Universitat Politècnica de Catalunya
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Master thesis

Optimal Management of Microgrids

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To the only thing that I can believe:

the Mathematics, the Science...

Preface

The project of this thesis was carried out in the IREC (Institut de Recerca en Energia de Catalunya) in the Area of Electricitat i Electrònica de Potència within the group of Energy Economics, under support of the KIC Innoenergy within the framework of the KIC-EVCITY project.

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Abstract

Keywords: Smart grids, microgrid, energy system optimization, electric vehicle

Current mankind is facing a global dilemma with energy demand increasing, while diminishing traditional energy resources. Increase energy efficiency and sustainability are becoming more necessary. In this framework, smart grids and microgrids are the key in the near future where a decentralization of energy generation is expected. An advantage of these type of grids is that balancing between energy generation, storage, and consumption can be realized most efficiently the closer the physical location of generation, storage and demand is the controller. This reduces the need for centralized communication, enables autonomous operations of increasingly smaller sections of the distribution grid and decreases the losses by distant distribution.

Within this framework and from the point of view of microgrid energy management, economic scheduling for generation devices, storage systems and loads is a crucial problem. Performance an optimization process is necessary to minimize the operating costs while several operational constraints are taken into account. Energy management is carried out by MCC (Microgrid Central Controller) in three steps: tertiary, secondary and primary controls. The first management step is executed one day-ahead and has two objectives. The first is economic optimization using a program based on an Economic Dispatch and an Unit Commitment problem. The second objective is to improve the profitability of the supply and demand balance by interacting with the grid and taking advantage of the V2G (vehicle−to−grid) capability of the charging spot, and to generate a schedule over all components of the microgrid. The rest of the controls are executed on day of operation in order to adjust the output power levels. The secondary control receives the scheduling plan created by tertiary control and taking into account current data, corrects the power outputs of generation units.Exchanged power with the grid and storage states of charge programmed by the tertiary control are ensured.Finally, the primary control regulates the energy flow in real time and ensures a proper operation to address any unexpected issues although, this control is not considered in the project.

The Energy Management System has been tested over different scenarios. One of them is based on a smart house with a photovoltaic module, a micro wind turbine and one electric vehicle charging spot. The household load can be divided into three different profiles: critical, adjustable and shiftable loads. The selected profiles, both mobility of EV and household load, have been measured during a working day. The other scenario is based on a large building where one micro gas turbine and one storage device have been added to the rest of units.

After analysing the results, several conclusions have been deduced such as a change in curve of load and a lower cost for the user. Generally, the consumption over peak periods is decreased or is almost zero in some test cases, while the demand overnight is increased.

Contents

Chapter 1
Introduction

The objective of this project is to develop an energy management algorithm for microgrids through two optimization problems. To guarantee a better understanding of the objective, some concepts and definitions associated with this framework should be explained.

The first two concepts are DG (Distributed Generation) and DER (Distributed Energy Resources). Most countries generate electricity in large centralized facilities, such as coal, nuclear or hydropower plants. However, in the future a significant portion of energy consumption may be supplied by domestic or small scale generation. Distributed generation, also called on-site generation or decentralized energy, generates electricity from many small energy sources and in most cases, from small renewable sources causing lower environmental impact. Distributed generation improves supply security due to the reduction in the amount of energy lost in transmitting electricity because the electricity is generated near where it is required, perhaps even in the same building. This also reduces the size and number of power lines that may be installed and maintained.

DER systems are the controllable load, the power generation technologies and storage devices in small-scale (2 kW to 10 MW range). Current connection practice is based on “fit and forget” approach. This policy leads to inefficiency and costly investment in distribution infrastructure. At the moment, DER can only displace energy produced by central generation i.e., decrease the energy amount generated by traditional generation units, but cannot displace/decrease installed generation capacity. The lack of controllability of DER implies that system control and security must continue to be provided by central generation. However, previous projects have demonstrated that the implementation of a microgrid system will provide a solid framework for a full integration of DG and demand.

Another key factor is the *smart grid.* The term smart grid refers to a modernization of the electricity delivery system so that it monitors, protects, and automatically optimizes the operation of its interconnected elements. These elements include the central and distributed generation through the high−voltage transmission network, industrial users and building automation system, energy storage installations, and end−use consumers and their thermostats, electric vehicles, appliances, and other household device [**2**].

When these concepts are assimilated, understanding the *Microgrid definition* is clearer. A microgrid is a localized group of distributed energy recourses that can be operated coordinately as an energy generator, as an energy storage and as a load. It normally operates connected to a traditional centralized grid (macrogrid or general grid) to provide maximum electrical efficiency with a minimum incidence to loads profile in the local power grid [**8**].
Such systems can sometimes be operated in emergency operation, also called islanded mode, if the single point of common coupling with the macrogrid has been disconnected. Although a microgrid is capable of handling both states, its main benefits will arise from grid-connected [**9**]. In addition, this microgrid concept serves multiple economic, technical, and environmental aims, and reduces the number of intermediary parties.

An example of microgrid is shown in Figure 1:

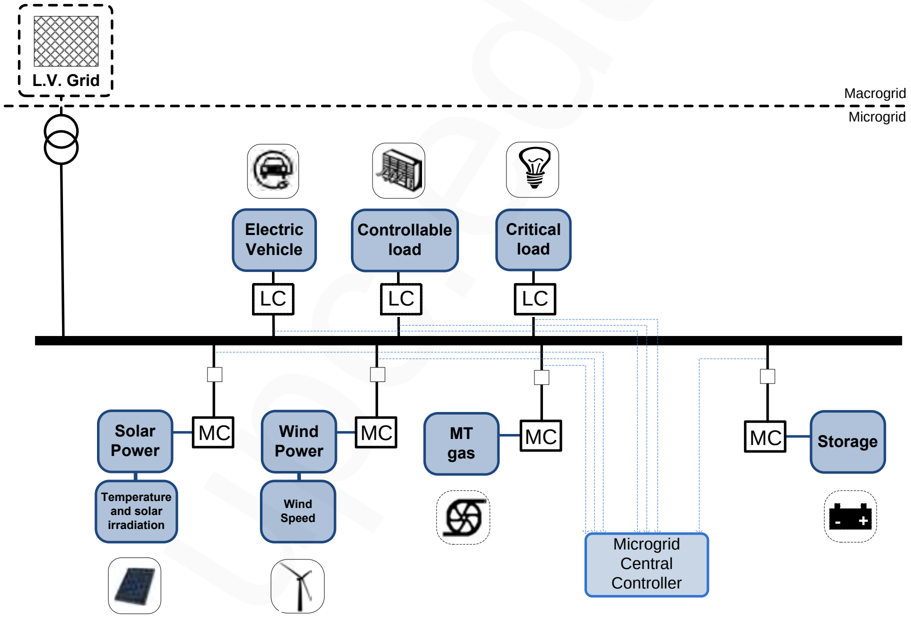


FIG. 1. Microgrid diagram.

The diagram shows generation units, load sources, a storage device, the controller for each component, the point of common connection and the connection with the grid. All microgrid components will be explained in the third chapter.

1. Motivations and objectives

The origin of this project lies in the important role that microgrids could play in the near future due to initiatives where strategies focus on more efficient electricity use. One of these initiatives is the 2020 Strategy in the European Electrical Sector where committed to CO_2 reduction, increasing renewables in the generation mix and efficient energy management.

Included in strategies for CO_2 reduction is the promotion increment of EV (electric vehicle) use and how, at the same time, it could also help the integration of renewable power sources such as wind power by storing the energy surplus produced during windy periods and providing it back to the microgrid during high load periods. To take advantage of these actions, a V2G system is necessary. V2G is a system in which plug-in electric vehicles communicate with the power grid delivering electricity into the grid or decreasing or shifting their charging rate.

Thus, taking into account the possible benefits provided by electric vehicle use and integration in microgrids, the following objectives have been set to contribute to european energy initiatives.

General objective:

- Develop an optimal energy management algorithm for the IREC' microgrid facilities in order to improve the research about these small grids.

Specific objectives:

- To formulate problems associated with the different control levels of the microgrids.
- To obtain a GAMS based implementation for the off-line solution of the tertiary optimal control problem.
- To develop a C based implementation for the on-line solution of the secondary microgrid optimal problem.
- To implement the algorithm for the secondary optimal control problem in the microgrid's emulator of the IREC.
- To use the optimal energy management algorithm to test the introduction of the microgrids in the energy market and, at the same time, to study the electric vehicle as a new component in the microgrid.

2. Contents

The document structure is as follow:

- *Chapter 1: Introduction.* This chapter introduces all the basic concepts needed to understand what is a microgrid and its framework. The second section outlines the motivations of the project and its objectives. The last part of the chapter summarizes of the contents.

- *Chapter 2: Microgrid's regulatory environment.* This chapter presents a brief introduction of the Spanish energy market and its current regulation associated with microgrid framework. The chapter ends with a prospective of a new agent for the participation of microgrids in the energy market.
- *Chapter 3: Microgrid's components modelling.* Chapter 3 defines the considered components of the microgrid included in the test cases. For each component is presented its definition, main characteristics and in the last section, its modelling.
- *Chapter 4: The microgrid central controller optimization problem.* This chapter includes a brief introduction of microgrid controller and the optimization problems associated with them. For the two problems, tertiary and secondary control, the mathematical formulation is presented considering the microgrid's components modelling.
- *Chapter 5: Implementation and results.* Chapter 5 includes the optimal management algorithm, a description of microgrid's emulator of the IREC and the test cases. There are two main test cases splitted into three cases with different hypothesis. Finally, the results obtained with the algorithm for each test case and a comparison between them, are commented.
- *Chapter 6: Conclusions and further research.* General conclusions of the results generated by this project and further research are discussed.
- *Appendix.* This appendix provides a glossary where the symbols and abbreviations used in this project are described.

Chapter 2
Microgrid's regulatory environment

1. Present situation

The current situation in the Spanish Electricity Market has been based on a liberalized system since December 1997, when the Electricity Sector Act provided for the creation of an independent market operator that would uphold a liberalized system for the generation and supply of electricity.

The organization of the electricity market was stipulated through Law 54/1997 and Royal Decree 2019/1997 whose basic principle was to allow to trade for producers, resellers and consumers. The Ministry of Economy must approve the rules and terms governing the operation and settlement of the production market according to European regulations. In addition since 1 January 2003, consumers have acquired free market status and can therefore choose their supplier.

To participate in the MIBEL (Mercado Ibérico de la Electricidad) there are two main ways. The first option is the trading by bilateral contracts between the generation company and a qualified consumer. The contract stipulates the electricity amount that the company must supply, the price and the duration of the delivery period. The second and most important way are the regulated markets, they consist of seven sessions where the agents involved in the electricity market can participate to buy or sale energy. The first and main session is the daily market, followed by six subsequent sessions to the intraday markets distributed throughout 24 hours of the day. In addition, a process of technical management enables trading to guarantee the security and reliability of the electricity system.

The operation of the national electricity system depends on two independent entities the MO (Market Operator) and the SO (System Operator). The main role of each operator is economic management for MO (in Spain the Operador del Mercado Ibérico de la Energía−Polo Español, S.A. OMEL) and technical management for SO (Red Eléctrica de España, S.A). The coordination between these two entities is essential in order to guarantee that market transactions are physically feasible and fulfill security criteria.

In the Figure 1 the general diagram of the present Spanish Energy Market is shown with the different agents, operators and the possible flows between them:

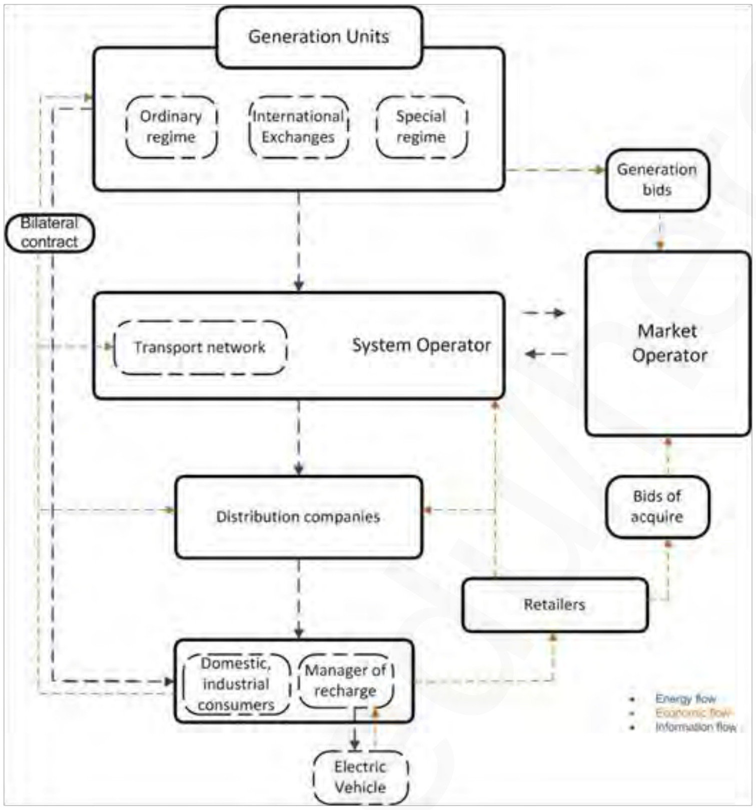


FIG. 1. General diagram of Spanish Energy Market.

Included in generation units framework, it is important to take into account the special regime to introduce microgrids in the present framework.

The main difference between ordinary and special regimes is the opportunity to choose between two different economic mechanisms. One option is to transfer all power to the system through distributed and transport networks, receiving a regulated tariff depending on the generation technology. The generation units in special regime can sell the power in the MIBEL as in the case of ordinary regimes. In this case, the price will be the price resulted in the organized market, complemented with a premium depending on the technology.

The type and power of electrical installations which can operate in a special regime are regulated in article 79.7 of the law with number 54/1997. However, the possibility of a regulated tariff is not available for new installations, pending a new regulation.

2. Trend toward Distributed Energy Sources (DER)

2.1. European framework. Since 1991 when the first energy efficiency program was approved by the European council, the laws concerning savings and energetic efficiency have been linked to the development of the EU, its energy policy and the requirements derived from climate change.

The legislations with more features in this sphere have been the action plan of 200/2006 and the Green Book of 2006 about European strategy for energy where the Commission notes that the EU can reduce energy consumption expected for 2020 by 20%. This level of energy savings will strengthen the competitiveness of European industry and will allow the EU to meet its Kyoto commitments and reduce CO_2 emissions.

In January 2008, the European Commission presented a draft Directive on the promotion of the use of energy from Renewable Energy Sources (RES) which contains a series of elements to create the necessary legislative framework to enable a 20% renewable energy share to become a reality.

Directive 2009/28/EC of the European Parliament and the Council of April 23, concerns the promotion of the use of RES and states that each Member State shall establish a National Action Plan on Renewable Energy (NAPRE) to achieve the national targets set in the Directive.

For this, the Plan de Accion Nacional de Energias Renovables 2011−2020 has been created in Spain, where the framework and aims for each type of renewable technology are set. The evolution of energy consumption in Spain, rising oil prices and the intensification of the savings plans and energy efficiency have been taken into account in preparing an energy map for 2020. In more detail, it is anticipated that in 2012 the participation of renewable energies will be 15% (compared to the expected value 11%) and in 2016, participation will be 18%.

Within the Action Plan, the increase of NZEB (net zero energy buildings) will be adopted taking into account the approval of the European directive (Directive 2010/31/UE) that requires all new buildings built, from 31/12/2020, must be of this type. A definition of NZEB can be: a building or installation which create as much energy as it consumes, by on-site renewable energy, thereby providing a significant reduction in both demand and emission.

2.2. Spanish framework. To guarantee the European targets, two Royal Decrees have recently been approved.

RD (Royal Decree) 1699/2011 concerns the management and technical conditions for connection to grid. In this RD is regulated the gradual entry of facilities of electrical energy production of low power (Microgrids), to modify the centralized model by promoting a new system of increasingly distributed generation. This change will involve lower losses of energy in the grid, the reduction of economic investment in transport and distribution and primary energy savings; and for consumers, a better electrical autonomy and security of supply.

Possible the most important concept regulated in this RD is the possibility of working island, a main characteristic of microgrids. About this, article 12 says:

> "*1. Connection schemes should respond to the principle of minimizing losses in the system, favoring the maintenance of security and quality of supply and enabling the island to work on its own consumption, never feed other network users.*"

Moreover, the creation of a new royal decree about own consumptions is mentioned in the Article 18 of this RD:

> "*The Minister of Industry, Tourism and Trade, within four months after the entry into force of this Royal Decree, will raise a royal decree proposal to the Government regulating the administrative, technical and economic electrical energy consumption produced within the grid of a consumer for their own consumption.*"

And the possibility of exporting and importing power at the same time but independently:

> "*In cases where the production facility will sell only the surplus energy will be allowed the option of installing a single measurement device with records independent of generation and consumption. In this case, require the signing of two contracts for access, one for generation and other one for consumption.*"

A previous Royal Decree, 647/2011, has created a new participant specifically to manage the recharges of plug−in electric vehicle (an important component in our studies of microgrids), namely "*gestor de cargas*" (charging manager) and shown in the Figure 1. The charging managers are those mercantile companies that provide services of energy recharge defined in the art. 9 h) of the law with number 54/1997 which, being consumers, are entitled to the resale of electric energy for energetic recharge services for electric vehicle. In addition, the model to be implemented will not be of concession but one in which any entity can obtain administrative permission to install recharging posts, buy and resell energy within the service recharge of electric vehicle batteries [**12**]. In the future, other expected operations for these managers is the possibility to receive set points from Distribution System Operator (DSO) through a management center to optimize the network operation.

3. Prospective

Currently, there are three main agents in the Spanish market; generation company, market operator and retailer. Since the emergence of microgrids, a new agent called the aggregator is proposed. Its role would be to represent a group of one or more microgrids for their management in different sessions of the energy market.

More specifically, the aggregator would receive supply needs and generation offers from each microgrid then, with this information, could offer buying and selling bids in the different markets of the system by optimization of the overall benefit of the represented microgrids. After the participation in the market, the aggregator might communicate the set points for generation or buying of energy to each microgrid. In addition, the aggregator should provide the information about each microgrid to its corresponding distributor.

The aggregator adds another possibility into the system. The microgrid could participate into the transportation network actions and to provide services to its distribution network.

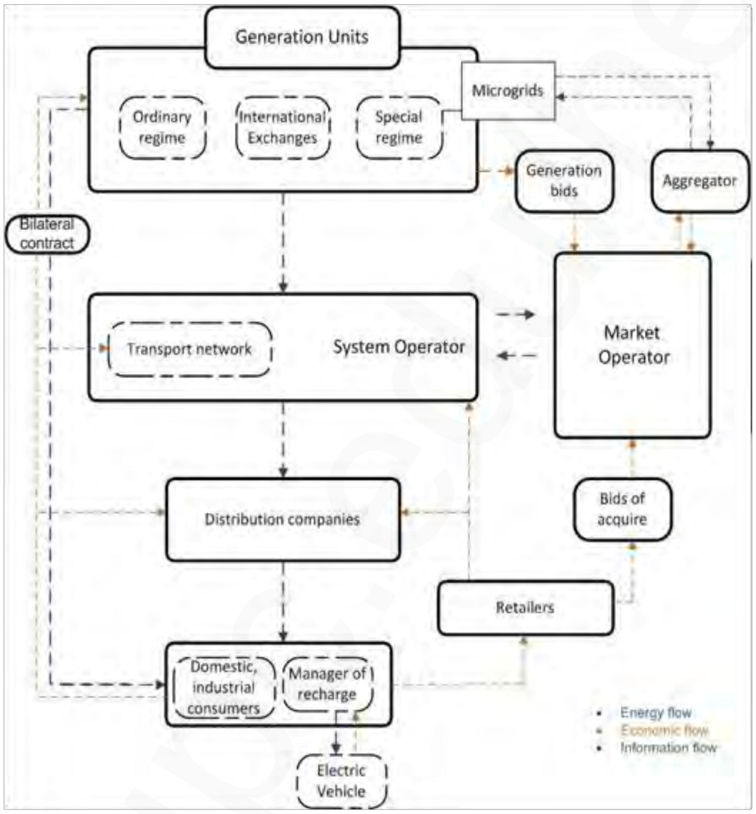


FIG. 2. General diagram of Spanish Energy Market with microgrids.

Chapter 3
Microgrid components modelling

1. Technical specification of microgrid components

The considered components of the microgrids include microgrid's considered components have been the most suitable elements for the test cases, which are briefly described in Chapter 5. These elements are presented below, and likewise, the main features for the modelling of each component will be detailed later.

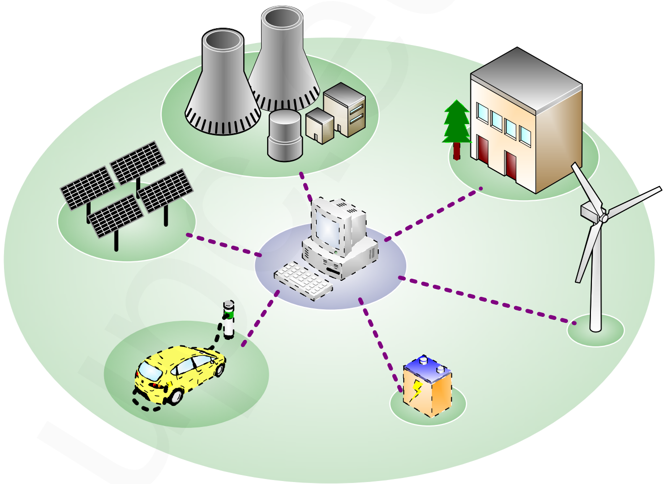


Fig. 1. Representation of a microgrid.

1.1. Demand. The electric demand of a Microgrid can be grouped into three different profiles depending on the way in which this demand is managed or not.

- Critical demand
The critical demand (or non−controllable demand) comes from devices or systems which demand must be instantly supplied and does not shift through time, or when its postponement could create a user dissatisfaction i.e., the demand generated by the lighting cannot be postponed

because it would create a blackout lighting [**3**].
Some examples of non-controllable devices are:

- Illumination
- House equipment
- Elevators

- Adjustable demand
These devices can not be totally managed, but can be adjusted. If a demand management is necessary, the user (or remotely) can change a characteristic of the device decreasing the level of consumpion during a pre established period. For example:

- Air conditioning and central heating

- Shiftable demand
The demand profile for these devices will be shiftable in the planning horizon as explained later. For example:

- Washing machines
- Electric Vehicle: the demand from EV is also shiftable through time, but it must be taken into account the mobility profile that bounds the available time to meet the load

1.2. Photovoltaic module. A photovoltaic module (PV) or solar panel is an interconnected collection of solar cells combined into one item only which is used to convert energy contained in the sun rays into electricity.
When an installation contains several panels, is commonly referred as photovoltaic array. Arrays are a great way to increase the potential of a solar electricity system, to provide a greater output of electricity. However in this project, a single module is only considered.

To model the PV module, the parameters below are needed to describe its functioning:

- Environmental factors such as solar radiation and ambient temperature
- Technical values, for example: efficiency factor, nominal capacity installed, surface area and nominal operating cell temperature
- Other adjustable factors: tilting of plaque

Both technical and environmental factor, which are needed to the constraints set below, must be taken into account for such modelling.

- Capacity of supply depending on solar irradiation and ambient temperature.

1.3. Micro-wind turbine. Micro wind turbine is a general term used for small scale wind turbines that are typically deployed near buildings.It is used to generate electricity from wind and transmitting it directly to the owner.

In this case, the parameters involved in the modelling of micro-wind turbines are the following:

- In a simplified model, the only environmental input is wind speed. Depending on the type of modelling, other factors such as type of ambient (humid, dry...) can be taken into account.
- Different speeds of turbine: cut-in, cut-out and rated speed.
- Technical inputs such as efficiency factor, nominal capacity installed and swept area

Both technical and environmental factor, which are needed to the constraints set below, must be taken into account for such modelling

- The unit initial operation status
- Capacity of supply depending on wind speed

1.4. Micro gas turbine. The third kind of generation unit is a micro gas turbine whose basic principles are based on micro combustion. The process consists in burning a mixture of compressed air and fuel under specific conditions of constant pressure. Consequently, the mechanic energy is generated when the hot gas has expanded.

The micro gas turbine could generate the energy that renewable energy units can not supply. The following technical inputs should be considered:

- Installed capacity
- Maximum and minimum instantaneous power
- Ramp down and ramp up limits
- Minimum start-up and shut-down times

The constraints to be taken into account must comply with all the above factors.

- Initial state of connection
- Maximum and minimum instantaneous power
- Ramp down and ramp up limits
- Minimum start-up and shut-down times

1.5. Electric Vehicle. A charging spot connected to the microgrid for electric vehicles has been considered due to the benefits provided by the EV mentioned in Chapter 1.

On other hand, there are two important concepts related to batteries.

- SOC: State of Charge is defined as how much a battery is charged (or how full it is). If a battery is half charged, then the state of charge is 50%. This is commonly written as 50% SOC.
- DOD: Depth of Discharge is the opposite state of charge. For instance, it is how much a battery is discharged. If a battery is fully discharged (empty) then its depth of discharge is 100%, commonly written as 100% DOD, then the state of charge is 0%.

The DOD acquires importance in relation to lithium−ion batteries, because if a lithium−ion battery is fully discharged frequently, its performance is drastically affected. However, these type of batteries are one of the three most common types of batteries used for electric and hybrid electric vehicles due to its loading capacity, lifecycle performance and environmental impact.

The parameters of the EV model are:

- Mobility profile: demand and available time to V2G
- Minimum SOC allowed before leaving
- Efficiency of battery
- Energy storage capacity
- Maximum instantaneous power
- Maximum depth of discharge (DOD)

The constraints that must be considered are:

- Battery change balance: how the state of charge varies from one period to another considering the amount charged and discharged during this period
- Minimum level of ending charge: minimum amount of battery charge at which the vehicle can leave the station once decided it will be connected
- Storage capacity
- Limitations by mobility

1.6. Storage device. An energy storage system is defined as any device storing energy in any form such as chemical (batteries), thermal, mechanical (flywheel), electrical (capacitor), or another type of energy for its usage at another time.

Since the use of the electric vehicle battery is limited by the mobility profile, a storage device is considered for a better performance of the microgrid allowing a higher self-supply.

In this way, the needed parameters are:

- Efficiency of battery
- Energy storage capacity
- Maximum number of cycles
- Maximum instantaneous power of charging and discharging
- Maximum depth of discharge (DOD)
- Initial battery's state of charge
- Final battery's state of charge

The constraints that must be taken into account are similar to the constraints of EV:

- Storage balance from one period to another period
- Limits of instantaneous charging/discharging power

- Limits of recommended DOD

1.7. Point of interconnection to the grid. The microgrid has a point of interconnection to the grid. The access will be regulated through a tariff with two terms. The first term is a constant depending on the capacity and use of the access. The second term is variable in time and depends on the amount of exchanged energy with the grid. For instance, if the microgrid needs external power, this term will be a cost; but if the microgrid has power surplus, this term will represent a economic profit to the microgrid owners.

2. Mathematical modelling of microgrid's components

Each component has been modelling according with the needs of the optimization problems, which will be presented in Chapter 4, and the characteristics presented above.

2.1. Micro−wind turbine. On the microgrid basis, the only important thing of the micro−wind turbine is the power that the turbine can produce in each period. Due to this fact, an unique set of constraint is necessary to guarantee these bounds.

Let p_t^W the wind power signal at time t then, the variables will be bounded between zero(if wind has not enough speed) and available wind power :

$$0 \leq p_t^W \leq \bar{P}_t^W, \;\; t \in T$$

where T will be a set of time periods.

To calculate the available wind power $\bar{P}_t^W$, the following piecewise function has been considered [**4**]:

$$\bar{P}_t^W = \begin{cases} 0 & \text{if} \quad v_t < v_{in} \text{ or } v_t \geq v_{co} \\ A^W \eta (a v_t^3 - b N^W) & \text{if} \quad v_{ci} \leq v_t \leq v_r \\ A^W \eta N^W & \text{if} \quad v_r \leq v_t < v_{co} \end{cases}$$

where both $a = \dfrac{N^W}{v_r^3 - v_{ci}^3}$ and $b = \dfrac{v_{ci}^3}{v_r^3 - v_{ci}^3}$ are constants, η is the efficiency factor, N^W (kW) is nominal power and A^W is the swept area by wind turbine blades. In addition, this function depends on wind speed v_t (m/s) and three speed characteristics of the turbine: v_{ci} cut-in speed , v_r rated speed and v_{co} cut-out speed (m/s) as seen the Figure 2.

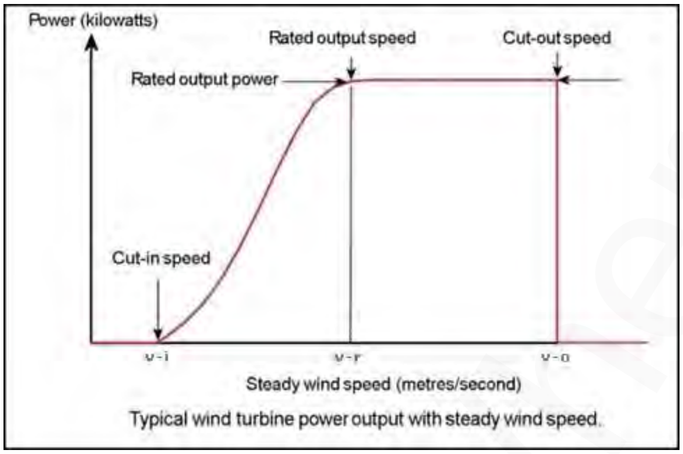


FIG. 2. Wind turbine power output.

The wind speed v_t, is not obtained directly because the wind data are taken at a reference height (v_{ref_t} at h_r). Thus, the wind speed at hub height h can be calculated by using a power-law equation:

$$v_t = v_{ref_t} \left(\frac{h}{h_r} \right)^{\alpha}$$

where α is the power law exponent which value is usually 1/7 if there is not a specific site data [**13**].

2.2. Solar power available. This case is similar to the previous subsection in the sense that the set of constraints is the same kind. The power provides by the photovoltaic module is technically bounded by its characteristics and weather factors.

Let p_t^{PV} be a signal solar power at period t then the constraints are:

$$0 \leq p_t^{PV} \leq \bar{P}_t^{PV}$$

Where $\bar{P}_t^{PV}$ is the maximum available solar power at interval t. The used model to estimate these bounds is part of another IREC internal project where the following linear equation was developed to calculate the generated power by PV modules:

$$\bar{P}_t^{PV} = (a_1 Ir_t + a_2) T_t^C + a_3 Ir_t + a_4$$

Where the coefficients a_j were calculated using least squares methodology. The term T_t^C is the cell temperature which was calculated under standard conditions by a simple linear model using the direct normal irradiation Ir_t and ambient temperature T_t^a. Once again, least squares methodology has been used to carry out the calculation:

$$T_t^{C} = b_1 + b_2 T_t^a + b_3 Ir_t$$

2.3. Micro gas turbine. To schedule when start-up or shut-down the micro gas turbine, the formulation of thesis [**6**] have been followed .

Let $u_t^{MT} \in \{0,1\}$ binary variable expressing the off-on operating status of the micro−gas turbine over the t^{th} interval ($u_t^{MT} = 1$ if committed,$u_t^{MT} = 0$ if uncommitted). The values of u_t^{MT} and u_{t+1}^{MT} must obey certain operating rules in order to meet the limits of the minimum time in service and idle. Thus, it is necessary to introduce two extra binary variables e_t^{MT} and a_t^{MT} for each u_t^{MT}. Let $e_t^{MT} \in \{0,1\}$ be a start-up indicator. It has a value of one in all intervals t where the MT unit has changed from $u_{t-1}^{MT} = 0$ to $u_t^{MT} = 1$, and zero elsewhere. Similarly, $a_t^{MT} \in \{0,1\}$ is a shut-down indicator. It should have a value of one in all intervals t where $u_{t-1}^{MT} = 1$ changes the value to $u_t^{MT} = 0$, and zero otherwise.

The relation between these binary variables is modelled through the following sets of constraints:

$$\begin{aligned}
&u_t^{MT} - u_{t-1}^{MT} - e_t^{MT} + a_t^{MT} = 0 && t \in T \\
&e_t^{MT} + \sum_{k=t}^{\sigma_t} a_k^{MT} \leq 1 && t \in T \\
&a_t^{MT} + \sum_{k=t+1}^{\tau_t} e_k^{MT} \leq 1 && t \in T
\end{aligned}$$

where σ_t and τ_t are the minimum between $|T|$ and t plus the minimum start-up and shut-down times respectively. Let p_t^{MT} be a positive variable for the signal power to micro−gas turbine at period t. These semicontinuous variables take values in the set $\{0\} \cup \{\underline{P}^{MT}, \bar{P}^{MT}\}$ depending on the value of u_t^{MT}. If the micro gas turbine is in operation state at time t then $u_t^{MT} = 1$ and the power available has a range of possible values between the two bounds of instantaneous power $\underline{P}^{MT}$ and $\bar{P}^{MT}$, in otherwise, the micro−gas turbine is idle and p_t^{MT} is zero.

$$u_t^{MT} \underline{P}^{MT} \leq p_t^{MT} \leq u_t^{MT} \bar{P}^{MT}, \; t \in T$$

On other hand, if the micro−gas turbine is committed, the variable p_t^{MT} must take values within a range depending on the value of the previous variable p_{t-1}^{MT}. The difference between the generation level at period $t-1$ and generation level at period t, if it varies, must vary within a range (R_l,R_u). The range depends on the machine characteristics and these constraints are called ramp limits.

$$R_l \leq p_t^{MT} - p_{t-1}^{MT} \leq R_u,\ \ t \in T \backslash \{1\}$$

2.4. Storage device. As already mentioned above, the storage device can be charged, if the total power output of the generation units is higher than the energy demand, or can provide power if it is discharged. Due to this dual process, two sets of positive variables are needed to model the performance of the storage device.

Let p_t^{Sc} be a positive variable for the charged power to storage device at period t. Let also p_t^{Sd} be a positive variable for the discharged power from the storage device at period t. Both variables take positive values between technical bounds but are never higher than zero in the same period:

$$\begin{array}{ll} p_t^{Sd} \leq \bar{P}^{Sd} x_t^{S} & t \in T \\ p_t^{S} \leq \bar{P}^{Sc}(1 - x_t^{S}) & t \in T \end{array}$$

where $x_t^{S} \in \{0, 1\}$ are binary variables expressing the direction operating status of the storage over the t^{th} interval ($x_t^{S} = 1$ if discharged,$x_t^{S} = 0$ if charged). Binary variables are needed because in the objective function of the tertiary and second optimization problems, only the discharged process has a cost, as will be seen later. This way, the charged power is separated of the discharged power.

Let SOC_t^{S} be a SOC indicator at period t. The storage balance is ensured by the following equation where, from an interval to another, the amount of charged/discharged power is taking into account with its corresponding efficiency factor e_c and e_d:

$$\begin{array}{ll} N^{S} SOC_t^{S} = N^{S} SOC_{t-1}^{S} + (p_t^{Sc}/e_c - e_d p_t^{Sd})\Delta & t = \in T \backslash \{1\} \\ N^{S} SOC_1^{S} = N^{S} SOC_0^{S} + (p_1^{Sc}/e_c - e_d p_1^{Sd})\Delta & \\ SOC_{|T|}^{S} = SOC_F^{S} & \end{array}$$

where N^{S} is the storage's nominal capacity. The efficiency factor is a performance index, which expresses the relationship between the provided power for the microgrid and the real stored power in the form of percentage. The efficiency factor have been considered from the microgrid point of view. For instance, if the battery requires power then, the microgrid must provide more amount of power than the required to take into account the losses.

In many types of batteries, the full stored energy cannot be completely discharged without causing serious damage to the storage device. Thus, there are recommended maximum and minimum rate for the DOD. Taking into account these recommended DOD and the relation between SOC and DOD ($DOD + SOC = 1$), the bounds for the state of charge in each t are the following:

$$1 - \overline{DOD} \leq SOC_t^{s} \leq 1 - \underline{DOD},\ \ t \in T$$

2.5. Electric vehicle. The model for a single electrical vehicle is similar to the storage device modelling but considering the mobility profile.

Let $U^{EV} \subseteq T$ a set of periods where the EV is connected to the microgrid. The variables associated with the provided power p^{EVd} and required power p^{EVc} between the microgrid and the EV, are defined in this set.

Since the previous case, if a process (charge/discharge)is not active at period t then, the bound for the associated variable, is zero in this period. However, if the process is active then the bound will be the allowed maximum $\bar{P}^{EV}$ which is the same in two process:

$$p_t^{EVc} \leq \bar{P}^{EV} x_t^{EV}$$
$$p_t^{EVd} \leq (1 - x_t^{EV})\bar{P}^{EV}$$

where x_t^{EV} are binary variables expressing the direction operating status of the EV battery over the t^{sh} period in U^{EV} ($x_t^{EV} = 1$ if the EV is charged, $x_t^{EV} = 0$ in otherwise).

Let D^{EV} the required energy by the vehicle while is not connected i.e., in the periods $t \in T \setminus U^{EV}$. This demand does not affect directly to the Microgrid. However, it affects to the state of charge SOC_t^{EV} which must be calculated in all periods considering the following piecewise function which depends on $t \geq 1$:

$$N^{EV} SOC_t^{EV} = \begin{cases} N^{EV} SOC_{t-1}^{EV} + (p_t^{EVc}/e_c - e_d p_t^{EVd})\Delta & \text{if} \quad t \in U^{EV} \\ N^{EV} SOC_{t-1}^{EV} - D_t^{EV} & \text{if} \quad t \in T \setminus U^{EV} \end{cases}$$

If $t = 1$, the function is:

$$N^{EV} SOC_1^{EV} = N^{EV} SOC_0^{EV} + P_0^{EV}$$

where

$$P_0^{EV} = \begin{cases} (p_1^{EVc}/e_c - e_d p_1^{EVd})\Delta & \text{if} \quad 1 \in U^{EV} \\ -D_1^{EV} & \text{if} \quad 1 \in T \setminus U^{EV} \end{cases}$$

where N^{EV} is the EV battery's nominal capacity and e_c, e_d are the efficiency factor.

To guarantee a best performance of the battery life, a maximum % for the DOD must be imposed if the EV is connected to the Microgrid. The value of this maximum will be higher in the periods before the next displacement to ensure the EV demand. About the upper bounds of SOC^{EV} will be 100% due to the lithium−ion batteries can be charged fully.

$$SOC_t^{EV} \geq \begin{cases} 1 - \overline{DOD} & \text{if} \quad t,\ t+1 \in U^{EV} \\ \underline{SOC} & \text{if} \quad t \in U^{EV}\ \&\ t+1 \in T \setminus U^{EV} \\ 0 & \text{if} \quad t \in T \setminus U^{EV} \end{cases}$$

$$SOC_t^{EV} \leq 1 \ \ t \in T$$

2.6. Demand.

2.6.1. *Shiftable demand.* The shiftable demand has a profile defined by a number of subintervals $|L|$ with $L \subseteq T$ and a power profile D^{SH} in L. The decision will be to choose the period t which to start to supply this demand.

Let $x_t^{SH} \in \{0,1\}$ variables expressing the initial interval t where the shiftable demand starts to be supplied for the next $|L|$ hours. Thus, if $x_t^{SH} = 1$ then, only the variables associated to x_t^{SH} : d_t^{SH} , $d_{t+1}^{SH}, \cdots, d_{t+(L-1)}^{SH}$, take positive values, and more specifically, each d_{t+j}^{SH} takes the value D_{l+1}^{SH} exactly. Only the first $T-L+1$ binary variables can be defined because each x_t^{SH} variable is associated with the next $|L-1|$ d_t^{SH} variables. Another way to see the relationship between the different variables, it is from the power variables point of view: each variable d_t^{SH} is associated to the following $L-1$ binary variables. This way, the constraints are:

$$d_t^{SH} = \sum_{l=1}^{|L|} D_l^{SH} x_{t-l+1}^{SH} \qquad t = 1..T$$

Considering that the shiftable demand profile starts just once, one binary variable only can take the value one:

$$\sum_{t=1}^{T-(L-1)} x_t^{SH} = 1$$

2.6.2. *Critical and adjustable demand.* Critical demand, D_t^C , is forecasted for each interval t and it must be supplied completely but it can not be possible. To avoid an imbalance in the microgrid, an adjustable rate demand has been introduced. For instance, if at interval t the peak demand is too high, the supply can be decreased until an assumed maximum f^C, taking into account that the critical demands not supplied has a penalty in the objective function.

Let d_t^C be a positive variable indicating the supplied critical demand at period t, and let also d_t^A be a positive variable indicating the demand not supplied in the same period. Considering that f^C is a percentage of adjustable demand, which is also a fraction of the critical demand, the constraints are the following:

$$\begin{aligned} d_t^C + d_t^A &= D_t^C \quad && t \in T \\ d_t^A &\leq f^C D_t^C && t \in T \end{aligned}$$

2.7. Point of interconnection to the grid. The interconnection point also has two actions: exporting and importing power. In addition, the constant cost of the access tariff must be always paid regardless the microgrid buys or sells power to the grid. For these facts, binary variables are needed again and also, two sets of positive variables to avoid the absolute value in the objective function.

Let x_t^i be a indicator of the flow direction in the interconnection at period t. x_t^i takes the value 1 if the microgrid is selling the power surplus, and takes the value 0 when the grid provides power to the microgrid. Let p_t^{Ib} be a positive variable to calculate the amount of acquired power from the grid at period t^{sh}, and let also p_t^{Is} be a positive variable to account the amount of power sold to the grid at period t^{sh}. Considering the bounds of interchangeable power between the grid and microgrid and the above variables, which cannot be higher than zero at same period, the constraints are as follows:

$$\begin{cases} p_t^{Is} \leq x_t \bar{P}^{I}, & t \in T \\ p_t^{Ib} \leq (1 - x_t) \bar{P}^{I}, & t \in T \end{cases}$$

Chapter 4

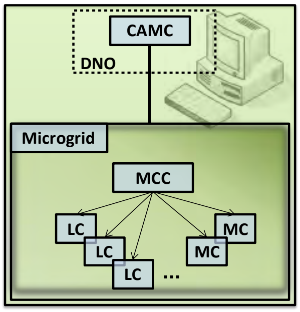
The microgrid central controller optimization problem

From the point of view of the microgrids energy management, the economic scheduling of generation units, storage systems and loads is a crucial problem where the optimization methods can be the most important tool to face it. This management is carried out by the MCC (Microgrid Central Controller) receiving/sending signals to local controllers of each component and receiving external inputs (price, weather,...).

1. Overview of the microgrid central controller problem

A microgrid must ensure the supply of electrical energy at any time. For this fact, a supervisory control ,either centralized or decentralized, is necessary. This supervisory control is splitted into three hierarchical levels:

1 Central Autonomous Management Controller (CAMC) belonging to the distribution network operator (DNO)
2 Microgrid central controller
3 Local controllers splitted into Microsource Controllers (MCs) and Load Controllers (LCs)



The first controller does not belong to the microgrid, it is delegated of the macrogrid controllers. The main interface between this control level and microgrid, is the MCC. The MCC is responsible of the optimization of its operation according to the cost supply price, the microgrid controllable components and the expected loads. To manage the microgrid components, the MCC also must coordinate local controllers associated with each component. To carry out these objectives, the MCC has two main functional modules which are EMM (Energy Management Module) and PCM (Protection Co-ordination Module). On this project basis, the EMM operations are important. The EMM communicates the set points, such as active and reactive power output, voltage and frequency, to each local controller [**1**]. Thus, the EMM is in charged to ensure the profitability of microgrid, which definitely is a key factor for its deployment. Microgrid control strategies can be divided in the following types: real-time optimization, expert system control and decentralized control [**14**].

1.1. Long-term planning. The Long-term management has a scope of 2-10 years. Its purpose is to design the topology of a new microgrid, what technologies will be included and their installed capacity. Other goals can be when to start operation in order to match future loads and when to retire old units.

1.2. Short-term management. The scope for short-term management is 1 day in this project. Its main purpose is to decide when the units must be turn-on or turn-off, the amount of generated power at each period by each unit, to manage the storage device use and the exchangeable power with the general grid through the interconnection point while meeting several operational constraints.

Included in this level of management are three sublevels which can be distinguished depending on the time frame (always in the context of a day) and the performed functions. These three sublevels are described below:

a) Tertiary control: economic

The tertiary control has a scope of 24 hours with periods of 15 minutes and has two objectives. The first is the economic optimization using a program based on an Unit Commitment problem. The second is to improve the profitability of the supply and demand balance by interacting with the grid. These aims are realized taking into account daily forecasts regarding weather, energy price and demand data. On economic optimization, the signals for the controllable units are calculated allowing the system to find out an optimal unit commitment considering future values by exploring the price differences between on-peak and off-peak periods during a day. The final result is a schedule of the power outputs for each period within the optimization range.

As already mentioned above, the optimization procedure depends on energy price. However, in a higher level, the procedure depends on the market policy adopted in the microgrid operation. The main role in the two possible policies is played by the MCC.

In the first case, the MCC supplies the total demand of the microgrid only using its local production from generation units and storage devices and, trying not export power to the distribution grid. In the second policy, the MCC tries to maximize the value of the microgrid participating in the open market i.e., buying and selling power to the grid [**11**]. If the microgrid want to participate in the market, a daily schedule of production is necessary because the energy markets set their operations with a day-ahead. This schedule could be the tertiary control program.

We will focus on the second policy but eventually, an optimal solution to our model could be a mixing of both policies: with and without net energy exchange depending on the the time period.

b) Secondary control: power quality

The secondary control runs each 15 minutes with periods of 30 seconds (more or less depending on the time range to obtain the real data available), and it is in charge of power quality optimization and to minimize the average of all deviations compared to the tertiary control program. For doing so, the controller must take into account current weather data, operation data of generation units while ensures the exchanged power with the grid and storages states of charge programmed above.

This optimization problem is resolved by a cascade programming (Fig. 1). Included in the procedure is an optimization problem in each iteration. The solution of one subproblem is used as a start point for the next subproblem which will have one period time less and data more current. Finally, the procedure combines the solutions of the subproblems to reach an overall solution.

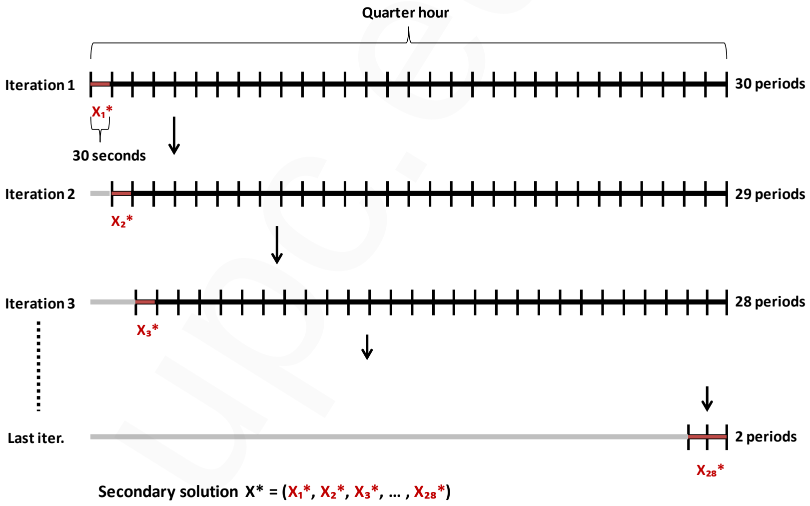


FIG. 1. Cascade procedure for the secondary control optimization problem.

c) Primary control: power reliability

The primary controls, also called momentary controls, are executed in real-time each second. Its objective is ensured the balance between generation and demand against any unexpected issue. However, the primary control is not considered in this project because it is not a optimization problem.

The tertiary and secondary optimization problems are formulated mathematically below.

2. Tertiary control optimization problem

To formulate the model of the tertiary control problem, we are going to take into account the mathematical modelling of each microgrid component, which have been explained in Chapter 3, but adding the balance constraints between demand and generation and an economic objective function.

2.1. Objective function. The goal is to minimize the generation costs of the micro−gas turbine and the economic costs associated with the exchanged energy between the grid and the microgrid:

$$\begin{aligned} Min \quad & \sum_{t\in T} C^{MTu} e_t^{MT} + C^{MTd} a_t^{MT} + \Delta C^{MT} p_t^{MT} + \\ & + \sum_{t\in T} \Delta (C^{I2}(p_t^{Ib} + p_t^{Is}) + C_t^{I1}(p_t^{Ib} - p_t^{Is})) \\ & + \sum_{t\in T} \Delta (C^{Sd} p_t^{Sd} + C^{EVd} p_t^{EVd} + K^{A} d_t^{A}) \end{aligned}$$

where:

C^{MTu}	Start-up cost of MT	€
C^{MTd}	Shut-down cost of MT	€
C^{MT}	Generation cost of MT	€/kWh
C^{I2}	Constant cost of access tariff	€/kWh
C_t^{I1}	Variable cost of energy	€/kWh

In addition, an economic cost for each battery discharging process, based on the reduction in the number of complete charge/discharge cycles a battery can perform before its nominal capacity falls below 80% of its initial capacity [**10**], and an economic penalty for the not supplied demand, are evaluated. These penalties have been tested by a sensitivity analysis.

One of the main problems with electric cars and its owners is the range anxiety concept. Range anxiety is the fear of running out of electricity before destination has been reached. To minimize this potential problem, the user has the option to choose an objective function less economical but more secure. The following term will be added to the objective function in some test cases. Its new goal will be to minimize costs and to encourage a greater charging battery.

$$\sum_{t\in U^{EV}} K^{RA}(1 - SOC_t^{EV})N^{EV}$$

where K^{RA} is the economic penalty whose value has been tested with different values by a sensitivity analysis as will be explained in Chapter 5. This term minimizes the energy amount missing to have a fully charge at each period $t \in U^{EV}$.

2.2. Power balance constraint. To ensure a balancing between generated energy, storage and load, the following constraints are essentials.

$$p_t^{W} + p_t^{PV} + p_t^{MT} + p_t^{EVd} + p_t^{Sd} + p_t^{Ib} = d_t^{C} + d_t^{SH} + p_t^{EVc} + p_t^{Sc} + p_t^{Is}, \quad t \in T$$

On the left hand side of the balance equation are the variables associated with the generated power by micro−wind turbine, PV module and micro−gas turbine, the discharged power from the storage device or EV battery and the purchased power to the grid. On the right hand side appears the variables associated with required power by the load, both storage and EV batteries and the sold surplus power to the grid.

2.3. Mathematical Formulation. Due to the size of the tertiary control optimization problem, a summary of the formulation is shown below:

$$Min \qquad (1) \quad \text{Objective Function: minimize overall cost}$$

$$\text{s.t.} \left\{ \begin{array}{rl} (2) & \text{microgrid balance} \\ (3-8) & \text{Storage device constraints} \\ (9-14) & \text{EV constraints} \\ (15-16) & \text{Shiftable demand constraints} \\ (17-18) & \text{Critial and adjustable demand constraints} \\ (19-23) & \text{MT contraints} \\ (24-25) & \text{Interconnection point constraints} \\ (26) & \text{Wind power constraints} \\ (27) & \text{Solar power constraints} \end{array} \right.$$

Finally, the mathematical formulation is presented.

$$\begin{aligned} Min \quad & \sum_{t=1}^{|T|} C^{MTu} e_t^{MT} + C^{MTd} a_t^{MT} + \Delta C^{MT} p_t^{MT} + \\ & + \sum_{t=1}^{|T|} \Delta (C^{I2} (p_t^{Ib} + p_t^{Is}) + C^{I1} (p_t^{Ib} - p_t^{Is})) \\ & + \sum_{t=1}^{|T|} \Delta (C^{Sd} p_t^{Sd} + C^{EVd} p_t^{EVd} + K^{A} d_t^{A}) \end{aligned} \tag{1}$$

$$s.t. \quad p_t^{W} + p_t^{PV} + p_t^{MT} + p_t^{Sd} + p_t^{i,b} = d_t^{C} + d_t^{SH} + p_t^{EV} p_t^{Sc} + p_t^{Is} \qquad t \in T \tag{2}$$

$$N^{S} SOC_t^{S} = N^{S} SOC_{t-1}^{S} + (\frac{p_t^{Sc}}{e_c} - e_d p_t^{Sd}) \Delta \qquad t \in T \backslash \{1\} \tag{3}$$

$$SOC_1^s = SOC_0^s (\frac{p_1^{Sc}}{e_c} - e_d p_1^{Sd}) \Delta \tag{4}$$

$$SOC_{|T|}^s = SOC_F^s \tag{5}$$

$$l_d \leq SOC_t^s \leq l_u \qquad t \in T \tag{6}$$

$$p_t^{Sd} \leq \bar{P}^{Sd} x_t^{S} \qquad t \in T \tag{7}$$

$$p_t^{Sc} \leq \bar{P}^{Sc} (1 - x_t^{S}) \qquad t \in T \tag{8}$$

$$N^{EV} SOC_t^{EV} = N^{EV} SOC_{t-1}^{EV} + (\frac{p_t^{EVc}}{e_c} - e_d p_t^{EVd}) \Delta \qquad t \in U^{EV} \tag{9}$$

$$N^{EV} SOC_t^{EV} = N^{EV} SOC_{t-1}^{EV} - D_t^{EV} \qquad t \in T \backslash U^{EV} \tag{10}$$

$$N^{EV} SOC_1^{EV} = N^{EV} SOC_0^{EV} + P_0^{EV} \tag{11}$$

$$\underline{SOC}_t^{EV} \leq SOC^{EV} \leq 1 \qquad t \in T \tag{12}$$

$$p_t^{EVc} \leq \bar{P}^{EV} x_t^{EV} \qquad t \in U^{EV} \tag{13}$$

$$p_t^{EVd} \leq (1 - x_t^{EV}) \bar{P}^{EV} \qquad t \in U^{EV} \tag{14}$$

$$d_t^{SH} = \sum_{l=1}^{|L|} D_l^{SH} x_{t-l+1}^{SH} \qquad t \in T \tag{15}$$

$$\sum_{t=1}^{|T|-|L|+1} x_t^{SH} = 1 \tag{16}$$

$$d_t^c + d_t^a = D_t^{C} \qquad t \in T \tag{17}$$

$$d_t^a \leq f^{A} D_t^{C} \qquad t \in T \tag{18}$$

$$R_l \leq p_t^{MT} - p_{t-1}^{MT} \leq R_u \qquad t \in T \quad (19)$$

$$u_t^{MT} \underline{P}^{MT} \leq p_t^{MT} \leq u_t^{MT} \bar{P}^{MT} \qquad t \in T \quad (20)$$

$$u_t^{MT} - u_{t-1}^{MT} - e_t^{MT} + a_t^{MT} = 0 \qquad t \in T \quad (21)$$

$$e_t^{MT} + \sum_{k=t}^{\sigma_t} a_k^{MT} \leq 1 \qquad t \in T \quad (22)$$

$$a_t^{MT} + \sum_{k=t+1}^{\tau_t} e_k^{MT} \leq 1 \qquad t \in T \quad (23)$$

$$p_t^{Ib} \leq x_t^I \bar{P}^I \qquad t \in T \quad (24)$$

$$p_t^{Is} \leq (1 - x_t^I) \bar{P}^I \qquad t \in T \quad (25)$$

$$0 \leq p_t^W \leq \bar{P}_t^W \qquad t \in T \quad (26)$$

$$0 \leq p_t^{PV} \leq \bar{P}_t^{PV} \qquad t \in T \quad (27)$$

The equations (1)-(27) define a mixed−integer linear program (MILP) and has been implemented in both General Algebraic Modelling System (GAMS) and C language with the help of the Visual Studio platform. In both cases the model has been solved using CPLEX with standard options.

3. Secondary control optimization problem

To formulate the secondary control optimization problem, it is not possible to use directly the mathematical modelling of microgrid components presented in Chapter 3. In the secondary control, some variables of the mathematical modellings become parameters fixed by the tertiary control. For instance, the exchanged power with the grid, storage states of charge and the committed periods for the MT are ensured in each quarter hour. These changes are explained below for each microgrid component except the micro−wind turbine and the PV module because its models don't change.

3.1. Mathematical modelling of microgrid components for the secondary control.

3.1.1. *Micro−gas turbine.* In the micro−gas turbine modelling for secondary control, the three sets of binary variables u^{MT},e^{MT} and a^{MT} became fixed because the tertiary control decided previously when the unit is committed. Let $\bar{U}_t^{MT}$ be a operation state indicator which is equal to one if the MT is committed at quarter hour t and zero in otherwise. Thus, the news constraints are the following:

$$\bar{U}_t^{MT} \underline{P}^{MT} \leq p_j^{MT} \leq \bar{U}_t^{MT} \bar{P}^{MT}, \; j \in J$$

where J will be the set of periods for the secondary control. To note that the operation state is constant in the set J.

The ramp limits constraints remain equal:

$$R_l \leq p_j^{MT} - p_{j-1}^{MT} \leq R_u,\ \ j \in J\backslash\{1\}$$

The rest of micro−gas turbine constraints are not needed in secondary control.

3.1.2. *Storage device.* The storage device constraints remain equal to the constraints defined in Chapter 3. However, a new condition about the final state of charge programmed by the tertiary control $\overline{SOC}_F^S$, is added.

Let s_+^S be a slack measuring the positive deviation over the final SOC and let s_-^S be a slack measuring the negative deviation from the expected final SOC. Both variables are bounded by a fraction $f^{S s}$ of the final SOC, $\overline{SOC}_F^S$.

$$\begin{gathered} SOC_{|J|}^S + s_+^S - s_-^S = \overline{SOC}_F^S \\ 0 \leq s_+^S, s_-^S \leq f^{S s}\overline{SOC}_F^S \end{gathered}$$

3.1.3. *Electric Vehicle.* Let t the quarter hour to optimize by the secondary control then, it is necessary to introduce a parameter $\bar{U}^{EV}$ which takes the value one if $t \in U^{EV}$ and zero otherwise. Thus, the EV modelling is the following:

$$\begin{gathered} 0 \leq p_j^{EVc} \leq \bar{U}^{EV}\bar{P}^{EV}x_j^{EV} \quad j \in J \\ 0 \leq p_j^{EVd} \leq \bar{U}^{EV}\bar{P}^{EV}(1 - x_j^{EV}) \quad j \in J \end{gathered}$$

$$\begin{gathered} N^{EV}SOC_j^{EV} = N^{EV}SOC_{j-1}^{EV} + (\frac{p_j^{EVc}}{e_c} - e_d p_j^{EVd})\Delta \quad j \in J\backslash\{1\} \\ N^{EV}SOC_1^{EV} = N^{EV}SOC_0^{EV} + (\frac{p_1^{EVc}}{e_c} - e_d p_1^{EVd})\Delta \end{gathered}$$

As in the storage device modelling, the final SOC appears fixed by the tertiary control. Nonetheless, any unexpected event could happen and the final state of charge would vary. For this reason, two extra positive variables are necessary.

Let s_+^{EV} be a slack measuring the positive deviation over the final SOC and let s_-^{EV} be a slack measuring the negative deviation from the expected final SOC. Both variables are bounded by a fraction f^{EVs} of the final SOC, $\overline{SOC}_F^{EV}$.

$$\begin{gathered} SOC_{|J|}^{EV} + s_+^{EV} - s_-^{EV} = \overline{SOC}_F^{EV} \\ 0 \leq s_+^{EV}, s_-^{EV} \leq f^{EVs}\overline{SOC}_F^{EV} \end{gathered}$$

3.1.4. *Demand.* In the secondary control optimization problem only have two different profiles of demand: critical and adjustable. The shiftable demand has been programmed by the tertiary control and for the secondary control, this demand is only part of the critical demand in the committed quarter hours.

Thus, the constraints are the ones defined in Chapter 3 for critical and adjustable demand.

$$\begin{array}{ll} d_j^{C} + d_j^{A} = D_j^{C} & j \in J \\ d_j^{A} \leq f^{C} D_j^{C} & j \in J \end{array}$$

3.1.5. *Point of interconnection to the grid.* The tertiary control optimization problem programms the exchangeable power with the general grid for each quarter hour t. The secondary control must ensure this amount but in average in the $|J|$ intervals.

Let $\bar{P}_t^{Ib}$ and $\bar{P}_t^{Is}$ the solution of tertiary control for the interconnection then, the constraint for the average is:

$$\sum_{j \in J} p_j^{Ib} - p_j^{Is} = |J|(\bar{P}_t^{Ib} - \bar{P}_t^{Is})$$

3.1.6. *Power balance constraint.* There is an unique difference in the power balance constraint between the tertiary control and the secondary control: the shiftable demand variable became an parameter $\bar{D}_t^{SH}$. The parameter value is zero if the tertiary control didn't decide to supply the shiftable demand at quarter hour t, and it is positive in otherwise.

$$p_j^{W} + p_j^{PV} + p_j^{MT} + p_j^{EVd} + p_j^{Sd} + p_j^{Ib} = d_j^{C} + \bar{D}_t^{SH} + p_j^{EVc} + p_j^{Sc} + p_j^{Is}, \; j \in J$$

As in the previous problem, on the left hand side of the balance equation are the variables associated with the generated power by micro−wind turbine, PV module and micro−gas turbine, the discharged power from the storage device or EV battery and the purchased power to the grid. On the right hand side appears the variables associated with required power by the load, both storage and EV batteries and the sold surplus power to the grid.

3.2. Objective function. As in the previous problem, the criteria is to minimize overall cost.

$$\begin{array}{ll} Min & \displaystyle\sum_{j \in J} \delta C^{MT} p_j^{MT} \\ & \displaystyle + \sum_{j \in J} \delta (C^{Sd} p_j^{Sd} + C^{EVd} p_j^{EVd} + K^{A} d_j^{A}) + \\ & -\bar{C}_t^{S} (s_+^{S} + s_-^{S}) - \bar{C}_t^{EV} (s_+^{EV} + s_-^{EV}) \end{array}$$

where:

C^{MT}	Generation cost of MT	€/kWh

C^{Sd}	Discharged storage cost	€/kWh
C^{EVd}	Discharged EV cost	€/kWh
K^{A}	Economic penalty of not supplied demand	€/kWh

and where $\bar{C}_t^{S}$ and $\bar{C}_t^{EV}$ are the shadow prices of the SOC constraints (in both cases, storage device and EV battery) at period t in tertiary control optimization problem. These constraints are equality equations and an increase in the right hand side means a "free increase" in the SOC value. As an "free increase" in the SOC value results into a lower cost then, the shadow prices are negative. Thus, we should change the sign, becoming this value in a positive term, in order to penalize any deviation.

3.3. Mathematical Formulation. The following summary is created to help the mathematical formulation visualization. The constraints are grouped by components.

$$Min \qquad (28) \quad \text{Objective Function: minimize overall cost}$$

$$\text{s.t.} \left\{ \begin{array}{rl} (29) & \text{microgrid balance} \\ (30-36) & \text{Storage device constraints} \\ (37-43) & \text{EV constraints} \\ (44-45) & \text{Critial and adjustable demand constraints} \\ (46-47) & \text{MT contraints} \\ (48-50) & \text{Interconnection point constraints} \\ (51) & \text{Wind power constraints} \\ (52) & \text{Solar power constraints} \end{array} \right.$$

Finally, the mathematical formulation is presented.

$$\begin{aligned} Min \quad & \sum_{j \in J} \delta C^{MT} p_j^{MT} \\ & + \sum_{j \in J} \delta (C^{Sd} p_j^{Sd} + C^{EVd} p_j^{EVd} + K^{A} d_j^{A}) + \\ & - \bar{C}_t^{S} (s_+^{S} + s_-^{S}) - \bar{C}_t^{EV} (s_+^{EV} + s_-^{EV}) \end{aligned} \tag{28}$$

$$s.t. \quad p_j^{W} + p_j^{PV} + p_j^{MT} + p_j^{EVd} + p_j^{Sd} + p_j^{Ib} = d_j^{C} + p_j^{EVc} + p_j^{Sc} + p_j^{Is} + \bar{D}_t^{SH} \qquad j \in J \tag{29}$$

$$N^{S} SOC_j^{S} = N^{S} SOC_{j-1}^{S} + \delta\left(\frac{p_j^{Sc}}{e^{c}} - e^{d} p_j^{Sd}\right) \qquad j \in J \backslash \{1\} \tag{30}$$

$$N^{S} SOC_{1}^{S} = N^{S} SOC_{t_0}^{S} + \delta(\frac{p_1^{Sc}}{e^c} - e^d p_1^{Sd})) \tag{31}$$

$$SOC_{|J|}^{S} + s_{+}^{S} - s_{-}^{S} = \overline{SOC}_{F}^{S} \tag{32}$$

$$\underline{SOC} \leq SOC_{j}^{S} \leq \overline{SOC} \qquad j \in J \tag{33}$$

$$p_{j}^{Sd} \leq \bar{P}^{Sd} x_{j}^{S} \qquad j \in J \tag{34}$$

$$p_{j}^{Sc} \leq \bar{P}^{Sc}(1 - x_{j}^{S}) \qquad j \in J \tag{35}$$

$$0 \leq s_{+}^{S}, s_{-}^{S} \leq f^{Ss}\overline{SOC}_{F}^{S} \qquad \in J \tag{36}$$

$$N^{EV} SOC_{j}^{EV} = N^{EV} SOC_{j-1}^{EV} + \delta(\frac{p_t^{EVc}}{e^c} - e^d p_j^{EVd})) \qquad j \in J\backslash\{1\} \tag{37}$$

$$N^{EV} SOC_{1}^{EV} = (1 - U_{t}^{EV})N^{EV} SOC_{t+1}^{EV} + U_{t}^{EV} SOC_{t}^{EV} + \delta(\frac{p_1^{EVc}}{e^c} - e^d p_1^{EVd})) \tag{38}$$

$$SOC_{|J|}^{EV} + s_{+}^{EV} - s_{-}^{EV} = \overline{SOC}_{F}^{EV} \tag{39}$$

$$\underline{SOC} \leq SOC_{j}^{EV} \leq 1 \qquad j \in J \tag{40}$$

$$0 \leq p_{j}^{EVc} \leq \bar{U}_{t}^{EV} \bar{P}^{EV} x_{j}^{EV} \qquad j \in J \tag{41}$$

$$0 \leq p_{j}^{EVd} \leq \bar{U}_{t}^{EV} \bar{P}^{EV} (1 - x_{j}^{EV}) \qquad j \in J \tag{42}$$

$$0 \leq s_{+}^{EV}, s_{-}^{EV} \leq f^{EVs}\overline{SOC}_{F}^{EV} \qquad \in J \tag{43}$$

$$d_{j}^{C} + d_{j}^{A} = D_j \qquad j \in J \tag{44}$$

$$0 \leq d^{A} \leq f^{A} D_t \qquad \in J \tag{45}$$

$$-R_l \leq p_{j}^{MT} - p_{j-1}^{MT} \leq R_u \qquad j \in J\backslash\{1\} \tag{46}$$

$$U_{t}^{MT} \underline{P}^{MT} \leq p_{j}^{MT} \leq U_{t}^{MT} \bar{P}^{MT} \qquad j \in J \tag{47}$$

$$p_{j}^{Ib} \leq x_j \bar{P}^{I} \qquad j \in J \tag{48}$$

$$p_{j}^{Is} \leq (1 - x_j)\bar{P}^{I} \qquad j \in J \tag{49}$$

$$\sum_{j} p_{j}^{Ib} - p_{j}^{Is} = |J|(\bar{P}_{t}^{Ib} - \bar{P}_{t}^{Is}) \qquad j \in J \tag{50}$$

$$0 \leq p_{t}^{W} \leq \bar{P}_{t}^{W} \qquad \in J \tag{51}$$

$$0 \leq p_{t}^{PV} \leq \bar{P}_{t}^{PV} \qquad \in J \tag{52}$$

The equations (28)-(52) define a mixed−integer linear program (MILP) and has been implemented in both General Algebraic Modelling System (GAMS) and C language with the help of the Visual Studio platform. In both cases the model has been solved using CPLEX with standard options. However, the cascade procedure has only been implemented in C language.

Chapter 5
Implementation and results

1. Implementation

The implementation has been done in GAMS and C language with the help of the Visual Studio platform. GAMS has been used for testing the optimization problems by sensibility analysis of penalties. However, the algorithms for the IREC's microgrid facilities can only be programmed in C language, which is also more efficient for programming of the cascade procedure.

Different configurations can be chosen in the algorithm implemented in C language depending on load selected types, generation units taken into account and other factors such as the range anxiety. Depending on the selected configuration, the program generates the correct MILP problem and solves it using CPLEX (with default options). It creates the scheduling graph associated with the solution and creates the needed files to the secondary control.

In the secondary control algorithm, the data of the elements previously selected are collected for the corresponding quarter hour and then, the cascade procedure is executed. Every three hours, when there are new weather forecast data, the tertiary problem is refreshed from the current quarter hour. Afterwards, the secondary control problem continues from the last corrected period.

In order to have a better understanding of the general procedure, the Figure 1 shows a flow diagram of the energy management algorithm.

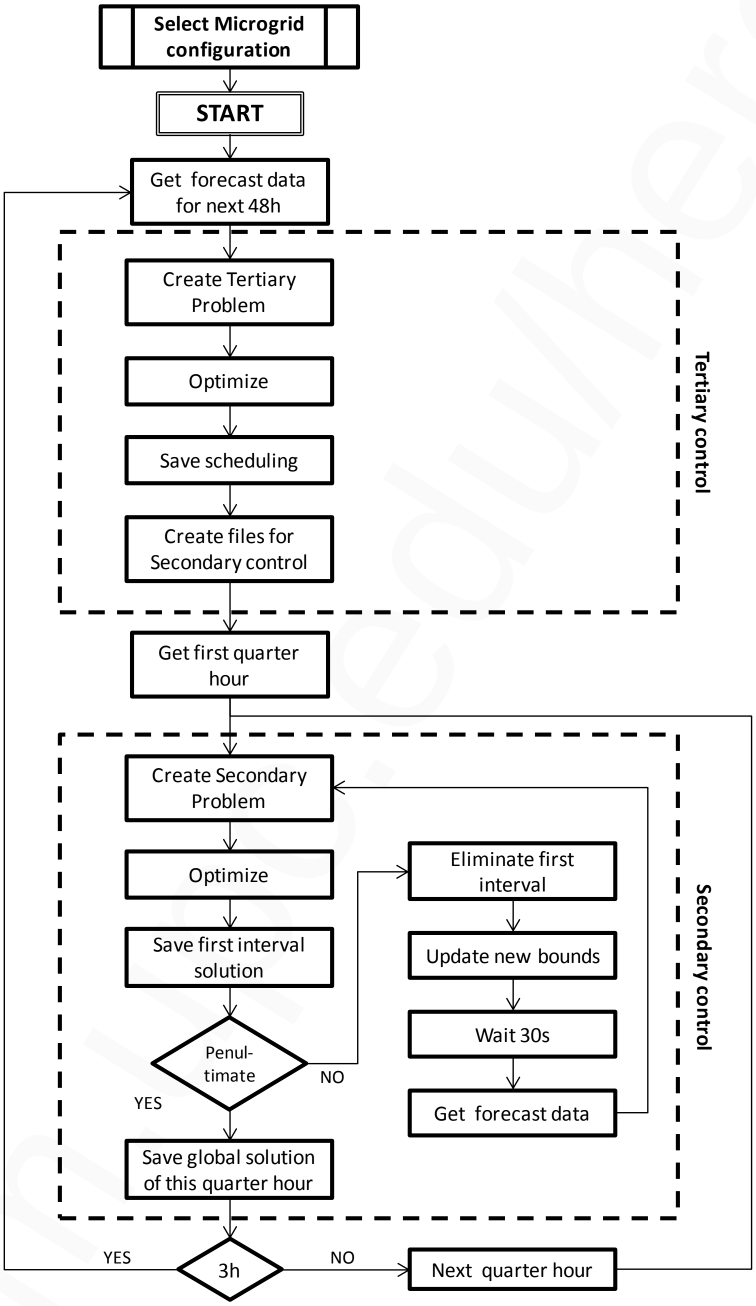


Fig. 1. Flow diagram of Energy Management System

Figure 2 represents a flow diagram of the “create problem” module for tertiary and secondary problems.

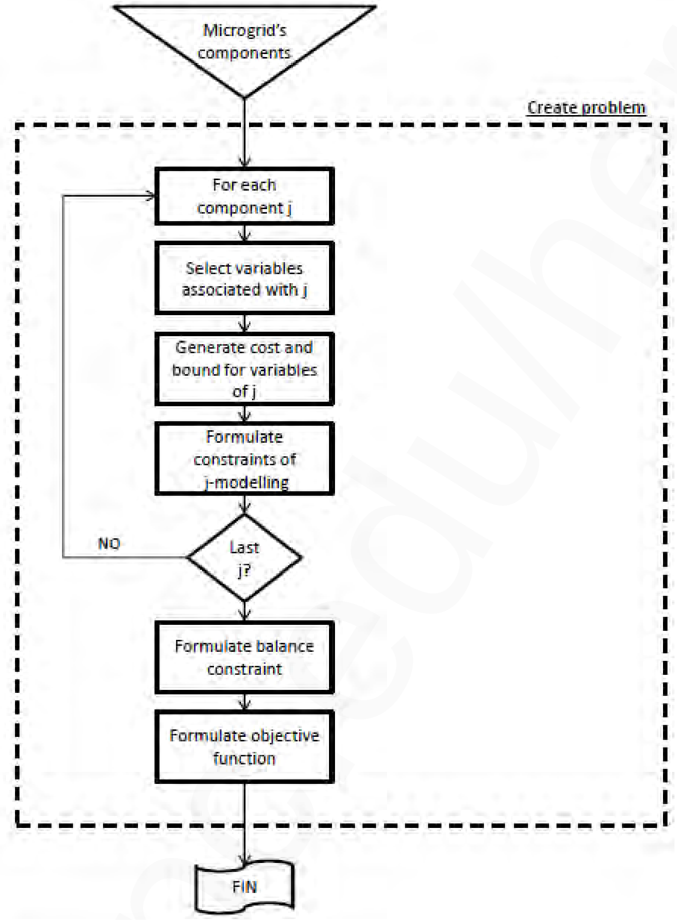


FIG. 2. Generic flow diagram of the “create problem” module

And Figure 3 shows how the secondary control updates the initial data from one iteration to the next one by a flow diagram.

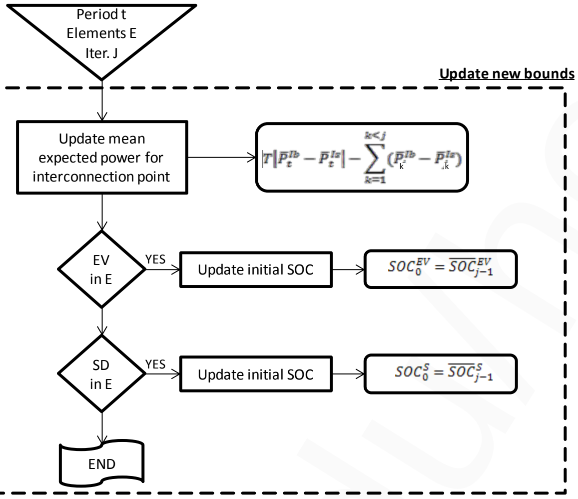


FIG. 3. Flow diagram of the initial data in cascade procedure

where the parameters $\overline{SOC}_{j-1}^{EV}$ and $\overline{SOC}_{j-1}^{EV}$ represent the optimal values of the variables SOC_1^{EV} and SOC_1^{EV} in the iteration $j-1$.

2. The IREC's microgrid emulator

IREC's microgrid is a 40kW low voltage test platform. This microgrid is composed by different devices capable of emulating the behaviour of real distributed energy resources with profiles of generation, storage and load. Additionally, a sort of four non-emulated devices that are going to be installed on the emplacement of the microgrid will provide real solar and wind generation, 20kWh lithium storage battery and a peaking power source and consumption based on ultracapacitors. These devices are currently programmed to work as emulators but, when available, they are going to be used to transform the energy coming from the renewable energy sources on the rooftop of IREC's building into the microgrid.

The possibility to work with emulators gives great flexibility to the whole microgrid in terms of giving the ability to reproduce any kind of situation and the possibility of performing any kind of test environment independently of the meteorological (wind and sun) conditions. The emulators of IREC's microgrid are devices able to act as any kind of electrical nodes and able to perform any kind of V2G test.

Due to time limitations, the results presented in this work have been obtained computationally using a Dell Latitude E5400 Intel Duo with 3.49 Gb of RAM memory and two processor at 2.53GHz.

3. Test cases

3.1. IREC's project test case. A task in the IREC's projects is to test advantage of the V2G capability of charging spot for minimizing the amount of energy consumed from the utility grid during peak period pricing and, consequently, the household energy bill. In order to validate the technical viability of such application, this test case has been proposed to be carried out in IREC's microgrid facilities with the optimization problems presented in this project.

The Figure 4 shows the selected elements that participate in the IREC's project.

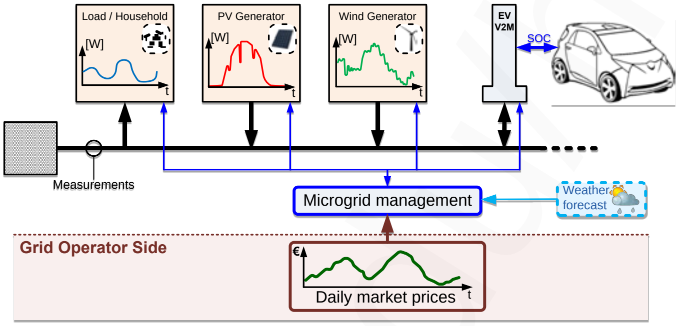


Fig. 4. Selected elements for the IREC's project: house load, renewable energy resources that be installed at the building and the electrical vehicle charger spot.

In addition, the project has been adapted to the actual capabilities of EVs considering the restrictions caused by the mobility needs of EV users. For doing so, this project has been splitted into three test cases:

$I.1$: The objective of this test case is to guarantee a better comparison of the effects of the EV usage by disconnecting the V2G system. This means that the discharging process is not available and the battery cannot be used for supplying the household load. Thus, the discharging cost in the objective function and the variables of discharging process are not considered and, consequently, the binary variables are not needed.

$I.2$: The objective of the second test case is to use the storage system of EV for saving money by means of buying energy during low price periods (off-peak hours) and discharging of the battery when prices are highest (peak hours) doing use of V2G system.

$I.3$: In the last test case, the objective function will be modified by adding the term associated with the range anxiety. The objective is to prioritize minimization of the range anxiety, although the discharging process is available.

For all cases, the selected profiles both EV mobility and household load have been measured during a standard working day. The weather data used in the project were measured at summer. The source and details of data and parameters have not been specified because they are part of IREC's internal projects.

3.2. Extended test case. The extended test is similar to the IREC's project case but including a storage device and one micro−gas turbine. With these two units connected to the microgrid, the results can be more interesting due to a higher opportunity to distribute the use of the external power during the day without creating overload at peak hours. Furthermore, the shiftable demand is tested in the extended case because it could be included in IREC's project case later.

The Table I presents a summary of the main characteristics of all test cases.

TABLE I
Test cases

Test cases	IREC's project	Extended case
I.1	V2G: off Range anxiety: off	IREC's project: + Storage + MT
I.2	V2G: on Range anxiety: off	
I.3	V2G: on Range anxiety: on	

4. Results for the tertiary control problem

Table II provides the main information of the tertiary control problem associated with every test case.

TABLE II
Tertiary control optimization problem

	Test case	Total variables	Binary variables	Total constraints	Execution time [ms]	O.F value [€]	Generation Cost [€]
IREC	*I*.1	1240	192	768	63	17.33	17.33
	I.2	1416	280	944	71	17.04	16.66
	I.3	1608	280	1136	77	18.34	17.45
Extended	*I*.3	3544	1152	3075	1529	16.64	16.24
	I.1	3720	1240	3251	1746	16.51	15.8
	I.2	3912	1240	3443	1772	17.59	16.6

Note that the problem has been finally solved for 192 periods due to the low computational cost and given that the weather forecast data are always available for the next 48h. The issues associated with final state of charge at the last periods of the 24h are avoided considering this greater horizon. However, the solution graph shows the firsts 96 periods (one day), which are the most important.

4.1. IREC's project test case. In the generation scheduling figures for the tertiary control solution, the generated power is in the top and the power supplied in the bottom of the plot. In each period, the amount of energy provided or demanded by each source or device is represented with a different color. The black line represents the variable energy price in €/kWh and its values are shown in the secondary axis. The grey zones show the periods of connection to the grid of the EV.

4.1.1. *I*.1 *V2G off.* The first test case is the simplest. The only goal is to choose the cheapest periods to charge the EV battery. However, as it will be seen later, this option is better than not use the energy management program. The Figure 5 shows the result of the test case where the V2G system is not available and the range anxiety is not considered.

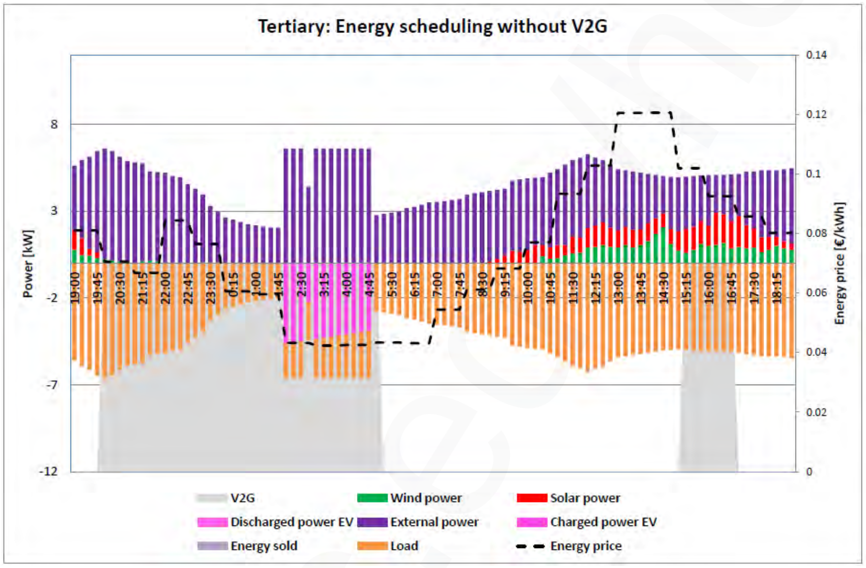


FIG. 5. Tertiary energy scheduling of IREC's *I*.1 case

As seen in the figure, the EV battery is charged during the last set of hours it is connected to the microgrid. In this test, these hours correspond to 1:45−5:00 at night. The electric vechicle SOC reaches the 100% and it is not necessary other charge during the day.

4.1.2. *I*.2 *V2G on.* Figure 6 represents the result of the second test case. As can be observed in the figure, when the EV is connected to the microgrid (grey zones), the EV battery is charged in off-peak periods such as during night hours, and discharged in on-peak periods namely in the afternoon. In addition, in these last periods, the microgrid does not need external power because it is cheaper to discharge the EV battery. It is a example of the profits derived from the V2G system.

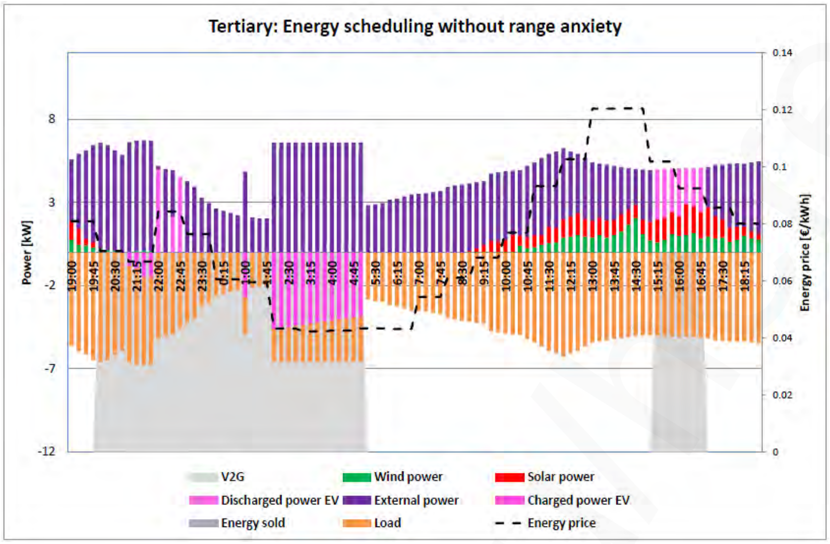


FIG. 6. Energy scheduling for the IREC's project case without range anxiety

4.1.3. *I*.3 *Range anxiety on.* Before presenting the result with the range anxiety, it is necessary to analyse how this term affects to state of charge. For doing so, the following sensitivity analysis has been done:

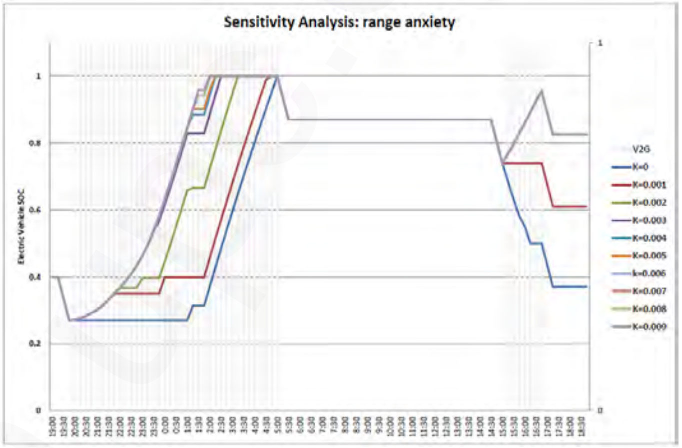


FIG. 7. Sensitivity analysis for range anxiety penalty

In Figure 7, it is observed how the electric vehicle SOC changes at connected periods (periods with horizontal lines) depending on the value of range anxiety penalty. As can be seen, the values can be grouped in three levels: low, medium and maximum; with the corresponding values $K^{RA} = 0$ (case $I.2$), $K^{RA} = 0.001$ where the EV battery is not discharged but it is charged in off−peak periods, and $K^{RA} = 0.002$ where the anxiety is highest and the EV battery is charged as soon as possible.

For this test case, the value $K^{RA} = 0.001$ is chosen. However, in the future, the microgrid owner will choose the modality more adequate for its necessities.

With the K^{RA} value fixed, the test results are shown in Figure 8.

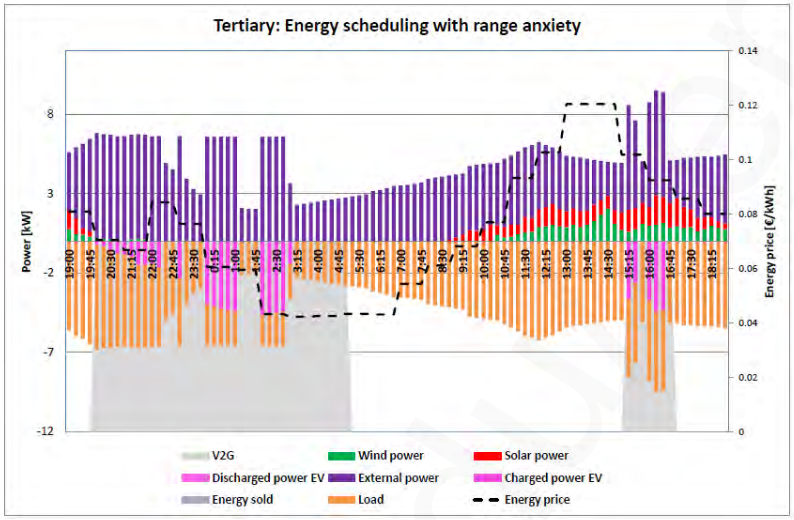


FIG. 8. Tertiary energy scheduling of IREC's $I.3$ case

As can be seen, the range anxiety affects to the EV battery performance. In this case, the EV battery is never discharged in order to ensure a better SOC as soon as possible, but without waiting for off-peak hours completely. For this reason, the interconnection point is always providing external power.

4.1.4. *Comparison: IREC's project case.* In order to provide a better general vision of the various results, Figure 9 shows a comparison between the three cases and the cost associated with the household load and EV without an energy management program.

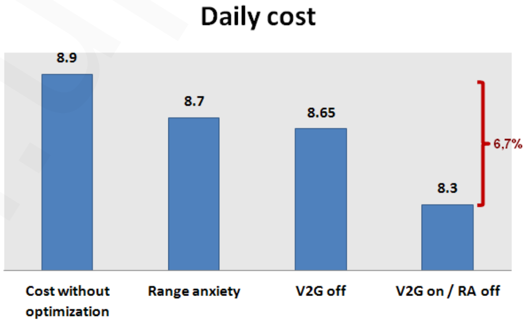


FIG. 9. Supply costs depending on the case

In the plot, each bar is associated with the cost of a test case. The order of appearance of the test cases, left to right, is the following: $I.0$, $I.3$, $I.1$ and $I.2$.

$I.0$ corresponds with a case where V2G system is not available and the range anxiety is connected. This case represents the behaviour of an owner without energy management system: always start charging the battery as soon as the EV is connected.

The results of the cases $I.3$ and $I.1$ are very similar because the freedom to manage the devices is low. However, as it has be seen in the $I.2$ test case, where the V2G is connected and the range anxiety is not considered, the saving reaches the $6,7\%$ of the cost.

4.2. Extended test case. In the extended test case, the adjustable demand is only allowed in extreme situations i.e., if there is a unexpected issue and the demand cannot be completely supplied. To regulate this, a study about the different penalty values (K) has been performed. In the Figure 10, the supplied demand behaviour is shown in several cases:

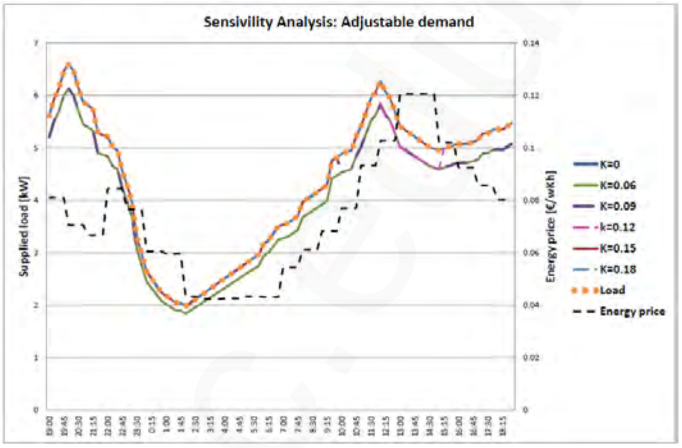


FIG. 10. Sensitivity analysis for adjustable demand penalty

Each line corresponds to a different penalty value K^{A}. The real demand is the orange point line and the other lines change between this one and the $K^{A} = 0$ blue solid line, where it is " free " to decrease the adjustable load and the allowed minimum for adjustable demand is reached. In this case, the value $K^{A} = 0.15$ is selected because is the first value that supplies the total demand (knowing that with this data it is possible to do).

4.2.1. $I.1$ *V2G off.* In the first test case, the possibility to use the discharging process in the EV battery and the range anxiety concept are not considered. On the other hand, the storage device can discharge power at any time. Figure 11 shows the obtained results.

As can be seen in the figure, the storage device is able to take advantage of the difference between on−peak and off−peak periods. The power required by the EV is supplied during the last night hours, which are cheapest, and does not need to be charged in the afternoon. It is also seen how the shiftable demand is supplied

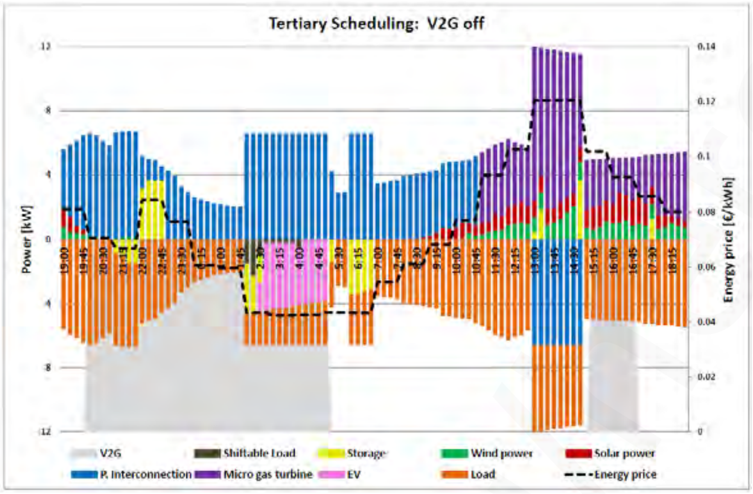


FIG. 11. Tertiary energy scheduling: extended case, I.1 test.

before the EV battery during off−peak hours. In the on−peak hours, the MT is turned on. In these periods, the MT costs are hight but the tariff of interconnection is higher. To compensate this cost, the excess of power generated by the MT is sold to the grid during the major on−peak hours.

4.2.2. *I.2 V2G on/Range anxiety off.* As in the previous I.2 test case of IREC's project, the energy management program has freedom to choose the periods of charging/discharging the EV battery. Furthermore, it is adds the possibility to use the storage device and micro−gas turbine.

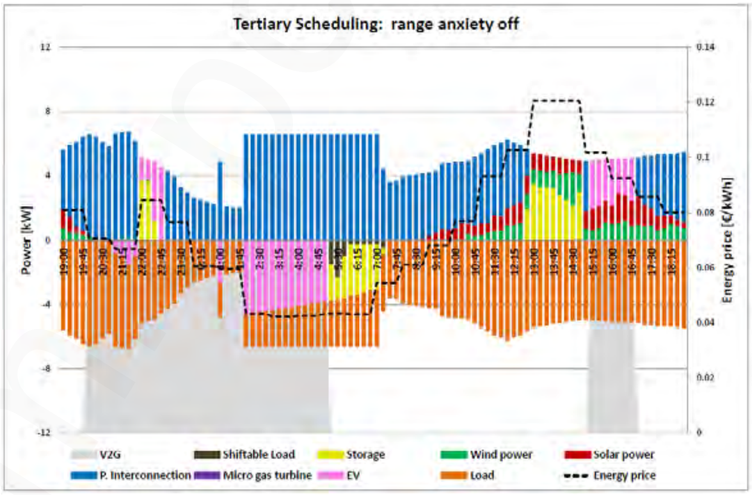


FIG. 12. Tertiary results. Extended case without range anxiety

In Figure 12 can be seen how the power discharged from EV battery and storage device is enough to supply the demand during the on−peak hours. The number of hours where the interconnection point doesn't provide power to the microgrid is higher than in the IREC's case. Notice also that the micro−gas turbine has never been committed due to its higher cost. Also it is shown how the shiftable demand is supplied when the EV battery is full and the following periods are still off−peak hours.

4.2.3. *I*.3 *Range anxiety on.* Considering the same hypothesis as in the previous section but adding the range anxiety, the obtained results have been summarized in Figure 13.

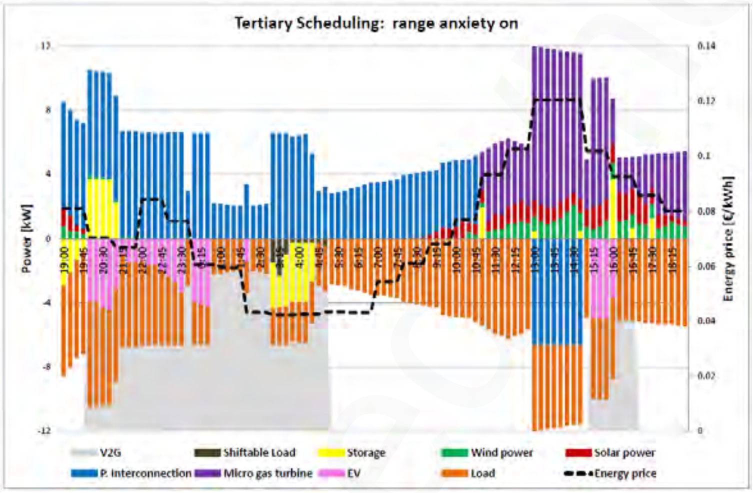


FIG. 13. Tertiary energy scheduling: extended case, *I*.3 test.

The main difference with the previous case is the micro−gas turbine. Due to the fact that the EV battery cannot be discharged in this case, the storage device is not enough to supply the total load during the on−peak hours and then, the MT is turned on. As in the first test case of this section, to compensate the MT cost the surplus power is sold to the grid during the on−peak hours. The shiftable demand is supplied a little earlier with respect to previous case, and in addition, the storage device is used to provide power to the EV battery during the first periods of connection. For this reason, the range anxiety effects decrease compared with the IREC's case.

4.2.4. *Comparison: extended case.* The start point to compare the results obtained in extended test cases is the above case *I*.0 where the range anxiety is considered and the V2G system is disconnected. The cost for 48h associated with this case is 16, 73€. If it is compared with the more optimal case (*I*.2), the saving reaches the 5.5% of the cost.

5. Results for the secondary control problem

For this problem, single period has been selected from the previous three cases. The solution obtained with this procedure and the comparison with the tertiary's solution are shown below.

5.1. IREC's project test case. The selected period corresponds to the interval 16:15-16.30 of the *I*.3 case where all considered units are working at the same time. The main characteristic of this problem are shown in Table III. The columns of total variables and total constraints are referred to the total variables and constraints used throughout the procedure.

TABLE III
SECONDARY CONTROL OPTIMIZATION PROBLEM. CASCADE OPTIMIZATION PROCEDURE (COP)

	Test case	Total variables	Binary variables	Total constraints	Execution time [ms]	O.F value first iter. [€]	O.F value after COP [€]
IREC	*I*.3	4186	925	2828	1125	0.1893	0.1858

The idea is to ensure the interconnection set points of tertiary control solution. This is due to the fact that the energy market regulation establishes economic penalties associated with the deviations of the agreed schedules. Considering this hypothesis, the EV is the unique controllable device in this case.

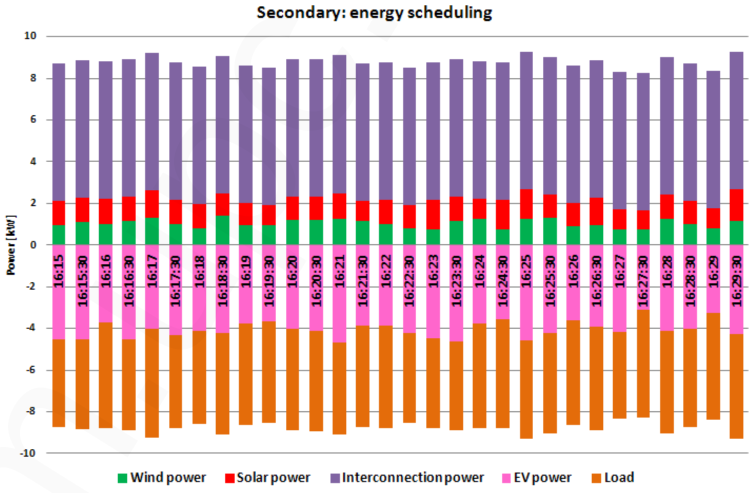
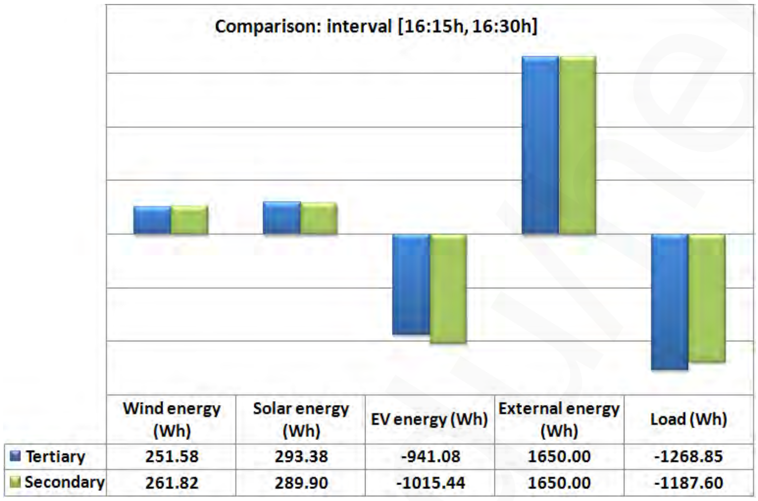


FIG. 14. Secondary result: IREC's project case at period [16:15, 16:30] of *I*.3 test.

Figure 14 shows as for every interval of 30 seconds, the secondary control balances the total power provided by the renewable energy sources and the committed power with the grid, by loading to the EV battery.

To compare these results with the energy scheduled by tertiary control, the Figure 15 shows the expected energy in blue and the energy scheduled by the cascade procedure in green. As in the previous figures, the generated power is in the top and the supplied power is in the bottom of the plot.



	Wind energy (Wh)	Solar energy (Wh)	EV energy (Wh)	External energy (Wh)	Load (Wh)
🟦 Tertiary	251.58	293.38	-941.08	1650.00	-1268.85
🟩 Secondary	261.82	289.90	-1015.44	1650.00	-1187.60

FIG. 15. Expected results by tertiary control versus corrected results by secondary control in IREC's project case

Due to the increase on the expected wind energy and the decrease in the load, the electric vehicle battery has higher charging than in the schedule of tertiary control.

5.2. Extended test case. To test the extended case by the cascade optimization procedure for the secondary control, the time range selected is [16:00, 16:15] of $I.2$ subcase because this period is the unique interval where the storage device, EVB and the micro−gas turbine are working at the same time. The characteristics of this optimization procedure have been summarized in Table IV.

TABLE IV
SECONDARY CONTROL OPTIMIZATION PROBLEM. CASCADE OPTIMIZATION PROCEDURE (COP)

	Test case	Total variables	Binary variables	Total constraints	Execution time [ms]	O.F value first iter. [€]	O.F value after COP [€]
Extended	$I.3$	7504	1494	5572	1516	0.1724	0.1715

In this case, it can be seen how the secondary control distributes the load of the EV throughout the quarter hour and decides the power generated by the micro−gas turbine depending on the power imbalance between the rest of components.

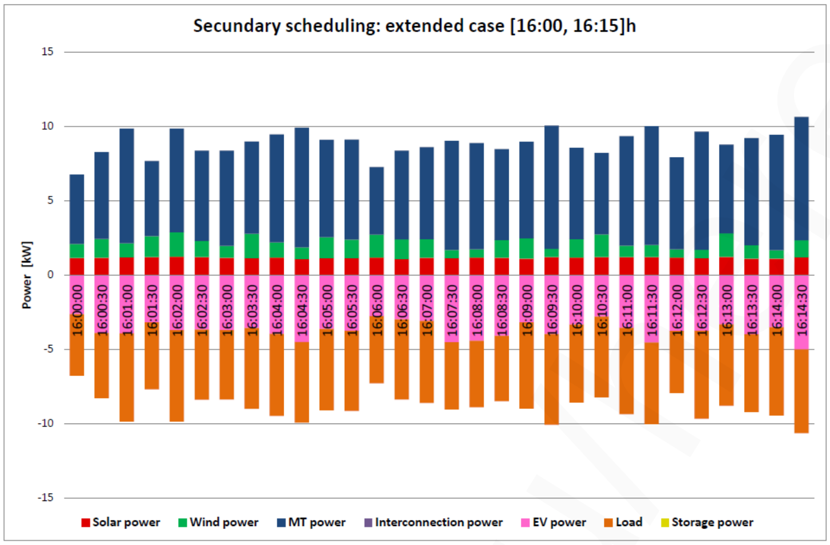


FIG. 16. Secondary result: Extended case at interval [16:00, 16:15] of $I.3$ test.

As in the previous cases, the Figure 16 shows the generated power in the top and the demanded power in the bottom of the plot. In the results, it is not observed any unexpected event during this interval and consequently, the schedule of tertiary control is correctly met.

However, there are some small deviations due to the increase on the household load as it can seen in the Figure 17.

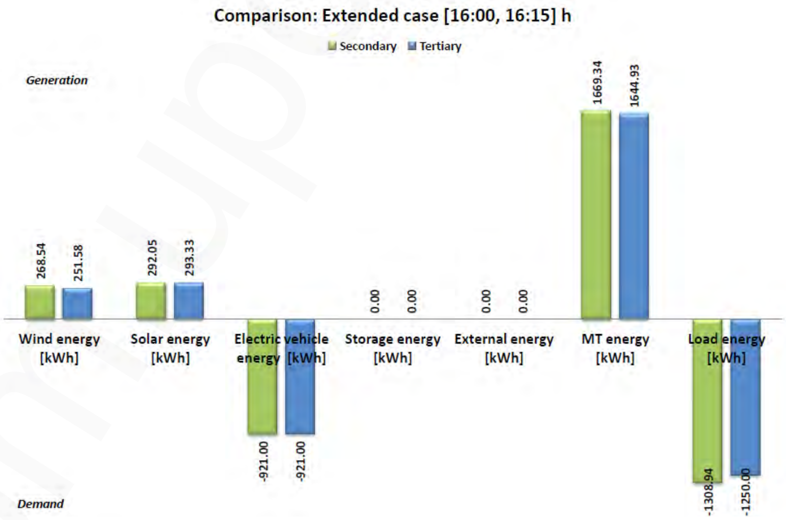


FIG. 17. Scheduled results of the tertiary control versus corrected results by secondary control in extended case

Chapter 6

Conclusions and further research

Microgrids are going to be a key element within the future smart grid environment providing economic and environmental benefits compared to the current power system. Economic benefits are visible through the opportunity to manage load, available generation units and electric vehicle. Electric vehicle usage provides the associated environmental benefits derived from the zero emissions and increases electricity system capacity for hosting renewable energy sources. Considering that electricity can not be stored on large scale, electric vehicles could be used to store energy during the night (for example, with power surplus from wind turbines), making the system much more efficient. Thus, the possibility of the vehicles providing energy to the grid when it is needed, will improve the balance between production and consumption (enabling V2G concept). As it has been observed in the results, the load profile obtained in the cases with V2G, is optimal in the sense that the power consumption over peak periods is almost zero, while overnight demand is increased. From the electricity system point of view, this tendency would smooth overall electric load curve, reducing energy price during peak periods and decreasing investment needs on the distribution network. For private owners, the cost is also reduced as can be seen in Table V.

TABLE V
Results summary

Test cases	Characteristics	IREC's project	Extended case
$I.1$	V2G: off Range anxiety: off	17.33 €	16.24 €
$I.2$	V2G: on Range anxiety: off	16.66 €	15.8 €
$I.3$	V2G: on Range anxiety: on	17.45 €	16.6 €
Best saving compared with $I.0$		6.7%	5.5%

From the energy management algorithm point of view, the schedule programmed by the tertiary control has proved to be a good starting point for the secondary control. In the future this fact could be useful for microgrids integration in the energy market. Secondary control has also proved to be an efficient tool for ensuring the fulfilment of tertiary scheduling each 15 minutes. Nonetheless, as other external perturbations (such as meteorological variations, unexpected demand changes,...) can arise in the real time, the next step is the inclusion of the primary control ensuring short time correct operation.

Notice that this master thesis has helped to introduce on IREC's energy economics research group, new microgrid management and analysis methodologies based on advanced optimization techniques.

Further research.

i) The most obvious further research in the optimization framework, is the extension to the stochastic model for the tertiary control. For example, it is known that the wind speed can be modelled with a Weibull distribution [**5**]− [**7**]. Taking advantage of these studies, the forecasted schedule can be improved.
ii) In order to allow the implementation in larger buildings or EV parks, a generalization in the electric vehicle number that the system is able to manage should be addressed. Similarly, increasing the number of the shiftable demand profiles to consider any controllable device would increase management system capability to owner needs.
iii) On the technical side, an improvement could be to consider the reactive power by introducing an optimal network flow control in the energy management system. However, this only makes sense in a larger microgrid such as a university campus where longer distances between the microgrid components are found.

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Notation

Acronyms	
$CAMC$	Central Autonomous Management Controller
DER	Distributed energy resources
DG	Distributed generation
DOD	Depth of discharge
DNO	Distribution Network Operator
EMM	Energy Management Module
EV	Electric vehicle
EVB	Electric vehicle battery
$GAMS$	General Algebraic Modeling System
$IREC$	Institut de Reserca en Energía de Catalunya
LC	Local Controller
MC	Microsource Controller
MCC	Microgrid Central Controller
MG	Microgrid
$MIBEL$	Mercado Ibérico de la Electricidad
$MILP$	Mixed-Integer Linear Programming
MO	Market operator
$NAPRE$	National Action Plan on Renewable Energy
$NZEB$	Net Zero Energy Building
PCM	Protection Co-ordination Module
RD	Royal Decree
RES	Renewable energy sorces
SD	Storage device
SO	System Operator
SOS	State of charge
$V2G$	Vehicle to grid

Sets		
T	Period set of tertiary control optimization problem	$\mathbb{N}$
J	Period set of secondary control optimization problem	$\mathbb{N}$
U^{EV}	Periods where the EV is connected to the MG	$\mathbb{N}$
L	Period set of shiftable demand profile	$\mathbb{N}$
Parameters		
Δ	Duration time of one period in tertiary control problem	h
δ	Duration time of one period in secondary control problem	h
$\bar{P}$	Power upper bound	kW
$\underline{P}$	Power lower bound	kW
C^{MTu}	Start−up cost of MT	€
C^{MTd}	Shut−down cost of MT	€
C^{MT}	Generation cost of MT	€/kWh
C^{I2}	Constant cost of access tariff	€/kWh
C_t^{I1}	Variable cost of energy	€/kWh
C^{Sd}	Discharging cost of S	€/kWh
C^{EVd}	Discharging cost of EV	€/kWh
K^{A}	Economic penalty of not supplied demand	€/kWh
K^{RA}	Economic penalty of range anxiety	€/kWh
$\overline{C}$	Shadow price	€/ %
Wind turbine		
N^{W}	Nominal capacity	kW
A	Swept area	m^2
ρ	Efficiency factor	%
v_{ci}	Cut-in speed	m/s
v_r	Rated speed	m/s
v_{co}	Cut-out speed	m/s
$v_{t,j}$	Wind speed	m/s
h	Hub height	m
h_r	Reference height	m
α	Exponential law	
$\bar{P}_{t,j}^{W}$	Wind power available	kW
Solar panel		
$I_{r_{t,j}}$	Solar irradiation	kW/m^2
$T_{t,j}^{a}$	Ambient temperature	$^{\circ}C$
$T_{t,j}^{c}$	Cell temperature	$^{\circ}C$
$\bar{P}_{t,j}^{PV}$	Solar power available	kW

Batteries		
N^{EV}	Nominal capacity	kWh
N^{S}	Nominal capacity	kWh
SOC_0	Initial state of charge	%
SOC_F	Final state of charge	%
$\overline{DOD}$	Maximum DOD	%
$\underline{DOD}$	Minimum DOD	%
e_c	Efficiency factor of charge	%
e_d	Efficiency factor of discharge	%
Gas turbine		
R_u	Upper ramp limit	kW
R_l	Lower ramp limit	kW
σ_t	Minimum run time	$\mathbb{N}$
τ_t	Minimum idle time	$\mathbb{N}$
$\overline{U}$	Committed period by tertiary control	$\mathbb{N}$
Loads		
$D_{t,j}$	Critical demand	kW
D_l^{SH}	Shiftable demand	kW
D^{EV}	Demand of EV profile at $t \in T \backslash U^{EV}$	kWh
f^{C}	Percentage of critical demand	%
$\underline{Variables}$		
$p_{t,j}$	power output	kW
$d_{t,j}$	power to supplied demand	kW
$x_{t,j}$	flow direction	$\{0,1\}$
$SOC_{t,j}$	State of charge	%
u_t	connection state micro−gas turbine	$\{0,1\}$
a_t	start-up micro−gas turbine	$\{0,1\}$
e_t	shut-down micro−gas turbine	$\{0,1\}$
s_+	positive slack for final SOC	kW
s_-	negative slack for final SOC	kW

Superscripts

W	Micro−wind turbine
PV	Photovoltaic module
MT	Micro−gas turbine
S	Storage device
Sc	Charging process for S
Sd	Discharging process for S
EV	Electric vehicle
EVc	Charging process for EV
EVd	Discharging process for EV
I	Point of interconnection to the grid
Is	Selling process in I
Ib	Buying process in I
C	Critical demand
A	Adjustable demand
SH	Shiftable demand