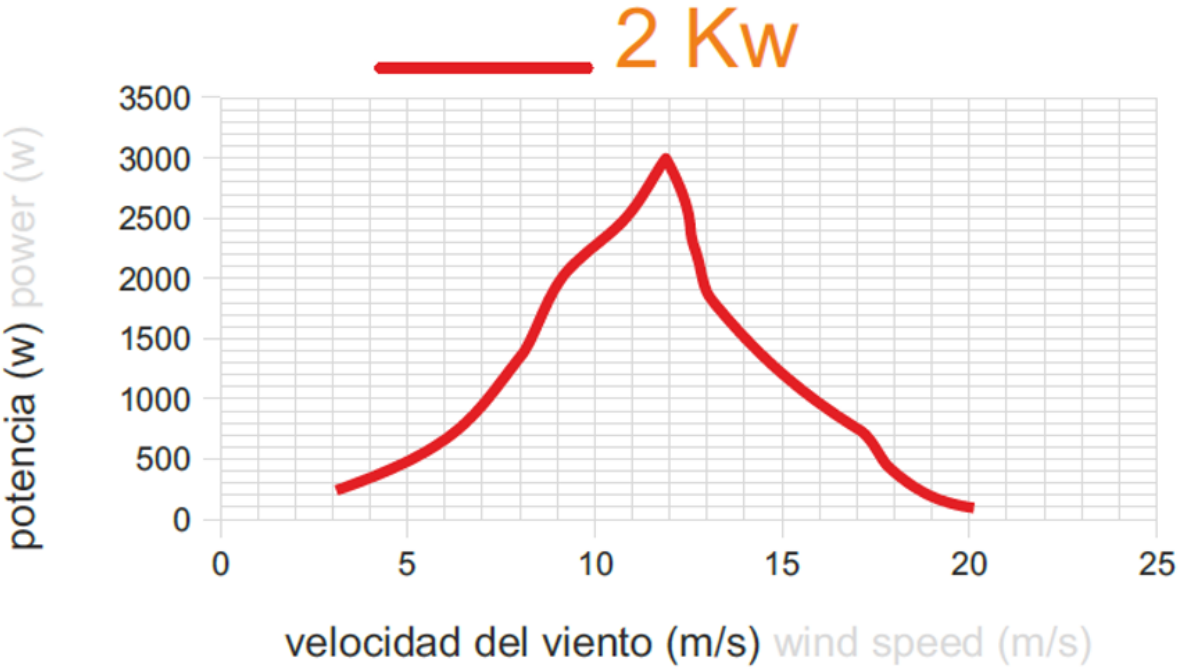


Figure L.2: Power/Wind velocity curve of the wind turbine model. Extracted from [20]

Appendix M

Bus input data for the MATPOWER load-flow simulation

type	Pd	Qd	Gs	Bs	area	Vm	Va	baseKV	zone	Vmax	Vmin
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9

type	Pd	Qd	Gs	Bs	area	Vm	Va	baseKV	zone	Vmax	Vmin
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9

type	Pd	Qd	Gs	Bs	area	Vm	Va	baseKV	zone	Vmax	Vmin
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
3			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9
1			0	0	1	1	0	0,23	1	1,1	0,9

Table M.1: Bus input data for the MATPOWER simulation procedure

Appendix N

Generator input data for the MATPOWER load-flow simulation

Bus	PG	QG	Qmax	Qmin	Vg	mBase	Status	Pmax	Pmin	Pc1	Pc2	Qc1min	Qc1max	Qc2min	Qc2max	ramp_agc
1			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
2			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
3			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
4			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
5			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
6			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
7			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
8			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
9			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
10			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
11			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
12			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
13			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
14			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
15			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
16			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
17			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
18			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
19			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
20			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
21			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
22			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
23			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
24			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
25			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
26			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
27			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
28			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
29			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
30			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
31			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
32			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
33			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
34			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
35			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
36			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
37			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
38			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
39			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
40			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
41			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
42			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
43			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
44			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
45			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0

Bus	PG	QG	Qmax	Qmin	Vg	mBase	Status	Pmax	Pmin	Pc1	Pc2	Qc1min	Qc1max	Qc2min	Qc2max	ramp_agc
46			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
47			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
48			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
49			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
50			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
51			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
52			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
53			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
54			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
55			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
56			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
57			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
58			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
59			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
60			300	-300	1	0,001	1	0,002	0	0	0	0	0	0	0	0
61			300	-300	1	0,001	1	0,003	0	0	0	0	0	0	0	0
62			300	-300	1	0,001	1	0,001	0	0	0	0	0	0	0	0
63			300	-300	1	0,001	1	100	0	0	0	0	0	0	0	0
64			300	-300	1	0,001	1	100	0	0	0	0	0	0	0	0
65			300	-300	1	0,001	1	100	0	0	0	0	0	0	0	0

Table N.1: Generator input data for the MATPOWER simulation procedure

Appendix O

Sun irradiation data

APRIL SUNNY

	HH	MM	W/m2
1	0	0	0
2	0	15	0
3	0	30	0
4	0	45	0
5	1	0	0
6	1	15	0
7	1	30	0
8	1	45	0
9	2	0	0
10	2	15	0
11	2	30	0
12	2	45	0
13	3	0	0
14	3	15	0
15	3	30	0
16	3	45	0
17	4	0	0
18	4	15	0
19	4	30	0
20	4	45	0
21	5	0	0
22	5	15	0
23	5	30	0
24	5	45	0
25	6	0	0
26	6	15	302
27	6	30	382
28	6	45	450
29	7	0	508
30	7	15	558

APRIL LITTLE CLOUDY

	HH	MM	W/m2
1	0	0	0
2	0	15	0
3	0	30	0
4	0	45	0
5	1	0	0
6	1	15	0
7	1	30	0
8	1	45	0
9	2	0	0
10	2	15	0
11	2	30	0
12	2	45	0
13	3	0	0
14	3	15	0
15	3	30	0
16	3	45	0
17	4	0	0
18	4	15	0
19	4	30	0
20	4	45	0
21	5	0	0
22	5	15	0
23	5	30	0
24	5	45	0
25	6	0	0
26	6	15	202
27	6	30	255
28	6	45	300
29	7	0	339
30	7	15	372

APRIL VERY CLOUDY

	HH	MM	W/m2
1	0	0	0
2	0	15	0
3	0	30	0
4	0	45	0
5	1	0	0
6	1	15	0
7	1	30	0
8	1	45	0
9	2	0	0
10	2	15	0
11	2	30	0
12	2	45	0
13	3	0	0
14	3	15	0
15	3	30	0
16	3	45	0
17	4	0	0
18	4	15	0
19	4	30	0
20	4	45	0
21	5	0	0
22	5	15	0
23	5	30	0
24	5	45	0
25	6	0	0
26	6	15	0
27	6	30	0
28	6	45	27,65
29	7	0	104,3
30	7	15	120,4

	HH	MM	W/m2
31	7	30	601
32	7	45	639
33	8	0	672
34	8	15	701
35	8	30	727
36	8	45	749
37	9	0	769
38	9	15	787
39	9	30	802
40	9	45	816
41	10	0	827
42	10	15	838
43	10	30	846
44	10	45	854
45	11	0	860
46	11	15	864
47	11	30	868
48	11	45	870
49	12	0	871
50	12	15	871
51	12	30	870
52	12	45	868
53	13	0	864
54	13	15	860
55	13	30	854
56	13	45	846
57	14	0	838
58	14	15	827
59	14	30	816
60	14	45	802
61	15	0	787
62	15	15	769

	HH	MM	W/m2
31	7	30	401
32	7	45	426
33	8	0	448
34	8	15	467
35	8	30	485
36	8	45	500
37	9	0	513
38	9	15	525
39	9	30	535
40	9	45	544
41	10	0	552
42	10	15	559
43	10	30	564
44	10	45	569
45	11	0	573
46	11	15	576
47	11	30	579
48	11	45	580
49	12	0	581
50	12	15	581
51	12	30	580
52	12	45	579
53	13	0	576
54	13	15	573
55	13	30	569
56	13	45	564
57	14	0	559
58	14	15	552
59	14	30	544
60	14	45	535
61	15	0	525
62	15	15	513

	HH	MM	W/m2
31	7	30	133,7
32	7	45	70
33	8	0	0
34	8	15	0
35	8	30	0
36	8	45	112,35
37	9	0	182,7
38	9	15	187,6
39	9	30	191,8
40	9	45	195,65
41	10	0	140
42	10	15	135,45
43	10	30	122,5
44	10	45	168
45	11	0	206,85
46	11	15	89,25
47	11	30	76,65
48	11	45	208,95
49	12	0	208,95
50	12	15	208,6
51	12	30	207,9
52	12	45	112,35
53	13	0	149,8
54	13	15	203,35
55	13	30	201,25
56	13	45	43,4
57	14	0	0
58	14	15	0
59	14	30	0
60	14	45	71,75
61	15	0	131,25
62	15	15	170,8

	HH	MM	W/m2
63	15	30	749
64	15	45	727
65	16	0	701
66	16	15	672
67	16	30	639
68	16	45	601
69	17	0	558
70	17	15	508
71	17	30	450
72	17	45	382
73	18	0	302
74	18	15	0
75	18	30	0
76	18	45	0
77	19	0	0
78	19	15	0
79	19	30	0
80	19	45	0
81	20	0	0
82	20	15	0
83	20	30	0
84	20	45	0
85	21	0	0
86	21	15	0
87	21	30	0
88	21	45	0
89	22	0	0
90	22	15	0
91	22	30	0
92	22	45	0

	HH	MM	W/m2
63	15	30	500
64	15	45	485
65	16	0	467
66	16	15	448
67	16	30	426
68	16	45	401
69	17	0	372
70	17	15	339
71	17	30	300
72	17	45	255
73	18	0	202
74	18	15	0
75	18	30	0
76	18	45	0
77	19	0	0
78	19	15	0
79	19	30	0
80	19	45	0
81	20	0	0
82	20	15	0
83	20	30	0
84	20	45	0
85	21	0	0
86	21	15	0
87	21	30	0
88	21	45	0
89	22	0	0
90	22	15	0
91	22	30	0
92	22	45	0

	HH	MM	W/m2
63	15	30	163,45
64	15	45	155,05
65	16	0	145,25
66	16	15	133,7
67	16	30	0
68	16	45	0
69	17	0	85,4
70	17	15	63
71	17	30	39,2
72	17	45	0
73	18	0	0
74	18	15	0
75	18	30	0
76	18	45	0
77	19	0	0
78	19	15	0
79	19	30	0
80	19	45	0
81	20	0	0
82	20	15	0
83	20	30	0
84	20	45	0
85	21	0	0
86	21	15	0
87	21	30	0
88	21	45	0
89	22	0	0
90	22	15	0
91	22	30	0
92	22	45	0

	HH	MM	W/m2
93	23	0	0
94	23	15	0
95	23	30	0
96	23	45	0

	HH	MM	W/m2
93	23	0	0
94	23	15	0
95	23	30	0
96	23	45	0

	HH	MM	W/m2
93	23	0	0
94	23	15	0
95	23	30	0
96	23	45	0

Table O.1: Sun irradiation data for April (average) in Barcelona

Appendix P

Wind speed data

Average day Barcelona

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
1	0	0	3,75	381,053	0,3811	0,0381
2	0	15	3,75	381,053	0,3811	0,0381
3	0	30	3,8	383,568	0,3836	0,0384
4	0	45	3,8	383,568	0,3836	0,0384
5	1	0	3,8	383,568	0,3836	0,0384
6	1	15	3,8	383,568	0,3836	0,0384
7	1	30	3,85	386,122	0,3861	0,0386
8	1	45	3,85	386,122	0,3861	0,0386
9	2	0	3,85	386,122	0,3861	0,0386
10	2	15	3,85	386,122	0,3861	0,0386
11	2	30	3,9	388,718	0,3887	0,0389
12	2	45	3,9	388,718	0,3887	0,0389
13	3	0	3,9	388,718	0,3887	0,0389
14	3	15	3,9	388,718	0,3887	0,0389
15	3	30	3,95	391,355	0,3914	0,0391
16	3	45	3,95	391,355	0,3914	0,0391
17	4	0	3,95	391,355	0,3914	0,0391
18	4	15	3,95	391,355	0,3914	0,0391
19	4	30	3,95	391,355	0,3914	0,0391
20	4	45	3,9	388,718	0,3887	0,0389
21	5	0	3,9	388,718	0,3887	0,0389
22	5	15	3,85	386,122	0,3861	0,0386
23	5	30	3,85	386,122	0,3861	0,0386
24	5	45	3,8	383,568	0,3836	0,0384
25	6	0	3,8	383,568	0,3836	0,0384
26	6	15	3,8	383,568	0,3836	0,0384
27	6	30	3,75	381,053	0,3811	0,0381
28	6	45	3,75	381,053	0,3811	0,0381
29	7	0	3,75	381,053	0,3811	0,0381
30	7	15	3,75	381,053	0,3811	0,0381

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
31	7	30	3,8	383,568	0,3836	0,0384
32	7	45	3,8	383,568	0,3836	0,0384
33	8	0	3,85	386,122	0,3861	0,0386
34	8	15	3,9	388,718	0,3887	0,0389
35	8	30	3,95	391,355	0,3914	0,0391
36	8	45	4	394,036	0,3940	0,0394
37	9	0	4,05	396,761	0,3968	0,0397
38	9	15	4,1	399,533	0,3995	0,0400
39	9	30	4,15	402,353	0,4024	0,0402
40	9	45	4,2	405,221	0,4052	0,0405
41	10	0	4,25	408,140	0,4081	0,0408
42	10	15	4,3	411,110	0,4111	0,0411
43	10	30	4,4	417,209	0,4172	0,0417
44	10	45	4,45	420,340	0,4203	0,0420
45	11	0	4,5	423,528	0,4235	0,0424
46	11	15	4,6	430,075	0,4301	0,0430
47	11	30	4,675	435,141	0,4351	0,0435
48	11	45	4,75	440,344	0,4403	0,0440
49	12	0	4,8	443,891	0,4439	0,0444
50	12	15	4,875	449,329	0,4493	0,0449
51	12	30	4,925	453,035	0,4530	0,0453
52	12	45	5	458,718	0,4587	0,0459
53	13	0	5,15	470,536	0,4705	0,0471
54	13	15	5,2	474,612	0,4746	0,0475
55	13	30	5,225	476,676	0,4767	0,0477
56	13	45	5,25	478,758	0,4788	0,0479
57	14	0	5,275	480,858	0,4809	0,0481
58	14	15	5,3	482,975	0,4830	0,0483
59	14	30	5,325	485,110	0,4851	0,0485
60	14	45	5,35	487,263	0,4873	0,0487
61	15	0	5,375	489,434	0,4894	0,0489
62	15	15	5,4	491,623	0,4916	0,0492

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
63	15	30	5,425	493,830	0,4938	0,0494
64	15	45	5,45	496,056	0,4961	0,0496
65	16	0	5,475	498,299	0,4983	0,0498
66	16	15	5,475	498,299	0,4983	0,0498
67	16	30	5,5	500,561	0,5006	0,0501
68	16	45	5,5	500,561	0,5006	0,0501
69	17	0	5,5	500,561	0,5006	0,0501
70	17	15	5,5	500,561	0,5006	0,0501
71	17	30	5,475	498,299	0,4983	0,0498
72	17	45	5,45	496,056	0,4961	0,0496
73	18	0	5,4	491,623	0,4916	0,0492
74	18	15	5,35	487,263	0,4873	0,0487
75	18	30	5,3	482,975	0,4830	0,0483
76	18	45	5,225	476,676	0,4767	0,0477
77	19	0	5,2	474,612	0,4746	0,0475
78	19	15	5,1	466,528	0,4665	0,0467
79	19	30	5	458,718	0,4587	0,0459
80	19	45	4,8	443,891	0,4439	0,0444
81	20	0	4,7	436,860	0,4369	0,0437
82	20	15	4,6	430,075	0,4301	0,0430
83	20	30	4,5	423,528	0,4235	0,0424
84	20	45	4,4	417,209	0,4172	0,0417
85	21	0	4,3	411,110	0,4111	0,0411
86	21	15	4,2	405,221	0,4052	0,0405
87	21	30	4,15	402,353	0,4024	0,0402
88	21	45	4,1	399,533	0,3995	0,0400
89	22	0	4	394,036	0,3940	0,0394
90	22	15	3,9	388,718	0,3887	0,0389
91	22	30	3,8	383,568	0,3836	0,0384
92	22	45	3,75	381,053	0,3811	0,0381

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
93	23	0	3,75	381,053	0,3811	0,0381
94	23	15	3,725	379,809	0,3798	0,0380
95	23	30	3,725	379,809	0,3798	0,0380
96	23	45	3,7	378,575	0,3786	0,0379

Table P.1: Average wind speed in April in Barcelona

Windy day Barcelona

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
1	0	0	8,1	840,734	0,8407	0,0841
2	0	15	8,15	849,234	0,8492	0,0849
3	0	30	8,175	853,508	0,8535	0,0854
4	0	45	8,2	857,799	0,8578	0,0858
5	1	0	8,225	862,104	0,8621	0,0862
6	1	15	8,25	866,426	0,8664	0,0866
7	1	30	8,3	875,116	0,8751	0,0875
8	1	45	8,4	892,679	0,8927	0,0893
9	2	0	8,55	919,466	0,9195	0,0919
10	2	15	8,65	937,606	0,9376	0,0938
11	2	30	8,75	955,961	0,9560	0,0956
12	2	45	9	1002,727	1,0027	0,1003
13	3	0	9,2	1040,956	1,0410	0,1041
14	3	15	9,35	1070,044	1,0700	0,1070
15	3	30	9,6	1119,197	1,1192	0,1119
16	3	45	9,7	1139,056	1,1391	0,1139
17	4	0	9,85	1169,013	1,1690	0,1169
18	4	15	10	1199,130	1,1991	0,1199
19	4	30	10,1	1219,272	1,2193	0,1219
20	4	45	10,1	1219,272	1,2193	0,1219
21	5	0	10,1	1219,272	1,2193	0,1219
22	5	15	10,1	1219,272	1,2193	0,1219
23	5	30	10,1	1219,272	1,2193	0,1219
24	5	45	10,1	1219,272	1,2193	0,1219
25	6	0	10,1	1219,272	1,2193	0,1219
26	6	15	10,15	1229,356	1,2294	0,1229
27	6	30	10,2	1239,447	1,2394	0,1239
28	6	45	10,25	1249,541	1,2495	0,1250
29	7	0	10,3	1259,638	1,2596	0,1260
30	7	15	10,325	1264,687	1,2647	0,1265

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
31	7	30	10,35	1269,736	1,2697	0,1270
32	7	45	10,6	1320,151	1,3202	0,1320
33	8	0	10,75	1350,264	1,3503	0,1350
34	8	15	10,95	1390,129	1,3901	0,1390
35	8	30	11,15	1429,528	1,4295	0,1430
36	8	45	11,05	1409,897	1,4099	0,1410
37	9	0	11	1400,029	1,4000	0,1400
38	9	15	10,95	1390,129	1,3901	0,1390
39	9	30	10,85	1370,245	1,3702	0,1370
40	9	45	10,75	1350,264	1,3503	0,1350
41	10	0	10,7	1340,243	1,3402	0,1340
42	10	15	10,6	1320,151	1,3202	0,1320
43	10	30	10,55	1310,084	1,3101	0,1310
44	10	45	10,65	1330,204	1,3302	0,1330
45	11	0	10,7	1340,243	1,3402	0,1340
46	11	15	10,75	1350,264	1,3503	0,1350
47	11	30	10,85	1370,245	1,3702	0,1370
48	11	45	10,95	1390,129	1,3901	0,1390
49	12	0	11	1400,029	1,4000	0,1400
50	12	15	11,25	1449,003	1,4490	0,1449
51	12	30	11,4	1477,878	1,4779	0,1478
52	12	45	11,5	1496,872	1,4969	0,1497
53	13	0	11,6	1515,636	1,5156	0,1516
54	13	15	11,75	1543,302	1,5433	0,1543
55	13	30	11,85	1561,393	1,5614	0,1561
56	13	45	11,9	1570,324	1,5703	0,1570
57	14	0	11,95	1579,175	1,5792	0,1579
58	14	15	11,95	1579,175	1,5792	0,1579
59	14	30	12	1587,943	1,5879	0,1588
60	14	45	11,95	1579,175	1,5792	0,1579
61	15	0	11,9	1570,324	1,5703	0,1570
62	15	15	11,85	1561,393	1,5614	0,1561

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
63	15	30	11,8	1552,385	1,5524	0,1552
64	15	45	11,5	1496,872	1,4969	0,1497
65	16	0	11,3	1458,676	1,4587	0,1459
66	16	15	11,1	1419,731	1,4197	0,1420
67	16	30	10,8	1360,265	1,3603	0,1360
68	16	45	10,5	1300,007	1,3000	0,1300
69	17	0	10	1199,130	1,1991	0,1199
70	17	15	9,5	1099,445	1,0994	0,1099
71	17	30	9,2	1040,956	1,0410	0,1041
72	17	45	8,8	965,217	0,9652	0,0965
73	18	0	8,4	892,679	0,8927	0,0893
74	18	15	8,3	875,116	0,8751	0,0875
75	18	30	8,2	857,799	0,8578	0,0858
76	18	45	8,1	840,734	0,8407	0,0841
77	19	0	7,95	815,628	0,8156	0,0816
78	19	15	7,85	799,227	0,7992	0,0799
79	19	30	7,7	775,145	0,7751	0,0775
80	19	45	7,5	744,035	0,7440	0,0744
81	20	0	7,15	692,445	0,6924	0,0692
82	20	15	6,85	651,210	0,6512	0,0651
83	20	30	6,6	619,000	0,6190	0,0619
84	20	45	6,6	619,000	0,6190	0,0619
85	21	0	6,6	619,000	0,6190	0,0619
86	21	15	6,6	619,000	0,6190	0,0619
87	21	30	6,65	625,284	0,6253	0,0625
88	21	45	7	671,478	0,6715	0,0671
89	22	0	7,3	714,103	0,7141	0,0714
90	22	15	7,7	775,145	0,7751	0,0775
91	22	30	8	823,930	0,8239	0,0824
92	22	45	7,5	744,035	0,7440	0,0744

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
93	23	0	7	671,478	0,6715	0,0671
94	23	15	6,5	606,668	0,6067	0,0607
95	23	30	6	549,741	0,5497	0,0550
96	23	45	5,5	500,561	0,5006	0,0501

Table P.2: Fast wind speed in April in Barcelona

Quiet day Barcelona						
	HH	MM	m/s	P (W)	P (KW)	Q (KW)
1	0	0	5,2	474,612	0,4746	0,0475
2	0	15	5,1	466,528	0,4665	0,0467
3	0	30	5	458,718	0,4587	0,0459
4	0	45	4,95	454,913	0,4549	0,0455
5	1	0	4,875	449,329	0,4493	0,0449
6	1	15	4,8	443,891	0,4439	0,0444
7	1	30	4,7	436,860	0,4369	0,0437
8	1	45	4,6	430,075	0,4301	0,0430
9	2	0	4,5	423,528	0,4235	0,0424
10	2	15	4,4	417,209	0,4172	0,0417
11	2	30	4,275	409,618	0,4096	0,0410
12	2	45	4,15	402,353	0,4024	0,0402
13	3	0	4,1	399,533	0,3995	0,0400
14	3	15	4	394,036	0,3940	0,0394
15	3	30	3,9	388,718	0,3887	0,0389
16	3	45	3,85	386,122	0,3861	0,0386
17	4	0	3,8	383,568	0,3836	0,0384
18	4	15	3,8	383,568	0,3836	0,0384
19	4	30	3,75	381,053	0,3811	0,0381
20	4	45	3,725	379,809	0,3798	0,0380
21	5	0	3,7	378,575	0,3786	0,0379
22	5	15	3,7	378,575	0,3786	0,0379
23	5	30	3,675	377,350	0,3774	0,0377
24	5	45	3,65	376,134	0,3761	0,0376
25	6	0	3,6	373,727	0,3737	0,0374
26	6	15	3,4	364,416	0,3644	0,0364
27	6	30	3,1	351,209	0,3512	0,0351
28	6	45	2,85	0,000	0,0000	0,0000
29	7	0	2,65	0,000	0,0000	0,0000
30	7	15	2,4	0,000	0,0000	0,0000

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
31	7	30	2,2	0,000	0,0000	0,0000
32	7	45	2	0,000	0,0000	0,0000
33	8	0	1,85	0,000	0,0000	0,0000
34	8	15	1,65	0,000	0,0000	0,0000
35	8	30	1,5	0,000	0,0000	0,0000
36	8	45	1,25	0,000	0,0000	0,0000
37	9	0	1,05	0,000	0,0000	0,0000
38	9	15	0,7	0,000	0,0000	0,0000
39	9	30	0,65	0,000	0,0000	0,0000
40	9	45	0,61	0,000	0,0000	0,0000
41	10	0	0,6	0,000	0,0000	0,0000
42	10	15	0,55	0,000	0,0000	0,0000
43	10	30	0,5	0,000	0,0000	0,0000
44	10	45	0,7	0,000	0,0000	0,0000
45	11	0	1,05	0,000	0,0000	0,0000
46	11	15	1,3	0,000	0,0000	0,0000
47	11	30	1,6	0,000	0,0000	0,0000
48	11	45	1,8	0,000	0,0000	0,0000
49	12	0	2	0,000	0,0000	0,0000
50	12	15	2,2	0,000	0,0000	0,0000
51	12	30	2,35	0,000	0,0000	0,0000
52	12	45	2,45	0,000	0,0000	0,0000
53	13	0	2,6	0,000	0,0000	0,0000
54	13	15	2,7	0,000	0,0000	0,0000
55	13	30	2,85	0,000	0,0000	0,0000
56	13	45	2,95	0,000	0,0000	0,0000
57	14	0	3,05	349,074	0,3491	0,0349
58	14	15	3,15	353,360	0,3534	0,0353
59	14	30	3,25	357,716	0,3577	0,0358
60	14	45	3,22	356,401	0,3564	0,0356
61	15	0	3,2	355,528	0,3555	0,0356
62	15	15	3,19	355,093	0,3551	0,0355

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
63	15	30	3,18	354,659	0,3547	0,0355
64	15	45	3,05	349,074	0,3491	0,0349
65	16	0	2,9	0,000	0,0000	0,0000
66	16	15	2,75	0,000	0,0000	0,0000
67	16	30	2,6	0,000	0,0000	0,0000
68	16	45	2,5	0,000	0,0000	0,0000
69	17	0	2,4	0,000	0,0000	0,0000
70	17	15	2,3	0,000	0,0000	0,0000
71	17	30	2,2	0,000	0,0000	0,0000
72	17	45	2,4	0,000	0,0000	0,0000
73	18	0	2,8	0,000	0,0000	0,0000
74	18	15	3	346,954	0,3470	0,0347
75	18	30	3,2	355,528	0,3555	0,0356
76	18	45	3,4	364,416	0,3644	0,0364
77	19	0	3,6	373,727	0,3737	0,0374
78	19	15	3,75	381,053	0,3811	0,0381
79	19	30	3,85	386,122	0,3861	0,0386
80	19	45	3,95	391,355	0,3914	0,0391
81	20	0	4,05	396,761	0,3968	0,0397
82	20	15	4,15	402,353	0,4024	0,0402
83	20	30	4,25	408,140	0,4081	0,0408
84	20	45	4,25	408,140	0,4081	0,0408
85	21	0	4,25	408,140	0,4081	0,0408
86	21	15	4,25	408,140	0,4081	0,0408
87	21	30	4,25	408,140	0,4081	0,0408
88	21	45	4,1	399,533	0,3995	0,0400
89	22	0	4	394,036	0,3940	0,0394
90	22	15	3,85	386,122	0,3861	0,0386
91	22	30	3,75	381,053	0,3811	0,0381
92	22	45	3,5	369,012	0,3690	0,0369

	HH	MM	m/s	P (W)	P (KW)	Q (KW)
93	23	0	3,3	359,926	0,3599	0,0360
94	23	15	3,1	351,209	0,3512	0,0351
95	23	30	2,9	0,000	0,0000	0,0000
96	23	45	2,7	0,000	0,0000	0,0000

Table P.3: Slow wind speed in April in Barcelona

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