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Máster en Sistemas de Energía Eléctrica

Estado del Arte sobre Diseño y Dimensionamiento de Microrredes Eléctricas

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Master's Thesis
Master in Electric Energy Systems

State of the Art for the Design and Sizing of Electric Microgrids

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The Court designated to judge the Project previously indicated, constituted by the following members:

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Abstract

The current electric grid, taken to the limit as much in size as in complexity, faces new challenges and needs of restructuring due to the growth of demand, power quality and emissions of greenhouse gases. Distributed grid architectures are acquiring a role increasingly important as alternative solutions to the centralized power grid. Among these architectures are the electric microgrids, low voltage distribution systems constituted by loads and distributed energy resources that, coordinated in an efficient way, allow to optimize the operation of the whole system.

As part of current projects for the development of microgrids, the present project is a preliminary study for the design and sizing of a microgrid. This case study will be carried out on the School of Engineering of the University of Seville and it will consist of studying the current generation resources of the building, analysing its consumption pattern and proposing and sizing other energy resources based on renewable energy to reach a sufficient generation capability.

After the elaboration of this project, a possible generation scenario for the previous purpose has been obtained. Generation capability of current generation resources (the Solar Cooling Plant and the Backup Generator Set) is well-known. In addition, making use of the consumption pattern obtained, a photovoltaic plant and a storage system have been sized taking a relationship of commitment between cost and storage capability into account.

Among the most important conclusions, it can be mentioned, in relation with the theoretical part, the importance of studies in island mode and the lack of regulation for microgrids connection to the network in Europe. In relation with the case study, a yearly consumption pattern very representative has been obtained, current generation resources have been characterized and a photovoltaic plant for different scenarios has been sized, being the most interesting one in which there is storage.

Index

Acknowledgment **i**

Abstract **iii**

Index **v**

Index of Figures **ix**

Index of Tables **xi**

List of acronyms **xiii**

1. Introduction **1**

1.1. Introduction on Electric Microgrids *1*

1.2. Objective of the Project *2*

1.3. Scope of the Project *2*

1.4. Justification of the project *3*

1.5. Structure of the Document *3*

2. About Microgrids **5**

2.1. Concept of Microgrid *5*
2.1.1. What it is? 5
2.1.2. What it is not? 6

2.2. Types of microgrids *7*
2.2.1. A classification provided by the Microgrid Institute 7
2.2.2. A classification provided by the IEEE 1547 8

2.3. Microgrid Operation Modes *12*
2.3.1. Normal parallel operation 12
2.3.2. Transition-to-island mode 12
2.3.3. Island mode 13
2.3.4. Reconnection mode 13

2.4. Microgrid stakeholders *13*

2.5. Operation and Control of Microgrids 14
  2.5.1. Microgrid Control Architecture 14
  2.5.2. Control strategies 15
  2.5.3. Operation strategies of microgrids 16

2.6. Benefits of using Microgrids 16
  2.6.1. Economic Benefits of a Microgrid 17
  2.6.2. Technical Benefits of a Microgrid 18
  2.6.3. Environmental and Social Benefits of a Microgrid 18

3. Design of Microgrids 19

3.1. Load requirements and planning 19
  3.1.1. Load considerations 19
  3.1.2. Reactive power considerations 19
  3.1.3. Transformers 20
  3.1.4. Motors 20
  3.1.5. Lighting 20
  3.1.6. Sensitive loads 20
  3.1.7. Load power quality 20

3.2. EPS requirements and planning 21
  3.2.1. Compatibility of grounding among the DR, transformer and EPS 21
  3.2.2. Voltage regulation 21
  3.2.3. Frequency regulation 22
  3.2.4. Protection coordination 22

3.3. DR requirements and planning 23
  3.3.1. Aggregation of multiple DR 23
  3.3.2. Adjustments of DR settings 23
  3.3.3. Voltage and frequency regulation 23

3.4. System studies 24
  3.4.1. Generation capability planning 24
  3.4.2. Load-flow studies 24
  3.4.3. Short-circuit and protection coordination studies 24
  3.4.4. Stability of a DR island system 24
  3.4.5. Motor starting studies 25
  3.4.6. Additional planning considerations 25

4. Requirements for Microgrid connection to the Electrical Network 27

4.1. General requirements 27
  4.1.1. Voltage regulation 27
  4.1.2. Integration with Area EPS grounding 28
  4.1.3. Synchronization 28
  4.1.4. Inadvertent energization of the area EPS 28
  4.1.5. Monitoring provisions 28
  4.1.6. Isolation device 29
  4.1.7. Interconnection integrity 29

4.2. Response to Area EPS abnormal conditions 29
  4.2.1. Area EPS faults 29
  4.2.2. Area EPS reclosing 29
  4.2.3. Voltage regulation 29
  4.2.4. Frequency regulation 30

4.2.5. Loss of synchronism 30
4.2.6. Microgrid reconnection 31

4.3. Power quality 31
4.3.1. Limitation of dc injection 31
4.3.2. Limitation of flicker 31
4.3.3. Harmonics limitation 31

4.4. Island operation 31

5. Case study: The School of Engineering 33

5.1. Type of microgrid 33

5.2. Stakeholders involved 34

5.3. Distributed resources 35

5.4. Control strategy 36

5.5. Operation strategy 36

6. Generation Capability Planning 39

6.1. Load Planning 39
6.1.1. Methodology to follow 40
6.1.2. Calculations to obtain daily load curves 40
6.1.3. Daily load curves obtained 42

6.2. Analysis of the Solar Cooling Plant 42
6.2.1. Operation data according to the seasonal mode 43
6.2.2. Electric energy savings provided by the Solar Plant 46

6.3. Analysis of the Backup Generator Set 49
6.3.1. Rated power 49
6.3.2. Operating mode 50

6.4. Sizing of the Photovoltaic Plant 50
6.4.1. Operating scenarios of the PV plant 50
6.4.2. Methodology to follow 51
6.4.3. PV plant design 52
6.4.4. Obtaining of results 55
6.4.5. Treatment of results 56

6.5. Sizing of the Storage System 63
6.5.1. Analysis of the possible sizes 63
6.5.2. Selection of the storage system 64

7. Conclusions and Future Work 65

7.1. Starting considerations 65

7.2. Results 66

7.3. Conclusions 67

7.4. Future work 69

Bibliography 71

Annex 1. Calculations for information processing 73

Annex 2. Daily Load Curves **79**

Annex 3. Summary **85**

Index of Figures

Illustration 2-1. Microgrid scheme 6
Illustration 2-2. Types of DR island systems 8
Illustration 2-3. Facility island 9
Illustration 2-4. Secondary island 9
Illustration 2-5. Lateral island 10
Illustration 2-6. Circuit island 10
Illustration 2-7. Substation Bus Island 11
Illustration 2-8. Substation Island 11
Illustration 2-9. Adjacent Circuit Island 12
Illustration 2-10. Usual microgrid control architecture 15
Illustration 2-11. Relation between benefits and stakeholders 17
Illustration 4-1. Voltage limits of ANSI C84.1-1995 28
Illustration 5-1. School of Engineering of the University of Seville 33
Illustration 5-2. Possible connection of the School of Engineering in an American and European distribution system. 34
Illustration 5-3. Current generation resources of the School of Engineering 35
Illustration 6-1. Comparison of methods for the selection of the "model" daily load curve 41
Illustration 6-2. Solar Cooling Plant of the School of Engineering 42
Illustration 6-3. Operating days of the Solar Plant working in cooling mode 44
Illustration 6-4. Energy exchange in the absorption machine in cooling mode 44
Illustration 6-5. Approximation of the power curve 45
Illustration 6-6. Operating days of the Solar Plant working in heating mode 45
Illustration 6-7. Energy exchange in the absorption machine in heating mode 46
Illustration 6-8. Industrial heat pump of Daikin's Catalogue 47
Illustration 6-9. Diesel Generator Set of the HIMOINSA catalogue 49
Table 6-1. Available databases that meet the requirements 52
Illustration 6-10. The two stations of Metenorm located in Seville 53
Illustration 6-11. Field parameters. 54
Illustration 6-12. "Albasolar" catalogue; Grid-connected modules 55
Illustration 6-13. Curves extracted from August with a rated power of the PV plant of 100 kW when the SCP is not working 57
Illustration 6-14. Curves extracted from August with a rated power of the PV plant of 200 kW when the SCP is not working 58

Illustration 6-15. Curves extracted from August with a rated power of the PV plant of 300 kW when the SCP is not working......58
Illustration 6-16. Curves extracted from August with a rated power of the PV plant of 400 kW when the SCP is not working......59
Illustration 6-17. Curves extracted from August with a rated power of the PV plant of 350 kW when the SCP is not working......59
Illustration 6-18. Curves extracted from August with a rated power of the PV plant of 100 kW when the SCP is working......60
Illustration 6-19. Curves extracted from August with a rated power of the PV plant of 200 kW when the SCP is working......60
Illustration 6-20. Curves extracted from August with a rated power of the PV plant of 300 kW when the SCP is working......61
Illustration 0-1. Example of consumption graph: active power daily load curve of weekday of January......79

Index of Tables

Table 4-1. Interconnection system response to abnormal voltages 30
Table 4-2. Interconnection system response to abnormal frequencies 30
Table 4-3. Maximum harmonic current distortion in percent of current (I) 31
Table 6-1. Available databases that meet the requirements 52
Table 6-2. Rated power of the PV plant elements used in the tests 61
Table 6-3. Percentage of hours per year the net consumption is negative 62
Table 6-4. Energy and power of the storage system necessary for each rated power of the PV plant. 64

List of acronyms

AHU

Air handling unit, 46

CHP

Combined heat and power appliances, 5

DER

Distributed energy resources, 5

DG

Distributed generation, 6

DMS

Distribution management system, 15

DR

Distributed resource, 8

DSI

Demand side integration, 7

DSO

Distribution system operator, 14

EPS

Electric power system, 9

ESCO

Energy service company, 14, 35

GHG

Greenhouse gas, 18

IEEE

Institute of Electrical and Electronics Engineers, 8

IT

Information Technology, 1

LV

Low voltage, 5

MC

Microsurce controller, 14

MGCC

Mircrogrid central controller, 15

MIC

Monitoring, information exchange and control equipment, 12

MV

Medium voltage, 6

PCC

Point of common coupling, 5

PV

Photovoltaics, 5

RES

Renewable energy resource, 7

SCP

Solar Cooling Plant, 42

1. Introduction

This chapter offers an introduction about Electric Microgrids, the topic chosen for the project. Then, the objective, scope and justification of the Project are detailed, as well as a brief sum up of the content of each chapter.

1.1. Introduction on Electric Microgrids

Currently, there is an electric energy system that is mostly centralized, in which electricity is transported from powers generation plants to consumers through an electric macrogrid. In fact, the electrical network is defined by the U.S. National Academy of Engineering as the "most complex machine ever developed by humankind". However, more and more, alternative electric power systems to centralized generation systems are emerging in response to the new challenges and needs of restructuring that the current electric network faces, due to the increase of electricity demand and global emissions of greenhouse gases.

The increase of electricity demand and the requirement of a better quality of supply have led the electric network to reach their limits in both size and complexity. As a result, the current electrical infrastructure is facing problems such as security, reliability and quality of power supply.

On the other hand, the current efforts to combat the climate change pursue a more sustainable electric network and, precisely, the new distributed grid architectures give the possibility of installing distributed resources based on renewable energies.

One of these distributed electric generation systems are microgrids. About the year 2000, people started to talk about microgrids as alternative solutions to centralized generation. Today, microgrids constitute a good solution for critical infrastructures, campuses, remote communities, island networks or single buildings as factories, shopping malls or faculties.

There have been many discussions about the term "microgrid" to refer to this type of systems [1]. For some people the term "autonomous network" is more correct because it suggests that the system operates independently from other network but for others, such as the IT department, this term suggests that the system controls a group of networks, that is not the case of a microgrid. Finally, the industry has accepted the term "microgrid" as a more precise term. The “micro” refers to the fact that, in comparison with a great centralize grid, this system is much smaller. The “grid” is due to it simulates a utility grid.

A microgrid is a low voltage distribution system constituted by loads and distributed energy resources that are coordinated to optimize available resources and it can operate in parallel with the main grid or in an autonomous way. A series of clarifications that derive from this definition are explained in *Concept of Microgrid* section.

Since microgrids are new architectures that people are studying and trying to implement, there are not only technical challenges but also regulatory barriers or lack of regulation that hider the deployment of microgrids. In fact, there is not specific regulation about microgrids at the country level, as in Spain, thus, in case of being necessary, regulations that could be applied to the American network and not to the European should be consulted.

Currently, microgrids are common research topics in the United States, Canada, Japan and Europe in where many studies have been carried out in order to demonstrate the operation of a microgrid. As part of this common project for the development of microgrids, this project is a preliminary study for the design and sizing of a microgrid.

1.2. Objective of the Project

The objective of this project is to carry out a draft for the design and sizing of distributed generation resources that the School of Engineering of the University of Seville would need to function as an electric microgrid.

On the other hand, the purpose of this project is to present the Master’s Thesis by the student Luna Moreno Díaz with the title “State of the art for the Design and Sizing of Electric Microgrids” to obtain the Master in Electric Energy Systems Degree in the School of Engineering of the University of Seville.

1.3. Scope of the Project

The elaboration of this draft comprises the following milestones:

- To collect the literature of the state of the art of electric microgrids, focusing on the design of microgrids and the technical requirements for the connection of a microgrid to the Electrical Network.
- To apply the previous concepts to a case study: the School of Engineering. This case study is going to consist in a preliminary study to constitute an electric microgrid on the School of Engineering. The preliminary study is going to address the next issues:
    - Type of microgrid,
    - Stakeholders involved,
    - Current distributed generation resources,
    - Consumption pattern,
    - Control strategy,

  - Operation strategy.
- The preliminary study is going to delve into the design and sizing of the generation capability of the School necessary to function as a microgrid. To do this, the following tasks are required:
  - To analyse current generation resources to determine their rated power and their operation.
  - To analyse the yearly consumption pattern of the School to obtain representative daily load curves that allow to compare generation and consumption.
  - To propose and size other distributed generation resources that, together the current generation resources, allow to cover the consumption needs of the school to work in an autonomous way.

1.4. Justification of the project

This project arises from one of the investigation projects that is being studied currently in the Department of Electrical Engineering of the University of Seville about microgrids and is titled "Design, Development and Demonstration of an intelligent and active Micro-grid". As member of this project, Jose Luis Martinez Ramos, the tutor of this Master's Thesis, proposed me to carry out a study related to the design and sizing of microgrids applied to the School of Engineering.

The fact of choosing the School of Engineering as system object of study is because it is a building with a high consumption, that already has distributed generation resources, thus, to investigate if it could function as an electric microgrid would be interesting. In addition, to get information of this building will not be difficult because it has been studied before by other students and professors in different projects. In fact, the consumption information of the building has been taken from a previous End-of-Degree Project.

On the other hand, with the elaboration of this project, many of the concepts studied in the Master in Electrical Energy Systems will be strengthen. Concretely, this project is related with the subjects "Renewable electric generation", "Active distribution networks and load management" and "Quality and efficiency of electric supply", among others. In addition, digital competences will be improved with the use of Excel for information analysis and processing and the use of PVsyst, a powerful software to design and study photovoltaic plants.

1.5. Structure of the Document

This section tries to collect in a brief way the content of each chapter to offer the reader an overview of the document.

Chapter 2, entitled *About* Microgrids, addresses particularities about microgrids. First section describes in detail what is a microgrid and what is not with reference to other DG dominated structures that do not gather all the features of a microgrid; second section collects two classifications of microgrids, one provided by the Microgrid Institute and another specified in an IEEE Standard; third section talks about the possible stakeholders involved in a microgrid; fourth section addresses the main systems of a microgrid control architecture and the possible control and operation strategies; last section provides a qualitative overview of economic, technical and environmental benefits of microgrids.

Chapter 3, entitled *Design of Microgrids*, collects a series of requirements that loads, and distributed resources must meet for the correct operation of the microgrid. The requirements to assure a tight coordination between the microgrid and the area EPS to which is to be connected are also collected. Last subsection addresses some studies that should be performed to assure the quality of service that the microgrid provide to its customers.

Chapter 4, entitled *Requirements for Microgrid connection to the Electrical Network*, gathers the main technical requirements and specifications for interconnecting microgrids with Electric Power Systems. These requirements refer to the response to area EPS abnormal conditions, power quality and other general requirements.

Chapter 5, entitled *Case study: The School of Engineering*, describes the case study to which is going to be applied the concepts studied about microgrids, the School of Engineering. This building is characterized as a microgrid, being the type of microgrid, the stakeholders involved, its current distributed generation resources and the possible operation and control strategies determined. But, the study in which goes in depth this project is the design and sizing of generation capability of the building to function as a microgrid, topic in which is focused the next chapter.

Chapter 6, entitled *Generation Capability Planning*, carries out a study of the consumption and generation of the School of Engineering to design and size its generation capability in order to function as a microgrid. In first place, the consumption yearly pattern of the School of Engineering is studied to obtain a representative daily load curve for each month that allows to compare generation and consumption in a simple way. In second place, the current generation resources of the building are analysed: the Solar Cooling Plant, to know how much electric energy this resource saves for the School, and the generator set, to know their rated power and how it operates. Finally, to reach enough generation capability for the operation of the microgrid in island mode, two distributed generation resources are going to be sized: a photovoltaic plant and a storage system.

Chapter 7, entitled *Conclusions and Future Work*, gathers the conclusions of the study, as well as the future work needed to continue the study of an electric microgrid on the School of Engineering. This chapter starts with the hypothesis and considerations that have been made due to the lack of information both in consumption data and generation data. Next, it sums up the results obtained in the case study. The conclusions of this project are divided in two: those referred to the theoretical part and those referred to the case study.

2. About Microgrids

This chapter tries, in first place, to clarify the reader what it is a microgrid and, in second place, collects a series of particularities about microgrids such as, the classification of microgrids, the stakeholders involved, the operation modes and their benefits, among others things.

2.1. Concept of Microgrid

2.1.1. What it is?

According to several EU research projects [2] “a microgrid comprises LV distribution systems with distributed energy resources (DER) (microturbines, fuel cells, PV, etc.) together with storage devices (flywheels, energy capacitors and batteries) and flexible loads. Such systems can be operated in a non-autonomous way, if interconnected to the grid, or in an autonomous way, if disconnected from the main grid. The operation of microsources in the network can provide distinct benefits to the overall system performance, if managed and coordinated efficiently”.

Next, Illustration 2-1 shows a scheme of a microgrid. As it can be seen, the microgrid is constituted by loads, one part of them are controllable loads, and by a serial of DR[1] in which are collected all the casuistry: controllable generation, that can be combined heat and power appliances (CHP) or fuel cells, non-controllable generation, how the photovoltaic is, backup generator sets and energy storage systems. All these resources are controlled by a microgrid manager to optimize the operation of the system based on a specific objective. The microgrid is connected to the utility grid through the point of common coupling (PCC) and it can operate in parallel with this main grid or in an autonomous way, not connected to the main grid.

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[1] Distributed resources (DR) include both generators and energy storage technologies.

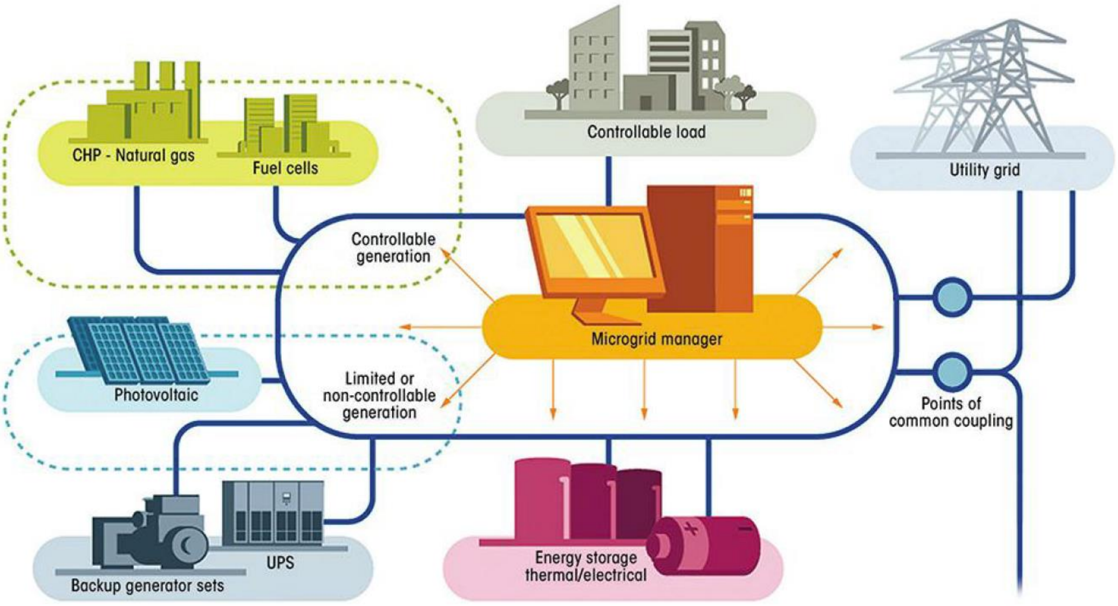

Illustration 2-1. Microgrid scheme

Some clarifications derive from this explanation:

- In the microgrid concept, the location of generators and loads gain a lot of importance compared with aggregator models of generators where the location is not considered.
- Microgrids are normally located in the LV network but could be also connected to the MV network for interconnection purposes.
- Microgrids will operate most of the time connected to the main network and will turn into islanding operation in few occasions (for example, when a fault on the main grid occurs).
- To operate in island mode almost continuously, microgrids must have enough capacity of storage and a robust generation that supply energy to loads when it is demanded or a not so robust generation with demand side management.
- The main difference and advantage of a microgrid respect to a passive grid penetrated by microsources is the aided functionalities that arise from the active monitoring, control and optimization of available resources. In the case of passive DG there is supply of energy without control. Furthermore, other advantage of microgrids is the capability of achieve an optimal solution for the different stakeholders involved.

2.1.2. What it is not?

The microgrid concept comprises some features inherent to this type of system. The following examples clarify what it is incorrectly understood such as a microgrid:

- Microgrids are isolated system without possibility to connect to the main grid: As it was explained earlier, microgrids can work in two states: connected to the grid, the state in which the system stays most of the time, or isolated to the distribution network, working in island mode, the state to which the system shifts when there is a failure in the main grid. However, a small island system can be considered a microgrid depends on the system size, the quantity of DR and the control complexity, because these systems coordinate their resources answering for the active monitoring and control that characterize microgrids.

- Users with their own energy resources constitute a microgrid: A system with DG does not constitute a microgrid by itself because it does not control and monitor the available resources, in whose case, it becomes an active system.
- Microgrids are subject to changes in renewable energy resources resulting in a loss of reliability: to manage the intermittent behaviour of renewable energy resources (RES), microgrids are composed by enough storage capacity when they work in island mode and have the support of the distribution network in case of grid-connection mode. In addition, the fact to have the possibility to commute to island mode when there is a failure in the network increases the system reliability.
- Today, microgrids are still too expensive to be used in real applications: first, microsources and storage technologies are evolving to cheaper solutions that will make microgrids economically interesting; second, the main cost to transform conventional distribution lines with DG into a microgrid lie in the control and communication infrastructure costs but, the advantages achieved with the improvement of the grid in terms of DR management compensate the investment.
- Microgrids control causes that demand has to adapt to renewable generation: Demand side integration (DSI) acts to optimize the demand of energy on devices that let to take advantage of thermal inertia and, devices that can work without supply during a period of time, such as electric thermos. For this reason, loads without this flexibility do not take part of DSI.
- Microgrids will avoid any supply interruption: when the microgrid commutes to island mode there is an inevitable loss of load that it only could be avoided with enough storage or generation capacity. Then, during the transition, several non-critical loads will lose their supply.

2.2. Types of microgrids

Because several microgrid classifications have been found, those that have been considered more representative are going to be addressed.

2.2.1. A classification provided by the Microgrid Institute

The Microgrid Institute [3] provides a classification that depends on autonomous operation and network magnitude of the microgrid. It is shown next:

- Utility-integrated campus microgrid: it usually works interconnected to a local electrical network but can works in island mode when there is a problem such as an outage in the utility grid. Examples of this case are university campus, prisons and military bases.

- Community microgrid: it is used to provide supply for the essential services of a community formed by several consumers.
- Off-grid microgrid: it is any microgrid not connected to the electrical grid that only works in island mode. Examples of this case are islands grids or electrical networks in faraway places.
- Nanogrids: it is the simplest case of a microgrid. It is formed by a unique building such as a factory, a shopping mall, a faculty or other systems such as pumping stations.

2.2.2. A classification provided by the IEEE 1547

Second, a classification based on operating configurations of microgrids is presented and is specified in the IEEE Standard 1547.4-2011 [4]. This classification depends on where the loads and distributed resources (DR) are connected in the distribution network and goes from lesser to greater magnitude of the island system. There could be more configurations that those presented next, but, in general, most of microgrids are represented in this classification. It is important to mention that this classification is based on American distribution system, hence, it could be extrapolated to the European system taking the differences between both systems into account. Below, *Illustration 2-2*Illustration 2-2. Types of DR island systems contains all the possible configurations.

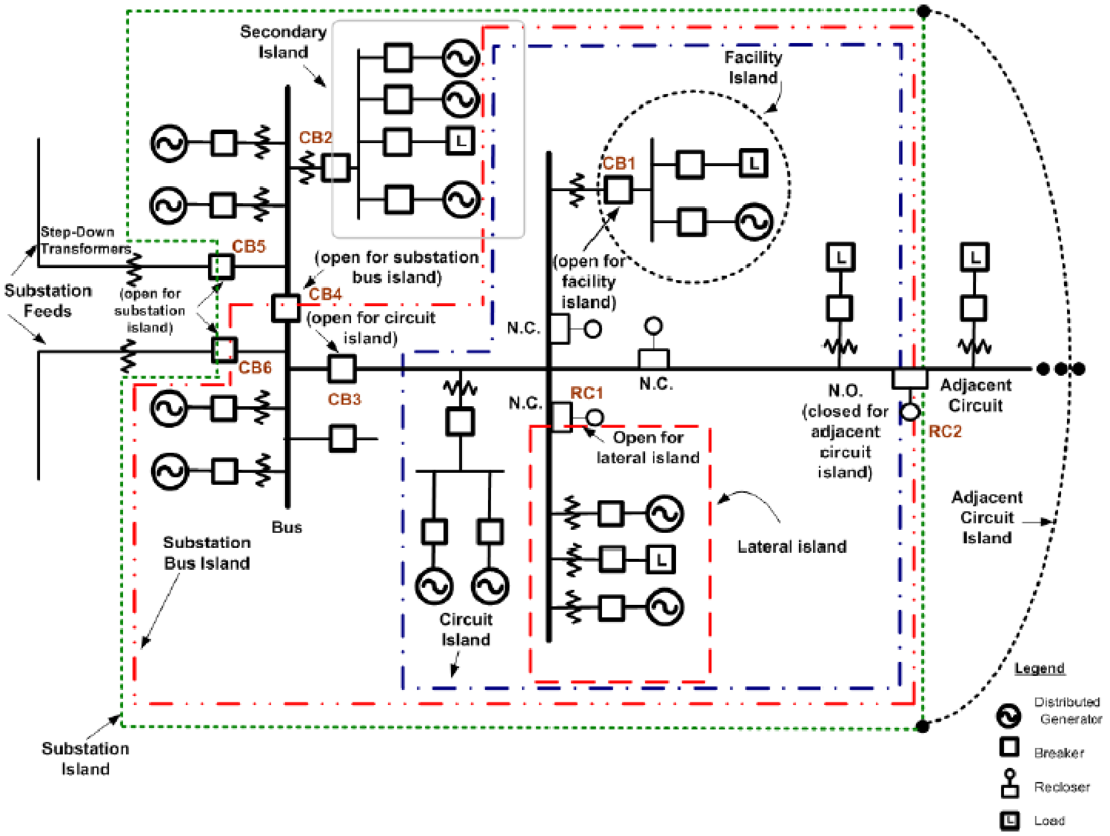

Illustration 2-2. Types of DR island systems

Types of microgrids represented in the previous figure are going to be explained next.

2.2.2.1. Local EPS island (Facility Island)

The microgrid is constituted by generation and load within a customer facility. The configuration is also known as Facility Island (*Illustration 2-3*). The system has PCC and works in island mode to feed the load when there is a loss of supply of the area EPS.

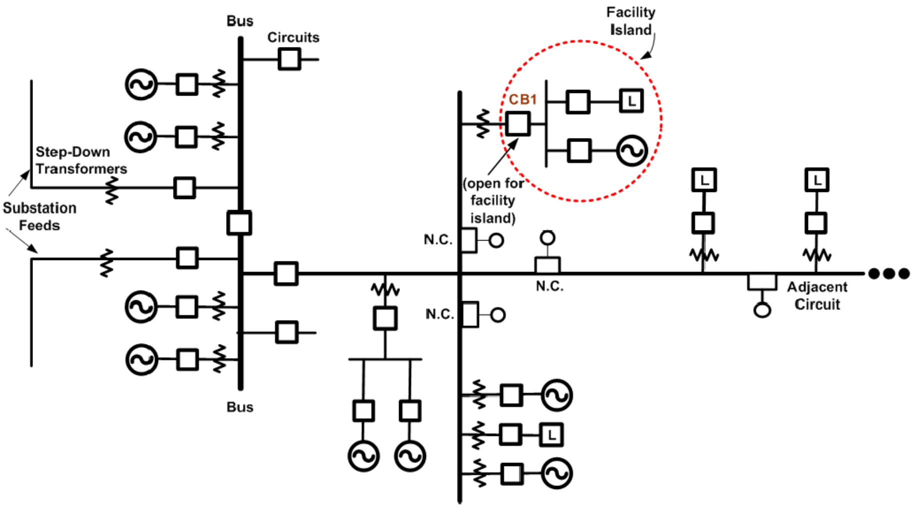

Illustration 2-3. Facility island

2.2.2.2. Secondary Island

In that case, the microgrid is formed by the load of several consumer facilities and one or more DR connected to the same secondary system[2] (*Illustration 2-4*). Some secondary islands could be connected to the same single distribution lateral.

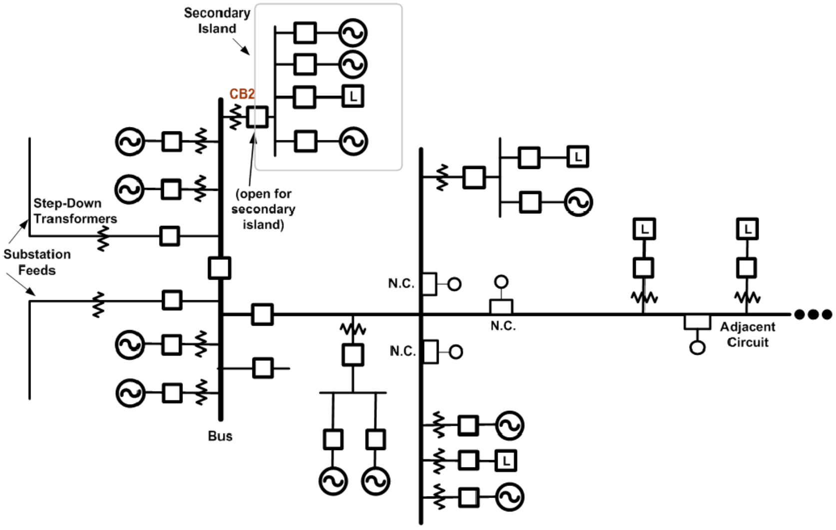

Illustration 2-4. Secondary island

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[2] Secondary system: electrical system connected to a single distribution lateral trough a single-phase transformer.

2.2.2.3. Lateral Island

The Lateral Island is formed form loads and DRs connected to a single distribution lateral (*Illustration 2-5*). When there is a loss of supply on the single distribution lateral, the DRs could serve the loads of the island.

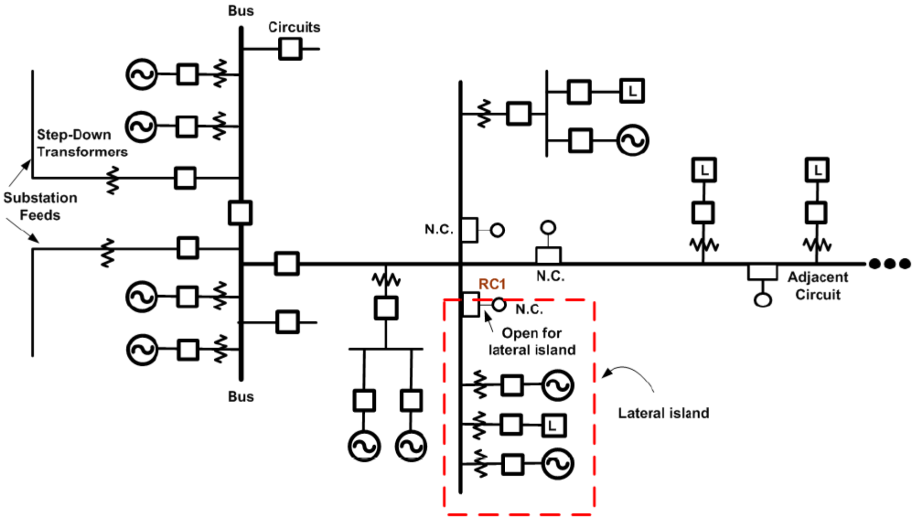

Illustration 2-5. Lateral island

2.2.2.4. Circuit Island

In that case, the microgrid is constituted by single distribution laterals with DRs and loads, with configurations such as those seen before, and loads and DRs directly connected to a single distribution circuit[3] (*Illustration 2-6*).

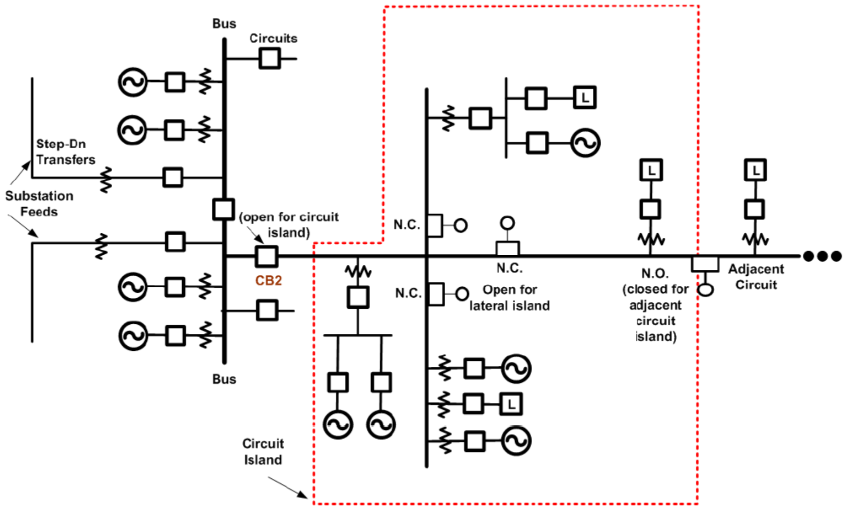

Illustration 2-6. Circuit island

2.2.2.5. Substation Bus Island

The substation bus island is formed by the system served from a single distribution circuit and DRs connected to the substation bus (*Illustration 2-7*). This configuration allows for

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[3] Single distribution circuit: is the 3-phase, 4-wire multigrounded primary coming from the substation bus.

supplying the single distribution circuit when there is a loss of supply form the substation or a fault in the distribution transformer.

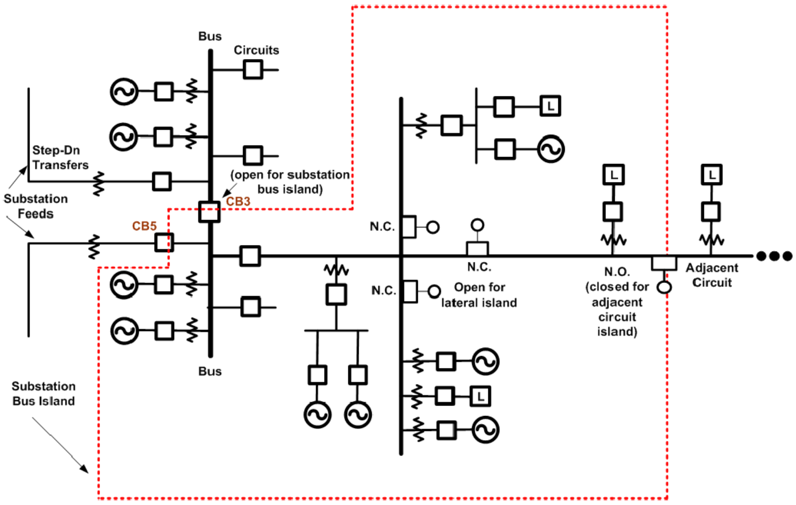

Illustration 2-7. Substation Bus Island

2.2.2.6. Substation Island

The substation island is constituted by load normally served from a single substation (*Illustration 2-8*). With this configuration is possible to feed the substation load when a loss of supply occurs due to the substation is out of service or one transformer is out of service and the other transformer cannot assume the entire load demanded. Even, the substation island could solve overload and voltage problems on the substation feeds.

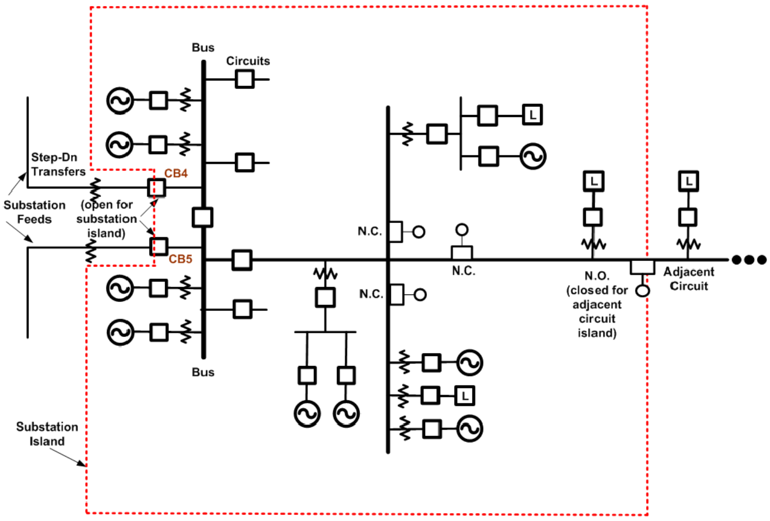

Illustration 2-8. Substation Island

2.2.2.7. Adjacent Circuit Island

The adjacent circuit island is formed by a substation island that serves load from an adjacent circuit (*Illustration 2-9*). This configuration could be performed when there is a substation island and a loss of supply in the adjacent circuit arises.

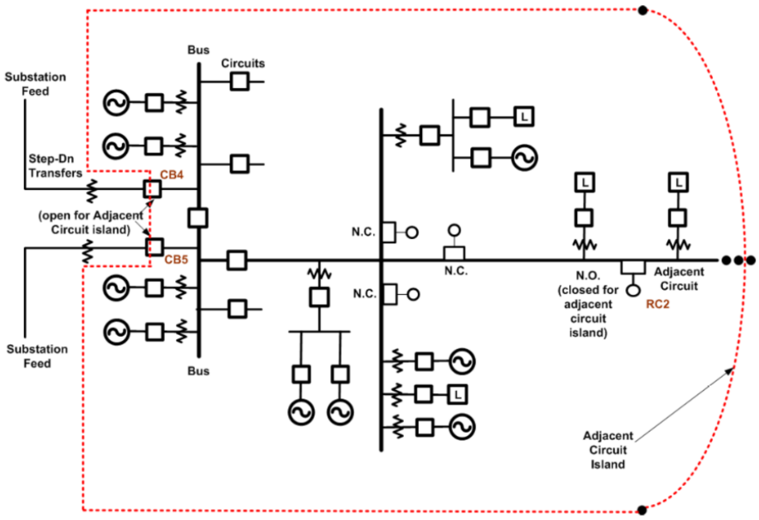

Illustration 2-9. Adjacent Circuit Island

2.3. Microgrid Operation Modes

This section addresses the normal operating modes of the microgrid [4]. These operating modes are the following: normal parallel operation mode, transition-to-island mode, island mode and reconnection mode. To perform the transition from parallel operation to island mode and vice versa, certain monitoring and control devices will be necessary and depending on control needs can be more or less sophisticated.

2.3.1. Normal parallel operation

In normal parallel operation, the microgrid works connected to the area EPS, that is, works in parallel with the main utility grid, for this reason, it is known as normal parallel operation. In this mode, DR of the microgrid must meet the requirements specified in IEEE Std 1547 [5] that will be addressed in a posterior section.

The monitoring, information exchange and control equipment (MIC) necessary to perform the transition to island mode must be working during parallel operation to have the information required for this mode change available.

2.3.2. Transition-to-island mode

The transition to island mode can be performed intentionally or can be an unexpected event. When there is an intentional transition, the duration of the intentional island is agreed between the stakeholders implicated. An unexpected transition is caused due to a fault in the area EPS and requires the MIC equipment was working in the previous mode to have information that facilitates a smooth change available. To achieve a successful transition, enough DR, being these DR well operated and designed, must be available to support voltage and frequency disturbances caused during the change of operating mode. If DR are not capable of performing the transition, additional supporting equipment will be included.

2.3.3. Island mode

When the microgrid works in island mode, a lot of considerations have to be taken into account related with the fact that the microgrid does not count on the area EPS support. Fundamentally, the microgrid must be designed to provide the real and reactive power demanded by loads and must have a proper voltage and frequency regulation to remain within the limits agreed between the parties.

Other considerations are specified next and will be addressed with more detail in the following sections:

- To allow for voltage and frequency regulation during island mode, regulation devices may need to adjust voltage and frequency limits. In that case, they may work without meeting the IEEE 1547 [5] requirements.
- Dynamic response of the island must be guaranteed knowing that the system does not count on the inertia of the area EPS.
- To coordinate load and generation, the technique that is adjusted in the best way possible with generation capability and loads characteristics should be used: load-following, load management, load shedding, etc.
- Protective coordination has to be maintained considering that short-circuit current contribution of DR is smaller than the area EPS contribution.

2.3.4. Reconnection mode

The reconnection must be performed when the area EPS and the microgrid are within acceptable voltage, frequency and phase angle limits. There are three reconnection modes:

- Active synchronization: a mechanical device is used to align voltage, frequency and phase angle of the microgrid with those of the area EPS.
- Passive synchronization: it is based on synchronization checks that do not allow for reconnection until systems limits are within acceptable values.
- Open-transition transfer: prior to the reconnection, loads and DR of the microgrid have been de-energized.

Both active and passive synchronization need knowing voltage, frequency and phase angle state of the microgrid and the area EPS to perform the reconnection. Unlike these, open-transition transfer does not need sensors, but requires stopping supply to loads during the transition.

2.4. Microgrid stakeholders

The main stakeholders involved in a microgrid are going to be described next [6]:

- Consumer: it can be a household customer or a medium or small company.
- DG owner/operator: normally, the owner of the DG units also performs their operation. It is assumed that most of DG will provide monitoring and control capabilities.

- Prosumer: It is a specific case of consumer who have installed DRs that can supply partially or totally the consumption of the building. The surplus could be injected into the main grid.
- Customer: in the term customer are included consumers, DG owner/operator and prosumers.
- Distribution system operator (DSO): is the agent responsible for the operation, maintenance and development of the distribution network.
- Energy service company (ESCO): regarding microgrids, it is a market agent that makes possible the participation of microgrid DRs in local energy markets.
- Microgrid operator: is the agent responsible for the operation, maintenance and development of the local EPS that constitutes the microgrid. This role can be performed by the DSO of the area EPS or by an independent DSO, that acts in benefit of microgrid customers.

2.5. Operation and Control of Microgrids

Part of this section has been taken from the book “Microgrids: Architectures and Control” [7]. In this book, there is a detailed explanation of Microgrid control issues among other things. Since the objective of this project in not the Microgrid control, only microgrid control architectures and control strategies are going to be addressed. In addition, in the last subsection, the possible operation strategies of a microgrid are going to be explained.

Before explaining the possible control and operation strategies of a Microgrid, the main systems of a microgrid control architecture are going to be addressed. Since control strategies depend on objectives of different stakeholders implicated and control responsibilities of different control systems, knowing stakeholders and control systems before is advisable.

2.5.1. Microgrid Control Architecture

The structure of a Microgrid control architecture depends on the type of microgrid or the infrastructure, so there is no a general structure. In *Illustration 2-10* is presented a possible microgrid control architecture. Unlike the architecture of a current distribution system, there is an additional control level at DRs and loads.

Main stakeholders implicated in microgrid control (described in *Microgrid stakeholders*) are the following:

- DG owner/operator.
- Distribution system operator (DSO).
- Energy service company (ESCO)
- Microgrid operator.

Control systems that comprise the microgrid control architecture are the following:

- Microsource controller (MC): this system performs the control and monitor of DRs and loads.

- Microgrid central controller (MGCC): is the interface between the microgrid and other agents such as the DSO or the ESCO. It can assume different level of responsibility: from supervising MCs to providing them with set points to maximize some parameters. It is located in the MV/LV substations.
- Distribution management system (DMS): In that context, the function of the DMS is to make possible the collaboration among the DSO, the ESCO and the microgrid operator.

In *Illustration 2-10* there are some DR and loads, all of them with its respective MC and energy meter. The MGCC will act on MCs to get a centralized control of the available resources.

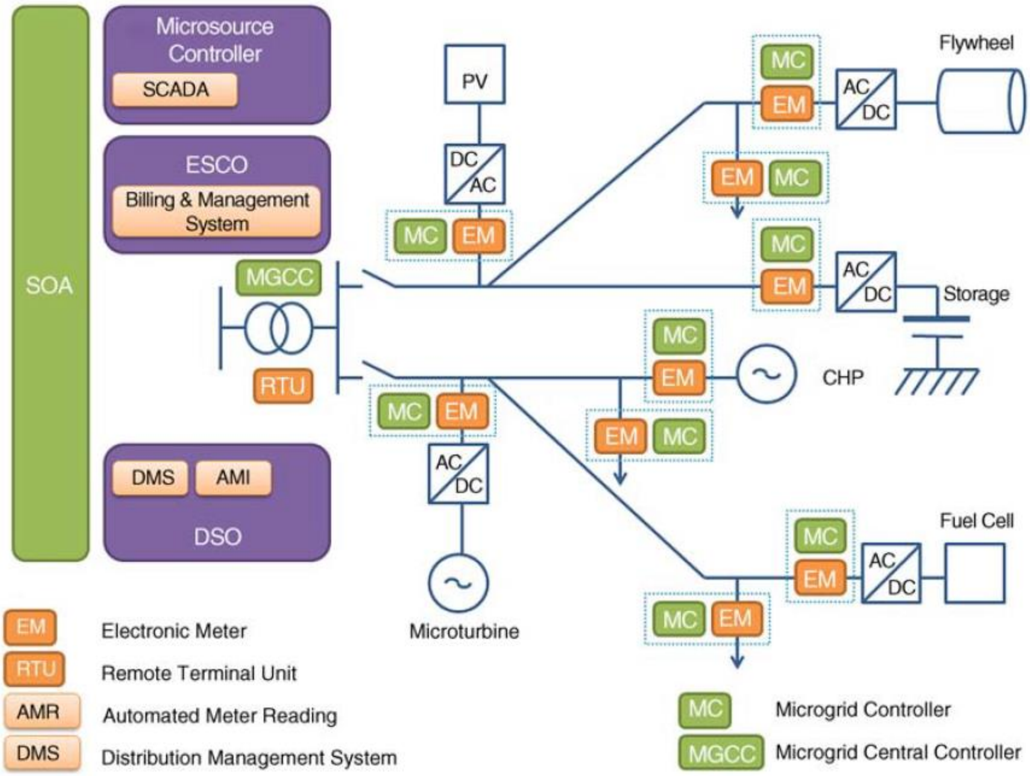

Illustration 2-10. Usual microgrid control architecture

2.5.2. Control strategies

The microgrid control can be performed with a centralized or decentralized strategy depending on objectives of agents implicated and control responsibilities of the different control systems. In the following subsections, both control ways are explained.

2.5.2.1. Centralized control

In general terms, a centralized control methodology defines a master-slave configuration between central system and distributed devices. According to the previous control system classification, in a centralized control, the MGCC assumes the responsibility to maximize the microgrid value, that is, to optimize the production and consumption of power and to decide the amount of power that the microgrid should import from the area EPS.

A centralized strategy is performed when agents of the microgrid (DG and load owners) have common interests. This situation could happen in case of an industrial microgrid where there is only an owner that finds to operate the system in the most economical way possible.

2.5.2.2. Decentralized control

In a decentralized strategy, distributed and intelligent devices perform a local control and communicate with each other. In the case of a microgrid, the different control nodes are loads and DR since on each household or DR is solved an optimization local problem. In load nodes is provided load shedding capability and in DR nodes power reserve.

Decentralized strategy is demanded in the market environment of a microgrid where controllers are required to be competitive and with a certain independence and intelligence level. And not only that, agents can also have other goals besides selling energy such us producing heat for an installation, maintaining the voltage within a range in any point of the system or assuring the operation of a critical load in case of system failure. This could happen in the case of a residential microgrid where each customer may demand different power needs at the same time. For this reason, the optimization problem in these cases becomes complex because modelling all household requirements and technical constraints of all appliances in a single problem is not an easy task.

2.5.3. Operation strategies of microgrids

The operation strategy of a microgrid depends on interests of different stakeholders involved. As it will be seen next, the operation scheme objective can be economic, technical, environmental or a combination of the above.

- Economic option: the objective function is to minimize total cost of the system without taking into the impact on the network account. This strategy is typical of DG owners that are not care about emissions and their only limitations are technical constraints of DG.
- Technical option: the objective function is to minimize power losses, voltage variations, etc. without considering DR productions costs. This strategy is commonly of system operators.
- Environmental option: the objective function is to minimize DG emission levels without considering economical or technical issues. This operation strategy is performed to accomplish an emission target imposed by regulatory schemes.

Finally, a combined optimization problem will consider all economic, technical and environment aspects, solving a multi-objective dispatch problem. This strategy may be interesting to agents that participate in energy markets where are demanded not only energy, but also network services or emission certificates.

2.6. Benefits of using Microgrids

In the following subsections, a qualitative overview of economic, technical and environmental benefits of microgrids [8] will be provided. These benefits depend on microgrid operation strategies that were seen in the prior section.

Since a microgrid has different stakeholders, what aspects benefit each one are going to be distinguished. In *Illustration 2-11*, a relation between benefits and stakeholders is established. These relations will be discussed on each subsection.

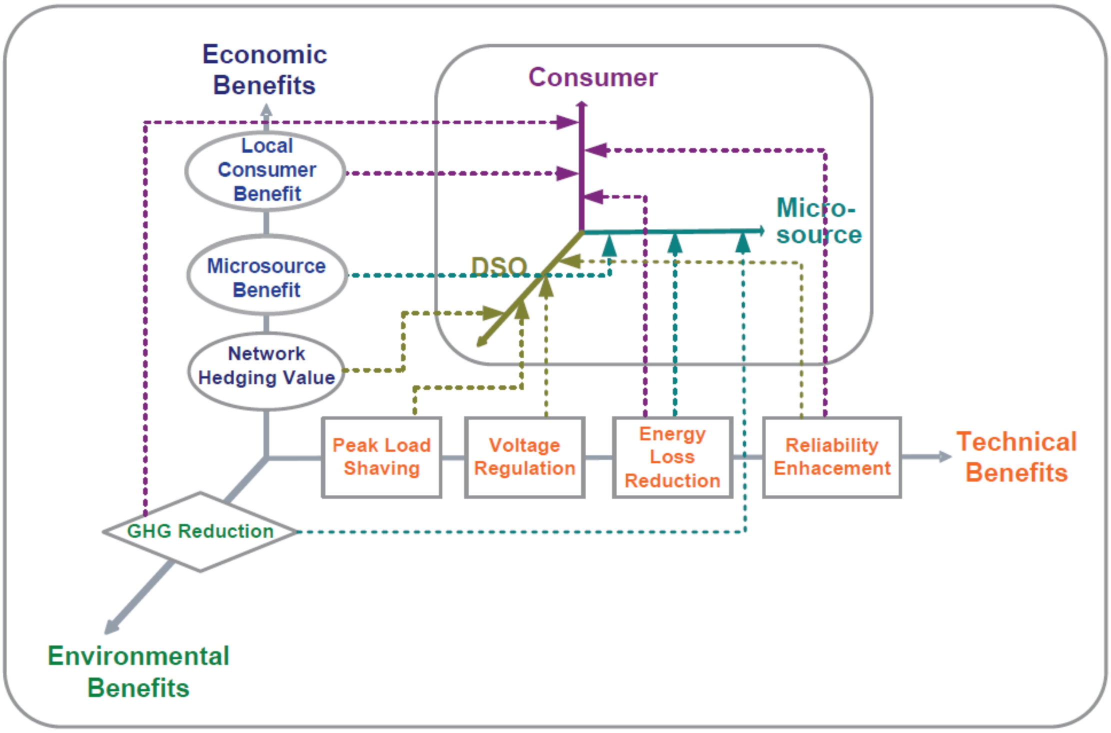

Illustration 2-11. Relation between benefits and stakeholders

2.6.1. Economic Benefits of a Microgrid

Economic benefits of a microgrid can be classified in two: locality benefit and selectivity benefit. Locality benefit consists on the creation of an internal energy market that is more economically beneficial to DG owners than the wholesale market and to consumers than the retail market. So, this benefit can be assigned to the consumer and the DG owner, relation that can be seen in the left half of *Illustration 2-11*. With respect to selectivity benefit, this consists on the optimization of economic dispatch decisions.

Analysing these benefits from a macro-economic perspective, locality benefits can be divided in the following aspects:

- Microgrid could act as a local retail and service market.
- Microgrid can minimize the risk of price volatility, outages, load growth, etc. This benefit adds a hedging tool to the distribution network that allows to improve the customer service. Hence, this benefit is assigned to the DSO.

The selectivity benefits can also be grouped in two aspects:

- Microgrid can act as an interest mediator of different stakeholders.
- Microgrid adds stakeholders from both sides of the balance: suppliers and consumers.

2.6.2. Technical Benefits of a Microgrid

The microgrid can provide technical benefits to the DSO that can improve distribution network operation in which is connected. These benefits are the following:

- Energy loss reduction. When the microgrid provides supply to the distribution network, line power flows are decreased.
- Voltage quality improvement by a coordination of reactive power control of both systems.
- Alleviation of power elements over-loaded. For example, in peak hours, by a proper dispatch of DG, lines of other devices can be decongested.

When the number of microgrids in a LV network is large enough, their influence could reach to upstream networks, that is, the technical benefits would spread to the MV network.

With respect to consumers of the microgrid, the main technical benefit provided is the supply reliability improvement. When a loss of main grid occurs, the microgrid can operate in islanding mode. This improvement also benefits the DSO.

The level of technical benefit achieved depend on how much optimal is DR allocation and coordination degree accomplished by stakeholders involved.

2.6.3. Environmental and Social Benefits of a Microgrid

Environmental benefits provide by a microgrid come with the use of low-emission fuels, such as gas natural and the implementation of energy supply solutions more efficient, such as the combination of heat and power applications, together with demand side integration. These benefits can be attributed to either the consumer and the DG owner.

Regarding social benefits of a microgrid, the following can be mentioned:

- To promote energy saving and greenhouse gas (GHG) emissions reduction.
- To create research ang job opportunities.
- To electrify remote or underdeveloped areas.

These social benefits can be considered log-term effects of the microgrid operation.

3. Design of Microgrids

To design a microgrid, a series of requirements in regard to loads and DRs have to be considered and a tight coordination with the area EPS to which is to be connected has to be assured. In addition, last subsection addresses some studies that should be performed to assure the quality of service that the microgrid provide to its customers. This information has been taken from the IEEE Standard 1547-4 [4].

3.1. Load requirements and planning

Loads of a microgrid must meet several requirements to assure a correct operation in a system that is not as robust as the area EPS. Most of the loading issues addressed here are due to the fact that microgrids do not have the balancing effect and the inertia of EPSs. Hence, the problems of motors or transformers in critical conditions may be accentuated when they work in a microgrid.

3.1.1. Load considerations

Upon the necessary information for the load analysis, it is needed: point and phase of load connection, historical demand profiles, load typology (residential, commercial or industrial), detail of large punctual loads such as motors and a realistic profile of the instantaneous loads.

Related to load imbalance, a study of load configuration is necessary to assure that loads are as balanced as possible, and it has been considered that a change of configuration may be required when the system works in island mode.

Other important issue to take into account is cold load pickup after service restoration. In that situation, the microgrid must have enough capacity to pick up the loads or perform sectionalizing manoeuvres to start the system in steps.

3.1.2. Reactive power considerations

The microgird must have enough reactive resources when the system works in island mode. Concretely, reactive resource is needed to satisfy reactive power demand in normal conditions and demands when the system is experiencing a transitory such as a motor starting.

3.1.3. Transformers

The problem addressed in this section is due to the inrush current that appears when transformers are re-energized during a switching operation. These currents cause an unnecessary tripping of the overcurrent protective device because, depending on the type of transformer, inrush current can be 20 to 25 the rated current. In a microgrid these problems could happen as a consequence of momentary outages on the area EPS supply. To solve the problem, series reactance, impedance starting, or special overcurrent devices could be used.

3.1.4. Motors

Upon motor operation in a microgrid, three problems arise:

- Inrush current aggravate voltage drop in the microgrid. In consequence, starting motor manoeuvre gets worse or a loss of generation can occur. To solve this problem, soft-start controllers or reduced voltage starters on large motors could be used.
- Voltage drops during motor-starting can be accentuated due to the fact that Thevenin impedance of a microgrid is largely greater than the area EPS impedance. As in the previous case, special motor-starting techniques should be considered.
- Large motors can experience unusual inrush currents when switch from one energized power source to another because, the residual voltage of the motor is not in phase with the voltage source to which it has been connected. As a result, internal motor damages may occur, even damage to the driven load.

Therefore, all these considerations must be taken into account when design motors within a microgrid.

3.1.5. Lighting

The most important issue related to lighting in a microgrid is to assure that the power source of emergency lighting loads can provide supply during the longest predictable power outage. In addition, it should be considered, depending on the need for lighting, the time required to restore the full illumination after a momentary outage caused by a microgrid transition. This time depends on the type of lighting. Finally, some types of lights cause harmonics that have to be considered, above all in island mode.

3.1.6. Sensitive loads

Sensitive loads refer to electronic computer equipment that require that several parameters such as voltages and frequency meet strict values to ensure the continuous operation of these loads. To satisfy this need of operation, a single installation of auxiliary equipment is necessary.

3.1.7. Load power quality

In terms of power quality, the main issues are the following:

- Voltage drops: since Thevenin impedance of a microgrid is largely greater than the area EPS impedance, voltages drops are accentuated when the microgrid transfers to island mode.
- Harmonics: in first place, harmonic loads have a bigger negative effect in the microgrid that in the area EPS. These waves distortion can cause more losses in transformers and motors, can affect sensitive and neighbouring loads and can cause the appearance of ripple in the output waves of ac/dc power supplies. To reduce system harmonic content, harmonic loads must be reduced, adding filtering or selecting a more adequate transformer.
- Voltage imbalance: load imbalance causes imbalanced phase voltages that can lead to ripple currents. These currents can damage inverters of inverter-based DRs, energy source such as batteries and fuel cells and generators. In addition, imbalance in the distribution system may cause negative sequence currents that could damage equipment with limited negative sequence capability.

3.2. EPS requirements and planning

To make possible the operation of a microgrid connected to an area EPS, there should be enough coordination between both systems. Hence, to assure the compatibility of the systems in different aspects such as the grounding, the voltage and frequency regulation and the protection coordination is necessary.

3.2.1. Compatibility of grounding among the DR, transformer and EPS

The main consideration here is that the microgrid must keep the same grounding scheme that the area EPS and the well-operation of the grounding system cannot be affected.

The typical grounding configuration of DR transformers when the area EPS has a four-wire multi-grounding neutral system is a wye connection on the high side with a delta low-side connection. With this configuration, using a grounding impedance in the high-side (wye neutral connection to ground) is usual to limit circulation of high currents. Also, a wye connection on both transformer sides is common.

The grounding configuration that should be avoided is a delta connection on the high transformer side because overvoltage problems could be caused.

In any case, there are more DR transformer configurations such as T-connection, open-delta, etc. whose impact on the existing grounded scheme is necessary to study.

3.2.2. Voltage regulation

In first place, there should be coordination among voltage control scheme of the area EPS and the microgrid. In second place, the power demand must be evaluated under parallel and island mode to size the voltage regulation equipment.

Working in island mode, several considerations must be examined:

- One of the DR has to regulate voltage and be coordinated with other voltage regulating devices of the system.

- The fact to have DR in the microgrid could make necessary power-flow-based controls for good operation of line voltage regulators. Otherwise, the regulator control could lead to harmful voltage levels when power flow is reversed. In any case, line voltage regulator operation within a microgrid must be studied in detail.

In many cases, specific voltage levels could be demanded at the substation or particular buses to smooth the transfer to island mode or other needs. These additional voltage requirements should be considered to size voltage regulation equipment.

3.2.3. Frequency regulation

As for frequency regulation, it is expectable that the microgrid will not get a regulation range as tight as the area EPS. The method of frequency regulation has to be chosen and frequency sensitivity of loads has to be considered.

On island mode, the following problems arise:

- Some DRs are not able to recover to normal state when frequency is too low. In this case, frequency limits must be adjusted to allow operating in island mode.
- The participant DRs on frequency regulation may need to change its control scheme to consider load shedding in underfrequency conditions.

3.2.4. Protection coordination

When a microgrid is created in an area EPS, adjustment may be necessary on protective devices and reclosing practices to consider the changes introduced by the microgrid.

Most of protection problems arise because a microgrid energized only by DR may not be able to produce enough fault current to assure the good operation of existing protective devices during short-circuit currents. As a result of this situation, the following problems happen:

- When using single-phase protective devices between the area EPS source and the DR, DR contribution to fault current can make these protections to lose sensitivity and to cause the contrary effect to protections located beyond the DR during normal operation.
- There may be coordination problems between protective devices of the area EPS and protection DR associated with the area EPS.

It should be verified if inverter-based DRs are able to produce the required fault current. If it is not enough, the use of other protection scheme must be considered.

In short, the test that all faults of the microgrid will be cleared must be checked and the necessary adjustments to get coordination between both protection schemes should be made. When working in island mode, to establish selectivity for the entire island can be very complicated. Not make changes could be better because is a situation of short duration.

3.3. DR requirements and planning

In this section, DR requirements are going to be addressed when the microgrid works as an intentional island, particularly referred to voltage and frequency regulation. Also, operation with multiple DR are going to be talked about.

3.3.1. Aggregation of multiple DR

When there are different DRs within the microgrid, generation capabilities of each one has to be considered to achieve a tight coordination between them. In addition, it has to be verified if existing DRs of the microgrid can meet power requirements of loads and in case of a DR outage, if the rest DRs of the microgrid can serve the planned load.

Some DRs within the microgrid could be non-participating DR and in that case, they act as if they were connected to a larger EPS, that is, they perform a passive voltage and frequency control, but they must meet the IEEE 1547 [5] requirements.

3.3.2. Adjustments of DR settings

When the microgrid operates in island mode, to adjust control settings of DRs with respect to undervoltages and underfrequencies may be necessary. If the microgrid is configured to detect voltages and frequencies below a limit and act in consequence, this could cause generator tripping during island operation when a fault occurs and lead to an island outage if only exists a DR in the island.

3.3.3. Voltage and frequency regulation

This section addresses methods of voltage and frequency regulation when the microgrid works as an intentional island. It has to be considered that voltage and frequency limits in island mode could not be as tight as the limits when the microgrid works in parallel with the area EPS. The quality of voltage and frequency regulation will depend on DRs capabilities and load characteristics within the microgrid. Hence, these limits will be agreed between stakeholders implicate.

To assure the microgrid is capable of maintain system stability, recovery time and limits reached by system voltage and frequency should be checked in case of maximum loss of load or in case of maximum load demand.

3.3.3.1. Voltage regulation

Voltage regulation can be performed by either voltage droop or reactive power sharing.

Voltage droop consists on change the voltage set point as the reactive load changes. Concretely, when the reactive load increases, the voltage droop setting is reduced. The problem of this method is the droop operation need to uniform balance the reactive load between generators occasionally and the open loop control can make an unequal reactive load sharing.

In the reactive power sharing method, the system reactive load level is communicated to all generators operating in the common isolated bus to adjust its individual reactive power output to meet the reactive power requirements of the system. Unlike the voltage droop, to perform this method is necessary a high-speed communication system and a central control.

3.3.3.2. Frequency regulation

Frequency regulation can be performed by either speed droop or real power sharing.

Speed droop consists on change the speed set point as the load on the generator changes. Concretely, when the load on the generator increases, the speed droop setting is reduced. The problem of this method is the droop operation need to uniform balance the real load between generators occasionally and the open loop control can make an unequal real load sharing.

In the real power sharing method, the system real load level is communicated to all generators operating in the common isolated bus to adjust its individual real power output to meet the real power requirements of the system. Unlike the voltage droop, to perform this method is necessary a high-speed communication system and a central control.

3.4. System studies

There are many studies that should be performed to assure the quality of service that the microgrid provide to its customers. In the following subsections, these studies are going to be addressed in a brief way.

3.4.1. Generation capability planning

The objective of this study is to examine generation capability of microgrid DRs and to compare their characteristics with loads to verify if the system is compatible. In addition, black start capability and cold-load pickup issues should be studied.

3.4.2. Load-flow studies

A power-flow study must be performed to evaluate the balance between generation and load. This study should contain a voltage profile for significant load conditions. The interaction between voltage regulation devices has to be considered to perform the study.

3.4.3. Short-circuit and protection coordination studies

To assure clearing of fault conditions of any anticipated microgrid configuration, a short-circuit study must be performed. The study should be carried out when the microgrid works in parallel with the area EPS and when it works as an intentional island. In case of working as an intentional island, there is an important issue that must be considered: the short-circuit current capability of DRs. If protective devices are sized to work with the fault-current contribution of the area EPS, they may not trip working in island mode. In addition, if DRs are based on inverter, their fault-current contribution is smaller than the machine-based DR contribution. For this reason, all these issues must be considered when designing protective devices coordination of the microgrid in island mode.

3.4.4. Stability of a DR island system

The main issues that arise when studying stability of a microgrid are the following:

- The transition from a system with large inertia (the area EPS) to an intentional island leads to a different stability response when operating conditions change.
- During the transition to island mode, stability will be affected by voltage effects originated by redistribution of energy of inductive and capacitive elements at the PCC.
- The simplified dynamic equations and time constant commonly used in stability studies do not work with inverter-based DR. In that case, the study will require an explicit transient model of inverter-based DRs of the microgrid.

It should be pointed out that stability study requirements for an intentional island should be determined by stakeholders implicate or specific standard adopted by the industry for stability studies could be consulted.

3.4.5. Motor starting studies

The microgrid must assure a proper operation of motors and be able to start them considering the difficulties that emerge due to the operation in a microgrid. It has to be considered that voltage sags during motor-starting can be accentuated because Thevenin impedance of a microgrid is largely greater than the area EPS impedance.

3.4.6. Additional planning considerations

A contingency and operation plan must be designed for all operation modes of the microgrid: normal parallel operation mode, transition-to-island mode, island mode and reconnection mode.

4. Requirements for Microgrid connection to the Electrical Network

This section gathers the main technical requirements and specifications for interconnecting microgrids with Electric Power Systems. This information has been taken from the IEEE Standard 1547 [5] that addresses the interconnection of distributed resources with EPS. Since a microgrid is a local EPS, formed by DRs, that is connected to the main utility grid (defined as area EPS), the requirements of the Standard are applicable at the PCC.

It should be pointed out that this Standard is applicable to microgrids whose aggregated generation capability at the PCC is equal to or less than 10 MVA, connected to the usual primary or secondary distribution voltages. The requirements must be met by any DR type: machine-based DR or converter-based DR. It is assumed that DRs work at 60 Hz[4].

4.1. General requirements

4.1.1. Voltage regulation

The microgrid should not actively regulate voltage at the PCC. In addition, the microgrid should not cause that the area EPS service voltage makes that other local EPS not fulfil with voltage requirements of ANSI C84.1-1995, Range A (specified in *Illustration 4-1*).

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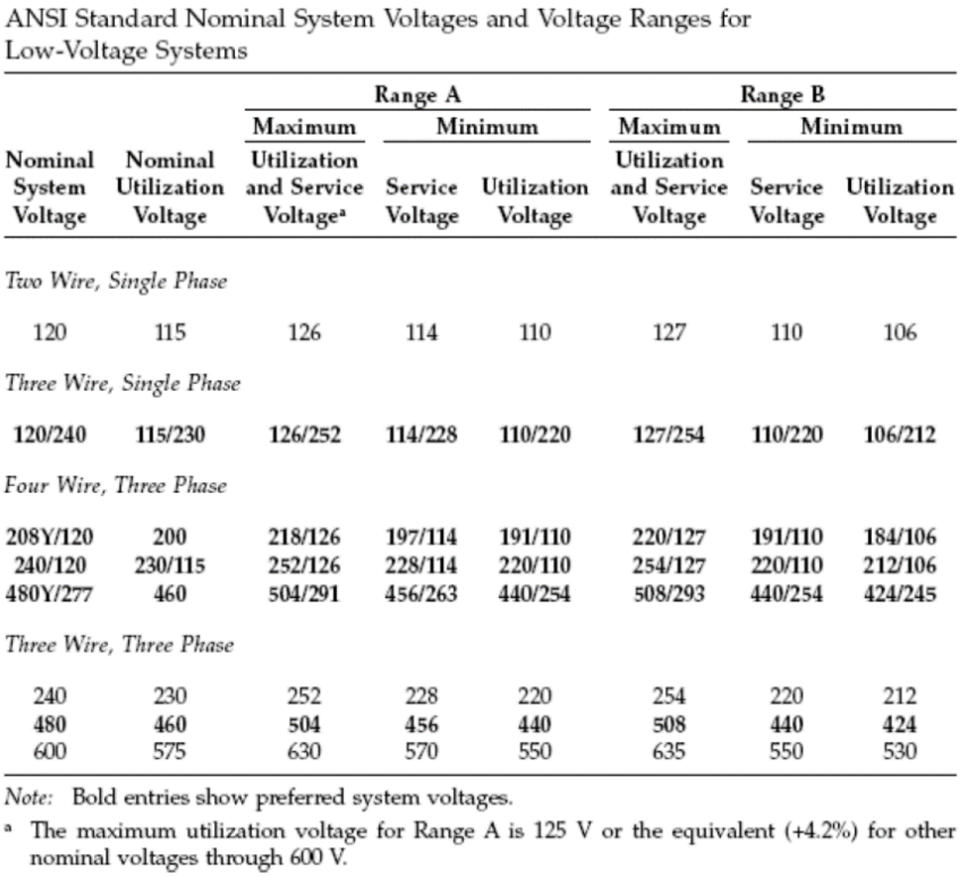
[4] Frequency limits will not be directly applicable to the European case where frequency is 50 Hz.



ANSI Standard Nominal System Voltages and Voltage Ranges for Low-Voltage Systems

		Range A			Range B		
		Maximum	Minimum		Maximum	Minimum	
Nominal System Voltage	Nominal Utilization Voltage	Utilization and Service Voltage[a]	Service Voltage	Utilization Voltage	Utilization and Service Voltage	Service Voltage	Utilization Voltage
Two Wire, Single Phase							
120	115	126	114	110	127	110	106
Three Wire, Single Phase							
120/240	**115/230**	**126/252**	**114/228**	**110/220**	**127/254**	**110/220**	**106/212**
Four Wire, Three Phase							
208Y/120	**200**	**218/126**	**197/114**	**191/110**	**220/127**	**191/110**	**184/106**
240/120	**230/115**	**252/126**	**228/114**	**220/110**	**254/127**	**220/110**	**212/106**
480Y/277	**460**	**504/291**	**456/263**	**440/254**	**508/293**	**440/254**	**424/245**
Three Wire, Three Phase							
240	230	252	228	220	254	220	212
480	**460**	**504**	**456**	**440**	**508**	**440**	**424**
600	575	630	570	550	635	550	530

Note: Bold entries show preferred system voltages.

[a] The maximum utilization voltage for Range A is 125 V or the equivalent (+4.2%) for other nominal voltages through 600 V.

Illustration 4-1. Voltage limits of ANSI C84.1-1995

4.1.2. Integration with Area EPS grounding

The microgrid grounding scheme should not cause overvoltages that surpass the overvoltage limit of the equipment connected to the area EPS and should not disturb the coordination of ground fault protection on the area EPS.

4.1.3. Synchronization

The microgrid shall not cause a voltage fluctuation at the PCC greater than ±5% of the predominant voltage level of the area EPS at the PCC.

4.1.4. Inadvertent energization of the area EPS

The microgrid shall not energize the area EPS when this is de-energized.

4.1.5. Monitoring provisions

Those DRs with a capacity (or aggregated capacity) more than or equal to 250 kVA should have the necessary resources to monitor its connection status, real and reactive power output and voltage at the point of DR connection.

4.1.6. Isolation device

When the operation of the area EPS requires it, the microgrid should incorporate an easily accessible, lockable and visible-break isolation device between the area EPS and the DR unit.

4.1.7. Interconnection integrity

4.1.7.1. Protection from electromagnetic interference

The interconnection system shall resist electromagnetic interference (EMI) environments conforming to IEEE Std C37.90.2-1995 and shall avoid that EMI causes a change of state or malfunction of the interconnection system.

4.1.7.2. Surge withstand performance

The interconnection system should resist overvoltages and overcurrents conforming to the environments described in IEEE Std C62.41.2-2002 or IEEE Std C37.90.1-2002 as appropriate.

4.1.7.3. Paralleling device

The interconnection system paralleling-device should resist 220% of the interconnection system rated voltage.

4.2. Response to Area EPS abnormal conditions

When a fault occurs in the area EPS, the microgrid should act to assure personal safety and to avoid device damages. For that reason, voltage and frequency limits specified next shall be met.

4.2.1. Area EPS faults

The microgrid shall stop to supply the area EPS when a fault has happened in a circuit of the area EPS to the microgrid is connected.

4.2.2. Area EPS reclosing

When area EPS protections are going to perform a reclosure, the microgrid should stop to energize the area EPS circuit to it is connected.

4.2.3. Voltage regulation

When voltage at the PCC is out of the limits indicated in *Table 4-1*, the microgrid shall stop to supply the area EPS within the clearing times specified in the second column of the table. The voltage to detect by protective devices at the PCC is the effective (rms) phase to phase voltage, being necessary to detect the effective phase-to-neutral voltage in the following cases:

- when the transformer that connect the microgrid to the area EPS has a grounded wye-wye configuration,
- when the local EPS is a single-phase facility.

Voltage set point and clearing times could be adjustable or fixed in case of DR less than 30kW and must be adjustable for DR more than 30 kW.

Table 4-1. Interconnection system response to abnormal voltages

Voltage ranges (% respect to rated voltage)	Clearing times (s)
V<50	0,16
50≤V<88	2,00
110<V<120	1,00
V≥120	0,16

The clearing times will be maximum for DR equal to or less than 30 kW and approximated for DR more than 30 kW.

In some cases, specified in the Standard, these voltage levels shall be detected also at the point of DR connection.

4.2.4. Frequency regulation

When frequency at the PCC is out of the limits indicated in *Table 4-2*[5], the microgrid shall stop to energize the area EPS within the clearing times specified in the second column of the table. Frequency set point and clearing times could be adjustable or fixed in case of DR less than 30kW and must be adjustable for DR more than 30 kW.

Clearing times adjustment in under-frequency conditions should be coordinated with the area EPS.

Table 4-2. Interconnection system response to abnormal frequencies

DR size	Frequency range (Hz)	Clearing time (s)
≤ 30 kW	> 60.5	0.16
	< 59.3	0.16
> 30 kW	> 60,5	0.16
	< {59.8 - 57.0} (adjustable set point)	Adjustable 0.16 to 300
	< 57.0	0.16

The clearing times will be maximum for DR equal to or less than 30 kW and approximated for DR more than 30 kW.

4.2.5. Loss of synchronism

Loss of synchronism protection is not required excepting if it would be necessary to meet the limitation of flicker induced by the microgrid.

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[5] These limits are not directly applicable to the European case where frequency is 50 Hz.

4.2.6. Microgrid reconnection

The reconnection to the area EPS can be performed when voltages are within Range B of ANSI C84.1-1995, Table 1, and frequency is within the range of 59.3 Hz to 60.5 Hz. To the previous consideration, it should be added that the reconnection system should incorporate a delay of time of at least 5 minutes once the area EPS has re-established the voltage and frequency within the ranges mentioned before.

4.3. Power quality

This subsection addresses microgrid power quality requirements, such as those related to voltage fluctuations and distortion of voltage waveform, among others.

4.3.1. Limitation of dc injection

The DR shall not introduce a dc current bigger than 0.5 % the full rated output current at the point of DR connection.

4.3.2. Limitation of flicker

The microgrid shall not cause objectionable flicker for customer served by the area EPS[6].

4.3.3. Harmonics limitation

The harmonic current distortion that the microgrid introduces into the area EPS has a series of limits depending on the harmonic order and are collected in *Table 4-3*.

Table 4-3. Maximum harmonic current distortion in percent of current (I)

Individual harmonic order h (odd harmonics)	h < 11	11 < h < 17	17 < h < 23	23 < h < 35	h ≥ 35	**Total demand distortion (TDD)**
Percent (%)	4.0	2.0	1.5	0.6	0.3	5.0

I: the greater of the Local EPS maximum load current integrated demand (15 or 30 minutes) without the DR unit, or the DR unit rated current capacity (transformed to the PCC when a transformer exits between the DR unit and the PCC).

4.4. Island operation

This Standard considers the case in which a DR operates in island with a part of the area EPS, that is defined as an intentional island. In that case, the DR shall detect the island operation and stop to energize the portion of the area EPS within two seconds after the creation of the island. The same action should be carried out with a microgrid.

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[6] Flicker is considered objectionable when causes human discomfort or equipment malfunction.

5. Case study: The School of Engineering

To put in practice the concepts studied about microgrids, a draft is going to be carried out, in regards to the design and sizing, to know if the School of Engineering (*Illustration 5-1*) could work as a microgrid.

The study is going to be developed on the main building of the School, that is, without taking the building workshop and laboratories into account. This institution belongs to the University of Seville and is located in “Isla de la Cartuja”.

Illustration 5-1. School of Engineering of the University of Seville

In the following subsections, information of interest for the study such as stakeholders involved and current distributed resources of the building, among others, is going to be described.

5.1. Type of microgrid

Regarding section 2.2, where types of microgrids are classified, the type of microgrid the School of Engineering is will be determined attending to its specific characteristics.

It has to be considered that two classifications were made: one provided by the microgrid institute and another provided by the IEEE 1547.

In relation with the classification of the Microgrid Institute, that depends on autonomous operation and network magnitude of the microgrid, the School of Engineering working as a microgrid would be a Nanogrid. A Nanogrid is formed by a single building that, in this case, is the main building of the faculty.

According to the classification of the IEEE 1547, that depends on where loads and DRs are connected, the School working as a microgrid would be a Circuit Island. Since the School is a building with a high power demand, it is connected to medium voltage, concretely to 20 kV, and it has its own transformer station. As it was mentioned in section 2.2, this classification is based on the American distribution system and the School of Engineering is connected to a European distribution system. However, this connection would be the same in both distribution systems because is made in medium voltage (the difference between both systems is in the low voltage level, as it can be seen in *Illustration 5-2*). Hence, as much in one case as in the other, the School would be connected to a 3-phase feeder in medium voltage or single distribution circuit (as it is known in the American system).

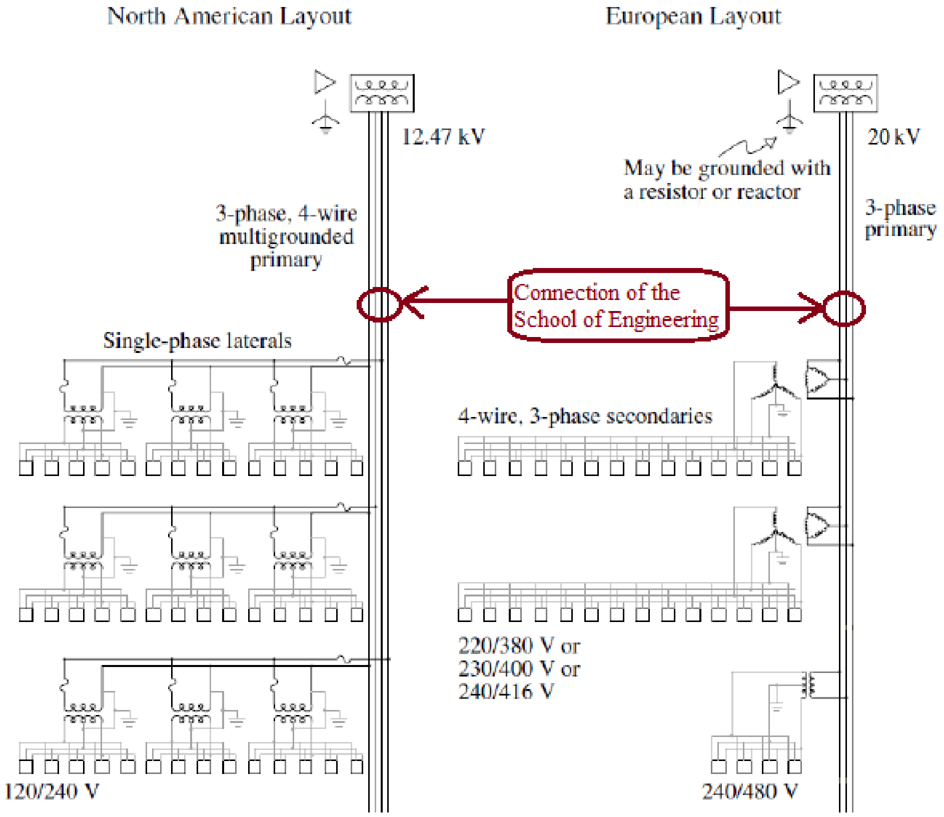

Illustration 5-2. Possible connection of the School of Engineering in an American and European distribution system[7].

5.2. Stakeholders involved

In relation with section 2.4, where the microgrid stakeholders are described, the potential stakeholders who would be involved in the School of Engineering will be sought.

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[7] As an example, in the American distribution system, a feeder of 12.47 kV is shown, one of the most characteristic of these networks.

- Consumer: it is the University of Seville. It is the entity that has a contract with a supplier company.
- DG owner/operator: currently, there are two generation distributed resources: The Solar Cooling Plant and a generator set. Both DRs are property of the University of Seville. The Solar Cooling plant is a pilot project of “Gas Natural Fenosa” company but the operator is the University, thus, it is also the owner. In subsequent sections, two additional DRs are going to be designed: a photovoltaic plant and a storage system. The University will also be the owner of this DRs.
- DSO: it is the “Endesa Distribución” company.
- ESCO: This agent would be the University of Seville that, by itself, would look for a supplier of electricity or a local energy market.
- Microgrid operator: This agent would be the University of Seville.

5.3. Distributed resources

As part of the design and sizing study of the School as a possible microgrid, it is necessary to plan generation capability to supply the loads when the microgrid works in island mode. First, the current generation capability of the School and its pattern of consumption must be analyzed. Then, other DRs that allow to reach the desirable generation capability have to be proposed.

As it was mentioned briefly in the previous subsection, the School of Engineering counts on two generation distributed resources currently: a Solar Cooling Plant and a generator set (represented in *Illustration 2-1*). Both DRs are going to be studied in subsequent sections in order to know how they operate and in what conditions, what it is their rated power and any other information that serves to characterize their operation.

Illustration 5-3. Current generation resources of the School of Engineering

To plan generation capability that the School should have to function as a microgrid, the consumption of the building must be characterized. Since it is difficult to get recent information about the consumption of the School, consumption data of an end-of-degree project of 2003 are going to be used, in them, measures of the active and reactive energy consumed in the School of Engineering were taken during the entire year.

After studying the generation and consumption of the School, we can have an idea of the generation capability needed for the operation of the School as a microgrid. This capability will depend on the technique used to coordinate generation and consumption: load-following, load management, load shedding, etc. To stablish the coordination technique, the consumption of the building must be characterized. However, we will know the consumption profile during a year, but we will not know other relevant information about loads: percentage of each kind of load (lighting, computer equipment, motors, etc.) unbalance percentage of loads, behavior of large punctual loads, etc. Hence, it is assumed that it will be followed a load-following technique, that is, generation capability of the building will have to supply all loads in island operation.

In order to reach the required generation capability, other DRs will be proposed and sized. Concretely, a photovoltaic plant and a storage system will be designed so that they cover, together the current DRs, the consumption needs of the School. The PV plant will be sized to be adjusted to the representative daily load curve of the month with less consumption. The storage system will be sized to manage the surplus of generation of the PV plant.

5.4. Control strategy

In relation with section 2.5.2, the control strategy of the School operating as a microgrid will be determined.

There are some reasons that make it more reasonable to carry out a centralized strategy than a decentralized strategy:

- Considering the unique stakeholder involved in the microgrid is the University of Seville (except for the DSO) would be logical to perform a centralize strategy. A decentralize strategy would be considered in case of a residential microgrid where there are different household consumers with their own power needs, that it is not the case.
- From an economic point of view, the centralize strategy is more interesting. To carry out a decentralize strategy would be necessary local intelligence of equipment and a more robust communication system which would need a higher initial investment.
- Considering the magnitude of the microgrid, a centralized strategy would make more sense to control a unique building.

5.5. Operation strategy

Finally, the operation strategy of this possible microgrid will be describe, regarding the last part of section 2.5.3. As in previous issues, control strategy will depend on interest of the different agents involved in the microgrid. In relation with the consumer and DG owner (the University of Seville), an economic operation strategy would be the most interesting. In relation with the DSO, it should be considered a technical operation strategy in combination with the previous.

In first place, the operation strategy of the microgrid would be one that would contribute to minimize total cost of the system. That is, an economic operation strategy would be implemented. As the theory says, this operation mode is typical of DG owners that are not care about emissions and their only limitations are technical constrains of DG. But in this case, distributed resources of the microgrid are based on renewable energy, except for the generator set that will only work in case of emergency. Hence, this microgrid can apply an economic operation strategy that in an indirect way is also an environmental operation because it will also minimize emissions levels.

In second place, economic benefits of carrying out network services could be interesting, such as minimize power losses, voltages variations etc. In this case, an economic and technical operation would be implemented. To do this, it would be necessary to study if our microgrid would have enough resources or enough capability to handle them in order to achieve this operation mode.

6. Generation Capability Planning

The main objective of this project is to carry out a preliminary study for the design and sizing of the generation capability of the School of Engineering that would be necessary to function as a microgrid. This chapter has several sections that are divided in two parts: one dedicated to consumption and other dedicated to generation (in turn, this part is divided in current DR and new DR). The purpose is to plan generation capability in order to cover the consumption of the school and, in this way, the microgrid can supply the loads when it works in island mode. Since this chapter is long, the main task addressed are collected next:

- To analyse the yearly consumption pattern of the School to obtain representative daily load curves that allow to compare generation and consumption.
- To analyse the current generation resources to determine their rated power and their operation. These resources are a Solar Cooling Plant and a backup generator set.
- To propose and size other distributed generation resources that, together the current generation resources, allow to cover the consumption needs of the school to work in an autonomous way. It has been decided to size a photovoltaic plant and an energy storage system.

6.1. Load Planning

To study generation capability needs for the School of Engineering, it is necessary to know the pattern consumption of the building. For that, we count on an Excel spreadsheet that contains consumption measures taken every five minutes throughout 2003 [9].

To make future comparisons between generation and consumption with monthly characteristic information, it has been decided to obtain a representative daily load curve for each month. In this section, the procedure to obtain these curves from the Excel spreadsheet mentioned are going to be explained.

6.1.1. Methodology to follow

Since measures were taken a long time ago, it is not worth to make a very accurate treatment of data. In case of having recent data, it would use a statistical program that would return a reliable consumption pattern. Hence, a simpler method has been proposed:

- For each month, two daily load curves are going to be obtained: one weekday curve and one weekend day curve. For that, it has to calculate the average hourly power of weekdays and weekend days. That is, it has to calculate 24 average power values for weekdays and 24 for weekend days, one for each hour of the day. Doing that, very important information is lost: the consumption of one hour is related with the next hour.
- Considering the previous problem, the following solution is proposed: the "model" daily load curve of each month (that is, the most representative) will be the curve that is closest to the average daily load curve calculated (actually, there will be two curves for each month: the "model" daily load curve of week and weekend).
- To assess dispersion of data, it will take the daily load curve in which more and less energy was consumed.

This is the procedure for active power.

Regarding the reactive power, the methodology is the following:

- The representative daily load curve will be that associated to the day with the representative daily load curve of active power.
- To assess dispersion of data in this case, it will make the same as in the active power case: to obtain the day with the biggest and the smallest reactive energy consumed.

The previous procedures will be detailed in the following subsection.

The tool that is going to be used to obtain the curves is Excel.

6.1.2. Calculations to obtain daily load curves

First, the curves will be calculated for one month, concretely, January. For that, an Excel file will be created with the data of January and the necessary calculations will be made to finally obtain the daily load curves desired. Then, using the copy and paste option, the "data" worksheet of the excel file of January will be substituted for the data of each month and excel will return all the curves automatically. Hence, we will have one Excel file for each month with all the daily load curves: two daily load curves of active power and two daily load curves of reactive power (one of between week and one of weekend).

Next, the steps carried out in excel for one month are collected:

1. To obtain the average hourly power of all hours of the month from five-minute power values.
2. To obtain the average daily load curve of the month. For that, the 24 average hourly power values of weekday and weekend day must be calculated from the hourly power values obtained in the prior step.

3. To select the day of the month whose daily load curve is closest to the average daily load curve calculated previously. This curve will be the “model” daily load curve. To make this selection there are different methods:
    - To select the day that has the minimum difference of area respect to the daily load curve calculated.
    - To select the day whose daily load curve shape looks more like the daily load curve calculated.

    In *Illustration 6-1*, daily load curves using both methods are represented:

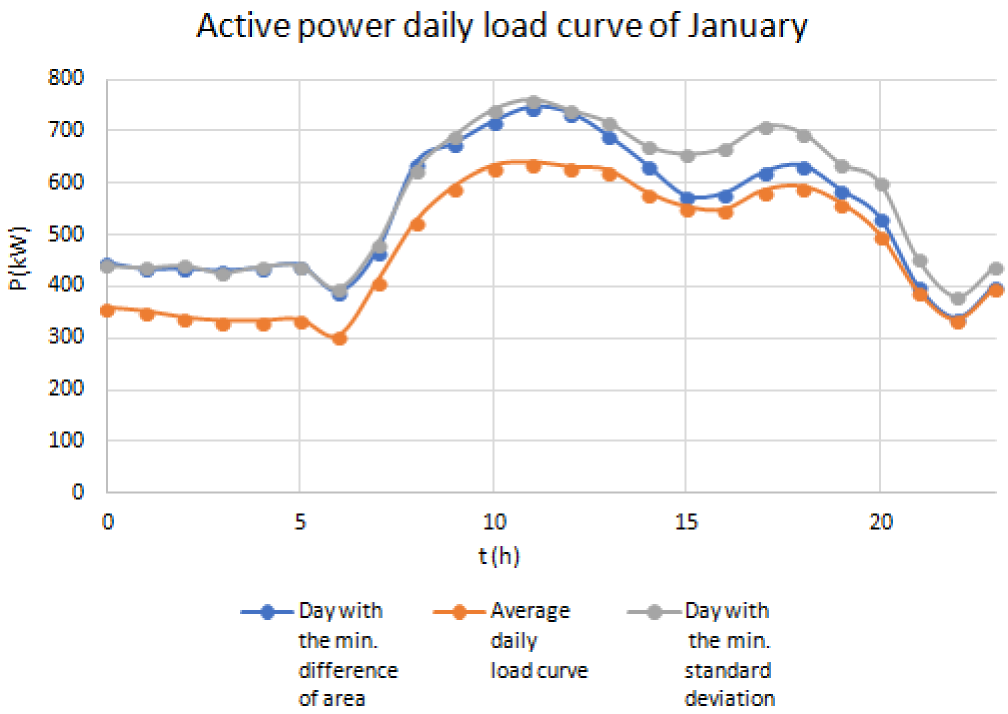

Illustration 6-1. Comparison of methods for the selection of the "model" daily load curve

Finally, the second method was chosen.

4. To obtain active and reactive energy consumed each day.
5. To select the days of the month with the biggest and the smallest active energy consumed. The same has to be done for reactive power.
6. To represent in 4 different spreadsheets the following graphs:
    - Active power daily load curve of weekday.
    - Active power daily load curve of weekend day.
    - Reactive power daily load curve of weekday.
    - Reactive power daily load curve of weekend day.

    On each graph, the average daily load curve calculated will be represented, as well as the representative daily load curve, the daily load curve of the day with the highest energy consumed and the daily load curve of the day of the lowest energy consumed.

Finally, all daily load curves that had to be obtained are ready. Now, the same has to be done with the remaining months. For that, it is only necessary to paste the data of each month on the worksheet "Datos" and excel will return the corresponding daily load curves.

The functions used and the problems that have arisen doing this task are explained in detail in *Annex 1. Calculations* .

6.1.3. Daily load curves obtained

Daily load curves obtained for each month are collected in *Annex 2. Daily Load Curves*.

6.2. Analysis of the Solar Cooling Plant

In this section, one of the current generation resources of the School of Engineering will be characterized, the Solar Cooling Plant (SCP). The objective is to know how much electric energy this resource saves the School.

This DR is a pilot project of "Gas Natural" to demonstrate the viability of this technology for the air conditioning of buildings. This technology takes advantage of solar energy to produce cool or heat using a Fresnel type collector (shown in *Illustration 6-2*) that reflects radiation from flat linear collectors to an absorber tube through which water circulates. The pilot plant works in parallel with the cooling system of the School. To find more detailed information about the SCP, go to [10] and [11].

Illustration 6-2. Solar Cooling Plant of the School of Engineering

Concretely, two situations should be characterized: one in which the Solar Plant is working and another in which the Plant is not working. Since the Solar Plant works in cooling mode in summer and in heating mode in winter[8], the situation in which the Plant is working will be different depending on the season, that is, the energy produced will be different depending on the season.

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[8] Actually, the Solar Plant works in cooling mode from April to October and in heating mode from November to March, but only summer and winter are mentioned to abridge the scope of the essay.

Then, to know how much energy the Solar Plant saves for the School of Engineering, the following steps are proposed:

- To obtain the average cooling energy the Solar Plant produces on a typical summer day and the average heating energy it produces on a typical winter day.
- To obtain the average number of hours the Plant works on a typical summer day and on a typical winter day.
- Having the previous values, the average cooling and heating power produced by the Solar Plant can be obtained.
- To consult the COP[9] of a cooling industrial equipment with the cooling and heating power previously obtained. Doing that, the electric energy consumed can be obtained by an air conditioning equipment that produces the same energy that the Solar Plant supplies. And, this electric energy consumed is, approximately, the electric energy the Solar Plant saves for the School.

To obtain the prior information, two End-of-Degree's Projects about the Solar Cooling Plant have been used [10], [11]. Finally, the information has been taken from [10] because the data are more recent than in [11] and, in addition, the first includes data of the accumulator that was added to the plant later.

6.2.1. Operation data according to the seasonal mode

In this section, a summary of the yearly operation of the Solar Cooling Plant is presented. The objective is to show how the average cooling and heating energy produced by the Plant has been obtained.

The information presented has been taken from [10] where the Plant operation was analysed during 2011. The operation during 2011 has been divided in two periods: one period from April to October in which the plant worked in cooling mode and another from November to March in which it worked in heating mode. On each period, the Solar Plant covers part of the heating or cooling demand of the School.

6.2.1.1. Cooling mode

In *Illustration 6-3*, operating days of the plant working in cooling mode are presented[10]:

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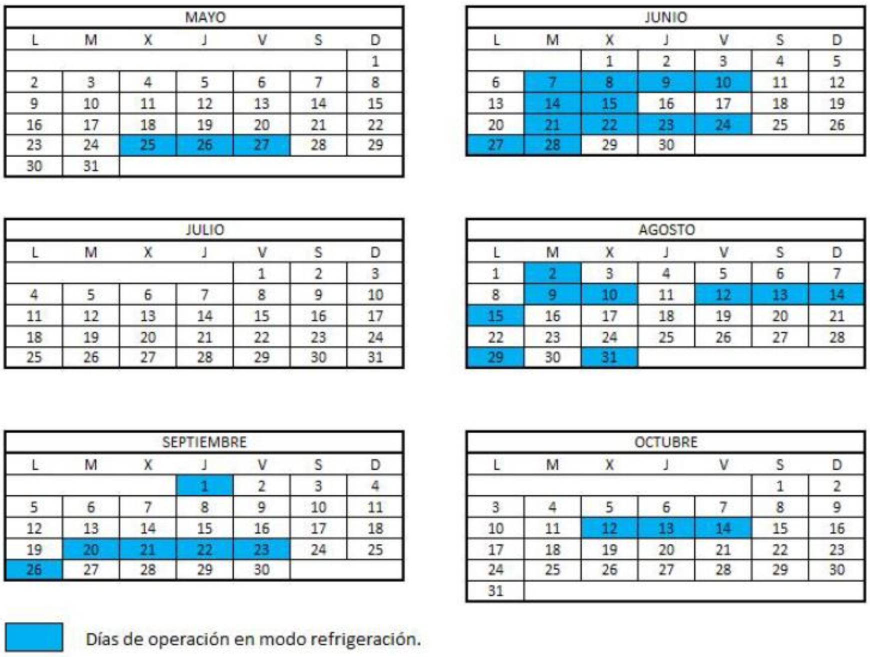
[9] The coefficient of performance (COP) of an air conditioning equipment is the quotient between the useful work of the equipment and the electric power consumed. In the case of a cooling equipment, the useful work is the heat extracted from the environment and in the case of a heating equipment, it is the heat introduced to the environment.

[10] The change to cooling mode was made on April but correct data were not taken until May.



MAYO

L	M	X	J	V	S	D
						1
2	3	4	5	6	7	8
9	10	11	12	13	14	15
16	17	18	19	20	21	22
23	24	25	26	27	28	29
30	31					

JUNIO

L	M	X	J	V	S	D
		1	2	3	4	5
6	7	8	9	10	11	12
13	14	15	16	17	18	19
20	21	22	23	24	25	26
27	28	29	30			

JULIO

L	M	X	J	V	S	D
				1	2	3
4	5	6	7	8	9	10
11	12	13	14	15	16	17
18	19	20	21	22	23	24
25	26	27	28	29	30	31

AGOSTO

L	M	X	J	V	S	D
1	2	3	4	5	6	7
8	9	10	11	12	13	14
15	16	17	18	19	20	21
22	23	24	25	26	27	28
29	30	31				

SEPTIEMBRE

L	M	X	J	V	S	D
			1	2	3	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30		

OCTUBRE

L	M	X	J	V	S	D
					1	2
3	4	5	6	7	8	9
10	11	12	13	14	15	16
17	18	19	20	21	22	23
24	25	26	27	28	29	30
31						

🟦 Días de operación en modo refrigeración.

Illustration 6-3. Operating days of the Solar Plant working in cooling mode

As it can be seen in the figure, there are a lot of days in which the plant does not work. But, the objective here is not to characterize what days the plant works and what days it does not. The information to be obtained is only how much energy the plant saves the School when it works.

And now, in *Illustration 6-4*, the evolution of the cooling power during a summer day is shown. In it, there is contribution of natural gas when there is not enough power in the solar circuit:

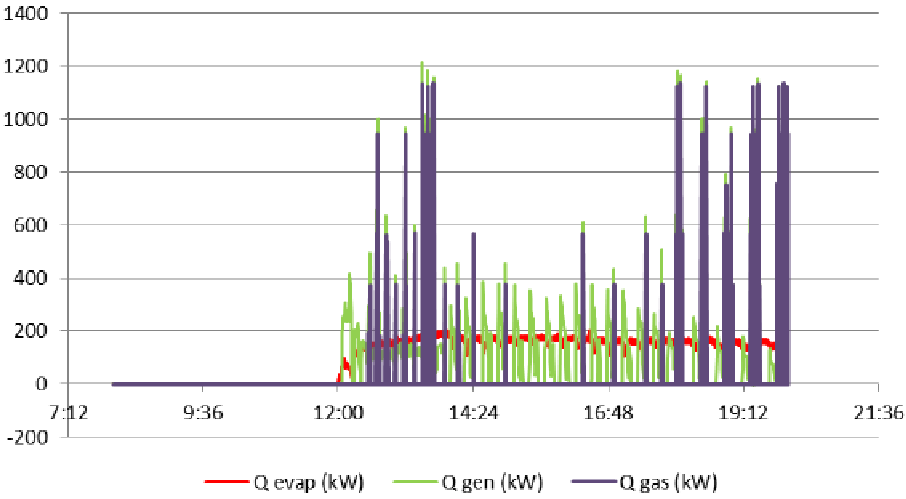


Illustration 6-4. Energy exchange in the absorption machine in cooling mode

In the prior graphic three powers are represented: the cooling power produced by the absorption machine (Qevap), the power provided by the natural gas combustion (Qgas) and the power provided to the generator (Qgen) that fluctuates a lot because of the solar component. The importance of that graphic is that it gives an idea of the number of hours that the Solar Plant works during a typical day of summer. It will be considered that it works 7,5 hours.

In the project consulted, the author took data of the main energy exchanges in the days in which the Plant worked in cooling mode and provides average values. Concretely, the average cooling energy the absorption machine produces on a typical summer day (Ema,f) is taken. Actually, the value in which we are interested is the cooling energy that is provided to the School that is equal to the cooling energy the absorption machine produces less the losses in the cooling circuit. But these losses are so small that the two energies are almost equal.

$$E_{ma,f} = 1102\ kWh \qquad \textbf{\textit{(6-1)}}$$

$$P_{ma,f} = \frac{E_{ma,f}}{h} = \frac{1102\ kWh}{7{,}5\ h} = 147\ kW \qquad \textbf{\textit{(6-2)}}$$

Hence, having the average cooling energy produced and the number of hours the plant works approximately on a typical summer day, the average cooling power produced during the operating hours of the plant (Pmaf) is 147 kW. That is, the daily power curve has been approximated by a step (as it can be seen in *Illustration 6-5*).

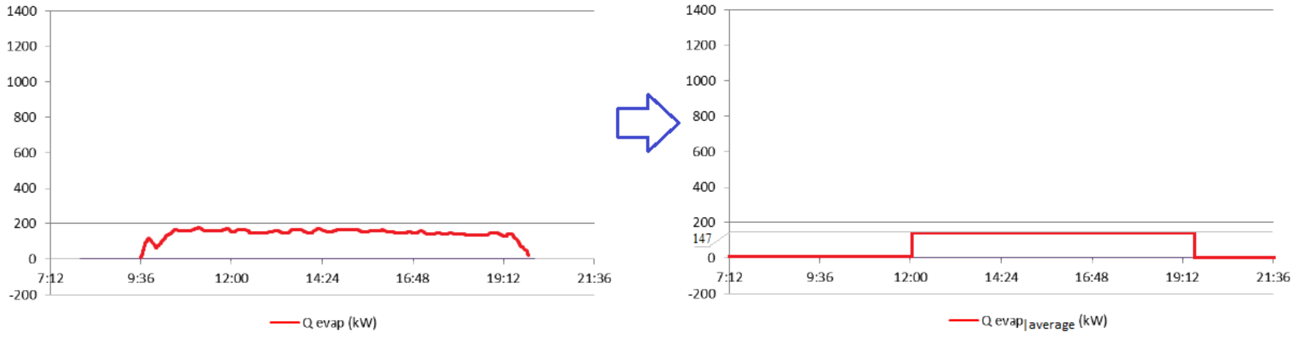
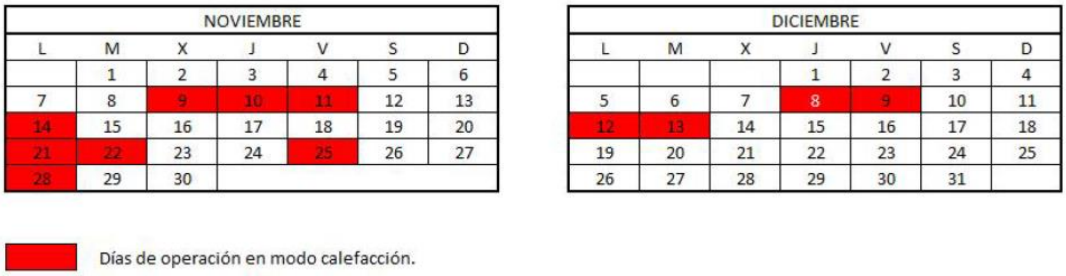


Illustration 6-5. Approximation of the power curve

6.2.1.2. Heating mode

Next, in *Illustration 6-6*, operating days of the plant in heating mode are presented[11]:



NOVIEMBRE

L	M	X	J	V	S	D
	1	2	3	4	5	6
7	8	🟥 9	🟥 10	🟥 11	12	13
🟥 14	15	16	17	18	19	20
🟥 21	🟥 22	23	24	🟥 25	26	27
🟥 28	29	30				

DICIEMBRE

L	M	X	J	V	S	D
			1	2	3	4
5	6	7	🟥 8	🟥 9	10	11
🟥 12	🟥 13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

🟥 Días de operación en modo calefacción.

Illustration 6-6. Operating days of the Solar Plant working in heating mode

As in the previous subsection, the evolution of the heating power during a winter day in which there is contribution of natural gas when there is not enough power in the solar circuit (*Illustration 6-7)* is shown.

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[11] The Solar plant also worked in heating mode from January to April, but incorrect data were taken in that period.

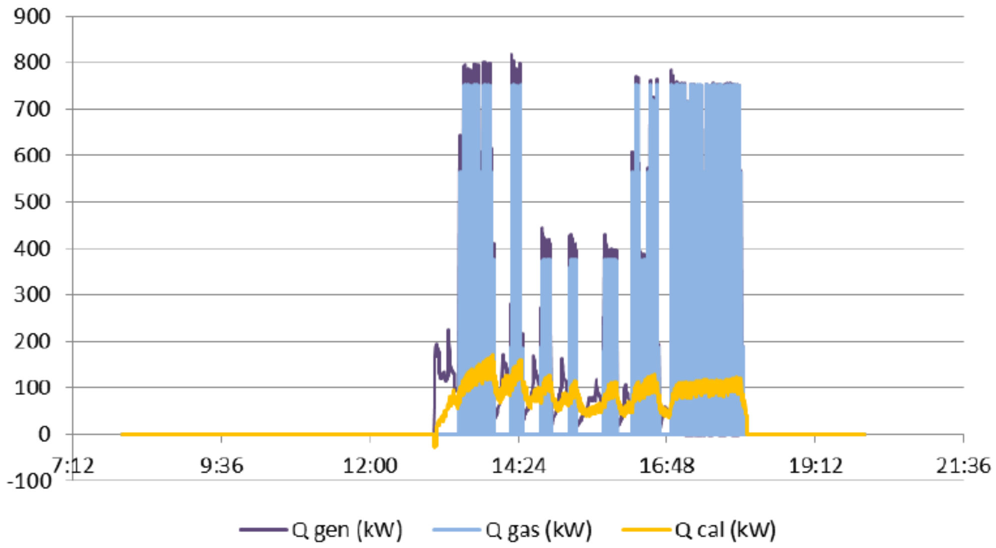


Illustration 6-7. Energy exchange in the absorption machine in heating mode

In the above graphic, the heating power produced by the absorption machine (Qcal) is represented. In this case, the power evolution is more variable but, as in cooling mode, the curve will be approximated by a step. Since the importance of the graphic is the operation time of the plant, it will be considered that it works 5 hours.

As in the prior subsection, the author took data of the main energy exchanges in the days in which the Plant worked in heating mode and provides average values. In this case, the average heating energy the absorption machine produces on a typical winter day (Ema,c) is taken.

$$E_{ma,c} = 289\ kWh \qquad (6\text{-}3)$$

$$P_{ma,c} = \frac{E_{ma,f}}{h} = \frac{289\ kWh}{5\ h} = 58\ kW \qquad (6\text{-}4)$$

The average heating power produced on a typical winter day (Pmac) is 58 kW.

6.2.2. Electric energy savings provided by the Solar Plant

Having the average cooling and heating power produced by the Solar Plant, the COP of a refrigerating machine has to be consulted with these cooling and heating powers. To know what refrigerating machine should be consulted, the refrigeration system of the School of Engineering will be analysed and then information in a catalogue will be studied.

6.2.2.1. Refrigeration system of the School

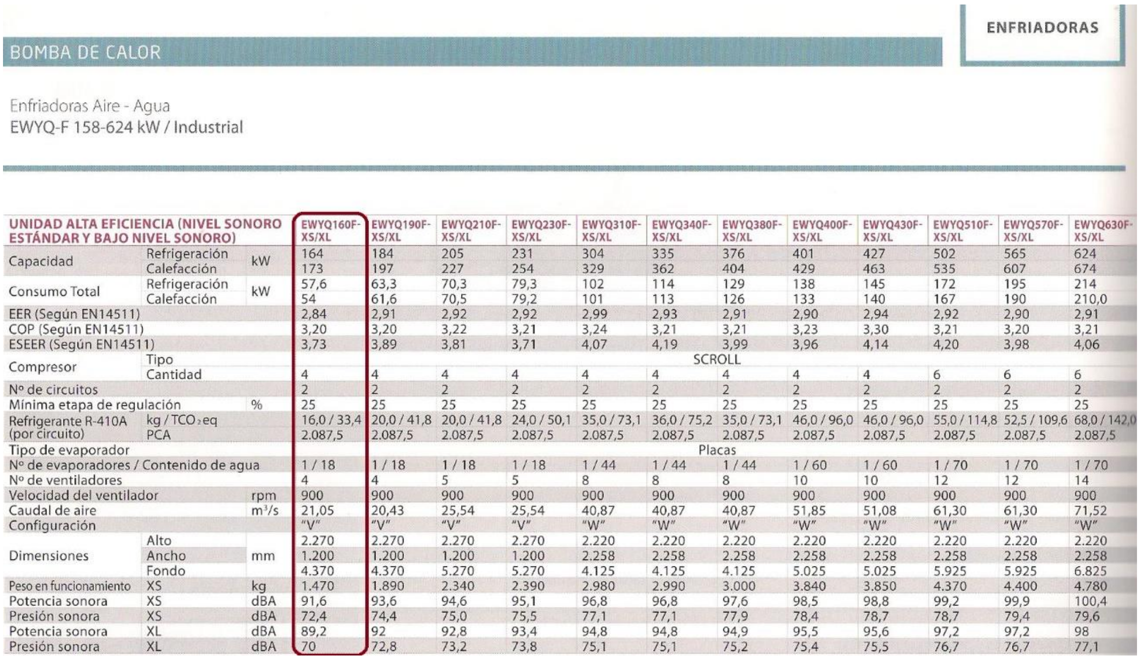
This system is constituted by an air handling unit (AHU) whose function is to treat the basic air parameters: renovation and cleanliness (low content of particles and dust), temperature control (both in summer and in winter) and relative humidity control. This system does not produce cool or heat by itself, but it comes from an external source, which in this case is a refrigerating machine [12].

The refrigerating machine is a reversible heat pump[12] that produces both cool and heat. That heat pump is of the air-water type, that is, it takes heat from the outdoor air and cedes it to the water that circulates through a water heating system [13].

The objective of this section is to discover how much energy the Solar Plant saves the School. It was proposed to consult the COP of a refrigerating machine, that now is well-known and is a reversible heat pump. That was proposed because the cooling or heating power the Solar Plant produces is power the reversible heat pump no longer has to produce. Hence, it is interesting to know the electricity consumption of the heat pump to give the cooling or heating power that now provides the Solar Plant. Because, that is energy that the Solar Plant saves for the School. But doing this, an error is being committed: the COP of a heat pump depends on its size, that is, its power. Hence, the COP of a heat pump with the cooling and heating power the Solar Plant produces will be slightly different to the COP of the real heat pump of the School. But, as it was mentioned in other occasions, it is an approximate study, thus, this error is assumed.

6.2.2.2. Obtaining of the COP and the electric energy savings

The COP has been studied in a catalogue of Daikin of 2017 [14]. The product studied is a reversible, air-water heat pump of industrial type. The product specifications are shown in *Illustration 6-8*.



ENFRIADORAS

BOMBA DE CALOR

Enfriadoras Aire - Agua
EWYQ-F 158-624 kW / Industrial

UNIDAD ALTA EFICIENCIA (NIVEL SONORO ESTÁNDAR Y BAJO NIVEL SONORO)			EWYQ160F-XS/XL	EWYQ190F-XS/XL	EWYQ210F-XS/XL	EWYQ230F-XS/XL	EWYQ310F-XS/XL	EWYQ340F-XS/XL	EWYQ380F-XS/XL	EWYQ400F-XS/XL	EWYQ430F-XS/XL	EWYQ510F-XS/XL	EWYQ570F-XS/XL	EWYQ630F-XS/XL
Capacidad	Refrigeración	kW	164	184	205	231	304	335	376	401	427	502	565	624
	Calefacción		173	197	227	254	329	362	404	429	463	535	607	674
Consumo Total	Refrigeración	kW	57,6	63,3	70,3	79,3	102	114	129	138	145	172	195	214
	Calefacción		54	61,6	70,5	79,2	101	113	126	133	140	167	190	210,0
EER (Según EN14511)			2,84	2,91	2,92	2,92	2,99	2,93	2,91	2,90	2,94	2,92	2,90	2,91
COP (Según EN14511)			3,20	3,20	3,22	3,21	3,24	3,21	3,21	3,23	3,30	3,21	3,20	3,21
ESEER (Según EN14511)			3,73	3,89	3,81	3,71	4,07	4,19	3,99	3,96	4,14	4,20	3,98	4,06
Compresor	Tipo		SCROLL											
	Cantidad		4	4	4	4	4	4	4	4	4	6	6	6
Nº de circuitos			2	2	2	2	2	2	2	2	2	2	2	2
Mínima etapa de regulación		%	25	25	25	25	25	25	25	25	25	25	25	25
Refrigerante R-410A (por circuito)	kg / TCO_2eq		16,0 / 33,4	20,0 / 41,8	20,0 / 41,8	24,0 / 50,1	35,0 / 73,1	36,0 / 75,2	35,0 / 73,1	46,0 / 96,0	46,0 / 96,0	55,0 / 114,8	52,5 / 109,6	68,0 / 142,0
	PCA		2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5	2.087,5
Tipo de evaporador			Placas											
Nº de evaporadores / Contenido de agua			1 / 18	1 / 18	1 / 18	1 / 18	1 / 44	1 / 44	1 / 44	1 / 60	1 / 60	1 / 70	1 / 70	1 / 70
Nº de ventiladores			4	4	5	5	8	8	8	10	10	12	12	14
Velocidad del ventilador		rpm	900	900	900	900	900	900	900	900	900	900	900	900
Caudal de aire		m^3/s	21,05	20,43	25,54	25,54	40,87	40,87	40,87	51,85	51,08	61,30	61,30	71,52
Configuración			"V"	"V"	"V"	"V"	"W"	"W"	"W"	"W"	"W"	"W"	"W"	"W"
Dimensiones	Alto	mm	2.270	2.270	2.270	2.270	2.220	2.220	2.220	2.220	2.220	2.220	2.220	2.220
	Ancho		1.200	1.200	1.200	1.200	2.258	2.258	2.258	2.258	2.258	2.258	2.258	2.258
	Fondo		4.370	4.370	5.270	5.270	4.125	4.125	4.125	5.025	5.025	5.925	5.925	6.825
Peso en funcionamiento	XS	kg	1.470	1.890	2.340	2.390	2.980	2.990	3.000	3.840	3.850	4.370	4.400	4.780
Potencia sonora	XS	dBA	91,6	93,6	94,6	95,1	96,8	96,8	97,6	98,5	98,8	99,2	99,9	100,4
Presión sonora	XS	dBA	72,4	74,4	75,0	75,5	77,1	77,1	77,9	78,4	78,7	78,7	79,4	79,6
Potencia sonora	XL	dBA	89,2	92	92,8	93,4	94,8	94,8	94,9	95,5	95,6	97,2	97,2	98
Presión sonora	XL	dBA	70	72,8	73,2	73,8	75,1	75,1	75,2	75,4	75,5	76,7	76,7	77,1

Illustration 6-8. Industrial heat pump of Daikin's Catalogue

The chosen heat pump has a rated cooling power of 164 kW and a rated heating power of 173 kW. This equipment has been chosen because it has the closest cooling power to 147 kW, the average cooling power the Solar plant produces. Since the heating power produced by the Solar plant is much lower than the rated heating power of an industrial heat pump, only the cooling power has been taken into account for the choice. In case the

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[12] This machine has an electric valve that changes the circulation sense of refrigerating fluid when the change winter-summer and vice versa happens. When the valve acts, the evaporator become more condense and conversely.

heat pump had to produce the 58 kW of heating power the Solar plant produces, it would run at partial load with fewer compressors working and this would affect the COP. Actually, in the School, there is a reversible heat pump of a much greater power: the cooling or heating power has to be provided to the whole building. Therefore, the Solar Plant action causes the real heat pump to operate at a level slightly below the rated load and in this case, the COP would be almost equal the rated COP. For this reason, the COP used to obtain the electric power consumed in the case of heating and cooling will be the rated COP.

Until now, a single COP has been mentioned but there are two COPs: one for cooling, that is known as EER and another for heating that is known as COP. The EER of the heat pump chosen is 2,84 and the COP is 3,2. Having the EER and the COP and the average cooling and heating power, the electric power consumed on each case can be obtained.

In the cooling case:

$$EER = \frac{Q_F}{W} \Rightarrow W = \frac{Q_F}{EER} = \frac{Q_{ma,f}}{EER} = \frac{147\ kW}{2{,}84} = 51{,}8\ kW \tag{6-5}$$

where:

Q_F is the cooling power in kW;

W is the electric power consumed in cooling mode in kW;

The previous equation means that to obtain 147 kW of thermal power (of cooling), the heat pump has to consume 51,8 kW of electrical power. Thus, the daily electric energy consumed by the equipment can be obtained as follows:

$$E_{cool} = W \cdot t = 51{,}8kW \cdot 7{,}5h = 388{,}5\ kWh \tag{6-6}$$

In the heating case:

$$COP = \frac{Q_C}{W} \Rightarrow W = \frac{Q_C}{COP} = \frac{Q_{ma,c}}{COP} = \frac{58\ kW}{3{,}2} = 18\ kW \tag{6-7}$$

$$E_{heat} = W \cdot t = 18kW \cdot 5h = 90\ kWh \tag{6-8}$$

where:

Q_C is the heating power in kW;

W is the electric power consumed in heating mode in kW;

The previous equation means that to obtain 58 kW of thermal power (of heating), the heat pump has to consume 18 kW of electrical power. The daily electric energy consumed by the equipment is 90 kWh.

Finally, the daily electric energy the Solar Cooling Plant saves the School is 388,5 kWh in cooling mode and 90 kWh in heating mode, approximately.

6.3. Analysis of the Backup Generator Set

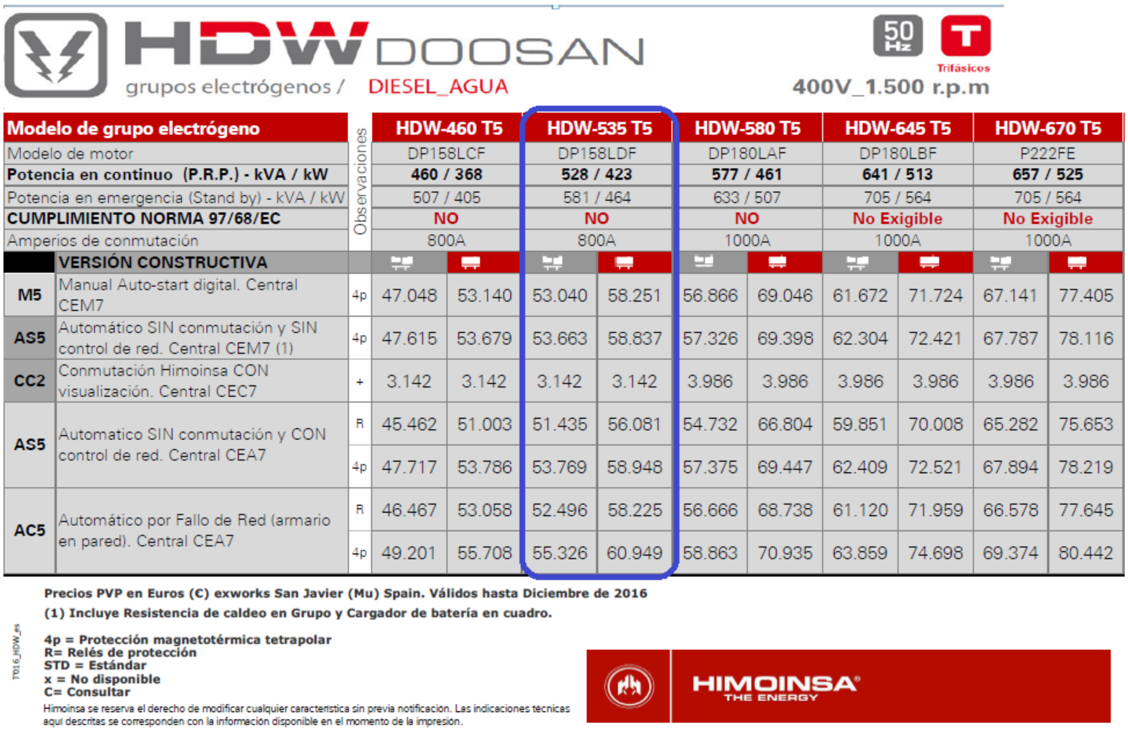
In this section, the other generation resource that the School counts on will be characterized: the generator set. As opposed to the previous case, there is no information about the generator set of the School, thus it will be necessary to make suppositions.

As it was mentioned in section 5.3, the information needed for each DR is its rated power and how it operates and in what conditions. This information will be detailed in the next subsections.

6.3.1. Rated power

Since the rated power of the generator set is unknown and the percentage of emergency loads is also unknown (if at least this information was well-known, the generator set could be sized), the generator rated power will be determined according the available consumption information. Hence, based on the consumption pattern defined in section 6.1, it could be considered that a generator set of 500 kW could be enough to cover the emergency loads.

Second, to be closer to a real case, a generator set will be selected from a catalogue considering the prior rated power. A catalogue from HIMOINSA company[13] of 2016 [15] is going to be used to select a generator set of the required rated power. The product selected is a diesel generator set whose specifications are shown in *Illustration 6-9.*



HDW DOOSAN
grupos electrógenos / DIESEL_AGUA

50 Hz
Trifásicos
400V_1.500 r.p.m

Modelo de grupo electrógeno		Observaciones	HDW-460 T5		HDW-535 T5		HDW-580 T5		HDW-645 T5		HDW-670 T5	
Modelo de motor			DP158LCF		DP158LDF		DP180LAF		DP180LBF		P222FE	
Potencia en continuo (P.R.P.) - kVA / kW			**460 / 368**		**528 / 423**		**577 / 461**		**641 / 513**		**657 / 525**	
Potencia en emergencia (Stand by) - kVA / kW			507 / 405		581 / 464		633 / 507		705 / 564		705 / 564	
CUMPLIMIENTO NORMA 97/68/EC			**NO**		**NO**		**NO**		**No Exigible**		**No Exigible**	
Amperios de conmutación			800A		800A		1000A		1000A		1000A	
	VERSIÓN CONSTRUCTIVA											
M5	Manual Auto-start digital. Central CEM7	4p	47.048	53.140	53.040	58.251	56.866	69.046	61.672	71.724	67.141	77.405
AS5	Automático SIN conmutación y SIN control de red. Central CEM7 (1)	4p	47.615	53.679	53.663	58.837	57.326	69.398	62.304	72.421	67.787	78.116
CC2	Conmutación Himoinsa CON visualización. Central CEC7	+	3.142	3.142	3.142	3.142	3.986	3.986	3.986	3.986	3.986	3.986
AS5	Automatico SIN conmutación y CON control de red. Central CEA7	R	45.462	51.003	51.435	56.081	54.732	66.804	59.851	70.008	65.282	75.653
		4p	47.717	53.786	53.769	58.948	57.375	69.447	62.409	72.521	67.894	78.219
AC5	Automático por Fallo de Red (armario en pared). Central CEA7	R	46.467	53.058	52.496	58.225	56.666	68.738	61.120	71.959	66.578	77.645
		4p	49.201	55.708	55.326	60.949	58.863	70.935	63.859	74.698	69.374	80.442

Precios PVP en Euros (€) exworks San Javier (Mu) Spain. Válidos hasta Diciembre de 2016

(1) Incluye Resistencia de caldeo en Grupo y Cargador de batería en cuadro.

T016_HDW_es

4p = Protección magnetotérmica tetrapolar
R= Relés de protección
STD = Estándar
x = No disponible
C= Consultar

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HIMOINSA® THE ENERGY

Illustration 6-9. Diesel Generator Set of the HIMOINSA catalogue

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[13] It is a company specialized in the design, manufacture and distribution of power generation equipment, from diesel and gas generator sets to hybrid generators and generators sets ready to be incorporated into solar power systems.

The chosen generator set has a rated power of 423 kW in continuous service and a standby power of 464 kW. It is a three-phase generator, of 50 Hz, 400 V and 1500 rmp. The prices of the different constructive versions that have two modalities are specified in the table: soundproof in red, and not soundproof in grey.

6.3.2. Operating mode

One of the most important aspect of this generation resource is that when the microgrid works in island mode, the generator set will be the voltage and frequency source of the island, that is, it will be the resource that energizes the system when the microgrid is not fed by the main network. In addition, this DR will carry out the primary frequency response.

6.4. Sizing of the Photovoltaic Plant

Since the School of Engineering has to count on enough distributed resources that let it works in island mode, a Photovoltaic (PV) Plant that covers part of the consumption needs of the School is going to be designed.

To design the PV plant, the program *PVsyst* will be used. It is a very powerful software to design and study PV plants. A very important feature of the program is that provides hourly simulations, allowing to compare the hourly generation data with the hourly consumption data that were obtained in section 6.1.

The process to design the PV plant will be explained in the next subsections together with the considerations that have been made.

6.4.1. Operating scenarios of the PV plant

The PV plant will be of the grid-connected type for self-consumption of all the electricity produced and two situations will be considered:

- PV plant without storage (operating scenario 1).
- PV plant with storage (operating scenario 2).

6.4.1.1. Operating scenario 1

It is the scenario in which the PV plant supplies the School without ever surpassing the consumption of the building. To meet this requirement, the PV plant should be designed to supply the day with the lowest consumption, which in theory could be a weekend day or a non-work day, but it is unknown a priopri what will be the day with less consumption. On the other hand, there is no need to be so restrictive because in order to have a zero-energy injection, the facility should be provided with a zero-injection meter[14]. Taking this into account and with the idea of designing a PV plant that supplies a representative part of the consumption, the PV plant should be designed for the representative weekday of the month with the lowest minimum power consumed during solar hours.

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[14] This device allows to handle the production of a PV grid-connected plant with self-consumption in order to avoid surplus injection to the grid.

In addition, in this scenario, one sub-scenario should be considered in which the Solar Cooling Plant is working and another in which is not working.

6.4.1.2. Operating scenario 2

It is the scenario in which, besides the PV plant, the School counts on storage resources. Hence, when the generation of the PV plant surpasses the consumption of the School, the surplus could be injected on the batteries with no need of zero-injection meter actuation.

As in the previous operating scenario, the PV plant will be designed for the sub-scenario in which the SCP is working and another in which is not working.

6.4.2. Methodology to follow

To each operating mode the methodology is different because the generation objectives are different.

6.4.2.1. Operating scenario 1

To search for the rated power of the PV plant in this scenario, two data sources have been used:

1. The consumption data of representative day of each month, that is, the representative daily load curve of each month.
2. The hourly consumption data of the whole year.

Both data sources have been used to compare results, since hourly data are more accurate but, from the beginning, the idea was to compare representative monthly consumption data. On each case, a data treatment has been necessary to compare generation and consumption data. This data treatment has been developed in excel and it will be explained next.

The methodology to follow on each case is described next:

1. To assign a rated power to the PV plant. Start with a small rated power.
2. To obtain the generation data.
3. To match up the generation and consumption data.
4. If negative net consumption does not exist, go back to step 1.

The methodology consists on a trial and error test in which, starting from a small rated power of the PV plant, the rated power that covers the maximum possible consumption without making the net consumption negative will be obtained.

6.4.2.2. Operating scenario 2

As it was mentioned in the past subsection, two data sources have been used to search for the rated power of the PV plant: monthly and hourly data. To design the storage system, it makes more sense to use hourly data because with monthly data the information is too synthesised.

The design of the storage system is going to be carried out in the *Sizing of the Storage System* section. The necessary storage system is going to be obtained to manage the consumption with the different rated powers of the PV plant designed in *Operating* *scenario 1*. Thus, different sizes of the storage system are going to be obtained, one per each rated power of the PV plant. The chosen storage system will be the one that has a reasonable size and this one, will determined the rated power of the PV plant that will be chosen finally.

6.4.3. PV plant design

Following the methodology previously explained, the estimated annual energy production (given for each hour) of a PV plant located in Seville is going to be calculated.

In the following subsections, the steps to design the PV plant in PVsyst are going to be explained.

6.4.3.1. Type of study

PVsyst allows to study different PV plants: grid-connected, stand alone, pumping and DC grid. A PV grid-connected plant for self-consumption is going to be designed.

Then, a main window appears that contains all the fields that must be defined.

6.4.3.2. Name of the study

First, the project name must be given. The name of this project will be "PV_Plant_TFM".

6.4.3.3. Location of the PV plant

There are different ways to obtain the meteorological data: the database of PVsyst can be used, as it provides meteorological data entering the location of the PV plant, or an external database can be used.

6.4.3.3.1. Sources of meteorological data [16]

PVsyst includes a meteorological database, "Meteonorm", and gives access to others that are available in the web and whose data can be imported in the program.

The databases that have data of Spain (Europe or worldwide), have hourly data and are free are collected in *Table 6-1*.

Table 6-1. Available databases that meet the requirements

Database	Region	Values	Source	Period	Variables	Availability	PVsyst import
Meteonorm	worldwide	Hourly	Synthetic generation	1960-1991 Averages 1995-2005 (V 6.0) Averages	Gh, Dh, Ta WindVel	Software	Direct by file
Satellight	Europe	Hourly	Meteosat Any pixel of about 5x7 km^2	1996-2000	Gh No Ta	Web free	Direct by file
WRDC	Worldwide	Hourly Daily Monthly	1195 stations	1964-1993 each	Gh No Ta	Web free	Direct by copy/paste

Since the most curent database is "Meteonorm" and is included in the software, is the database that is going to be used. This database provides hourly irradiance values that are not measured, but are synthetic data constructed from the monthly values[15]. The monthly values are available from about 1200 "stations" as averages of 1960-1991 (and also 1981-2000 in version 6.0, that is the version used). All "sations" of the main European countries are referenced in the PVsyst database. Data for any other site may be obtained by interpolation (usually between the 3 nearest "stations").

According to a recent study performed by the University of Geneva (that developed the program), the most reliable database in the market is SolarGIS, but is a paid access web.

6.4.3.3.2. Meteorological data of the PV plant

Since the database of PVsyst has been chosen, trough the localization tool of the program, the specific location of the School is introduced by its geographical coordinates: latitude 37.41, longitude -6 and altitude 34.

To know what geographical irradiance data the program uses to calculate the irradiance data of the School of Engineering, the Meteo database is analysed. In this database, data from a station located in Seville can be found. This station is located between East Seville and the airport, concretely its coordinates are: latitude 37.42, longitude -5.9 and altitude 23; and these data are supposed to be averaged within the period of 1991 to 2010. Hence, these are the data used to obtain the irradiance data of the School of Engineering.

According to the official website of Meteonorm [17], there are actually two stations in Seville, one that the program uses, and another located in Tablada, closer to the School but not considered in the program (as it can be seen in *Illustration 6-10*).

id: 809
WMO id: 83910
station: SEVILLA (CIV/MIL)
longitude: -5.9
latitude: 37.41
altitude: 31
station_type: 3

id: 808
WMO id: 83900
station: Sevilla/Tablada
longitude: -6
latitude: 37.37
altitude: 8
station_type: 10

Illustration 6-10. The two stations of Metenorm located in Seville

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[15] Synthetic data are "any data production applicable to a given situation that are not obtained by direct measurement". These data are generated to meet specific needs or certain conditions that may not be found in the original, real data [19]. In this case, the need is to obtain hourly data from monthly data.

6.4.3.4. Orientation and inclination

Selecting the tab “Orientation” a window where the field parameters are shown is opened. Those parameters, collected in *Illustration 6-11*, are the following:

- Field type: for a fixed PV facility, the option “Fixed Tilted Plane” or “Unlimited sheds” can be selected. When the first option is selected, losses produced by shading are calculated according to field layout. When the second option is selected, losses produced by shading can be optimized depending on the distance between sheds. In this case, the option “Fixed Tilted Plane” will be selected.
- Plane tilt: it is 30° by default and will not be modified.
- Azimuth[16]: it is 0° by default and will not be modified.

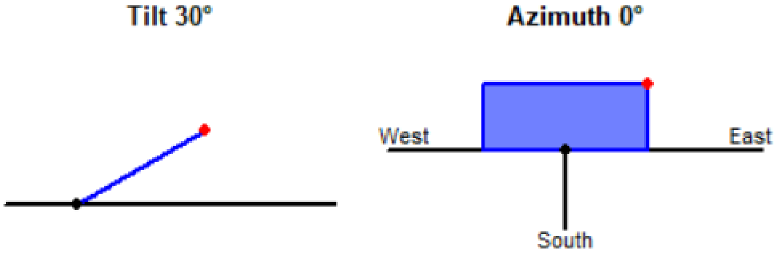

Illustration 6-11. Field parameters[17].

6.4.3.5. Grid-connected system elements

Selecting the tab “System” a window where the system elements can be chosen appears. These elements are listed next:

- PV module
- Inverter

To count on a current element catalogue as reference, the catalogue of “Albasolar”[18] of 2017 [18] is going to be used.

6.4.3.5.1. PV module

The program counts on a wide database of PV modules. To reduce the search, the catalogue of “Albasolar” is going to be studied. In the section of grid connected modules, a list of PV modules appears (shown in *Illustration 6-12*).

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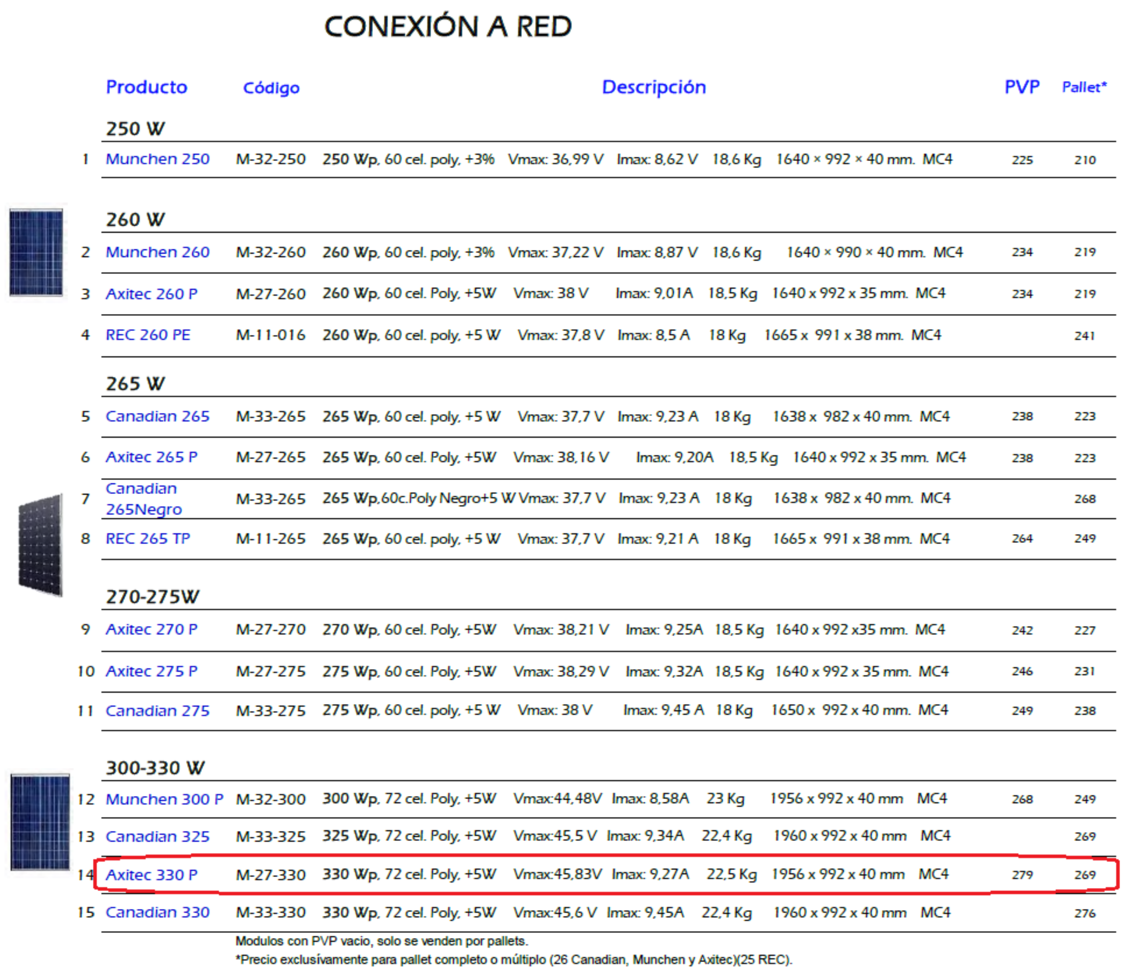
[16] Azimuth angle is defined as the angle between the projection on the horizontal plane of the normal to the surface of the module and the meridian of the place [19].

[17] The plane tilt and azimuth necessary to achieve the maximum solar energy caption are those in which solar rays fall upon the surface vertically. Since the solar position changes at all times, the ideal facility would be the one that counts on a mechanism that follows the solar trajectory, that it is not the case.

[18] “Albasolar” is a company specialised in the distribution of photovoltaic material.



CONEXIÓN A RED

	Producto	Código	Descripción	PVP	Pallet*
	250 W				
1	Munchen 250	M-32-250	250 Wp, 60 cel. poly, +3% Vmax: 36,99 V Imax: 8,62 V 18,6 Kg 1640 × 992 × 40 mm. MC4	225	210
	260 W				
2	Munchen 260	M-32-260	260 Wp, 60 cel. poly, +3% Vmax: 37,22 V Imax: 8,87 V 18,6 Kg 1640 × 990 × 40 mm. MC4	234	219
3	Axitec 260 P	M-27-260	260 Wp, 60 cel. Poly, +5W Vmax: 38 V Imax: 9,01A 18,5 Kg 1640 x 992 x 35 mm. MC4	234	219
4	REC 260 PE	M-11-016	260 Wp, 60 cel. poly, +5 W Vmax: 37,8 V Imax: 8,5 A 18 Kg 1665 x 991 x 38 mm. MC4		241
	265 W				
5	Canadian 265	M-33-265	265 Wp, 60 cel. poly, +5 W Vmax: 37,7 V Imax: 9,23 A 18 Kg 1638 x 982 x 40 mm. MC4	238	223
6	Axitec 265 P	M-27-265	265 Wp, 60 cel. Poly, +5W Vmax: 38,16 V Imax: 9,20A 18,5 Kg 1640 x 992 x 35 mm. MC4	238	223
7	Canadian 265Negro	M-33-265	265 Wp,60c.Poly Negro+5 W Vmax: 37,7 V Imax: 9,23 A 18 Kg 1638 x 982 x 40 mm. MC4		268
8	REC 265 TP	M-11-265	265 Wp, 60 cel. poly, +5 W Vmax: 37,7 V Imax: 9,21 A 18 Kg 1665 x 991 x 38 mm. MC4	264	249
	270-275W				
9	Axitec 270 P	M-27-270	270 Wp, 60 cel. Poly, +5W Vmax: 38,21 V Imax: 9,25A 18,5 Kg 1640 x 992 x35 mm. MC4	242	227
10	Axitec 275 P	M-27-275	275 Wp, 60 cel. Poly, +5W Vmax: 38,29 V Imax: 9,32A 18,5 Kg 1640 x 992 x 35 mm. MC4	246	231
11	Canadian 275	M-33-275	275 Wp, 60 cel. poly, +5 W Vmax: 38 V Imax: 9,45 A 18 Kg 1650 x 992 x 40 mm. MC4	249	238
	300-330 W				
12	Munchen 300 P	M-32-300	300 Wp, 72 cel. Poly, +5W Vmax:44,48V Imax: 8,58A 23 Kg 1956 x 992 x 40 mm MC4	268	249
13	Canadian 325	M-33-325	325 Wp, 72 cel. Poly, +5W Vmax:45,5 V Imax: 9,34A 22,4 Kg 1960 x 992 x 40 mm MC4		269
14	Axitec 330 P	M-27-330	330 Wp, 72 cel. Poly, +5W Vmax:45,83V Imax: 9,27A 22,5 Kg 1956 x 992 x 40 mm MC4	279	269
15	Canadian 330	M-33-330	330 Wp, 72 cel. Poly, +5W Vmax:45,6 V Imax: 9,45A 22,4 Kg 1960 x 992 x 40 mm MC4		276

Modulos con PVP vacio, solo se venden por pallets.
*Precio exclusívamente para pallet completo o múltiplo (26 Canadian, Munchen y Axitec)(25 REC).

Illustration 6-12. "Albasolar" catalogue; Grid-connected modules

The chosen PV module is from the company “Axitec Energy” and has 330 W. This manufacturer is included in the database of the program and thus, it can be selected directly with no need to enter its data. The power of the chosen module is the largest in the list since less space will be necessary with higher power modules.

6.4.3.5.2. Inverter

The chosen inverter depends on the rated power of the PV plant. Concretely, the rated power of the inverter will be the same or slightly lower than the rated power of the PV plant.

There are several well-known inverter manufacturers in the database: Greenpower, Sunpower, SMA, Siemens, ABB, Schneider, Ingeteam, etc. Generally, the inverter list of “Ingeteam” will be used, as it offers a wide variety of rated powers. On each test, the inverter that best matches the rated power of the PV plant will be selected.

6.4.4. Obtaining of results

The estimated annual energy production of the PV plant can be obtained in the tab “Simulation” and then in the tab “Output file”. The steps are the following:

1. To select the variable to be written on the spreadsheet file. In this case, the variable is the energy injected into the grid that is the energy production after considering all losses.
2. To write the filename in the section “Output on filename”.
3. To select the field format: select the separator “;” to obtain data in separate columns.
4. To go back to tab “Simulation” and select the option “Simulation”. After doing the simulation of the PV plant, a csv file appears in the folder “UserHourly” of the destination directory of the program.

6.4.5. Treatment of results

As it was described previously, two consumption data formats have been used: monthly and hourly consumption data. In the next subsections, the necessary calculations in Excel to obtain the consumption and generation data in both formats are going to be explained.

6.4.5.1. Monthly data

From the beginning, a representative daily load curve was decided to be obtained for each month to make future comparisons with monthly characteristic information.

6.4.5.1.1. Monthly consumption data

These data were obtained in the chapter “Building Consumption” and are collected in annex “2”.

6.4.5.1.2. Monthly generation data

Since the program provides hourly generation data, a representative daily generation curve must be obtained for each month to allow its comparison with the previous consumption data. To obtain data in this format, several calculations have been made in excel.

Next, steps carried out in excel are collected:

1. To calculate the average power produced in a day for each month (average daily generation curve), that is, calculate 24 hourly average power values for each month.
2. For each month, to select the day whose daily generation curve shape looks more like the average daily generation curve (representative daily generation curve).
3. For each month, to represent in a graph: the representative daily generation curve, the representative daily load curve and the net consumption (as a result of subtracting the generation curve to the load curve).

The functions used and the problems that have arisen doing this task are explained in detail in *Annex 1. Calculations* .

In the case the SCP is working, the Excel file has been modified to include the power contribution of this DR. Remember that the SCP works in cooling mode from April to October generating 51,8 kW between 12:00 and 19:30 hours and works in heating mode from November to March generating 18 kW between 12:30 and 16:30 hours (to simplify calculations, generation in heating mode has been shifted from 12:00 to 16:00).

6.4.5.1.3. Trial and error test

The prior spreadsheet allows us to enter hourly generation data and to obtain the net consumption curve. Hence, as the trial and error test explained in subsection 6.4.2.1 points out, the rated power PV plant that is adjusted with the consumption in the best way possible can be obtained. After doing the necessary tests, the more restrictive daily load curve is that of August, thus this will be the curve shown on each case tested.

The test is made when the SCP is working and when it is not working.

In the following illustrations the different cases tested when the SCP is not working are collected:

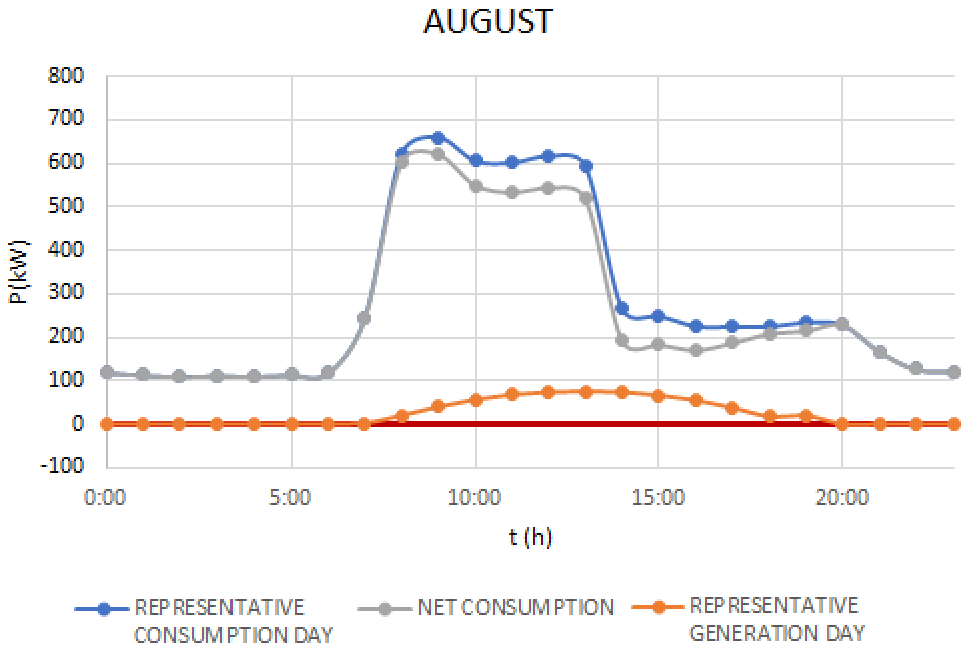


Illustration 6-13. Curves extracted from August with a rated power of the PV plant of 100 kW when the SCP is not working

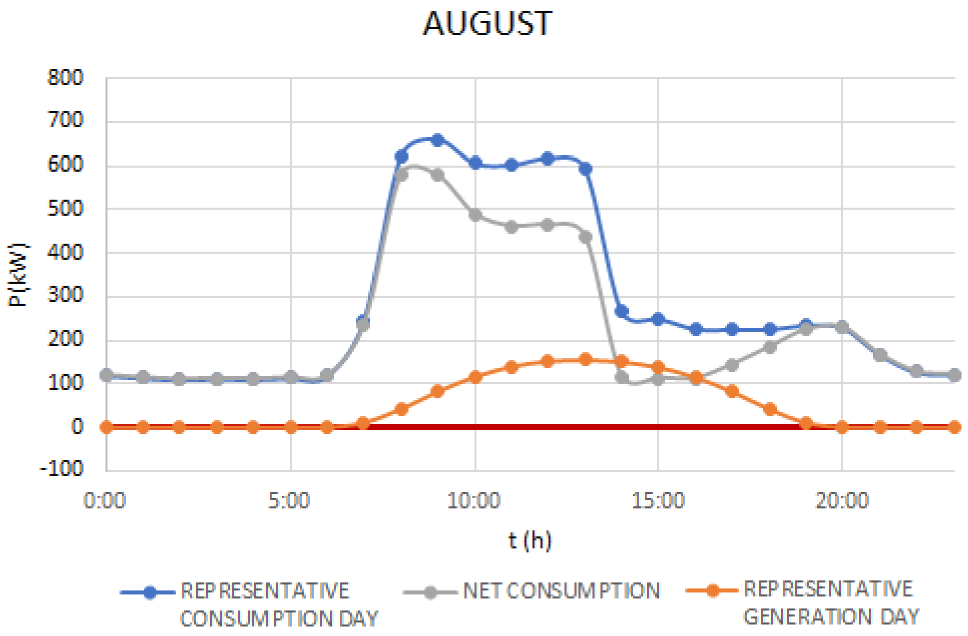


Illustration 6-14. Curves extracted from August with a rated power of the PV plant of 200 kW when the SCP is not working

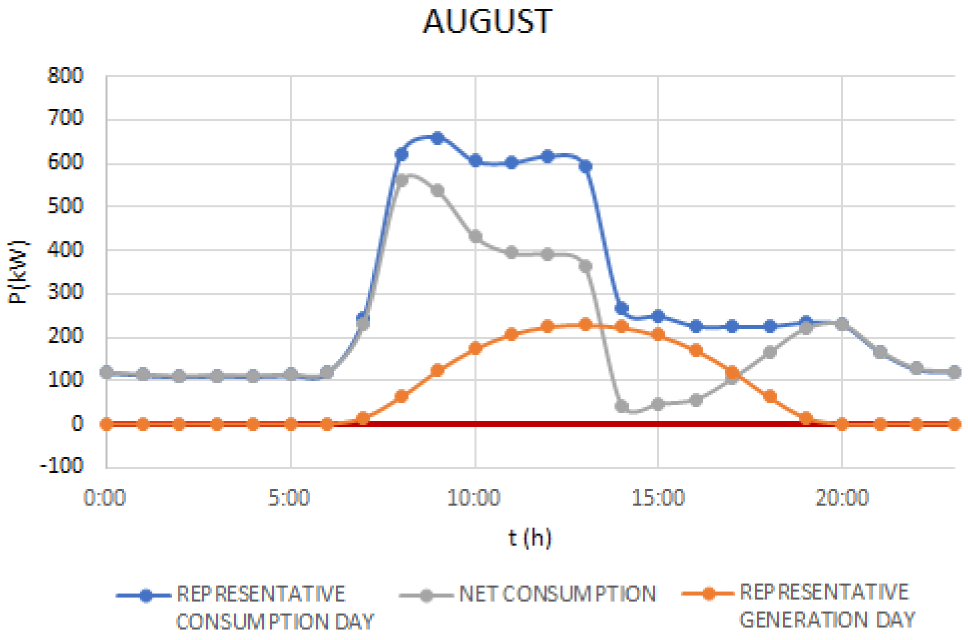


Illustration 6-15. Curves extracted from August with a rated power of the PV plant of 300 kW when the SCP is not working

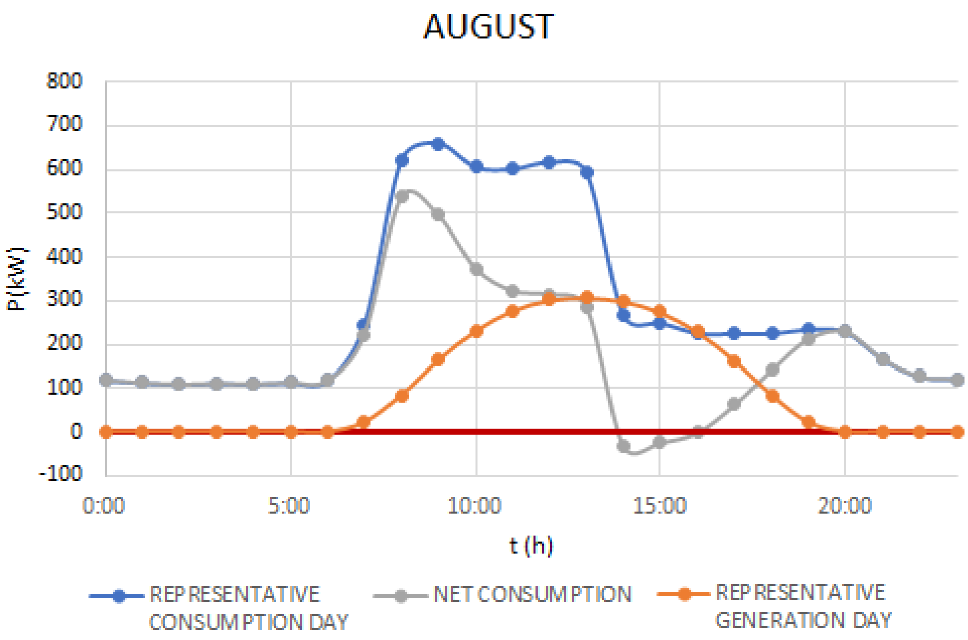


Illustration 6-16. Curves extracted from August with a rated power of the PV plant of 400 kW when the SCP is not working

The rated power of the PV plant studied is between 300 and 400 kW. Next, the test is made with a rated power of 350 kW.

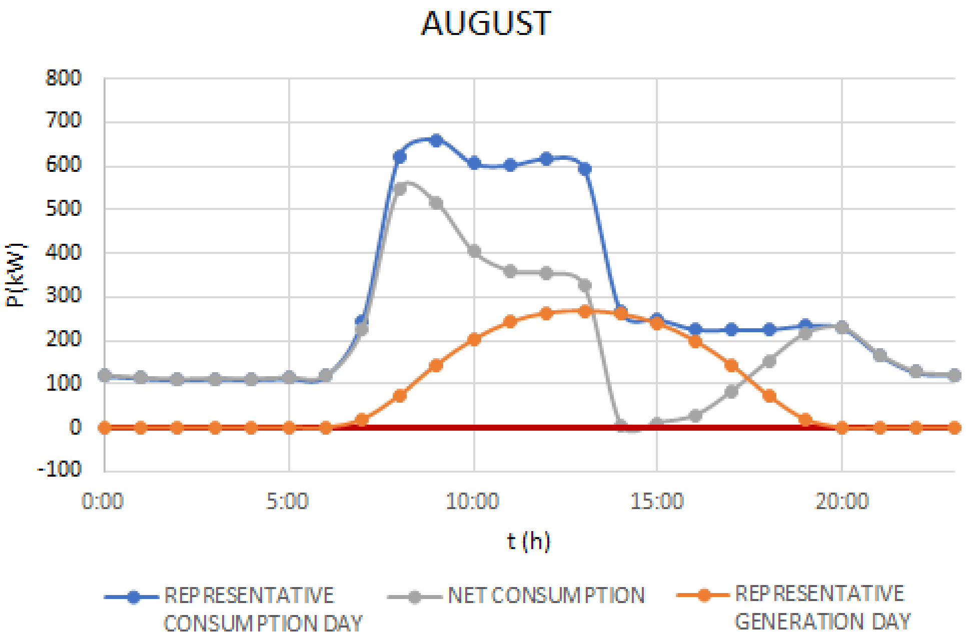


Illustration 6-17. Curves extracted from August with a rated power of the PV plant of 350 kW when the SCP is not working

In this case, the net consumption does not reach 0 but it stays very close, thus this value will be enough.

Now, the same will be done when the SCP is working. In the following illustrations, the different cases tested are collected:

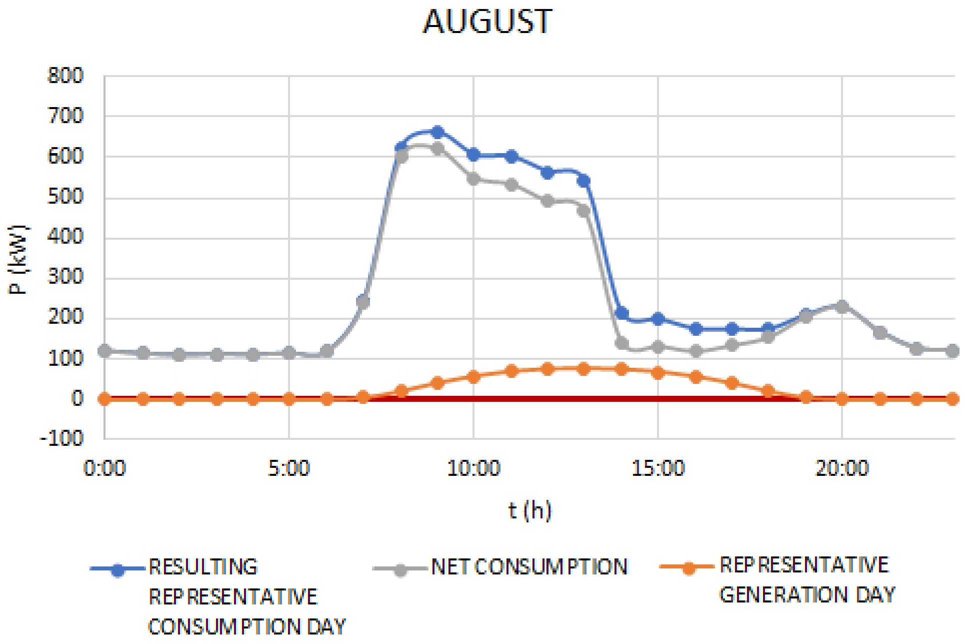


Illustration 6-18. Curves extracted from August with a rated power of the PV plant of 100 kW when the SCP is working

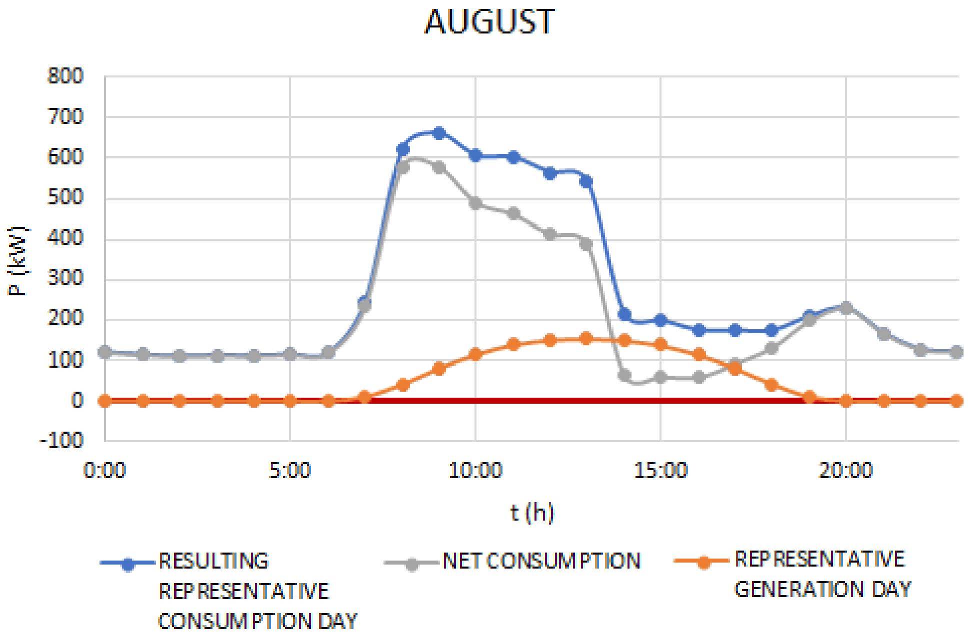


Illustration 6-19. Curves extracted from August with a rated power of the PV plant of 200 kW when the SCP is working

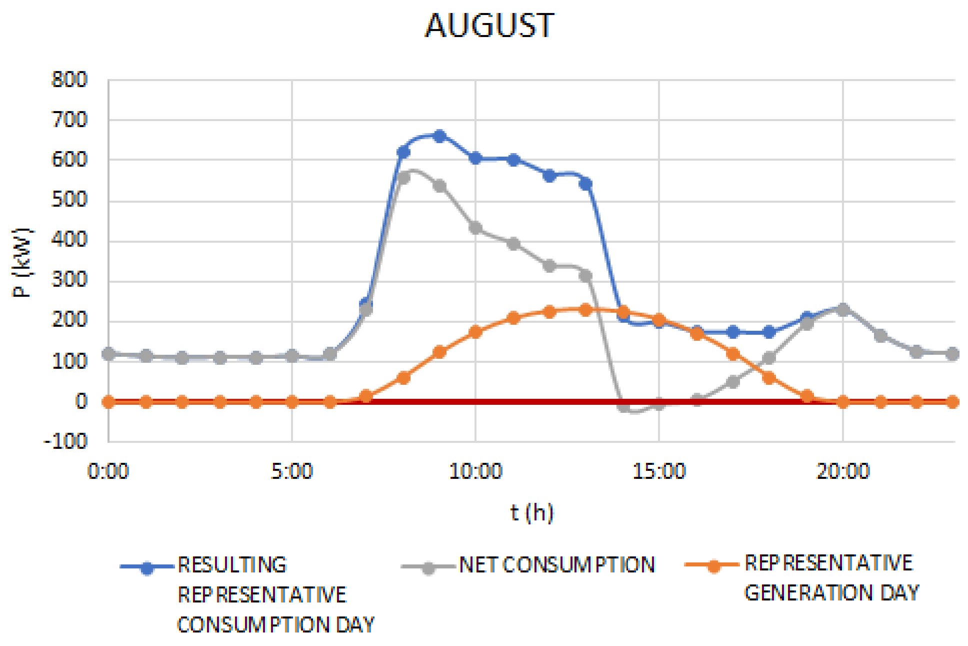


Illustration 6-20. Curves extracted from August with a rated power of the PV plant of 300 kW when the SCP is working

In this case, the net consumption is negative, but it stays very close to the zero consumption thus, this value will be enough.

In *Table 6-2*, the rated power of the PV plant elements used are collected:

Table 6-2. Rated power of the PV plant elements used in the tests

Pnom PV system (kW)	**System elements**	
100	PV module (Wp)	330
	Inverter (kW)	100
200	PV module (Wp)	330
	Inverter (kW)	200
350	PV module (Wp)	330
	Inverter (kW)	351
300	PV module (Wp)	330
	Inverter (kW)	300
400	PV module (Wp)	330
	Inverter (kW)	400

6.4.5.2. Hourly data

Since PVsyst provides hourly generation data of an entire year and we count on a spreadsheet of hourly consumption data, the comparison with hourly data was chosen to have a more accurate result and to know how many hours the net consumption is negative with the rated powers of the PV plant obtained with monthly data (it is supposed that with these rated powers the net consumption is never negative, but it is really not like that because using monthly data, information is compressed).

This case will only be analysed when the solar cooling plant is not working.

6.4.5.2.1. Hourly consumption data

Among data used for this project, there is a spreadsheet that contains consumption data every five minutes for a whole year. This information was treated to have hourly generation data but there are blank cells because all measures were not taken, or some were discarded. Hence, it is necessary to fill in blank cells with average consumption values.

To obtain data in this format, several steps have been made in excel:

- For each month, fill in blank cells with the corresponding average hourly power value.
- Create an excel file that contains hourly consumption of the whole year. In addition, in this file, hourly generation data will be introduced and the number of hours the net consumption is negative will be returned.

The functions used to do this task, are explained in detail in *Annex 1. Calculations* .

6.4.5.2.2. Hourly generation data

The program provides hourly generation data thus, the only necessary change has been to substitute the decimal separator "." by "," to allow to put data in number format.

6.4.5.2.3. Trial and error test

The spreadsheet created in subsection 6.4.5.2.1 allows to enter hourly generation data and to obtain the number of hours in which the net consumption is negative.

The rated power of the PV plant for which the net consumption is never negative is going to be obtained. Then, the number of hours the net consumption is negative will be obtained for the rated powers of the PV plant obtained with monthly data. This information is collected in *Table 6-3*.

Table 6-3. Percentage of hours per year the net consumption is negative

Pnom PV plant (kW)	Hours the net consumption is negative (%)
100	0
200	4,18
300	6,65
350	7,23
400	8,21

Observing *Table 6-3*, it can be seen that, using more accurate information, the rated power of the PV plant that never surpasses the consumption is 100 kW. On the other hand, using monthly data in the case in which the SCP is not working, it was obtained that the required rated power so as not to surpass the consumption is 350 kW. Actually, with that rated power the net consumption is negative during 7,23% hours of the year.

If the study of the PV plant was put into practice, the decision to take one or another rated power would come limited by the available space. This issue has not been addressed in this project because it is a draft. However, it has been considered that a possible location of the PV plant could be the car park in front of the School. The PV modules could be placed on a structure that provides shade to the car park.

6.5. Sizing of the Storage System

This chapter is dedicated to the sizing of an energy storage system for the possible microgrid of the School of Engineering. Counting on a storage resource involves that the microgrid can manage its generation or consumption. Next, the possible cases in which the storage can be used are collected:

- When there is surplus of generation, the storage system can absorb energy. This situation may arise in this case study during solar hours, in days of low consumption and high generation.
- When there is more consumption than generation. This situation is not a problem when the microgrid works in parallel with the area EPS, because the microgrid would import energy from the main grid. However, if the microgrid works in island mode and this situation occurs, two manoeuvres could be carried out:
    - To inject energy from storage system.
    - To carry out a strategy of load shedding if the energy from the different DR and the storage system is not enough to cover the consumption.
- The storage system can also be used to optimize the daily load curve, as for example, to reduce peak of power in hours of high electricity cost.

The situation in which this sizing study is focused is the use of storage when there is surplus of generation. As it was mentioned in section 6.4, a PV plant with storage was going to be sized in order to absorb the surplus generation when it was necessary. On the other hand, the second situation (more consumption than generation when the microgird works in island mode) is going to be analysed in section 6.5, once all DR have been studied. The last situation is not part of this preliminary study.

6.5.1. Analysis of the possible sizes

Starting from the information presented in *Table 6-3* and remembering that for the sizing of the storage system the hourly data are going to be used, a storage system is necessary when the PV plant has a rated power greater than 100 kW approximately.

For the different rated powers of the PV plant seen in section 6.4.5, the storage system necessary to absorb energy when the net consumption is negative has been sized. In Table 6-4 the prior information is collected.

Table 6-4. Energy and power of the storage system necessary for each rated power of the PV plant.

Pnom PV plant (kW)	E (kWh)	P (kW)
100	0	0
200	456	84
300	1047	166
350	1344	207

Observing *Table 6-4*, it can be seen that the storage system necessary for rated powers of the PV plant greater than 300 kW is very big and, therefore, very expensive. The storage system for a PV plant of 200 kW seems more reasonable.

6.5.2. Selection of the storage system

Until now, the type of storage system that would be used has not been addressed. Among the possible storage systems (of chemical, potential, kinetical or thermal energy), it has been though of storage of chemical energy, in particular, in batteries of Li-Ion.

As an example, one of the batteries made by Tesla[19] for applications on utility grids is proposed to be used. This battery, named “PowerPack” [19], has a rated power of 50 kW (CA) and a rated energy of 210 kWh (CA). With two modules of this battery (one of its characteristics is the scalability), the storage system would count on 100 kW of rated power and 220 kWh of rated energy, that it is, approximately, the power and energy needed to manage the surplus of energy with a PV plant of 200 kW.

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[19] Tesla is an American company that is specialized in the design and manufacturing of electric cars, lithium-ion battery energy storage, and residential photovoltaic panels. Among the batteries offered by Tesla are the Powerwall, for household applications and Powerpack, for applications in electric networks.

7. Conclusions and Future Work

Once the project has been explained, the conclusions of the study, as well as the future work are gathered. Since this project is a draft, its objective is to give a preliminary view that allows to develop the final investigation project. Due to the above, this study is not an exhaustive design and sizing project because some important data was not in our hands, thus, several considerations and hypothesis have been made. On the other hand, the information processing, both consumption and generation, has been made meticulously, in order to have a reliable base for future works on this project.

7.1. Starting considerations

As it was mentioned in the prior paragraph, several considerations have been made due to the lack of information. In relation to consumption, the following can be mentioned:

- Consumption data used for the study are from 2003 because recent consumption information of the School has been difficult to get. On the one hand, this information is very completed because contains active and reactive measures taken every five minutes throughout the whole year and, in addition, the measures have been depurated [9]. On the other hand, the information is from 13 years ago, hence, although the consumption pattern can be more or less the same, the total energy consumed has changed. Finally, these data were chosen for the study. In case of counting on recent consumption information, the different Excel programs created would allow to update load curves.
- There is relevant information about the loads that it is unknown: percentage of each kind of load (lighting, computer equipment, motors, etc.), large punctual loads, etc. Due to this lack of information, the coordination technique that is adjusted in the best way possible with generation capability and loads characteristics cannot be studied. Finally, a load-following technique is going to be followed.

In relation to generation, the following considerations can be mentioned:

- Regarding the backup generator set, to get information of this generation resource was not possible. Due to this, it has been necessary to suppose its rated power based on the consumption pattern of the building. Actually, this DER is essential when the microgrid works in island mode because it will be the voltage and frequency source of the system, thus, it is very relevant to know their rated power.

- With respect to the photovoltaic plant, the available space and the possible location have not been addressed because, it has been considered that, taking these variables into account for a preliminary study was not necessary.

7.2. Results

To put in practice the concepts studied about microgrids, a study of the consumption and generation of the School of Engineering is going to be carried out to design and size its generation capability to function as a microgrid. The results of this study are gathered next.

The School of Engineering working as microgrid would we a Nanogrid, with a main stakeholder: The University of Seville. Currently, the School counts on two distributed generation resources: A Solar Cooling Plant and a Backup generator set. To reach enough generation capability to function as a microgrid, to size a photovoltaic plant and a storage system is proposed. The control strategy of the School would be centralized considering stakeholders involved, the necessary investment and the magnitude of the system. The operation strategy of the microgrid would be an economic strategy that, in an indirect way, would also be environmental and, the benefits of a technical operation could be analysed.

The analyse of the consumption data of the building has allowed to obtain four representative daily load curves for each month: two of active power, of weekday and weekend day, and two of reactive power, of weekday and of weekend day.

Next, the results of the generation study are addressed.

The objective of studying the Solar Cooling Plant was to obtain the daily electric energy this resource saves for the refrigeration system of the School: in cooling mode the plant saves 355,5 kWh per day and in heating mode, 90 kWh per day.

In relation with the backup generator set, it is considered that its rated power is of 500 kW approximately, that would be enough to cover emergency loads. The backup generator set is a resource of vital importance when the microgrid works in island mode because it will be the voltage and frequency source of the system.

The sizing of the photovoltaic plant provides the rated power of the plant in different scenarios: without storage system and the SCP working and not working and with storage system. This study has been carried out with two data sources: monthly and hourly data. To use both data sources to compare results has been decided, since hourly data are more accurate but, from the beginning, the idea was to compare representative monthly data. Using monthly data, the results when there is no storage system are provided:

- The rated power of the PV plant when the SCP is not working is of 350 kW.
- The rated power of the PV plant when the SCP is working is of 300 kW.

Using hourly data, the results when there is no storage system are provided:

- The rated power of the PV plant when the SCP is not working is of 100 kW.

- The rated power of the PV plant when the SCP is working has not been studied but, without doubt, it will be lower than 100 kW.

As it would be expected, the results are not very close because, with monthly data, information is very summarized, but results obtained can give and idea of the needed rated power. The advantage of using hourly data is that the design adjusts better, avoiding to oversize equipment.

For the design of the storage system, using hourly data makes more sense. The situation in which is focused this sizing study is the use of storage when there is surplus of generation, in particular, of the PV plant (the SCP has not been taken into account because of the use of hourly data). Different sizes of the storage system have been obtained, one per each rated power of the PV plant. Considering a relationship of commitment between cost and storage capacity, a reasonable storage system would be that for a PV plant of 200 kW. The necessary storage system would be of 456 kWh and 84 kW.

7.3. Conclusions

Since this project has two parts, one theoretical part, obtained from the search of literature of the state of the art of microgrids and one practical part, obtained as a result of the application of the planning study of generation capability of a microgrid in the School of Engineering, the conclusions can also be divided in two parts, making reference to each one.

In relation with the theoretical study of microgrids, the following can be concluded:

- Each one of the clarifications derived from the concept of microgrids should be well understood in order to distinguish them from other passive grids penetrated by microsources. As more important concepts, microgrids usually work connected to the main grid but could work in an autonomous way when, for example, a fault occurs in the main grid, constituting this operation mode, one of their most interesting functionalities. It is also important to note that the optimization of the available resources characteristic of a microgrid derives from the active monitoring and control of these resources.
- The different types of microgrids are so varied and depend on a series of criteria such as magnitude of the system, normal operation mode, point of connection of the different resources, etc. thus, there is no a unique classification.
- Many of the studies that must be carried out to assure a good operation of the microgrid arise from the island mode operation. In that mode, a lot of considerations related with the fact that the system does not count on the support of the EPS must be considered: the fault current contribution of DERs is lower than the contribution of the EPS, the microgrid does not count on the inertia of the system, the Thevenin impedance of the microgrid is largely greater than the area EPS impedance, etc.
- Stakeholders involved in a microgrid can be carefully identified because many of the decisions related with control, operation, magnitude limits on island mode, etc. should be agreed among them.

- There is no much regulation about technical requirements for microgrid connection to the electric network. In this study, an IEEE standard that addresses the interconnection of distributed resources with the EPS has been consulted. It has been assumed that these requirements are applicable to microgrids, that are more than a grid with DRs. In addition, this standard is applied to American networks, thus, some requirements, such as frequency limits, are not directly applicable to a European network.

In relation with the case study of the project, the following can be concluded:

- As in any study, the available information is very important for the reliability of results obtained. In numerous occasions, to make suppositions due to the lack of information has been necessary but, these considerations are reasonable for this type of project: a draft or preliminary study.
- In the consumption study, the available data, although old, have allowed to obtain a representative daily load curve for each month. This simplified consumption pattern is very useful to make comparisons with generation and to have a general idea of the way to consume in the building.
- The study of the Solar Cooling Plant has allowed, besides to obtain the daily electric energy save provided by this resource to the School, to learn about an experimental technology based on solar energy for the air conditioning of buildings.
- After the trial and error tests for the design of the PV plant, it is concluded that the study with hourly data is more reliable and more useful because gives an idea of the number of hours per year that the generation surpass the consumption and, in addition, allows to size the storage system that would be necessary to manage the surplus of generation.
- The program PVsyst has been a very useful tool to obtain the estimated annual energy production of the PV plant. The fact to obtain hourly generation data has allowed to make a very completed comparison between generation and consumption.
- The scenario in which is considered the use of storage is much more interesting than the case in which is not use because, besides the main functionality for which has been conceived, it can be used for other interesting purposes such as the optimization of the daily load curve.

Finally, and giving a response to the objective defined in this project, a possible generation scenario for the operation of the School of Engineering as a microgrid has been obtained. Attending to the need of increasing the current generation capability of the building, it has been designed a PV plant that can go from lesser to greater rated power and, in this way, to cover more or less power demand, but with storage system, the solution is more limited.

7.4. Future work

Finally, this section addresses the future work necessary to continue with the study of an electric microgrid in the School of Engineering.

For the design of a microgrid, to carry out a broad study is necessary. This study takes a lot of requirements into account: requirements for loads, for DRs and requirements to assure a tight coordination between the microgrid and the area EPS. This study focuses on the generation capability planning of the active power of the School of Engineering to function as a microgrid.

In first place, and taking advantage of the consumption study, the reactive power that DRs should give to satisfy reactive power demand and the possible use of other resources such as capacitor banks could be studied.

In second place, a more detailed study of loads characteristics should be carried out, for which, it would be necessary to gather more information about loads: percentage of each kind of load (lighting, computer equipment, motors, etc.), unbalance percentage of loads, behavior of large punctual loads, etc. This would allow to define a tight coordination technique between generation and consumption.

In third place, and more related with the control of the microgrid, the voltage and frequency regulation could be studied when the microgrid works in parallel with the area EPS and when it works in island mode, operation mode in which to make specific actions may be necessary, such as to relax voltage or frequency limits.

Besides the prior proposals, there are much more studies to carry out because, as it was mentioned at the beginning of this section, the design of a microgrid is a broad study.

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Annex 1. Calculations for information processing

This annex contains the calculations carried out in excel to obtain consumption and generation data in the appropriate format.

Calculations of section 9

Next, the steps carried out in excel for one month are explained:

1. To obtain the average hourly power of all hours of the month from five-minute power values.

- To sum all the power values of one hour, the function "SUMIFS" has been used to sum power values that belong to a certain day and hour (that function allows to sum the values of cells that meet more than one criterion).
- There are 12 values of power for each hour (each measure is taken every five minutes). But, not all hours have 12 values of power. At the beginning, it has been decided to discard those hours and to operate only with hours that have all power values to simplify calculations.

2. To obtain the average daily load curve of the month.

- To divide hours in hours of weekdays and hours of weekend days, "INDEX" and "MATCH" functions have been used together. The "MATCH" function allows to select the rows that meet the following two criteria: the day and the hour. The "INDEX" function returns the value of a column for the row number given by "MATCH". Definitely, both functions allow to make a search with double criterion, action that cannot be carried out by the "VLOOKUP" function unless an additional column is created on the "data" worksheet.

  One problem that arises using the "MATCH" function is that it does not usually return the correct number row. The previous problem is because of the "MATCH" function with double criterion using the concatenation operator does not work as expected. Instead of looking for the day in column "A" and the hour in column "C" of the "data" worksheet, it looks for the concatenate value "day&hour" that matches with the concatenate value of "A" and "C" columns. As a result, the day number 11 and the hour number 0 can match with the day number 1 and the hour number 10 because the search is done with the concatenate value “110”. To solve this problem, the “MATCH” function has been modified to work with double criterion using the “IF” function instead of the concatenation operator. In that way, the two criteria are applied consecutively.

- The function “SUMIFS” has been used to sum all average power values of each hour of weekdays and weekend days. For that, the criteria used have been the hour, the kind of day and those values that have not been discarded for containing blank cells.
- It is necessary to know how many power values have been summed to get an average value of power for each hour. To obtain that number, the “COUNTIFS” function has been used. That function works the same as “SUMIFS”, that is, it counts the number of cells that meet a series of criteria. In that case, the criteria are those have been mentioned previously.
- Finally, with the total power and the number of values summed, the average hourly power of weekdays and weekend days has been obtained

3. To select the day whose daily load curve shape looks more like the daily load curve calculated. This curve will be the “model” (or representative) daily load curve.

- The average hourly power of each hour of the month must be subtracted to the corresponding average hourly power of the daily load curve calculated to obtain the difference of area between the daily load curve of each day and the average daily load curve. For that, the function “SUMIFS” is used.
- To compare the curve of each day with the curve calculated it is necessary to have 24 values of power of each curve. Previously, the hours with less than 12 values were discarded and that has made a lot of days don’t have 24 values of power. To fix this problem, it has been decided to obtain the average power of those hours with at least one value of power. That has allowed that 18 days were comparable in the case of January. To obtain the average hourly power considering that each hour can have a number of values between one and twelve, the function “COUNTIFS” has been used again.
- To obtain the day whose daily load curve shape looks more like the daily load curve calculated, it is necessary to calculate the standard deviation of the difference of area between curves. The day with the smallest standard deviation will be the day whose shape looks more like the daily load curve calculated. To do this, the “DESVEST.P” and “IF” functions have been used together to calculate the standard deviation of the values of difference of area (power) of each day doing a search with one criterion.
- To obtain the weekday and weekend day with the smallest standard deviation, it has been used the “MINIFS” function that allows to find the minimum value of a range of values applying one criterion (in this case, the criterion is the kind of day).

4. To obtain active and reactive energy consumed each day.

- For each day, the active and reactive energy consumed is obtained using the "SUMIFS" function that allows to sum the 24 power values of each day.

5. To select the days of the month with the biggest and the smallest active energy consumed. Do the same for reactive power.

- Applying a function "MINIFS" and "MAXIFS", the day with the biggest and the smallest active energy consumed, respectively, is obtained. The criterion applied to this function is that days compared are weekdays or weekend days.

6. To represent in 4 different spreadsheets the following graphs: active power daily load curve of weekday, active power daily load curve of weekend day, reactive power daily load curve of weekday and reactive power daily load curve of weekend day. On each graph, it is going to be represented: the average daily load curve calculated, the "model" (or representative) daily load curve, the daily load curve of the day with the highest energy consumed and the daily load curve of the day with the lowest energy consumed.

- "INDEX" and "MATCH" functions have been used together to update hourly power values of days selected.
- Power values are represented using dispersion graphs.

Calculations of section 11

Monthly generation data

Next, steps carried out in excel are collected:

1. To calculate the average power produced in a day for each month (average daily generation curve).

- First, for the 24 hours of the day, the total power produced on each hour has been obtained. For that, "SUMIFS" function has been used to sum powers that meet two criterions (a specific month and hour) within the range of hourly power of the whole year.
- To obtain the average hourly power, to know the number of addends of the total power value is necessary. To do this, "COUNTIFS" function has been used.
- Having the total power and the number of addends of each hour, the hourly average power can be calculated.

2. For each month, to select the day whose daily generation curve shape looks more like the average daily generation curve (representative daily generation curve).

- For each hour of the year, subtract its power value to the corresponding average hourly power value of the average daily generation curve. Thus, for each day of the year, a sample of values is obtained, whose standard deviation will give an idea of how much the curves are similar. To calculate these values, "MATCH" and "IF" functions have been used to make a search with double criterion.
- "DESVEST.P" and "IF" functions have been used together to calculate the standard deviation of the values of difference of power of each day doing a search with one criterion.

- To obtain the day with the smallest standard deviation, it has been used “MINIFS” function that allows to find the minimum value of a range of values applying one criterion (in this case, the criterion is the month).

3. For each month, to represent in a graph: the representative daily generation curve, the representative daily load curve and the net consumption (as a result of subtract the generation curve to the load curve).

- “INDEX” and “MATCH” functions have been used together to update hourly power values of days selected.
- Power values are represented using dispersion graphs.

Hourly consumption data

In this subsection, several steps have been made in excel:

1. For each month, to fill in blank cells whit the corresponding average hourly power value.

- The problem that arises doing this task is that blank cells do not have assigned the kind and number of day (remember that the kind of day could be weekday or weekend day and the number of day is the specific day of the week: Monday (1), Tuesday (2), Wednesday (3) and so on and so forth). To solve this problem, a column with every day of the month has been created and the corresponding number of day has been assigned making a search with “MATCH” and “IF” functions. This search cannot be made with “VLOOKUP” function because if the last coincidence found has a blank cell, it returns a blank cell.
- Having the previous information, the kind and number of day can be assigned to all hours of the month, even if they were blank cells. To do this, “VLOOKUP” function has been used.
- Having the hour and kind of day, a column that contains, for each hour of the month, the corresponding power of the average daily load curve, is created. For that, “INDEX” and “MATCH” functions are used to make a search with double criterion.
- Blank cells, which did not have power measurements, are assigned the corresponding power of the average daily load curve from the column that was created in the previous step.

2. To create an excel file that contains hourly consumption of the whole year. In addition, in this file, hourly generation data will be introduced and the number of hours the net consumption is negative will be returned.

- Consumption data obtained for each month in the previous step are introduced using “copy and paste” option.
- Generation data for each case tested will be introduced in other column using “copy and paste” option.
- Then, the difference between consumption and generation, the net consumption, will be calculated in another column.

- In other cell will be obtained the number of hours in which the net consumption is negative using “COUNTIFS” function.

Annex 2. Daily Load Curves

In this annex, the different consumption graphs obtained for each month have been collected. The graphs represented for each month are the following:

- Active power daily load curve of weekday.
- Active power daily load curve of weekend day.
- Reactive power daily load curve of weekday.
- Reactive power daily load curve of weekend day.

To reduce the space occupied by graphs, the legend has not been included. To know to what day is referred each curve, *Illustration 0-1* is presented.

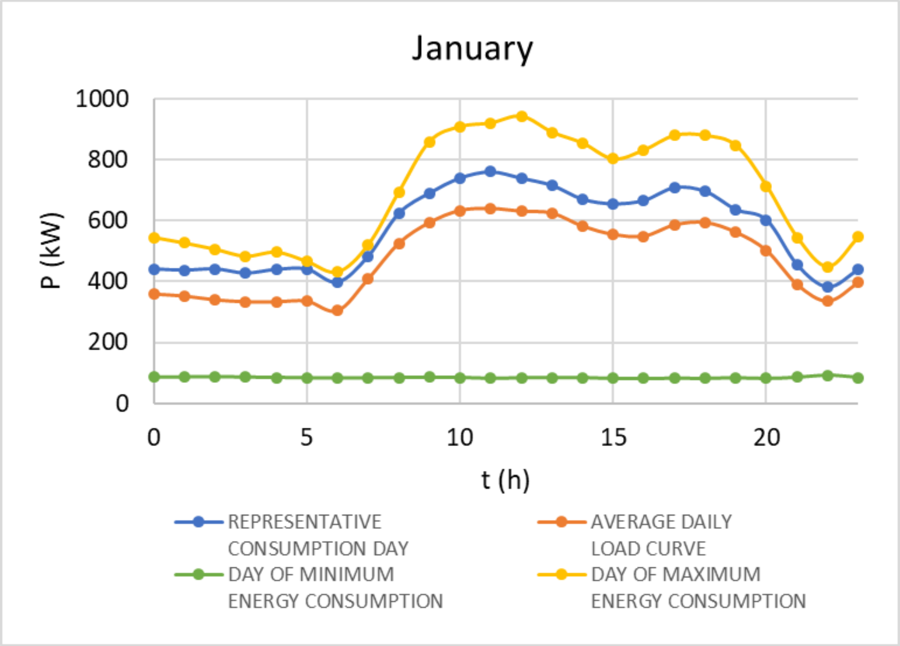
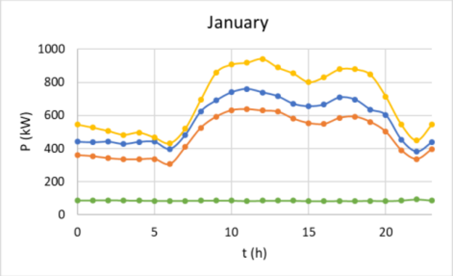
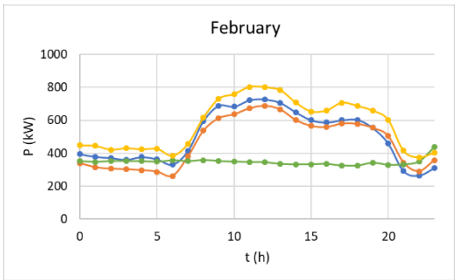


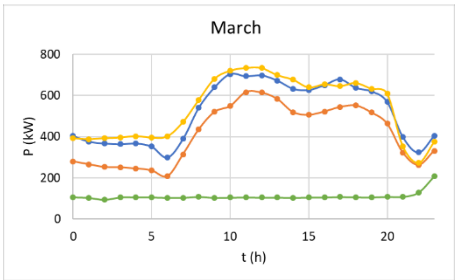
Illustration 0-1. Example of consumption graph: active power daily load curve of weekday of January

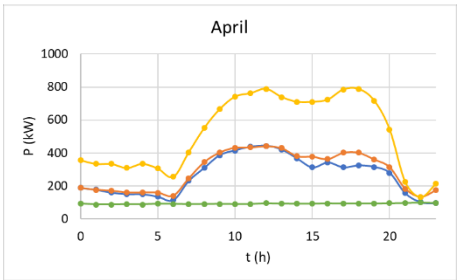
Observing the prior graph, it can be seen the colors associated to each curve (in all graphs, the same color code has been used).

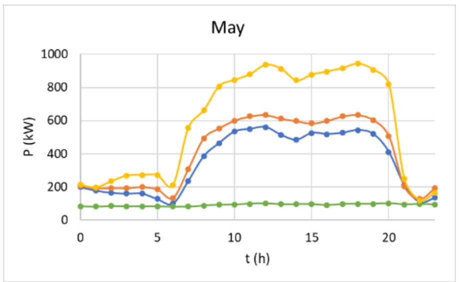
Daily load curves of active power of weekdays.

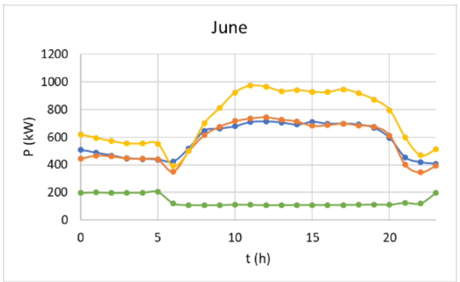


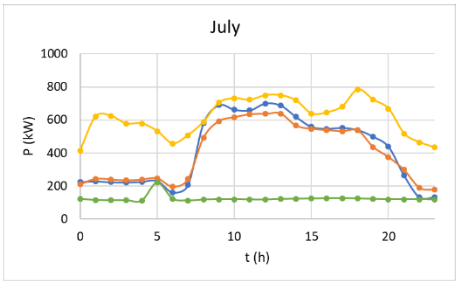


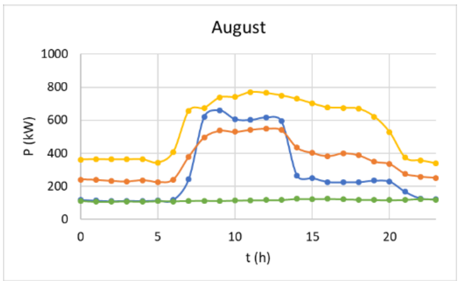


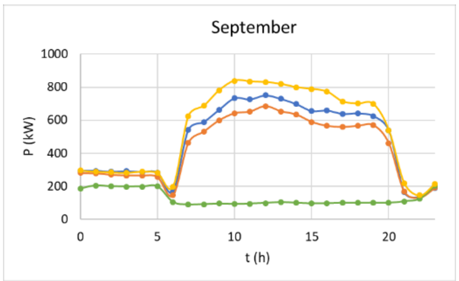


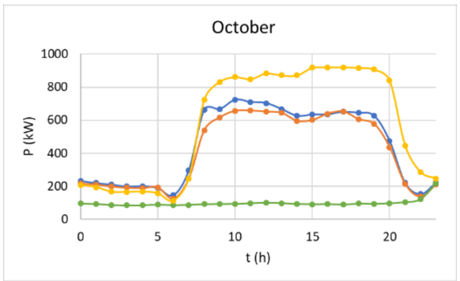


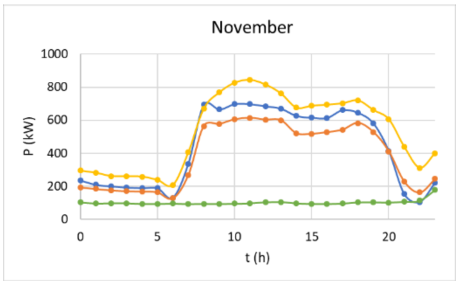


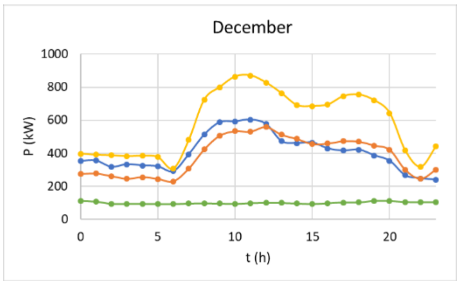




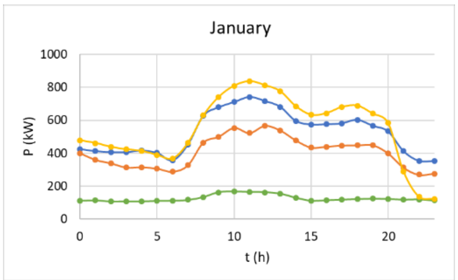


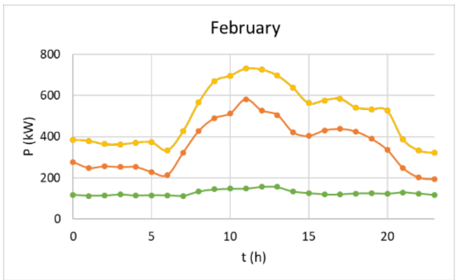


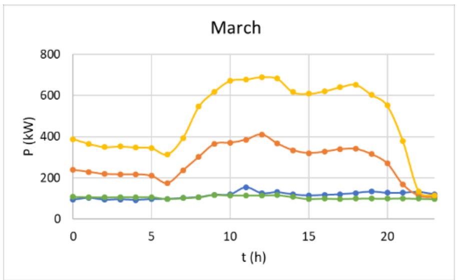


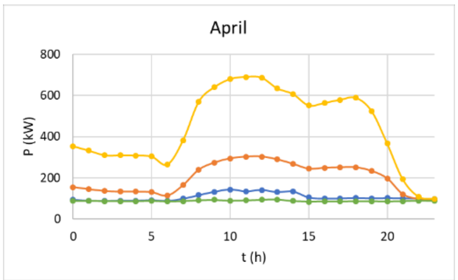


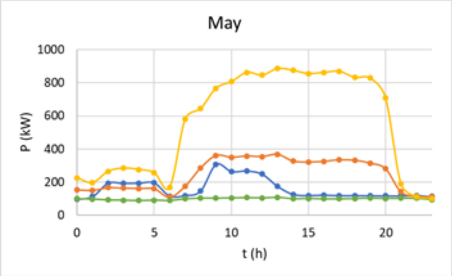
Daily load curves of active power of weekend days.

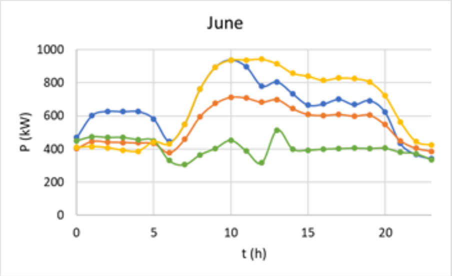


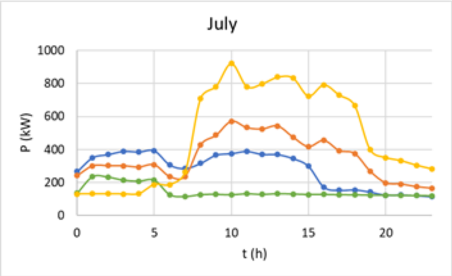


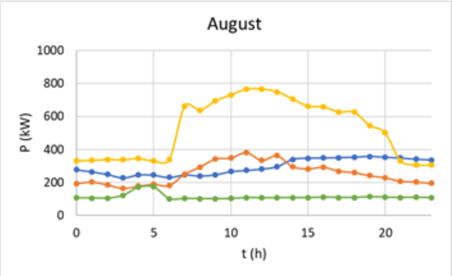


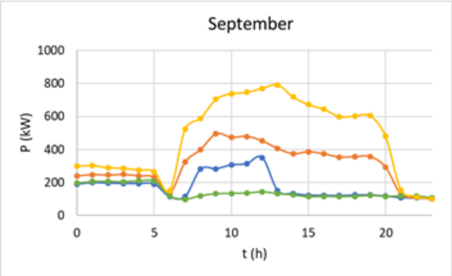


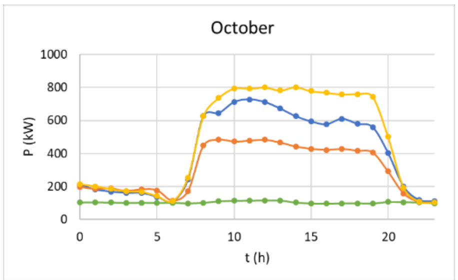


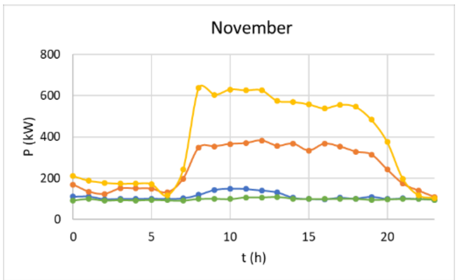


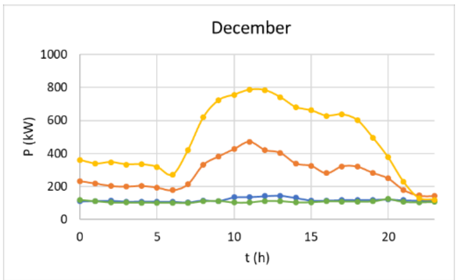




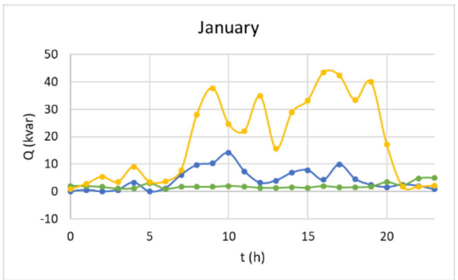


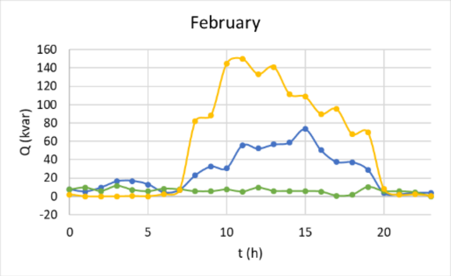


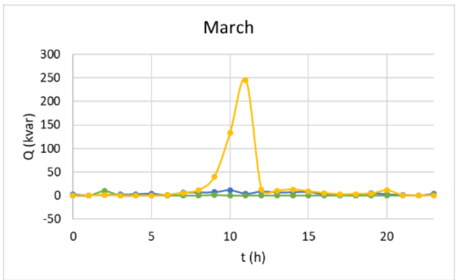


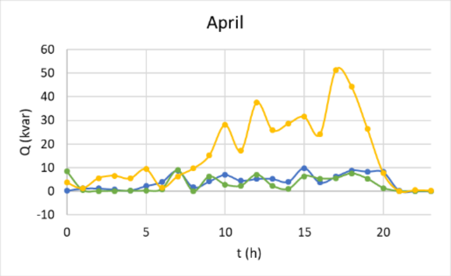


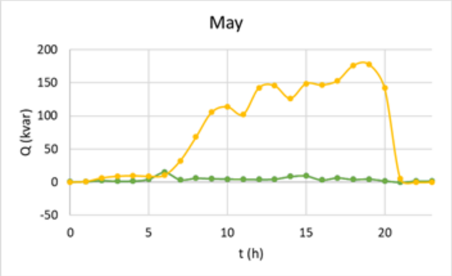
Daily load curves of reactive power of weekdays.

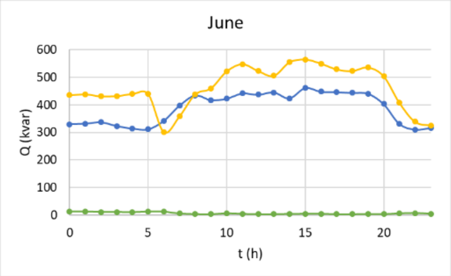


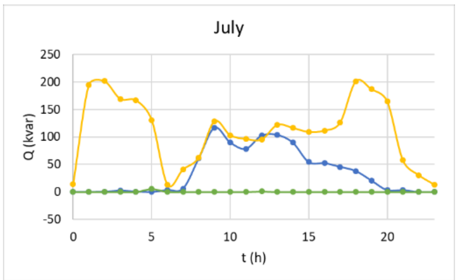


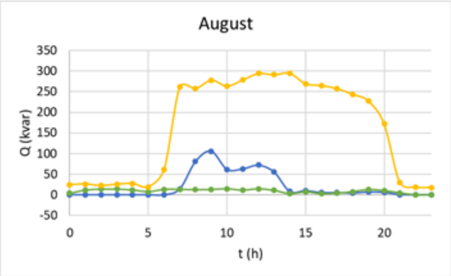


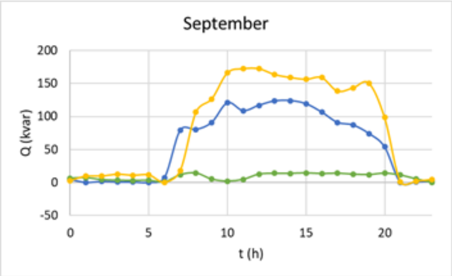


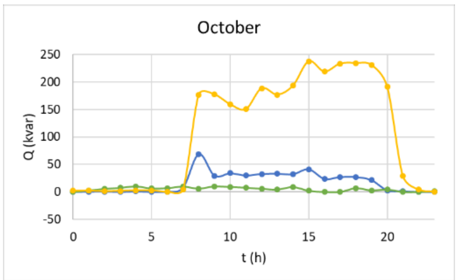


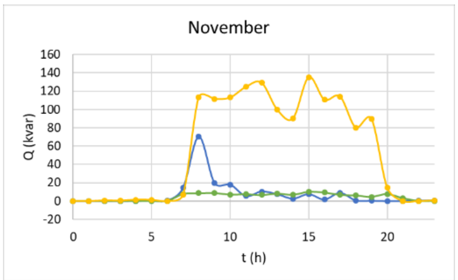


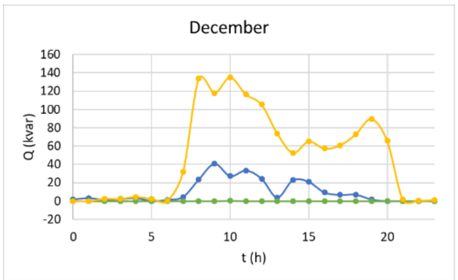




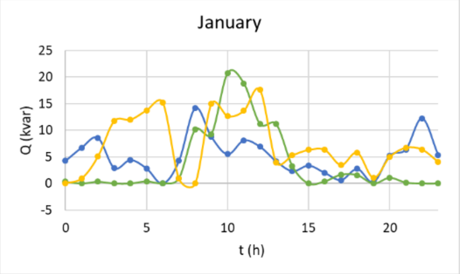


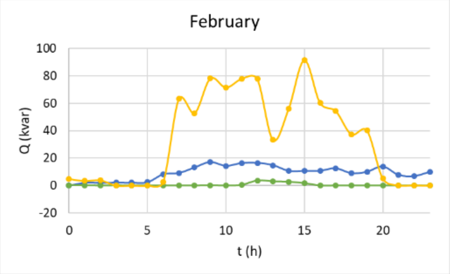


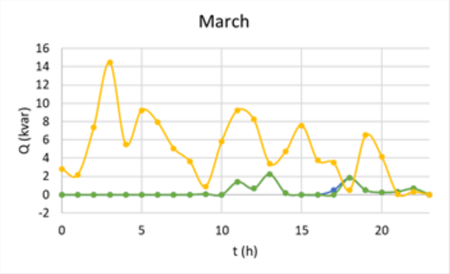


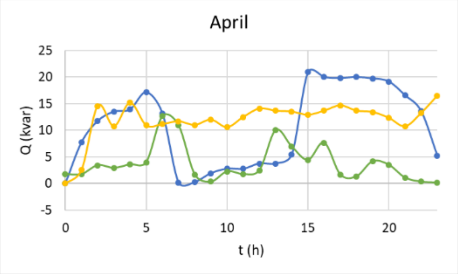


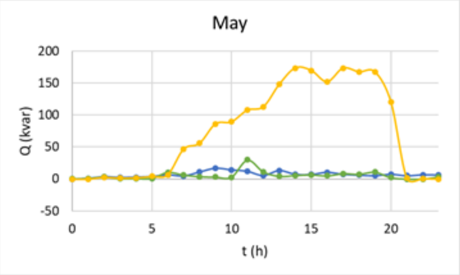
Daily load curves of reactive power of weekend days.

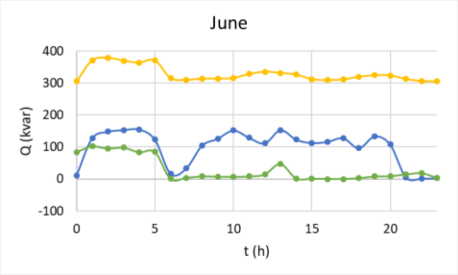


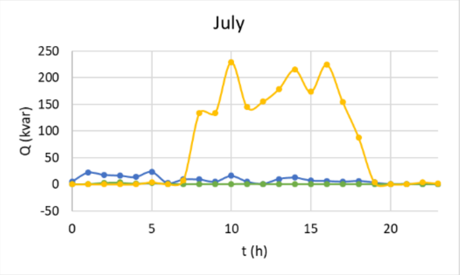


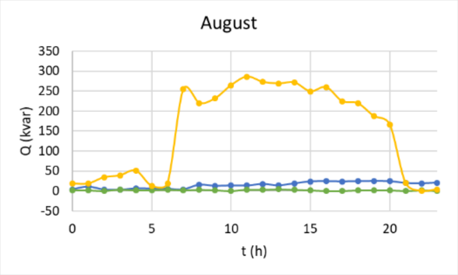


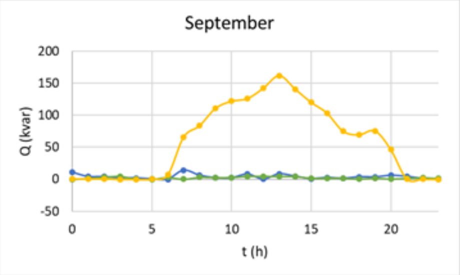


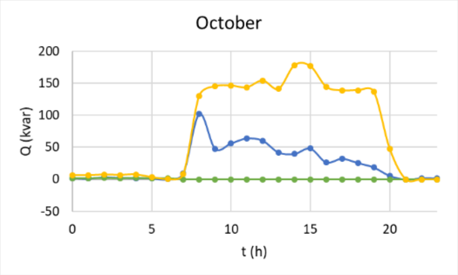


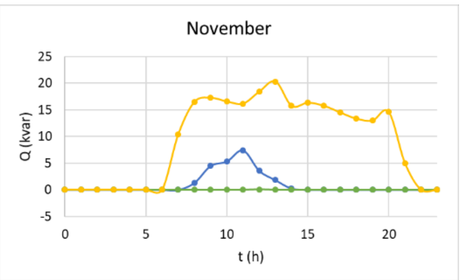


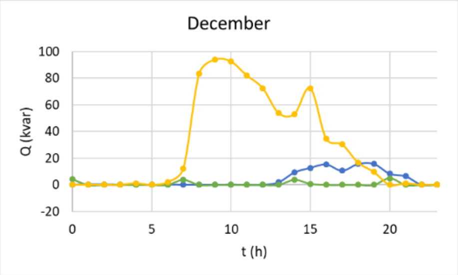












Annex 3. Summary

Estado del Arte sobre Diseño y Dimensionamiento de Microredes Eléctricas

Luna Moreno Díaz[1]

Abstract— **La red eléctrica actual, llevada a su límite tanto en tamaño como en complejidad, enfrenta nuevos retos y necesidades de reestructuración debido al aumento de la demanda, de la calidad de suministro y de las emisiones de GEI. Las arquitecturas de red distribuidas están adquiriendo un papel cada vez más relevante como soluciones alternativas a la red eléctrica centralizada. Entre dichas arquitecturas se encuentran las microredes eléctricas, sistemas de distribución de baja tensión constituidos por cargas y recursos de energía distribuidos que, coordinados de forma eficiente, permiten optimizar la operación de todo el sistema. Como parte de los proyectos actuales para el desarrollo de microredes, el presente trabajo es un estudio preliminar sobre el diseño y dimensionamiento de una microred. Este caso de estudio se llevará a cabo sobre la Escuela Técnica Superior de Ingeniería y consistirá en estudiar los recursos actuales de generación del edificio, su patrón de consumo y proponer y dimensionar otros recursos que permitan alcanzar una capacidad de generación suficiente. Entre las conclusiones más importantes pueden mencionarse la importancia de los estudios en modo isla y la escasez de normativa de conexión de microredes a la red eléctrica. En relación con el caso de estudio, se ha obtenido un patrón de consumo anual muy representativo, se han caracterizado los recursos actuales de generación del edificio y se ha dimensionado una planta PV para distintos escenarios, siendo el más interesante aquel en el que hay almacenamiento. Todo ello ha permitido obtener un posible escenario de generación para el funcinamiento de la Escuela como una microred.**

I. INTRODUCCIÓN

A. Introducción a las Microredes Eléctricas

Actualmente, existe un sistema de energía eléctrica que es mayoritariamente centralizado, en el que la electricidad es transportada desde las plantas de generaciíon hasta los consumidores a través de una macrored eléctrica. De hecho, la red eléctrica es definida por la Academia Nacional de Ingeniería de EE. UU. como la ”máquina más compleja desarrollada por la humanidad”. Sin embargo, cada vez más, están surgiendo sistemas de energía eléctrica alternativos a los sistemas centralizados, en respuesta a los nuevos retos y necesidades de reestructuración que enfrenta la red eléctrica actual, debido al incremento de la demanda de electricidad y de las emisiones globales de gases de efecto invernadero.

El incremento de la demanda de electricidad y el requerimiento de una mayor calidad de suministro han llevado a la red eléctrica a alcanzar sus límites, tanto en tamaño como en complejidad. Como resultado, la infraestructura eléctrica actual hace frente a problemas como la seguridad, la fiabilidad y la calidad de suminitro.

Por otro lado, los esfuerzos actuales por combatir el cambio climático persiguen, entre otras cosas, una red eléctrica más sostenible y, precisamente, las nuevas arquitecturas de red distribuidas dan la posibilidad de instalar recursos de generación basados en energías renovables.

Uno de dichos sistemas de generacíon distribuida son las microredes. En torno al año 2000, la gente empezó a hablar de microredes como soluciones alternativas a la generación centralizada. Hoy en día, las microredes constituyen una buena solución para infraestructuras críticas, campus, comunidades remotas, redes en isla o para un único edificio como fábricas, centros comerciales o facultades.

Actualmente, las microredes son temas de investigación comunes en Estados Unidos, Canadá, Japón y Europa, donde se están llevando a cabo numerosos estudios para demostrar la viabilidad de dichos sistemas. Como parte de este proyecto común para el desarrollo de microredes, el presente trabajo es un estudio preliminar sobre el diseño y dimensionamiento de una microred.

B. Objetivo del proyecto

El objetivo de este proyecto es llevar a cabo un anteproyecto sobre el diseño y dimensionado de los recursos de generación distribuida que necesitaría la Escuela Técnica Superior de Ingeniería de la Universidad de Sevilla para funcionar como una microred.

II. SOBRE MICROREDES

A. Concepto de Microred

De acuerdo con numerosos proyectos de investigación europeos sobre el estudio de Microredes [1], ”una microred es un sistema de distribución de baja tensión (BT) formado por recursos de energía distribuidos (RED) (microturbinas, pilas de combustible, fotovoltaica, etc.) junto con sistemas de almacenamiento (voltantes de inercia, baterías, ect.) y cargas flexibles. Este sistema puede ser operado de forma no autónoma, si está conectado a la red principal, o de forma autónoma, si está desconectado de dicha red. La utilización de microrecursos en el sistema puede proporcionar beneficios singulares, si se gestionan y coordinan de manera eficiente”.

En la figura 1 se muestra el esquema de una microred. Como puede verse, la microred está constituida por cargas, algunas las cuales son gestionables, y por una serie de RED en los que están presentes todo la casuística: generación controlable, como son los equipos de poducción combinada de frío y calor o las pilas de combustible, generación no controlada, como es la fotovoltaica, grupos electrógenos y sistemas de alamacenamiento.

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[1] Luna Moreno, de la Escuela Técnica Superior de Ingniería, Universidad de Sevilla, Sevilla, España

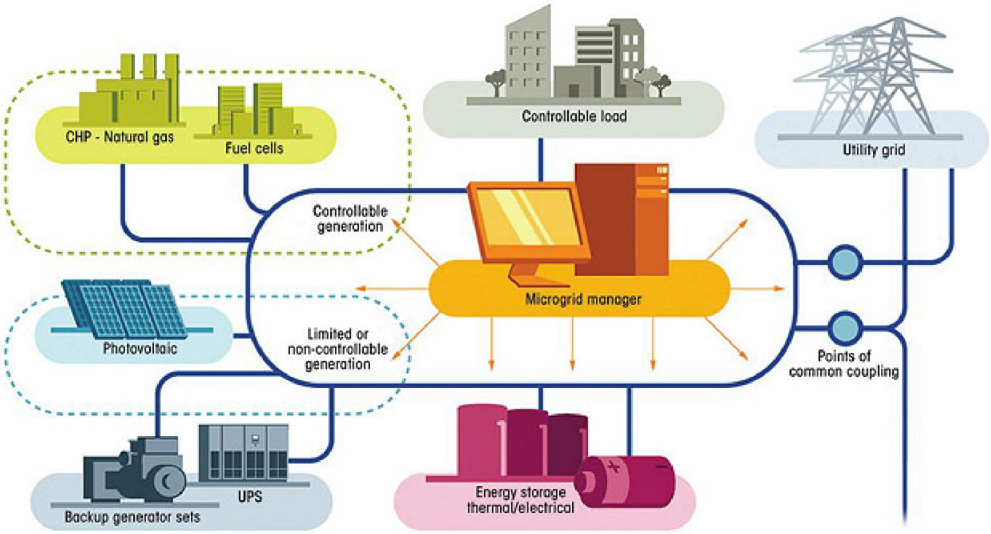

Fig. 1. Esquema de una Microred [11]

B. *Tipos de Microredes*

El instituto de Microredes [2] proporciona una clasificación que depende de la operación autónoma y de la magnitud del sistema de la microred:

- Microred ”Utility-integrated campus”: normalmente funciona conectada a una red eléctrica local pero puede funcionar en modo isla cuando hay un apagón en la red local. Ejemplos de este caso son campus universitarios, prisiones o bases militares.
- Microred comunitaria: se emplea para dar suministro a los servicios esenciales de una comunidad formada por numerosos consumidores.
- Microred aislada: es una microred que solo trabaja en modo isla, es decir, nunca se conecta a una red de distribución. Ejemplos de este caso son redes en isla en lugares remotos.
- Nanored: es el caso más simple de una microred. Está formada por un único edificio como por ejemplo, una fábrica, una centro comercial o una facultad.

Por otra parte, en la memoria del proyecto se detalla otra clasificación de microredes más extensa, especificada en el estándar 1547.4-2011 del IEEE [3].

C. *Modos de Operación de Microredes*

Los posibles modos de operación de una microred son los siguientes:

- Operación en paralelo con la red: la microred funciona en paralelo con la red de distribución principal. En este modo, los RED deben cumplir los requerimientos especificados en el estándar 1547 del IEEE [4]. Los equipos de monitoreo, intercambio de informacin y control (MIC) necesarios para llevar a cabo la transición a modo isla deben estar funcionando durante la operación en paralelo para tener disponible la información necesaria para el cambio de modo.
- Transición a modo isla: puede llevarse a cabo intencionadamente o puede ser un evento inesperado. Una transición inesperada es causada debido a una falta en el sistema eléctrico de potencia (SEP) y requiere que los MIC estuviesen funcionando en el modo previo. Para conseguir una transición exitosa, suficientes RED, estando estos recursos bien operados y diseñados, deben estar disponibles para soportar las variaciones de tensión y frecuencia causadas durante el cambio de modo de operación. Si los RED no son capaces de llevar a cabo la transición, se incluirán equipos de soporte adicionales.
- Modo isla: Cuando la microred trabaja en modo isla se deben tener en cuenta muchas consideraciones relacionadas con el hecho de que esta no cuenta con el soporte del SEP. Fundamentalmente, la microred debe diseñarse para proporcionar la potencia activa y reactiva demandada por las cargas y una adecuada regulación de tensión y frecuencia. Además de lo anterior, surgen otras consideraciones importantes en modo isla que deben ser bien examinadas:
  1. Para permitir la regulación de tensión y frecuencia durante este modo, los equipos de regulación quizás precisen ajustar los límites de tensión y frecuencia y en tal caso, podrían no cumplir los requisitos del estándar 1547 del IEEE [4].
  2. Debe garantizarse la respuesta dinámica sabiendo que el sistema no cuenta con la inercia del SEP.
  3. Debe usarse la técnica que mejor ajuste la capacidad de generación con las características del consumo: seguimiento de la carga, gestión del consumo o deslastre de carga.
  4. Debe mantenerse la coordinación de las protecciones considerando que la contribución de corriente de falta de los RED es inferior a la del SEP.
- Modo reconexión: la reconexión debe realizarse cuando

el SEP y la microred estén dentro de limites de tensión, frecuencia y ángulo de fase aceptables. Existen tres modos de reconexión: sincronización activa, sincronización pasiva y transferencia de transición abierta. Tanto la sincronización activa como pasiva necesitan conocer la tensión, frecuencia y fase de la microred y del SEP para llevar a cabo la reconexión. Por otra parte, la transición abierta no necesita sensores, pero requiere que se detenga el suministro durante la transición.

D. Interesados de una Microred

Los principales interesados implicados en una microred son:

- Consumidor: puede ser un cliente doméstico o una pequeña o mediana compañía.
- Operador/propietario de la microred: normalmente, el propietario del RED también suele llevar a cabo su operación.
- Prosumer: es un consumidor que tiene instalados RED para autoconsumo total o parcial.
- Operador de la red de distribución (DSO): es el agente responsable de la operación, mantenimiento y desarrollo de la red de distribución.
- Empresa de servicios energéticos (ESCO): es un agente de mercado que posibilita la participación de los RED en mercados locales de energía.
- Operador de la microred: es el agente responsable de la operación, mantenimiento y desarrollo de la microred. Este papel puede desempeñarlo el DSO del SEP o un DSO independiente que actúe en beneficio de los consumidores de la microred.

E. Estrategias de Control de Microredes

La microred puede llevar a cabo una estrategia centralizada o descentralizada, dependiendo de los objetivos de los interesados y de las responsabilidades de control de los diferentes sistemas de control.

- Control centralizado: con este tipo de control, el controlador central de la microred (interfaz entre la microred y otros agentes como el DSO o el ESCO) asume la responsabilidad de maximiar el valor de la microred, es decir, de optimizar la producción y el consumo y decidir la cantidad de energía que la microred debe importar del SEP. Se realiza cuando los interesados de la microred tienen intereses comunes.
- Control descentralizado: con este tipo de control se requiere más inteligencia local en los diferentes nodos de control, que serían las cargas y los RED. Los nodos con carga proporcionarían capacidad de deslastre y los nodos con generación, reserva de energía. Este control se demanda en mercados de microredes donde se requiere que los distintos controladores de la microred sean competitivos y tengan un cierto nivel de indepencia e inteligencia.

F. Estrategias de Operación de Microredes

Las estrategias de operación de una microred dependen de los intereses de los distintos interesados implicados.

- Operación económica: la función objetivo es minimizar el coste total del sistema sin considerar el impacto en la red. Esta estrategia es típica de los propietarios de los RED que no están preocupados por las emisiones y su únicas limitaciones son las restricciones técnicas de los RED.
- Operación técnica: la función objetivo es minimizar las pérdidas, las variaciones de tensión, etc. sin considerar los costes de producción de los RED. Esta estrategia es propia de los DSO.
- Operación medioambiental: la función objetivo es minimizar el nivel de emisiones sin considerar aspectos técnicos o económicos. Esta estrategia de operación se realiza para conseguir un objetivo de emisiones impuesto por algún esquema de regulación.

Finalmente, un problema de optimización combinado consideraría todos los apectos económicos, técnicos y medioambientales, resolviendo un problema multi-objetivo. Esta estrategia sería interesante en mercados de energía que no solo demandan energía, sino también servicios auxiliares de red o certificados de emisiones.

III. DISEÑO DE MICROREDES

Para diseñar una microred hay que considerar una serie de requerimientos por parte de las cargas y de los RED y asegurar una estrecha coordinación con el SEP al que se va a conectar. La información de esta sección se ha tomado del estándar 1547-4 del IEEE [3].

A. Planificación y Requeremientos de las Cargas

Las cargas de una microred deben cumplir una serie de requisitos para asegurar una correcta operación en un sistema que no es tan robusto como el SEP. Muchas de las cuestiones tratadas en esta sección tienen que ver con el hecho de que la microred no tiene la inercia del SEP.

Entre la información necesaria para el análisis de las cargas figura: punto y fase de conexión de las cargas, perfiles de demanda históricos, tipos de cargas (residenciales, comerciales o industriales), información sobre grandes cargas puntuales, estudio del porcentaje de desequilibrio actual de las cargas y necesidades de reactiva en condiciones normales y excepcionales.

Además de lo anterior, deberán tenerse en cuenta consideraciones particulares para los siguientes equipos: transformadores, motores, alumbrado y cargas sensibles. Estas consideraciones están recogidas en la memoria del documento [5].

B. Planificación y requerimientos del SEP

Para posibilitar el funcionamiento de la microred en paralelo con el SEP, deberá existir una estrecha coordinación entre ambos sistemas. Por tanto, será necesario asegurar la compatibilidad de ambos sistemas en diferentes aspectos como el sistema de puesta a tierra, la regulación de tensión y frecuencia y la coordinación del sistema de protecciones.

Con respecto al sistema de puesta a tierra, la microred debe mantener el mismo esquema de puesta a tierra que el SEP y no podrá afectar el buen funcionamiento del mismo.

Con respecto a la regulación de tensión, se deben tener en cuenta las siguientes consideraciones cuando se trabaje en modo isla:

- Uno de los recursos distribuidos tiene que regular la tensión y estar coordinado con otros dispositivos de regulación de tensión del sistema.
- El hecho de tener RED en la microred podría hacer necesario el uso de controles basados en el flujo de potencia para el buen funcionamiento de los reguladores de tensión de línea.

En relación con la regulación de frecuencia surgen los siguientes problemas:

- Algunos RED no son capaces de volver al estado normal cuando la frecuencia es demasiado baja. En este caso, deben ajustarse los limites de frecuencia para permitir la operación en modo isla.
- Los RED participantes en la regulación de frecuencia quizás necesiten cambiar su esquema de control para considerar deslastre de carga en condiciones de subfrecuencia.

En lo que respecta al sistema de protecciones, la mayoría de los problemas surgen porque la microred puede no ser capaz de producir suficiente corriente de falta para asegurar la buena operación de los dispositivos de protección existentes durante cortocircuitos. Por tanto, hay que verificar que los RED basados en inversores son capaces de producir la corriente de falta requerida o, si no es suficiente, cambiar el esquema de protección.

C. Planificación y requerimientos de los RED

En esta sección se abordan los requisitos de los RED cuando la microred funciona como una isla intencionada.

Cuando hay diferentes RED en la microred, hay que considerar la capacidad de generación de cada uno, verificar que pueden cubrir las necesidades de consumo de las cargas y en caso de apagón de un RED, el resto puedan alimentar las cargas.

Cuando se opere en modo isla podría ser necesario relajar los límites de subtensiones y subfrecuencias ya que, en caso de mantenerse, podría producirse el disparo de un RED cuando ocurra una falta y llevar a la isla a un apagón si solo existe un recurso de generación en el sistema.

Además de la anterior, en esta sección se abordan los métodos de regulación de tensión y frecuencia cuando la microred trabaja como una isla intencionada (dichos métodos se explican en detalle en la memoria del proyecto [5]). La calidad de dicha regulación dependerá de las capacidades de los RED y las características de las cargas. Por tanto, los límites de tensión y frecuencia serán acordados entre los interesados. Para asegurar que la microred es capaz de mantener la estabilidad del sistema, deberán chequearse los valores de tensión y frecuencia y los tiempos de recuperación en caso de máxima pérdida de carga y máxima demanda de carga.

D. Estudios del sistema

Hay una serie de estudios que deberían llevarse a cabo para analizar la calidad de suministro que la microred proporciona a sus consumidores: planificación de la capacidad de generación, estudios de flujo de carga, estudios de coordinación de protecciones y cortocircuito, estabilidad de la microred y arranque de motores, principalmente.

Este proyecto se centra en la planificación de la capacidad de generación. El objetivo de este estudio es examinar la capacidad de generación de los RED de la microred y compararla con el consumo para verificar que el sistema es compatible. Además, debería estudiarse la capacidad de arranque en frío y tras un apagón.

IV. REQUISITOS DE CONEXIÓN DE MICROREDES A LA RED ELÉCTRICA

En esta sección se recogen los principales requisitos y especificaciones de interconexión de microredes con SEP. Esta información se ha tomado del estándar 1547 del IEEE [4].

Además de los requisitos que se mencionan en esta sección, se exigen otros requisitos generales contemplados en el estándar [4].

A. Respuesta a condiciones anormales del SEP

Cuando ocurre una falta en el SEP, la microred debería actuar para mantener la seguridad de las personas y evitar daños en los equipos. A continuación, se detalla cómo debería comportarse la microred ante distintas situaciones:

- Falta en el SEP: La microred debe dejar de energizar el SEP cuando ocurre una falta en el circuito del SEP al que se conecta la microred.
- Reenganche del SEP: cuando las protecciones del SEP van a realizar un reenganche, la microred debería dejar de energizar el circuito del SEP al que está conectada.
- Regulación de tensión: cuando la tensión en el punto de acoplamiento común (PCC) está fuera de los límites indicados en la tabla 1, la microred debe dejar de energizar el SEP dentro de los tiempos especificados en la segunda columna de la tabla. Otras consideraciones vienen especificadas en la memoria del proyecto [5].

TABLE I

RESPUESTA DEL SISTEMA DE INTERCONEXÓN ANTE TENSIONES ANORMALES

Rangos de tensión (% respecto Vn)	Tiempos de despeje (s)
$V < 50$	0.16
$50 \leq V < 88$	2.00
$110 < V < 120$	1.00
$V \geq 120$	0.16

- Regulación de frecuencia: cuando la frecuencia en el PCC está fuera de los límites indicados en la tabla 2 [1],

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[1] Estos límites no son directamente aplicables al caso Europeo donde la frecuencia es de 50 Hz

la microred debe dejar de energizar el SEP dentro de los tiempos especificados en la segunda columna de la tabla. Otras consideraciones vienen especificadas en la memoria del proyecto [5].

TABLE II
RESPUESTA DEL SISTEMA DE INTERCONEXÓN ANTE FRECUENCIAS ANORMALES

Pn	Rangos de frecuencia (Hz)	Tiempos de despeje (s)
$\leq$ 30 kW	$>$ 60.5	0.16
$\leq$ 30 kW	$<$ 59.3	0.16
$>$ 30 kW	$>$ 60.5	0.16
$>$ 30 kW	$<$ { 59.8 - 57.0 } (ajustable)	0.16 - 300 (ajustable)
$>$ 30 kW	$<$ 57.0	0.16

- Pérdida de sincronismo: No se requiere protección de pérdida de sincronismo excepto en caso de que fuese necesario para cumplir la limitación de flicker inducida por la microred.
- Reconexión de la microred: deberá llevarse a cabo cuando lo límites de tensión y frecuencia están dentro de los rangos adecuados (ver norma [4]). Además, el sistema de reconexión debería incorporar un retraso de tiempo de al menos 5 minutos una vez que el SEP haya reestablecido la tensión y la frecuencia dentro de los límites anteriores.

B. *Calidad de suministro*

En esta sección se abordan los requirimientos para asegurar una adecuada calidad de suministro, concretamente, se especifica el límite de inyección de corriente continua, el límite de flicker y la limitación de armónicos.

C. *Operación en isla*

Cuando la microred opere en isla con una parte del SEP, esta debe detectar la operación en isla y dejar de energizar dicha porción del SEP dentro de los dos segundos después de la creación de la isla.

V. CASO DE ESTUDIO: LA ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ETSI)

Se va a llevar a cabo un estudio preliminar sobre el diseño y dimensionado de la capacidad de generación de la ETSI para funcionar como una microred. Este estudio se realizará sobre el edificio principal, es decir, sin tener en cuenta el edificio de laboratorios.

En los siguientes apartados se aplica lo estudiado sobre microredes a este caso de estudio.

A. *Tipo de Microred*

En relación con la clasificación del Instituto de Microredes, la Escuela de Ingeniería funcionando como una microred sería una Nanored.

B. *Interesados implicados*

Los interesados que estarían implicados en esta microred serían:

- Consumidor: la Universidad de Sevilla (US). Es la entidad que tiene un contrato con la comercializadora.
- Propietario/Operador de la microred: Tanto los recursos actuales de la Escuela, como los que se dimensionarán posteriormente, son propiedad de la US.
- DSO: es la compañía Endesa Distribución.
- ESCO: este agente sería la US que, por sí mismo, buscaría una comercializadora o acudiría a un mercado local de energía.
- Operador de la Microred: este agente sería la US.

C. *Recursos Distribuidos*

Para planificar la capacidad de generación deben analizarse los RED con los que cuenta la Escuela y el patrón de consumo del edificio. En segundo lugar, deben proponerse y dimensionarse otros RED para alcanzar la capacidad de generación deseada.

Actualmente, la Escuela cuenta con dos RED: una planta de refrigeración solar y un grupo electrógeno. Ambos recursos deben estudiarse para conocer su potencia nominal, cómo operan y cualquier información de interés para caracterizar su operación.

De igual forma, debe caracterizarse el patrón de consumo de la Escuela. Para ello, se van a usar medidas de potencia activa y reactiva de la Escuela tomadas durante el año 2003 [6].

Finalmente, para alcanzar la capacidad de generación requerida, se dimensionarán otros RED: una planta fotovoltaica (PV) y un sistema de almacenamiento que, junto con los recursos actuales, cubrirán las necesidades de consumo de la Escuela.

D. *Estrategia de Control*

Hay numerosas cuestiones que hacen más razonable llevar a cabo una estrategia de operación centralizada en lugar de una descentralizada:

- Considerando que el único interesado implicado en la Microred es la US (a excepción del DSO), sería lógico realizar un control centralizado. Se contemplaría una estrategia descentralizada en caso de tenerse una microred residencial donde los diferentes consumidores domésticos tienen sus propias necesidades, que no es el caso.
- Desde un punto de vista económico, la estrategia centralizada es más interesante. Para llevar a cabo una estrategia descentralizada sería necesaria inteligencia local de los equipos y un sistema de comunicación más robusto, lo que implicaría una mayor inversión.
- Considerando la magnitud de la microred, una estrategia centralizada tiene más sentido para controlar un único edificio.

E. *Estrategia de Operación*

En relación con los consumidores y operadores de los RED (que en este caso son todos un único interesado, la US), sería más interesante una estrategia de operación económica. En relación con el DSO, podría considerarse un operación técnica en combinación con la económica. Puesto que todos los RED de la microred estarían basados en energía renovable, a excepción del grupo electrógeno, de forma indirecta también se estaría llevando a cabo una operación medioambiental ya que se minimizarían los niveles de emisiones.

VI. PLANIFICACIÓN DE LA CAPACIDAD DE GENERACIÓN

Este capítulo tiene numerosas secciones que se dividen en dos partes: una dedicada al consumo y otra dedicada a la generación (que a su vez se divide en recursos de generación actuales y nuevos). El propósito del capítulo es planificar la capacidad de generación para cubrir el consumo de la Escuela cuando se trabaja en modo isla.

A. *Planificación de Consumo*

Partiendo de los datos de consumo mencionados anteriormente, se quiere obtener una curva de carga representativa para cada mes que permita comparar la generación y el consumo de forma simple.

Concretamente, se ha obtenido para cada mes una curva de carga de potencia activa y una curva de carga de potencia reactiva de entre semana y de fin de semana ya que, al tratarse de una facultad, el consumo entre semana y fin de semana cambia notablemente.

El tratamiento de datos se ha realizado en Excel y el procedimiento seguido viene detallado en la memoria del proyecto [5]. Es importante destacar que las curvas de carga obtenidas corresponden al consumo real de un día concreto: el día cuya curva de carga se parece más a la curva de carga promedio correspondiente. De esta forma no se pierde una información importante: el consumo de una hora está relacionado con el consumo de la siguiente hora.

A modo de ejemplo, en la figura 2 se muestra la gráfica de potencia activa de entre semana del mes de enero. En naranja se muestra la curva de carga promedio, en azul la curva de carga representativa (día que más se parece, en forma, a la promedio), en amarillo la curva de carga del día de mayor consumo y en verde la curva de carga del día de menor consumo (estas dos últimas sirven para caracterizar la dispersión de los datos).

B. *Análisis de la Planta de Refrigeración Solar (PRS)*

Este RED es un proyecto piloto de Gas Natural para demostrar la viabilidad de esta tecnología para la climatización de edificios. Esta tecnología aprovecha la energía solar para producir frío o calor utilizando unos colectores tipo Fresnel (mostrados en la figura 3). Esta planta trabaja en paralelo con el sistema de refrigeración de la Escuela. Para más información consultar [7] y [8].

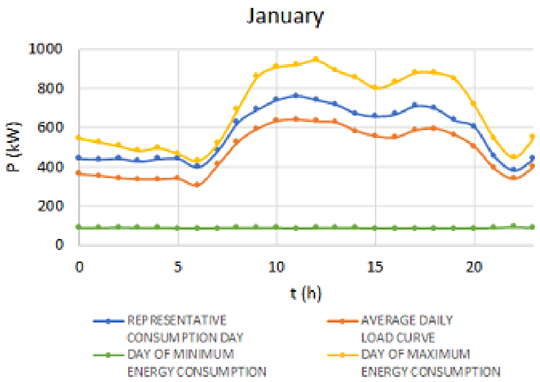

Fig. 2. Curvas de carga de potencia activa de entre semana del mes de enero

Fig. 3. Captador Solar Fresnel de la PRS [8]

De este RED se quiere conocer cuanta energía le ahorra a la Escuela. Esta energía dependerá del modo de funcionamiento: en verano trabaja en modo refrigeración y en invierno trabaja en modo calefacción. Para obtener esta información se han seguido los siguientes pasos:

- Obtener la energía promedio de refrigeración y de calefacción que la planta produce en un día típico de verano y de invierno, respectivamente.
- Obtener el número promedio de horas que la planta funciona un día de verano y un día de invierno.
- Teniendo los valores previos, obtener la potencia de refrigeración y calefacción producidad dirariamente por la planta.
- Consultar el COP de una bomba de calor reversible (máquina de refrigeración de la Escuela) con la potencia de calefacción y refrigeración previamente obtenidas. Haciendo esto puede obtenerse la energía eléctrica que consumiría la bomba de calor al producir la energía que suministra la PRS. Y, este consumo de energía eléctrica es, aproximadamente, la energía eléctrica que la PRS le ahorra a la Escuela.

La potencia de refrigeración promedio producida por la planta un día de verano es de 147 kW y la de calefacción un día de invierno es de 58 kW. Se ha consultado el COP de una bomba de calor de estas potencias en un catálogo de

Daikin [9]: COP=3.2, EER=2.84[2].

Finalmente se obtiene que la energía eléctrica que la PRS le ahorra a la Escuela diariamente es de 388,4 kWh en modo refrigeración y 90 kWh en modo calefacción, aproximadamente.

C. Análisis del Grupo Electrógeno

En esta sección se caracterizará otro de los recursos con los que cuenta la Escuela, el grupo electrógeno. Al contrario que en el caso anterior, no se dispone de información del grupo de la Escuela por lo que, será necesario hacer suposiciones.

En base al patrón de consumo definido, se considera que existe un grupo electrógeno de una potencia nominal de 500 kW aproximadamente, una potencia suficiente para cubrir las cargas de emergencia.

Uno de los aspecto más importantes de este recurso de generación es que, cuando la microred funcione en modo isla, el grupo será la fuente de tensión y frecuencia de la isla, es decir, será el recurso que energizará el sistema cuando la microred no esté alimentada por la red de distribución principal.

D. Dimensionamiento de la Planta Fotovoltaica

Para aumentar la capacidad de generación actual de la Escuela, se va a dimensionar un planta PV que cubra parte de las necesidades de consumo del edificio. Para ello, se va a emplear el programa PVsyst [10], un potente software para el diseño y estudio de plantas PV.

La planta PV será del tipo conectada a red para autoconsumo de todo la energía producida por la planta. Se considerarán dos situaciones:

- Planta PV sin almacenamiento: En este escenario la planta PV alimenta la Escuela sin sobrepasar el consumo del edificio, es decir, sin que sea necesaria exportar a la red la energía sobrante. Para ello, se va a dimensionar una planta PV tomando como referencia la curva de carga representativa del mes con menos consumo en las horas de sol. Además, se considerará un subescenario en que la PRS funciona y otro en que no funciona.
- Planta PV con almacenamiento: En este escenario, además de la planta PV, la Escuela contará con un sistema de almacenamiento. De esta forma, cuando la generación de la planta PV supere al consumo, el excedente será inyectado en el sistema de almacenamiento.

A continuación, se detalla la metodología a seguir en cada escenario de operación:

- Planta PV sin almacenamiento: para hallar la potencia nominal (Pn) de la planta en este escenario se han empleado dos fuentes de datos de consumo: información mensual e información horaria de todo el año. Se ha decidido usar ambas fuentes para comparar los resultados ya que, desde el principio, la idea fue usar curvas de carga representativas de cada mes pero, los datos horarios darán resultados más exactos. La metodología seguida es la siguiente:
  1. Asignar una potencial nominal a la planta PV. Empezar con una potencia pequeña.
  2. Obtener los producción anual de energía estimada de la planta con esa Pn de PVsyst.
  3. Casar los datos de generación y consumo.
  4. Si no hay consumo neto negativo, volver al paso 1.

  La metodología consiste en una prueba de ensayo y error en la que, partiendo de una pequeña Pn, se obtendrá la Pn de la planta que cubre el máximo consumo posible sin sobrepasarlo nunca.
- Planta PV con almacenamiento: para diseñar el sistema de almacenamiento tiene más sentido usar los datos de consumo horarios ya que con los datos de consumo mensuales la información está muy sintetizada. Se van a obtener diferentes tamaños del sistema de almacenamiento, el necesario para gestionar el excedente de generación para cada potencia nominal de la planta PV contemplada en la sección anterior. El sistema de almacenamiento elegido será aquel cuyo tamaño sea más razonable (estableciendo una relación de compromiso entre coste y capacidad de almacenamiento) y determinará la Pn de la planta PV finalmente elegida. Este estudio se lleva a cabo en la siguiente sección.

Los pasos necesarios para el diseño de una planta PV en PVsyst se detallan en la memoria del proyecto [5]. De forma resumida, los pasos son: definir el tipo de estudio, definir la ubicación de la planta (para cargar los datos meteorológicos), definir la orientación e inclinación de los paneles PV, seleccionar los elementos del sistema (paneles PV e inversores) y obtener la producción anual estimada horaria de todo el año.

A continuación, se detallan los resultados obtenidos en el escenario sin almacenamiento. Empleando datos de consumo mensuales, y tomando como referencia el mes de Agosto (mes de menos consumo), se obtiene que:

- La potencia nominal de la planta PV para no sobrepasar el consumo cuando no está funcionando la PRS es de 350 kW. En la figura 4 se muestra una gráfica con las curvas de generación y consumo en el mes de Agosto y se observa que, el consumo neto alcanza el valor 0 pero no llega a ser negativo.
- La potencia nominal de la planta PV para no sobrepasar el consumo cuando está funcionando la PRS es de 300 kW.

Por otro lado, empleando los datos de consumo horarios se obtiene que la Pn de la planta PV para la que el consumo neto nunca sea negativo es de 100 kW. Además, se obtiene el porcentaje de horas anuales en el que el consumo neto es negativo para las Pn de la planta obtenidas con datos mensuales (ver tabla 3).

Comparando ambos métodos, puede concluirse que el estudio con datos mensuales proporciona un resultado suficientemente bueno. Si este estudio se llevara a la práctica,

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[2] El coeficiente EER es la relación entre la potencia frigorífica producida y la potencia eléctrica cosumida en refrigeración. El COP es la relación entre la potencia de calefacción producida y la potencia eléctrica consumida en calefacción.

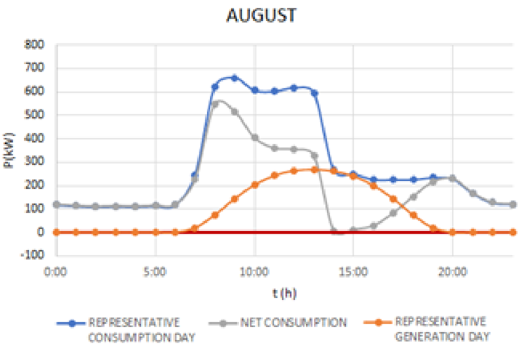

Fig. 4. Curvas resultantes en el mes de Agosto con una Pn de la planta PV de 350 kW cuando la PRS no está funcionando

TABLE III
PORCENTAJE DE HORAS AL AÑO EN EL QUE EL CONSUMO NETO ES NEGATIVO PARA DISTINTAS PN DE LA PLANTA PV

Pnom (kW)	Horas (%)
100	0
300	6.65
350	7.23

la decisión de tomar una u otra Pn estaría limitada por el espacio disponible, variable que no se ha tenido en cuenta en este proyeto por tratarse de un estudio preliminar.

E. Dimensionamiento del Sistema de Almacenamiento

El hecho de contar con un sistema de almacenamiento hace que la microred pueda gestionar su generación y consumo. De los posibles casos para los que podría usarse el almacenamiento, este estudio se centra en su uso cuando hay excedente de generación. Esta situación podría ocurrir en la microred durante las horas de sol, en días de bajo consumo y alta generación.

Recordando que el dimensionado del sist. de almacenamiento se hará con datos horarios y en relación a la tabla 3, será necesario almacenamiento cuando la Pn de la planta PV sea mayor de 100 kW.

Para las diferentes Pn de la planta contempladas en la sección anterior, se ha dimensionado el sist. de almacenamiento necesario para absorber el excedente de generación. Los resultados se muestran en la tabla 4.

TABLE IV
ENERGÍA Y POTENCIA DEL SIST. DE ALMACENAMIENTO NECESARIO PARA CADA PN DE LA PLANTA PV

Pn (kW)	E (kWh)	P(kW)
100	0	0
200	456	84
300	1047	166
350	1344	207

Observando la tabla 4, puede verse que el sist. de almacenamiento necesario para Pn de la planta PV iguales o superiores a 300 kW es demasiado grande, por lo que, sería muy costoso. El sist. de almacenamiento para una planta PV de 200 kW parece razonable.

Entre los posibles sist. de almacenamiento existentes (químico, potencial, cinético o térmico), se ha pensado en usar almacenamiento químico, en particular, baterias de ion-li. A modo de ejemplo, podrían usarse dos modulos de la bateria Powerback fabricada por Tesla, cuya potencia nominal es de 50 kW y su energía nominal de 210 kWh, para gestionar el excente de generación con una planta PV de 200 kW.

VII. CONCLUSIONES

Dado que este proyecto tiene dos partes, una parte teórica, obtenida de la búsqueda de literatura de estado del arte sobre microredes eléctricas, y otra parte práctica, obtenida como resultado de la aplicación del estudio de planificación de la capacidad de generación de una microred en la Escuela de Ingeniería, las conclusiones también pueden dividirse en dos partes.

En relación con el estudio teórico de microredes, puede concluirse lo siguiente:

- Cada una de las aclaraciones que derivan del concepto de microredes deberían ser bien entendidas para distinguir estas arquitectutas de otras redes pasivas penetradas por microrecursos.
- Los diferentes tipos de microredes son muy variados y dependen de una serie de criterios como la magnitud del sistema, el modo normal de operación, el punto de conexión de los diferentes recursos, etc. por tanto, no existe una clasificación única.
- La operación del sistema en modo isla hará necesario una serie de estudios debido a que la microred no cuenta con el soporte del SEP en este modo. En consecuencia, la contribución de corriente de falta de los DERs será menor que la del SEP, la microred no contará con la inercia del SEP y la impedancia Thévenin de la microred será mucho mayor que la del SEP. Esto implicará una serie de estudios para el buen funcionamiento de la microred.
- Los interesados implicados en una microred deben ser cuidadosamente identificados ya que muchas de las decisiones relacionadas con el control, la operación, los límites de ciertas magnitudes en modo isla, etc. deberían ser acordados entre ellos.
- No existe mucha regulación sobre requerimientos técnicos para la conexión de microredes al SEP. En este estudio se ha consultado un estándar que trata sobre la interconexión de REDs al sistema eléctrico.Se ha asumido que estos requerimientos son aplicables a microredes, que son arquitecturas más complejas que las redes pasivas con REDs. Además, este estándar se aplica sobre la red americana por lo que, algunos requerimientos no son directamente aplicables al caso europeo.

En relación con el caso de estudio del proyecto, puede concluirse lo siguiente:

- Como en cualquier estudio, la información disponible es muy importante para la fiabilidad de los resultados obtenidos. En numerosas ocasiones, ha sido necesario hacer suposiciones debido a la ausencia de información pero, estas consideraciones son razonables para este tipo de proyecto: un anteproyecto o estudio preliminar.
- En el estudio de consumo, la información disponible, aunque anticuada, ha permitido obtener una curva de carga representativa para cada mes. Este patrón de consumo simplificado es muy útil para hacer comparaciones con la generación y para tener una idea general de la forma de consumir en la Escuela.
- El estudio de la PRS ha permitido, además de obtener el ahorro energético proporcionado por este recurso a la Escuela, aprender sobre una tecnología experimental basada en energía solar para el acondicionamiento de edificios.
- Tras el ensayo de prueba y error para el diseño de la planta PV, se concluye que el estudio con datos horarios es más fiable y más útil porque da una idea del número de horas al año que la generación sobrepasa el consumo y, además, permite dimensionar el sistema de almacenamiento que sería necesario para gestionar el excedente de generación.
- El programa PVsyst ha sido una herramienta muy útil para estimar la podrucción de energía anual de la planta PV. El hecho de poder obtener datos de generación horarios ha permitido hacer una comparación muy completa entre generación y consumo.
- El escenario en el que se considera el uso de almacenamiento es mucho más interesante que el caso en el que no se considera porque, además de la funcionalidad principal para la que se ha concebido, puede usarse para otros propósitos interesantes como la optimización de la curva de carga diaria.

Finalmente, y dando respuesta al objetivo definido en este proyecto, se ha obtenido un posible escenario de generación para la operación de la Escuela como una microred. Atendiendo a la necesidad de incrementar la capacidad actual de generación del edificio, se ha diseñado una planta PV que puede ir de menores a mayores Pn y, de esta forma, cubrir más o menos demanda, pero con alamacenamiento, la solución es más limitada.

Este estudio se centra en la planificación de la capacidad de generación de potencia activa de la ETSI para funcionar como una microred. Sin embargo, el diseño de una microred conlleva un estudio muy amplio en el que deben tenerse en cuenta requisitos de las cargas, de los REDs y una estrecha coordinación entre la microred y el SEP.

Para continuar con el estudio de la microred eléctrica en la Escuela de Ingeniería se propone:

- Estudiar la potencia reactiva que deberían dar los RED para satisfacer la demanda de reactiva del sistema, aprovechando así el estudio de consumo del edificio, y analizar la necesidad del uso de otros recursos como bancos de capacitores.
- Llevar a cabo un estudio más detallado de las cargas, para lo cual sería necesario recoger más información sobre las mismas: porcentaje de cada tipo de carga (iluminación, equipos informáticos, motores, etc.), porcentaje de desequilibrio de las cargas, comportamiento de grandes cargas puntuales, etc. Esto permitiría definir una estrecha técnica de coordinación entre generación y consumo.
- En relación al control de la microred, debería estudiarse la regulación de tensión y frecuencia del sistema cuando la microred trabaja en paralelo con el SEP y cuando trabaja en modo isla, modo de operación en el que podría ser necesario hacer actuaciones como por ejemplo, relajar los límites de tensión y frecuencia del sistema.

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