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Renewable medium-small projects in Spain: Past and present of microgrid development

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ABSTRACT

This paper reviews the on-going research studies and microgrid pilot projects focusing on the Spanish case because of its renewable energy potential with the objective set on highlights the main investigation drifts in the field such as the used technologies, control methods and operation challenges. That way, several smart grids have been commented and compared, finding that photovoltaic and wind power are the favourites energy generation technologies. Although batteries are the most widespread energy storage systems, green hydrogen has a strong presence, showing up in a third of the Spanish smart grids. Traditional control strategies are being displaced by advanced ones such as MPC or fuzzy logic due to its higher efficiency. The reader will have a clear view of the potential of renewable energy penetration in the form of smart grids in Spain, through the study of the equipment involved in the different facilities contribution and the main control strategies implemented, in a comparative analysis of the key aspect of this emerging technology.

1. Introduction

The growing concern about the environmental impacts caused by coal-fired power plants and other fossil fuel usages, related to high amount of carbon dioxide emissions, has driven the transition toward a less aggressive electrical power generation environment. Governments and industries around the world are looking for methods and technologies to reduce greenhouse gas emissions in their operations, focusing primarily on the use and installation of sustainable energy systems. The need for much more efficient electricity management systems with clean energy sources has led to the development of innovative technologies and revolutionary ideas in the generation and transmission of energy. One of these solutions is to increase the implementation of distributed generation systems in the supply of electricity, based on the generation of electrical energy through energy sources in places as close as possible to consumers. Distributed generation can also include renewable energy systems, leading to a reduction in the emission of greenhouse gases.

Consequently, governments and energy regulatory authorities around the world are promoting the development of distributed generation systems based on renewable energies. However, the introduction of these micro-sources (small-scale photovoltaic panels, wind turbines and diesel generators) in the grid dramatically modifies its traditional radial structure, what triggers many problems unknown to network operators and engineers. The higher number of micro-sources with different levels of penetration in the grid invalidates the traditional methods of controlling the flow of energy, as the existing distribution systems are designed just to accept power from the transmission system and to distribute it to customers. On the other hand, active distribution networks (such as microgrids) add local distributed generators, which implies bidirectional energy flows that require a flexible and intelligent control of the grid, presenting technical challenges such as circuit protection, power quality, supply reliability, and stability issues [1–3].

In this framework, microgrids are presented as a solution capable of coordinating and managing renewable energy systems in a more decentralized way, reducing the need for centralized coordination and management systems [1,4–6]. A microgrid is a reduced electric system that is able to produce, store, and consume energy, operating both plugged and unplugged from the main grid and supplying high quality energy in a secure way. According to the Smart Grids European Technology Platform [7], a smart grid concerns an electricity network that can intelligently integrate the behaviour and actions of all users connected to it, in order to ensure a sustainable and economically efficient energy system, with low losses and high levels of quality and security of supply. However, there is still a long way to go into research and

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development to be able to definitively implement microgrids in the actual electric system [8].

Numerous projects have been popping up over the last few years all over the world, underlining the impact that this kind of technology will have in the near future [9]. The main operational projects are located in the United States (205 MW) [10], China (86 MW) [11] and Japan (68 MW) [12,13]. The Smart Grid Outlook 2017 [14] shows that in the European Union there are around 950 projects, being the largest ones in Greece [15], Germany [9] and Denmark [16]. The main areas of interest related to smart networks are management, and integration of distributed generation and storage, since the main priority of the European Commission in terms of renewable energy is energy efficiency [17].

In this sense, Spain is an outstanding candidate for the development and implementation of microgrids, as it is a world leader in the integration of variable renewable energy and has built a robust electricity system with high shares of wind and solar PV. At the end of 2019, the overall installed renewable energy capacity on the Spanish peninsula totalled 54,457 MW, of which 46% are wind, 16% photovoltaic and the rest corresponds to other renewable technologies [18,19]. As can be observed in the study of Lena Jansen et al., Spanish research in the field of smart grids covers all aspects related to this technology, although it focuses mainly on the generation and distributed energy resources and demand response. Surprisingly, there are almost no studies about cyber security, which is widely studied in countries such as the Netherlands or United Kingdom; and few ones in market and smart cities development [4].

Despite all this research, questions are raised about the viability of microgrids penetration, as well as the capacities and trends in smart-grid research in Spain. This review aims to provide an overlook to the most noticeable microgrid projects in this country because of its high potential of energy usage from renewable sources. That way, the main contributions of this article are:

- To present an overview of the state of the art of the main research and pilot smart-grid projects in Spain.
- To analyse in detail the equipment involved in the experimental smart-grids and the control strategies implemented.
- To carry out a comparative analysis of some key aspects such as the energy sources, storage systems, and control strategies.

The novelty of this study is that it provides a wide portrait of all the progress made in the microgrid field in Spain, showing the main trends, challenges, and future prospects.

The work is structured as follows. First, the Spanish policies on renewable energy and specifically on microgrids are discussed. Later, microgrid cases in Spain are explained in detail. Finally, a microgrid comparison and discussion is included, to close with the main conclusions of the review.

2. Microgrids policies in Spain

The energy and climate policy framework in Spain is determined by the European Union, which is acting in line with the requirements of the Paris Agreement to provide a coordinated international response to the climate change challenge. In this context, in 2016, the European Commission presented the "Clean energy for all Europeans" [20], and, in 2018 the text "A Clean Planet for All" [21]. These reports led to various regulations and directives on energy efficiency, renewable energy, electricity market design, and security of supply in all the member states. The main goal of these initiatives is to facilitate the accomplishment of the key targets for 2030, which are a 40% reduction in greenhouse gas emissions compared to 1990, a 32% share of renewable energy in total gross final energy consumption, a 32.5% improvement in energy efficiency and a 15% electricity interconnection between the member states [22].

Royal Decree 244/2019, of 5th of April [23], regulates the administrative, technical and economic conditions of self-consumption of electrical energy in Spain. This law implies a deep reform of self-consumption compared with the anterior one (RD 900/2015 [24]), opening a clear way for the development of microgrids by including the possibility of having shared self-consumption, simplifying administrative procedures in this area, eliminating the so called "sun tax" and simplifying from four to two the self-consumption modalities.

Self-consumption is defined as "the consumption by one or more consumers of electrical energy coming from generation installations close to and associated with consumption installations" according to the amendments introduced by Royal Decree-Law 15/2018 that modifies article 9 of Law 24/2013, of 26 December, on the Electricity Sector [25]. That way, self-consumption can be individual or collective, where several consumers will be able to join to the same generation installation and, what is more, a self-consumption facility may be located in more than one dwelling. The facilities will be named according to the conditions they meet: (i) installations close of internal grid; or (ii) installations close through the grid.

Two types of self-consumption are established: no surpluses and surpluses. Self-consumption without surplus corresponds to the modality defined in article 9.1 a) of Law 24/2013, of December 26 [26]. In this case, a mechanism must be installed to prevent the injection of surplus energy into the transport or distribution grid. Self-consumption with surplus corresponds to the modality defined in article 9.1 b) of Law 24/2013, of December 26. Here, in addition to supplying energy for self-consumption, the facilities will be able to inject surplus energy into the transport and distribution grid accessing voluntarily to benefits from a surplus compensation mechanism, as long as they comply with certain conditions. The modality with surpluses accepted for compensation includes cases in which the consumer and the producer decide to avail themselves of a surplus compensation mechanism if the source of primary energy is of renewable origin, the total power of the production facilities does not exceed 100 kW, and the consumer and the producer have registered a compensation contract for surplus of self-consumption. The modality with surpluses not accepted for compensation comprises all those cases that do not comply with the above-mentioned requirements.

The government of Spain recently approved the law July 2021 [27] on climatic change and energy transition. Inside the law appears the promotion of local energy cluster, which includes renewable energies, storage system and energy consumers (concept near to microgrids schemes), but the specific regulations have to be developed.

This regulatory framework will be reinforced by transposing the revision of the European directive on the promotion of renewable energies [28]. This directive, which promotes the creation of "Renewable Energies Communities" whose scheme resembles microgrids with the inclusion of renewable energies sources and energy storage systems, must be adopted by the 27 members of the European Union in the coming years.

3. Microgrid case studies in Spain

Spain has a great tradition of research in electrical networks covering all the links of the electricity production chain: universities, technology centres, equipment manufacturers and electricity companies themselves. Spain is also a pioneering country in the development and research of microgrids, investing in numerous projects at different scales, since they benefit the Spanish economy. Microgrids lead to an increase in productivity due to four main factors: (i) the increase in the energy efficiency of the system due to the reduction of losses related to the transport of electricity (the average losses of the current distribution system are around a 5–7% [29] and those losses can be reduced an extra 40% using a smart grid cooperative model [30]), (ii) the development of the Spanish energy and technology sectors, allowing these sectors to play a more active role in the process of reshaping the energy industry at a global level [31], (iii) the adjustment of the trade balance by reducing imports of primary fossil energy ranging from −8 TWh in 2010 to −25.2 TWh in 2020 [32], and (iv) the increase in the country's productivity derived from the improvement of the quality of the energy supply because of the reduction of interruptions, for example, with a reduction of the SAIDI from 6.029 h/yr to 3.041 h/yr and the CAIDI from 18.863 h to 11.852h [33].

The main Spanish microgrid projects are shown in Fig. 1, listed in Table 1, and explained below. For the sake of simplicity, a number has been assigned to each microgrid so they can be easily identified in the next tables and figures. At the end of the section, the reader can find a summary of the main items regading each one of the microgrids (Table 2).

3.1. Centro Nacional de Hidrógeno microgrid (CNH_2)

The National Hydrogen Centre (CNH2) has a three-phase alternating current microgrid, isolated from the electrical network. The grid feeds electrical loads from various laboratories. It has a 100 kW photovoltaic solar installation with 432 panels of 250 W peak power, arranged in fixed metallic structures with an inclination of 25°. As storage systems, a pack of 24 gel batteries (SONNENSCHEIN batteries, model A - 602/3270 SOLAR) with a capacity of 3266 Ah. Each vessel gives a voltage of 2 V adding up to 48 V after connecting in series so a maximum of 157 kWh can be stored. Besides, it includes green hydrogen technologies as power storage composed by a 30 kW HyPM LAB HD30 Heliocentrics polymeric fuel cell, a 60 kW G16D ERREDUE alkaline electrolyzer, and a hydrogen storage park comprising 16 bottles of 50 L and a 7500 L tank at a pressure of 10 bar, besides a hydrogen refuelling station. Also, there exists a system for the use of residual heat: the electrolyzer and the fuel cell of the microgrid have refrigeration systems implemented, which are activated when it is necessary to cool the equipment. To take advantage of this heat, a heat recovery system has been installed, which makes it

Table 1
Spanish microgrids.

Number	Microgrid
1	Centro Nacional de Hidrógeno (CNH2) microgrid
2	Centro Nacional de Hidrógeno Microgrids Laboratory I
3	Centro Nacional de Hidrógeno Microgrids Laboratory II
4	University of Navarra microgrid
5	University of Valencia microgrid
6	Gipuzkoa i-Sare microgrid
7	Atenea Cener microgrid
8	LIER-CIRCE microgrid
9	GISEP microgrid
10	LINTER microgrid
11	SEIL microgrid
12	Walqa microgrid
13	IREC microgrid
14	INTA microgrid
15	LABDER microgrid
16	ITE microgrid
17	Tecnalia InGRID microgrid
18	University of Oviedo microgrid
19	University of Seville microgrid
20	Málaga-Endesa microgrid
21	ICAI microgrid
22	CEDER-CIEMAT microgrid
23	ORMAZABAL microgrid

Fig. 1. Geographical distribution of the main microgrid projects in Spain.

Table 2
Summary table of Spanish microgrids.

Microgrid	Installed power (kW)	Renewable source power %	Storage capacity (kWh)	Use of hydrogen
1	100.0	100.00	285.34	YES
2	3.8	100.00	30.88	YES
3	30	0.00	76.81	YES
4	24.2	45.45	121.85	YES
5	32	0.00	20.00	–
6	242.4	21.62	122.14	–
7	119	37.82	325.38	–
8	184	7.61	32.02	–
9	15	33.33	0.00	–
10	60	90.83	0.00	–
11	67.5	0.00	47.50	–
12	735	100.00	104.80	YES
13	45	0.00	34.27	–
14	32.5	53.85	80.85	YES
15	17.1	100.00	26.13	YES
16	14.5	100.00	37.09	YES
17	171.8	6.87	344.82	–
18	455	0.00	10.00	–
19	10	40.00	91.78	YES
20	13035.0	2.34	120.00	–
21	348.0	0.00	3.00	–
22	133.0	100.00	123.00	–
23	2000731.0	0.01	60.00	–

possible to use the heat that was previously dissipated in the environment, in the air conditioning system of the National Hydrogen Centre.

The operating mode of the microgrid rewards the use of solar energy. As long as there is photovoltaic solar energy generation, the laboratories will be powered, and the surplus energy will be used to generate hydrogen through the electrolyzer and stored in the hydrogen storage park. If, once the laboratories and the electrolyzer have been powered, there is still surplus photovoltaic solar energy, it will be stored in the gel batteries. At times when photovoltaic generation is not enough to power the laboratories, the fuel cell will be used to generate the energy necessary for the laboratories to work properly. Likewise, if between photovoltaic solar energy and the fuel cell they cannot satisfy the demand of the laboratories, gel batteries will be used. It is important to highlight that, during the operation of the electrolyzer and the fuel cell, the residual heat will be used for the air conditioning system [34].

Besides, the CNH_2 includes a microgrid laboratory with different equipment for the development and testing of hydrogen-based systems applied in the field of microgrids, being an open platform for the integration of new microgrid components. It studies the optimization of microgrid resources to develop advanced energy management systems (EMS) making use of the TOMLAB solver [35], that allows the development of dynamic mixed logic algorithms.

The developed experimentation platform is made up of three bus bars distributed by power 90 kW, 30 kW, 1 kW. The experimental microgrid I is a network integrated into a 24 V DC bus, which has a real connection to both renewable energy generation systems (consisting of a mini wind turbine of 800 W and 3 kWp of photovoltaic field on the roof), as well as to electrical storage systems consisting of gel batteries (24 V, 1110 Ah) and to an H_2 cycle system consisting of a PEM electrolyzer (1 kW), chemical storage of hydrogen in metal hydrides (3 Nm^3) and a PEM fuel cell (1 kW). This microgrid can operate either in isolation or connected to the grid by means of a bidirectional inverter (2 kW).

The experimental microgrid II consists on a network integrated into a 400/230 V AC bus that has connection to a 30 kW network emulator, connection to both physical systems or under photovoltaic generation emulation (10 kWp, 30 kWp), wind power emulator (30 kW), supercapacitors (30 kW, 714 Wh), lithium-ion batteries (30 kW, 38.8 kWh) and an H_2 cycle system consisting of an alkaline electrolyzer (5 kW), a pressurized H_2 storage system (200 bar), and a PEM type fuel cell (5 kW). It also has integrated power electronics with the ability to integrate electrolyzers up to 30 kW (20–230 Vdc, 0-600 Adc) and fuel cells up to 15 kW (20–170 Vdc, Adc 0–400). This experimental microgrid has the possibility of operating either in isolation or connected to the network.

Finally, the experimental microgrid III has a 90 kW bus bar available for the integration of different components. Currently, there is only a 90 kW nominal power network emulator connected to an OPAL RT HIL 5600 equipment, so it allows to amplify the signal of results of real-time simulations carried out in Matlab, Simulink, and Simpower with complex models of electrical networks casuistry [36].

All power electronics devices are equipped with a Real Time Target platform model OPAL RT-OP4500 that allows direct programming of the power electronics controllers based on an algorithm developed in Matlab, Simulink and Simpower. The potentials of OPAL's HIL equipment together with network emulators, allows the integration of any casuistry, or simulation of complex networks with a high number of nodes by means of signal amplification of the simulation results, which is executed in real time. A platform has been created for the rapid prototyping of SCADA solutions applied to energy systems using LabVIEW, Visual.Net and Android, which allow the interoperability of the three microgrids. The microgrid is equipped with two network emulators (30 and 90 kW) integrated in the HIL OPAL RT-OP5600 platform with the possibility of emulating a complex network or a casuistic network connected to microgrids.

3.2. Microgrid of the University of Navarra

The Microgrids Laboratory of the Public University of Navarra (UPNA) serves as a platform for new control strategies and energy storage elements experimentation on microgrids. This microgrid, financed by the Government of Navarra and the European Regional Development Fund (ERDF), has been conceived so it can serve as a test bench for the generation, accumulation, conversion, monitoring and control of the different elements that are incorporated, with the objective set on the analysis of the behaviour of microgrids in urban environments and Smart Cities. As generation elements, it has a photovoltaic system and a wind turbine, and as electrochemical storage it has a lead-acid battery. These elements are connected to the grid through an Ingeteam Ingecon hybrid MS30 inverter. On the network side, there is a programmable electronic load that is capable of reproducing different consumption profiles that can be modified in real time by the control strategy. For data acquisition, there is a set of wattmeters, as well as a meteorological station that allows evaluating the operation of renewable or non-renewable generators. All these data are collected by the monitoring and control station and are used by the control strategy.

The photovoltaic field is composed of 48 BP585 panels. The total nominal power is 4080 W, although the current power under standard measurement conditions is 3600 W. The wind turbine is a Bornay INCLIN6000 model, with a nominal power of 6 kW, located next to the microgrid building, on a 20 m high tower. The battery pack is made up of 120 FIAMM SMG300 cells connected in series. The vessels are stationary 2 V lead-acid cells with a nominal C10 capacity of 300 Ah, for a total capacity of 72 kWh. The grid also accounts for an AMREL's electronic programmable load PLA7.5-600-400 of 7.5 kW and 300 Ah. On the other hand, the hydrogen bus is made up of a Heliocentrics PEM fuel cell system with 4 NEXA1200 cells of 1.2 kW each and a 35.2 Nm^3 hydrogen storage system. Also, the microgrid has a 16.5 kVA generator in the event that there is not enough renewable energy to keep certain loads active. For the monitoring and control of the microgrid, a total of 150 variables is handled every second, either for immediate use in the control strategy or for subsequent analysis of the elements of the microgrid [37].

This grid is a pioneer in the study of a hybrid storage system, comprised by a fuel cell and supercapacitors that resulted in a system that allows to guarantee supply throughout the year, providing fast dynamic responses to supply and demand on the grid [38]. Besides, it has validated energy management strategies for electro-thermal storage systems based on a control structure that depends on the SOC of the battery, what makes this strategy extrapolated to similar systems [39, 40]. They also successfully tested an energy management system based on fuzzy logic to control the grid according to the SOC of the power forecast error and the battery SOC [41].

3.3. Microgrid of the University of Valencia

The microgrid, set in the Industrial Electronic System Group laboratory at the Polytechnic University of Valencia (UPV), is made up of six connection nodes, each with an energy resource distributed (RED) connected. Node 1 includes a photovoltaic generator emulated by a programmable 32 kW DC source (AMREL SPS 800–12 DO13). Node 2 is a critical load emulated by a 5 kW DC electronic load (Chroma 63205A-1200-200). Node 3 takes in an energy storage emulated by a 20 kW bidirectional DC/DC source (Regatron TC.GSS.20.600.400.S.HMI). Node 4 comprises an ILC, 10 kVA three-phase inverter. Node 5 is formed by a common connection point (PPC-Point Common Couple) emulated by a 12 kW single-phase/three-phase AC source (Pacific, 360 AMX). Finally, Node 6 includes a non-critical resistive load of 750 W.

The microgrid is based on a DC bus and an AC bus, the latter connected to the common connection point of the public distribution network through a static switch. The interconnection between the DC and AC buses is carried out by a 10 kW single-phase Interlinked Converter (ILC) with a full bridge topology, which allows a bidirectional power flow. In grid-connected mode, the ILC functions as a current source that injects power into the AC bus in synchronized manner and regulates the voltage on the DC bus [42].

3.4. I-sare microgrid: Gipuzkoa's smart network

The main objective of the i-Sare project is to deploy an experimental microgrid which serves as a platform for the development of new products, equipment, systems, operation and maintenance procedures, and optimize energy storage systems sizing [43]. The i-Sare microgrid is located in the pioneering Enertic building, designed with high efficiency bioclimatic criteria, close to free of CO_2 emissions and equipped with an intelligent monitoring and control system. This building is an Innovation and Business Center developed with the goal of supporting the San Sebastián Renewable Energy, Energy Efficiency, and Smart Energy Cluster. The i-Sare project is managed by the Provincial Council of Gipuzkoa, in collaboration with the Cluster of Electronics, Informatics and Telecommunications of the Basque Country (GAIA-Cluster TEIC), and counts on many institutes and companies as collaborating partners.

The i-Sare microgrid has an installed generation power of 400 kW and several storage systems, loads and generators that can operate connected to the electrical distribution network or in an isolated manner. As renewable energy generation element, it has two wind turbines of 10 kW, one with a horizontal axis and the other with a vertical one; and 2 units of 20 kW of photovoltaic panels with different types of solar cells, to allow a comparison of the performance obtained with each of the technologies. It also includes a 70 kW micro gas turbine, a 120 kW diesel generator and a 5 kW fuel cell. The storage system includes lead-acid batteries (45 kWh), Li-ion batteries (22 kWh), two supercapacitors of 20 kW each and a 100 kW flywheel. Finally, the grid includes emulators of residential, industrial and domestic loads and connection point to electric vehicles.

The microgrid currently works in island mode. The power consumed by the loads will be, as far as possible, from renewable sources. If in the future the microgrid is connected to a medium voltage line it will be able to send the energy surpluses produced to the electrical network, so that the microgrid does not operate in isolation from the distribution network.

The information flow between the different units is carried out through an internal communications network based on EPICS (Experimental Physics and Industrial Control System), and a set of subnets that interconnect the generation and consumption equipment with the IOC (Input Output Controller). In addition, there is a system to record and monitor variables and alarms [44].

3.5. Atenea microgrid (CENER)

The facility is located on the premises of the Laboratory Wind Turbine Test (LEA) of CENER (National Renewable Energy Centre), in the Industrial Park Rocaforte Sanguesa, in Navarra and has been developed by the Department of Grid Integration of Renewable Energy. This grid is oriented to industrial application supplying part of the electric charges of the facilities of the LEA as well as part of the public lighting of the industrial park [35].

The ATENEA microgrid structure is based on an AC low voltage three-phase, four-wire bus.

(400 V, 50 Hz) connected to all of the equipment. It includes a 25 kWp photovoltaic installation and a 20 kW wind turbine as renewable energy generators. Power can also be supplied with a 55 kVA diesel Generator or a 30 kW gas microturbine. The storage equipment comprises a battery bank of lead acid gel technology, capable of supplying 50 kW continuously for 2 h; a vanadium battery that provides 50 kW for 4 h; a lithium-ion battery capable of supplying 50 kW for half an hour; and 30 kW supercapacitors. In the grid, the energy is consumed by a 120 kVA three-phase load bank, the lightning of the industrial park and LEA offices and a point of electric vehicle charge. The microgrid control and SCADA system has been fully designed in CENER [45].

Research done with this smart grid includes a study of different control strategies [46] and the best use of the diesel generator usage through a master-slave control [47].

3.6. Renewable energy integration laboratory microgrid (LIER-CIRCE)

The Renewable Energy Integration Laboratory (LIER) of CIRCE (Centre for Research on Energy Resources and Consumption) in Zaragoza has an installation that combines commercial equipment with emulation benches and power electronics systems for the simulation hardware. It has an asynchronous generation of squirrel cage, a synchronous generation of permanent magnets, a 4 kW wind generator and a 10 kW photovoltaic installation. The energy is stored in lithium-ion batteries and supercapacitors, and it is consumed by resistive loads, electric vehicle chargers, asynchronous and synchronous motors and a voltage dip generator.

The installation is modular and flexible, which allows one to easily test different topologies, evaluate the scalability of solutions, or propose different scenarios. In addition, the microgrid can work both connected to the network and in isolation [48].

3.7. Microgrid of the electric power systems research laboratory (GISEP)

This microgrid is located in the Electric Power Systems Laboratory (GISEP) in Zaragoza and integrates both wind (10 kW) and solar (5 kW) generation, supplying power to the microgrid through power converting equipment. Solar energy is obtained through solar panels while wind energy, is simulated through a motor coupled to the generator shaft that makes use of a variable frequency drive to simulate the different wind regimes. The consumption of the microgrid is variable and simulated through a motor that can vary its consumed power up to 3 kW. For safety reasons, some resistors up to 2 kW are included where part of the power can be dissipated. Regarding storage equipment, there is a battery (1 kW) connected to the grid through an inverter.

For the control of the microgrid, there is a Real Time Digital Simulator (RTDS) capable of simulating any network, with digital and analog inputs/outputs. Future plans for the microgrid include the installation of other storage systems, such as flywheel or supercapacitors, and include an electric vehicle charging centre [48].

3.8. Microgrid of the Interoperability Laboratory of smart grids of the gas natural fenosa foundation (LINTER)

LINTER or Intelligent Networks Interoperability Laboratory was inaugurated in Madrid in 2012 in one of the nerve centres of the Unión Fenosa Distribución network and close to the company's Network Operation Centre. The objective of this microgrid is to provide an environment where projects can be developed to validate the technologies used in microgrids, such as testing of new equipment, simulation of various network topologies, creation of scenarios to investigate detected anomalies, monitoring of equipment performance, management of the connection of solar panels and wind turbines, electric vehicles, batteries, inverters, and so on.

The laboratory equipment is in constant evolution and includes two transformation centres dedicated to the laboratory, mono and polycrystalline photovoltaic panels of 20 kW and amorphous photovoltaic panels of 11 kW, a 3.5 kW horizontal axis generator, and an internal combustion engine powered by natural gas (5.5 kW). It also includes electric vehicle charging posts and other consumer equipment such as office heat pumps, parking lot lighting, household loads, etc. Future plans include the installation of a battery energy storage plant and the implementation of a single manager to control the entire microgrid, grouping the individual applications of each equipment [48].

3.9. Microgrid of the intelligent energy integration laboratory of the IMDEA energy institute (SEIL)

The Intelligent Energy Integration Laboratory (SEIL) is designed to study electrical networks, including control, management strategies and the emulation of scenarios for the integration of microgrids. SEIL presents considerable flexibility in the application of control algorithms and simple access to all test and management data from anywhere on the network, and it is capable of recreating a large number of different events that occur in real power grids [49].

The SEIL is made up of a set of electronic power converters (4 × 15 kVA, 2 × 75 kVA), balanced and unbalanced programmable resistive load banks (2 × 30 kW), Li-Ion battery system with BMS (47.5 kWh), 90 kW bi-directional battery charger, distribution and monitoring panels, and control systems based on National Instruments cRIO technology [45]. This platform allows the analysis, development and testing of realistic scenarios for the integration of energy in both direct and alternating current networks. It also allows testing the operation of the distribution of energy networks, island networks, and microgrids [50]. It has been successfully operated with simple control strategies [51] using real residential users' energy demands [52].

3.10. Walqa Microgrid of the Aragón Hydrogen Foundation

The Walqa Technology Park is an initiative directed by the General Government of Aragon through the Aragon Development Institute and the Huesca City Council that aims to be a referent figure for other research centres in the development of practical renewable solutions [54]. It includes the electrical infrastructure located at the Aragón Hydrogen Foundation and other facilities at the Walqa Technology Park [55].

The small wind farm belonging to the Hydrogen Foundation is made up of three wind turbines (Vestas V29 turbine 225 kW, Enercon 33 turbine 330 kW and Lagerway L80 turbine 80 kW) with a combined power of 635 kW. These are "repowering" machines what means wind turbines that have already been installed and operating in other wind farms, have already been amortized and decided to replace them with state-of-the-art ones to repower their installation.

On the other hand, the photovoltaic installation is 100 kW and comprises different photovoltaic panel technologies (monocrystalline, polycrystalline and heterogeneous junction), different solar collection technologies with fixed installation and two-axis tracking (ADES solar tracker 20 kW, Deguer solar trackers 5 kW, MECASOLAR solar tracker 10 kW and an installation of a fixed plate installed in the car park canopies of 60 kW). Two-axis monitoring is carried out to take advantage of the maximum solar radiation according to the date of the year and time of day or by monitoring the point of maximum luminosity, where sensors detect solar radiation and place the tracker at all times in the position where there is greater solar radiation.

Regarding the hydrogen generation system, it is based on an IHT alkaline electrolyzer of 10 Nm^3/h, working at 33 bar and 85 °C, with an input voltage of 16 V and an input intensity of 3300 A. This device works thanks to the contribution of electricity in direct current from the wind and photovoltaic renewable energies of the park. For the final use of the hydrogen produced, the Aragón Hydrogen Foundation has developed a hydrogen dispensing infrastructure for a vehicle fleet so, once the hydrogen is generated, it is compressed to be dispensed at pressures of 200 bar and 350 bar into the hydrogen-powered vehicles [56].

Finally, the project has an interconnection centre in which, by means of an automation and SCADA system, it is possible to choose at any time whether to sell the electrical energy generated or if, on the contrary, the energy is sent to generate hydrogen [45].

3.11. Microgrid of the energy research institute of Catalonia (IREC)

The Department of Electrical Engineering of the Catalan Energy Research Institute (IREC) has a laboratory called IREC Energy SmartLab with a unique testing and emulation infrastructures and equipment. The microgrid is a 200kVA low voltage installation composed of several configurable units that include generation, storage, and consumption of different kinds to investigate and develop the technologies and tools related to distribution networks, integration of renewables, electric vehicles, management and control. It has been designed to allow the application of various management systems, including external readings and control strategies. Also, an architecture based on Local Controllers and Central Concentrator has been developed [57].

The IREC microgrid includes a network emulator (200 kVA), a lithium-ion battery (5 kVA), a stack of supercapacitors (5 kVA), a flywheel (4000 rpm, 5 kVA), and a Second Life Battery of an Electric Vehicle (10 kVA). Besides, an emulator equipment (5 × 5 kVA) can be configured to reproduce the electrical behaviour of different systems including renewable generation, consumption or storage systems. The motor-generator bench (3 × 5 kVA, 1 × 30 kVA) includes the main technologies such as SCIG, DFIG and PMSG, in addition to a 9-phase generator; which can behave as emulators of wind or marine generation. All is monitored through a SCADA system and this is integrated with MQTT for IoT-based systems [58]. The communication between the local systems and the concentrator is according to the IEC 61850 protocol, as in real substations, in addition the elements communicate with each other through CAN and/or MODBUS [45].

3.12. Microgrid of the National Institute of Aerospace Technology (INTA)

The microgrid of the National Institute of Aerospace Technology (INTA) is located in Huelva and is part of the experimental work of the AGERAR project (Storage and management of renewable energies in commercial and residential applications) [59]. This project was part of the Interreg 2014–2020 Cross-Border Cooperation Program (POCTEP), and its main objective was to promote energy efficiency and sustainability criteria in commercial and residential microgrids. AGERAR was led by the University of Seville and several institutes and universities participated.

This microgrid has a storage system comprised of Ion-Lithium (43 kWh) and Lead-Acid batteries (36 kWh). A hybrid system integrates electrical generation systems, storage systems and different loads, in AC and DC, connected by an internal 408 VDC (nominal value) bus, as well as a 230 VAC network connection. The DC generators correspond to various photovoltaic fields (12.5 kW), a wind turbine (5 kW), and fuel cells (4.2 kW). The grid contemplates the use of hydrogen as an energy vector, including its production through alkaline electrolysis (5 kW), low and high pressure storage, metal hydrides hydrogen storage, and consumption through fuel cells. Finally, the interconnection and injection from the DC bus to the grid through single-phase inverters is contemplated, as well as a programmable direct current load [60].

The entire system is monitored with voltage and current sensors, with the aim of proposing different energy management strategies based on empirical values measured in real time. The wireless sensor network comprises several LoRa sensors that collect information from the DC and AC circuits of the INTA microgrid. These devices communicate the recovered data through a LoRaWAN architecture made up of a Gateway, a Network Server, and an Application Server. The data from these sensors is also collected in a concentrator with different communication interfaces and taking into account the possibility of integrating different manufacturers and parameters. The communications device effectively manages the data from different sensor nodes, being able to send information in real time to the IoT platforms, as well as having on-site storage capabilities. The work carried out demonstrates how the management of renewable energy microgrids can be optimized through the deployment and implementation of low-power and low-cost wireless monitoring networks, based on LoRaWan technology, integrated into an IoT platform with a high capacity of data processing and storage [61]. In this sense, the Technological Institute of Galicia (ITG) has developed a technological tool, based on the Internet of Things (IoT) and Big Data, and has deployed it in INTA's experimental microgrid. The objective was to demonstrate how the use of information systems based on IoT, with high processing capacity and capable of performing advanced data analysis, contributes to improving decision-making in the management of this typology of microgrids [59].

3.13. Microgrid of the Institute of Energy Engineering in Valencia (LabDER)

The objective defined by the laboratory of distributed energy resources (LabDER) of the Institute of Energy Engineering of the Polytechnic University of Valencia is to study renewable hybrid systems in the kW range in order to design and participate in field experiences of greater power [63]. This laboratory includes different renewable sources such as photovoltaic (2.1 kW), wind (2.5 kW), biomass (10 kW) and fuel cell (1.2 kW), all of them interconnected by means of a controlled microgrid, to feed a 9 kW load with a pre-programmed demand curve, allowing to verify the potential of different renewable hybrid systems to satisfy a certain demand. The laboratory includes storage systems, based on batteries (12 kWh lead-acid batteries) and hydrogen (7 kW electrolyzer), in order to cover practically all the possible configurations of renewable hybrid systems that may be considered.

This microgrid is a mixed network that includes an initial stage working in DC, to which systems such as photovoltaic ones, which generate electricity in this mode, and another AC network that can be joined. All renewable electricity production and storage systems will be linked to a three-phase electrical microgrid, either directly, such as the gas engine and alternator group of the biomass plant, or through rectifier-inverter or directly inverter static converters, as is the case with photovoltaic solar panels. The microgrid joins a set of triphasic receivers, whose electrical demand can be programmed in order to obtain different load curves and study the behaviour and stability of the hybrid generation system in the face of different energy demands. All parts of the microgrid pass through a general protection and operation panel, from which connection or disconnection of any part can be carried out. The panel is provided with measuring devices in each circuit, which allow the operation of each part to be monitored. The current core of energy management is based on a Xantrex XW4548-230-50 device from Schneider Electric, which regulates the different flows between connected elements [64].

This complete grid has carried out deep studies to characterize the system [65] and define the control of an energy hydrogen buffer [66].

3.14. Microgrid of the Technological Institute of energy in Valencia (ITE)

In recent years, the facilities that the Technological Institute of Energy (ITE) has in Paterna (Valencia) have progressively evolved to jointly adopt the meaning of microgrid. The microgrid is made up of a network implemented in the ITE Interoperability Laboratory, also including distributed generation, storage and self-managed consumption resources, represented by the ITE building in the Renewable Energies Pilot Plant and the Active Management Laboratory of the ITE demand. As a whole, the entire system is designed and implemented to carry out research and development projects on its own and with companies interested in this technology.

The facilities include renewable energy generating elements, such as a photovoltaic generation plant (7.5 kW), a horizontal axis wind turbine (6 kW), a vertical axis mini-wind turbine (1 kW) and two PEM type hydrogen cells (1.2 kW and 4.5 kW). These systems are used as a distributed generation point (DER), allowing testing and validation of the developed systems, including distributed generation dispatch. All this is combined with an energy storage system in the form of batteries of different technologies (14.5 kW), supercapacitors (190 Wh) and hydrogen (under pressure and in metal hydrides). This hydrogen is consumed in a 6 kW electrolyzer. In addition, there is an industrial frequency network simulator, and another continuous network simulator. Regarding power consuming elements, there is a dedicated line for simulating domestic consumption equipped with manageable electrical appliances, smart plugs and monitoring equipment. On the other hand, the very building of the Technological Institute of Energy (ITE) is seen as a self-managed active node with the purpose of monitoring and managing its consumption and generation at the local level.

As part of this microgrid, the ITE facilities have an Interoperability and Communications Laboratory for Smart Devices, ITP and Smartgrids. In this laboratory, a set of passive, resistive and inductive loads is available to simulate various consumption scenarios. It also includes two unique facilities that allow to obtain load situations closer to reality, as the Low Voltage (LV) network can be configured in different topologies and line lengths, allowing to analyse the behaviour in the management of charges and communications over the network. As a novelty, the laboratory provides a platform that permits verifying the correct functionality of a Smart Grid through its various applications such as PLC-based interoperability (PRIME, DLMS/COSEM). In this sense, the communications network implemented has an architecture parallel to PRIME communication with monitoring and recording of individualized energy consumption, actuation devices and line cutting, visualization and remote control of signals from the air conditioning equipment, and additional sensitization for detection of people through photocells, tap water consumption, and a webcam with IP communication. As a complementary facility, there is a Partial Discharge Laboratory, in which measurements are made in high voltage switchgear (up to 300 kV), location of defects in cables, analysis of the PD waveform, measurements in cables up to 36 kV (resonant system for capacitive loads), dielectric strength tests on high voltage cables (AC, DC and lightning type), insulation resistance measurements, resistivity of semiconductors, cable aging, expert reports and failure analysis [48].

3.15. Tecnalia InGRID microgrid

Tecnalia, one of the leading R&D companies in Spain, has developed a flexible and modular microgrid laboratory at its headquarters, designed and oriented to meet the needs of electrical equipment manufacturers and utilities in the specification, development, validation and commercialization of innovative products for Smart Electric Grids.

The energy sources of the Tecnalia Microgrids Laboratory include non-renewable and renewable on-site generation, which consist of a diesel generator (2 × 55 kW), a microturbine (50 kW), a photovoltaic system (0.6 kW amorphous silicon, 1.6 kW monocrystalline and 3.6 kW polycrystalline photovoltaic sets), a wind turbine (6 kW) and a fuel cell (1 kVA). The storage system consists of an inertia flywheel (250 kV), lead-acid battery banks (1080 and 1925 Ah) and supercapacitors (5 kW for 6.5 min). Controllable load is also part of the microgrid lab's wide range of options with resistive (150 and 50 kW) and reactive (2 × 36 kVA) load banks. Finally, a network simulator is used as generation system capable of simulating the electrical network. It is composed of two 55 kW sources that provide a three-phase 228/132 Vac 500 Hz output, a 456/264 Vac power transformer, and a programmable controller [48].

3.16. Microgrid of the University of Oviedo

The working group in charge of this microgrid is called Laboratory for Enhanced Microgrids Unbalance Research (LEMUR) and its members are attached to the Department of Electronic, Computer and Systems Engineering of the University of Oviedo, being a multidisciplinary group that unites researchers from the areas of knowledge of different engineering. The scope of LEMUR's research is the study of the implementation and development of solutions in electrical distribution networks, particularly in microgrids. Its main objective is to check the operation of micro-generation systems, both in residential and in industrial areas where machinery can affect the behaviour of generation systems.

The microgrid is made up of a 100 kVA generator set, a three-phase converters of 50 kVA each, capable of master/slave operation, an active power filter for harmonic compensation with a capacity of 75 A, a doubly fed generator with a nominal power of 15 kW driven by an asynchronous motor governed from a converter in which the characteristic curves of the desired wind generator are programmed, three resistive type loads with a power of 30 kW each, non-linear type loads with a power of 100 kW, reactive energy compensation banks with a power of 20 kVAr, a kinetic energy storage system based on a 30 krpm flywheel, two single-phase converters of 40 kW each and a150 kW 4 kV power supply. The control of converters is carried out using DSP's from Texas Instruments.

The laboratory can design power converters and control systems for grid injection applications, electric drives and energy storage systems [67]. It also studies the operation of microgrids in unbalanced conditions and the load flows in electrical networks as well as the optimization of generation and demand strategies. Also, the impact on the Electricity Grid of Distributed Generation and of the Electric Vehicle is investigated, in addition to the reliability and the design and optimization of electric power circuits. Finally, some configuration of nanogrids and microgrids (defined as a lump of nanogrids) has been analysed testing power flow algorithm validated using the laboratory set up [68].

3.17. Microgrid of the University of Seville (HyLab)

The experimental microgrid of the HyLab laboratory is an installation developed at the Higher Technical School of Engineering of the University of Seville. The objective of the creation of this microgrid is the research on the combination of renewable energy sources using hydrogen as an energy vector as well as pioneering investigation to integrate different kinds of energy demand (electricity, cold and heat). Both, its design and its construction, were carried out within the framework of the Project "Application of novel control techniques to the storage of electrical energy of renewable origin using hydrogen", financed by the Ministry of Education and Science of Spain (DPI2016-78338-R) and then extended using budgets of the University of Seville. Nowadays, the project in course is the Hybuildings Project (PY18-RE-0028) funded by Consejería de Conocimiento, Investigación y Universidad of the Junta de Andalucía.

The Hylab Microgrid is an experimental installation conceived with a modular structure that gives it a high degree of flexibility, allowing the implementation and study of different modes of operation and control strategies [69]. This microgrid is also used to develop and experimentally validate mathematical models of both individual equipment and certain configurations [69].

The microgrid has undergone changes since it was installed in 2010 [70]. Nowadays, the installation is composed of a field of photovoltaic panels (4 kWp monocrystalline, 15 panels of 265 Wp) and a programmable electronic source (Powerbox 6 kW) to simulate generation profiles. As storage systems, there exists a bank of lead acid batteries (24 cells of 1100Ah) and a bank of lithium batteries (110 Ah and 19.2 kWh). As an alternative energy storage system, the installation has a hydrogen line, formed by a PEM electrolyser (Heliocentris ELS500) with the capacity to produce up to 500 Nl/h of hydrogen for a power consumption of 2.9 kW; two metal hydride tanks with the capacity to store up to 14 Nm^3 of hydrogen and a hydrogen fuel cell (Heliocentris) with the capacity to generate 1200 W with a hydrogen consumption of 15 Nl/minute. Also, a programmable electronic load (Amrel) that can dissipate a power of up to 2.5 kW, and work at voltages and intensities of up to 60 V and 1000 A is used to simulate demand profiles.

3.18. Microgrid Málaga Endesa

Malaga SmartCity is a renewable energy pilot facility focused on improving the distribution network operation [71]considering the integration of electric vehicle services [72]. The facility includes two primary substations and more than 70 Transformation Centres supplying an area with 11,000 domestic, 900 commercial, and 300 industrial customers besides the 200 efficient public lighting elements. The installation has around 11 MW of renewable generation capacity, including 9 PV residential installations (295 kW) and 2 wind turbines (10 kW). In addition, it has a non-renewable energy source such as two natural gas cogeneration facilities (10 + 2.73 MW). Two Li battery-based storage facilities (106 + 24 kWh) were installed to help manage the system. Regarding electric mobility, a network of recharging points was included and adapted to enable electric vehicle capacity.

Also, another large projects are being developed in the area, as Green eMotion (3-point implantation quick reload and tool development for the creation of a market of services of electric mobility), ZEM2ALL (1 site of fast recharging of the 9 that comprise the project, where the deployment of 200 electric vehicles for professionals and individuals is carried out, with 200 associated slow charging points); VICTORIA, a full-scale demonstration laboratory for wireless electrical charging of public buses by induction, which will mean the first implementation of these processes in static, dynamic and parking mode; and E + (development of an interaction platform between energy service providers, demand and generation aggregators, the power grid, etc.). Besides, there are several on-going projects (MONICA, PALOMA, Flexiciency, Smart Terminal) that search for solutions to improve the grid, focused on the monitoring and control of low and medium voltage grids, but also on the study of the energy losses, the impact of quickly charging electric buses and the integration of a micro electric grid along the seaside of Málaga [73].

3.19. Microgrid of the University of Comillas (ICAI)

The main use of ICAI laboratories is primarily for academic purposes in the engineering school but, in addition, applied research projects are developed there, as well as external tests. In this area, ICAI has participated in GRID4EU, SUSTAINA-BLE, ENERGOS and TWENTIES projects, among others.

ICAI microgrid includes, as generation sources, synchronous machines (8 of 5–15 kVA), DC machines (11 of 4–18 kW), a DC generator (90 kW) and an alternating current generator at variable frequency/voltage (85 kVA). The storage systems are different kind of Li batteries: 20 × 10Ah Ion-Li, 12 × 5 Ah Li-polymer and 20 × 4.5 Ah LiPo batteries. The energy is consumed by resistance banks (100 kW), induction motors

(15 power groups between 6 and 18 kW), reactances (20 × 1 kVAr) and capacitors [48].

3.20. Microgrid CEDER-CIEMAT

The CEDER-CIEMAT microgrid is located at the Centre for the Development of Renewable Energy Sources (Centro de Desarrollo de Energías Renovables, CEDER) facilities, which is part of the Centre for Energy, Environmental and Technological Research (Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, CIEMAT). It is composed of a wide range of renewable energy sources, distributed generation and distributed storage elements. The microgrid also includes prosumer profiles composed of two photovoltaic systems located on top of two of the buildings. In addition, several meters have been located at consumption and generation points with the aim to monitor and control it. All that makes a versatile installation with a remarkable strength of the electric configuration because of its ring topology, which allow to analyse the corresponding areas independently [74].

The grid is composed by three 2.8 kW unit loads, which can be used as single-phase or three-phase; 36 kW of resistive loads, two 4 kW of mobile resistive loads, 4 kW inductive loads and 2 kW of capacitive annually adjustable loads. Besides, there exists 2 electric boilers (90 kW) for heating water and several buildings, machinery and workrooms are also connected. The generation system includes wind turbines (50, 3.2, 3 and 1.5 kW), a mini-hydro generator of 40 kW and photovoltaic panels (12 + 8.28 kW photovoltaic roof and 15 kW photovoltaic collector). As storage system, it includes a Lead-Acid battery bank (35, 20 and 8 kW racks), lithium-ion battery bank of 60 kW and a 25 kW flywheel [75].

The particularity of this grid is its study on a low-cost kinetic energy storage system using flywheels and how to optimally include them in the energy management system [73]. Also, grids electric and communication levels were analysed to optimize the economy of the process, the energy efficiency and the promotion of renewable energy [76].

3.21. Microgrid ORMAZABAL

The demonstration and experimentation unit, consists of an experimental network designed as a platform to research, develop and verify equipment and systems in a real network in a risk-free environment. This network makes it possible to reproduce normal and anomalous situations by connecting it to the High Power Laboratory (HPL) that provide the necessary power to produce the actual medium voltage operating conditions [77].

The grid presents five different power sources: a utility grid 30 kV/630 kVA, a diesel generator of 630 kW, a photovoltaic plant of 100 kW, a wind plant of 1000 W and an HPL generator of 2500MVA. The storage system is composed by 60 kW of VRLA-Valve Regulated Lead Acid batteries. The load equipment includes underground cables (approximately 15 km), overhead cables (approximately 450 m), electric vehicle charging station, as well as resistive (4000 kW), capacitive (6000 kVAr) and inductive loads (300 kVAr) [78].

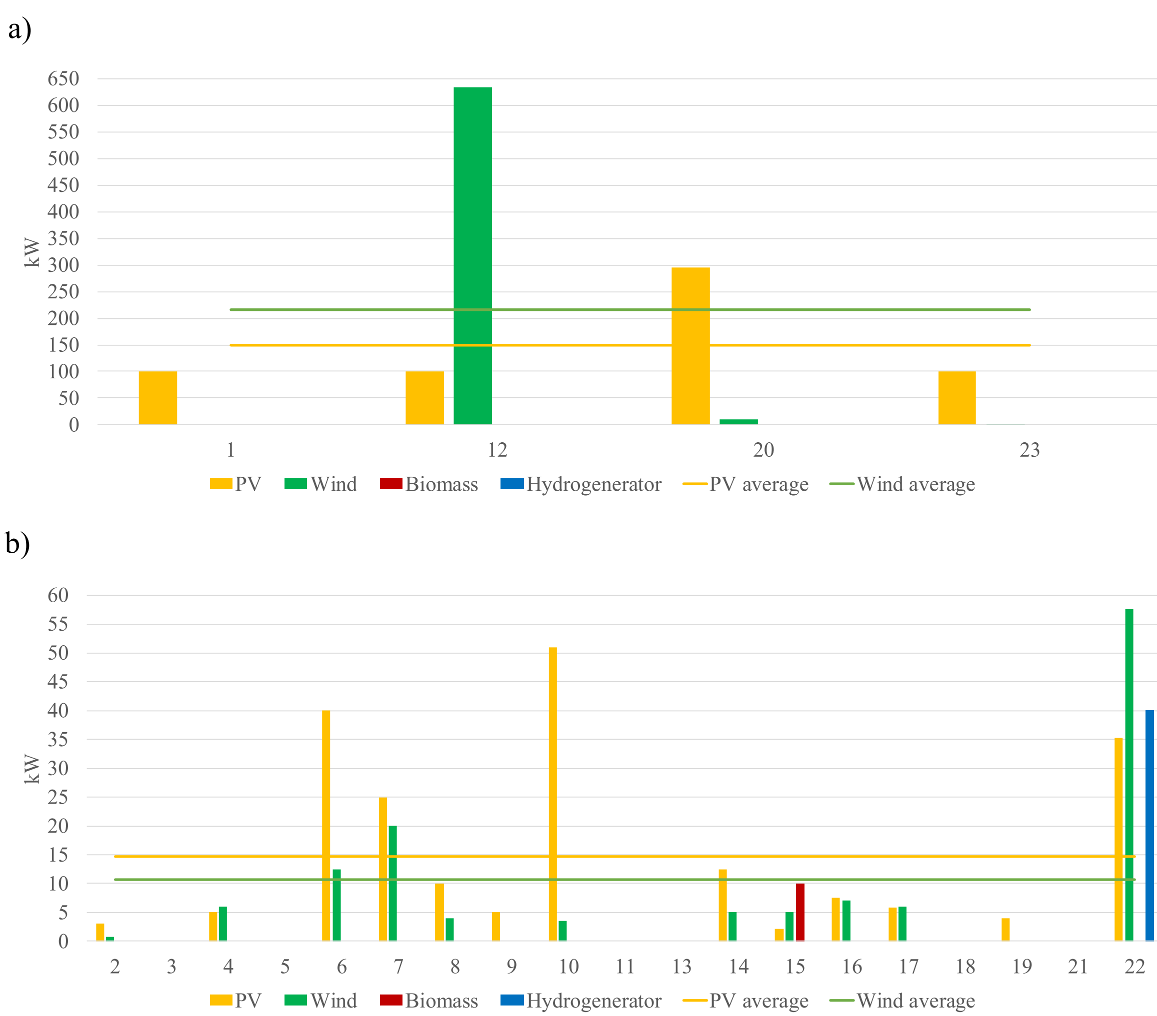

Fig. 2. Presence of Generation Sources by typology in Spanish microgrids.

4. Analysis of microgrids in Spain

4.1. Generation sources

The renewable generation technology is photovoltaic solar energy, since it is present in approximately 80% of the microgrids in Spain, followed by wind power. This makes sense considering that both technologies have experienced an outstanding development in this country during the last decade, and nowadays they comprise a 6.1% and 21.7% of the mix in the Spanish energy pool.

Fig. 2 represents the installed power of photovoltaic energy (kW) on each microgrid. As can be observed, there are four microgrids that outdo in photovoltaic installed power. These are the microgrid of the National Hydrogen Center, the Walqa Microgrid of the Aragón Hydrogen Foundation, the Málaga-Endesa microgrid and Ormazabal microgrid. All of them are exceptional, large microgrids capable of power buildings or city infrastructures, because of that, the figure is divided in two groups, being a) the four largest grid and b) the rest of microgrids projects.

4.2. Storage sources present in microgrids in Spain

Among the storage systems used in microgrids, batteries are mostly widespread. Approximately 90% of the microgrids in Spain include batteries as storage system (Fig. 3). This is not surprising since rechargeable battery is one of the most widely used energy storage system technologies in industry and daily life despite the fact of its relatively rapid deterioration and the fact that toxic chemical materials are used, what sets barriers for their posterior disposal or recycling. Lead-acid and lithium-ion ones are the most common, but also there is a strong bet for gel technology batteries (Fig. 4).

Green hydrogen is making its way into the energy storage systems, and it is present in a third of the Spanish microgrids. Fuel cell systems combined with electrolyzers and hydrogen storage can provide clean and reliable power, and in most of the microgrids that use these technologies, hydrogen storage energy capacity outstands batteries capacity. This development of renewable hydrogen is backed up by the approval of the Spanish Hydrogen Roadmap, which includes concrete measures and targets for 2030 in line with the European Hydrogen Strategy, such as the installation of 4 GW in electrolyzers [79]. In this sense, Iberdrola is building the largest green hydrogen plant for industrial use in Europe, with a 100 MW photovoltaic solar plant, 20 MWh of lithium-ion battery system and a 20 MW electrolytic hydrogen production system [80].

Flywheels are also considered as a storage option, since they can supply sufficient power in a short time period with modest capacity, although they are not used as a standalone backup power but operated along with batteries. Its main weakness is that they suffer from the idling losses during the time when the flywheel is on standby, what can lead to relatively high self-discharge [81].

4.3. Hydrogen production, storage, and fuel cell capacities

Hydrogen technologies are a relevant component in the existing microgrids, although not all microgrids are incorporating such technologies. In all hydrogen-based applications, its production is achieved by means of electrolysis (mostly alkaline), and hydrogen storage is achieved by means of either mechanical compression or metallic hydrides. The conversion of hydrogen to electricity is carried out in all cases by low temperature PEM fuel cells. Table 3 presents the main equipment and its sizing related to the overall power of each microgrid. A total of 11 of the microgrids analysed in this work involve hydrogen technologies, where two of them also include hydrogen refuelling capabilities from compressed hydrogen.

4.4. Control strategies applied to Spain microgrids

One of the main aspects to consider regarding the operation of microgrids is their controllability. Ranging from the simplest strategies like regulatory control to the most advanced ones, that imply the use of optimization, prediction models, etc.; all microgrids in Spain depend on these strategies to ensure a correct and secure operation of their components.

Starting from the microgrids that use the simplest strategies, Tecnalia [82], GISEP [48], and WALQA [52] make use of regulatory control of its equipment. This type of control allows a secure and stable operation, but not optimal, for example in terms of energy management. In this line can be also included LIER (CIRCE) [83], which specializes in the development of stability controllers for power electronic applications; ORMAZABAL [48], which focuses on power control; and Comillas [84], which stands out in the development of frequency control strategies.

The next level would be the ones that make use of hierarchic control of different levels and that could be centralized or decentralized. LINTER [48], Atenea de Cener [45], University of Oviedo [64,], and SEIL [53] make use of a centralized control strategy with a minimum of 2 levels of hierarchical control. For example, with regard to the control of the SEIL microgrid, there are two levels. Low-level control focuses on the control of each power converter and the emulation of the dynamic model of distributed energy resources, using Matlab/Simulink and Triphase Toolbox to design the control and emulation algorithms. The high-level control covers the control and supervision of the microgrids and carries out energy delivery strategies [56]. Meanwhile, I-Sare, Universidad de Valencia [48], LABDER [64], Málaga [35], and CEDER-CIEMAT [85] make use of a decentralized control strategy with the following highlights for some of them: I-Sare applies a hierarchic control of 4 levels (primary control is implemented in the local control of each inverter connected to the micro-grid and is responsible for the distribution of active and reactive power; secondary control re-stabilizes deviations in voltage and frequency and takes care of synchronization with the main network; tertiary control manages the energy in the entire grid and quaternary control is in charge of realizing the distribution of the real

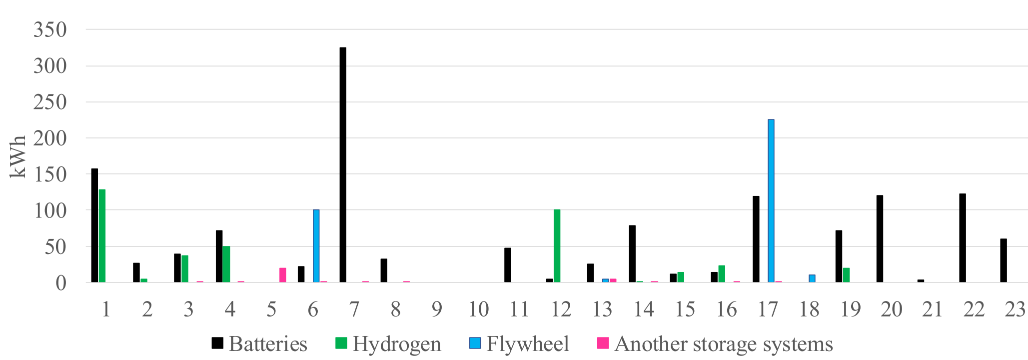

Fig. 3. Storage Sources by typology in Spanish microgrids.

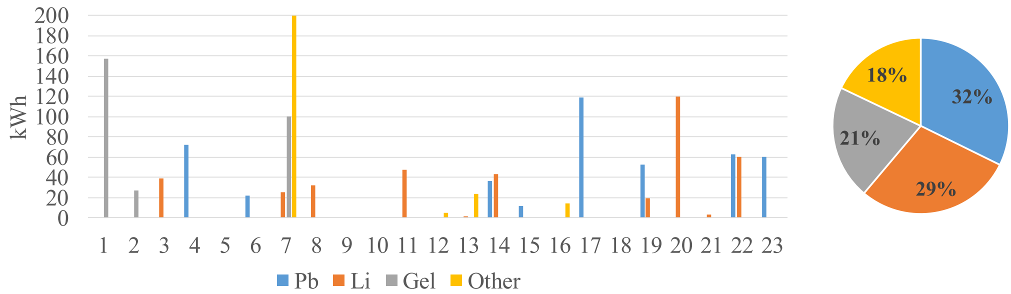

Fig. 4. Different battery technologies in Spanish microgrids.

Table 3
Main features and equipment sizing in hydrogen-based microgrids.

	CNH2	CNH2 mg-I	CNH2 mg-II	University of Navarra	Gipuzcoa i-Sare	Aragon H2 Foundation	INTA	IEE-LabDER	ITE	Tecnalia	University of Seville (HyLab)
PV (kW)	100	3	10–30	4.08	40	100	12.5	2.1	7.5	5.8	5
Wind (kW)	–	0.8	30	6	10	635	5	2.5	7	6	
Micro-GT (kW)	–	–	–	–	70	–	–	–	–	50	
Diesel generator (kW)	–	–	–	–	120	–	–	–	–	110	
Biomass (kW)	–	–	–	–	–	–	–	10			
Batteries	3266 Ah (gel)	1100 Ah (gel)	30 kW, 38.8 kWh (Li-ion)	120 × 300 Ah, 72 kWh (Lead-acid)	45 kWh (lead-acid) 22 kWh (Li-ion)	–	43 kWh (Li-ion) 36 kWh (Lead-acid)	12 kWh (Lead-acid)	14.5 kW	1080 and 1925 Ah (Lead-acid)	1100 Ah (Lead-acid) 110 Ah −19.2 kWh (Li-ion)
Flywheel (kW)	–	–	–	–	100	–	–	–	–	250	
Supercapacitors (kW)			30.714		40				0.190	5	
PEMFC (kW)	30	1	5	4.8	5		4.2	1.2	5.7	1	1.2
Electrolyser (kW)	60 (AEL)	1 (PEMEL)	5 (AEL)	–	–	52.8 (10 Nm^3/h) (AEL)	5 (AEL)	7 (AEL)	6 (AEL)	–	2.9 (AEL)
H2 storage	16 × 50L (200 bar) HRS 7500 L (10 bar) (14 kg)	MH (3 Nm^3) (0.25 kg)	200 bar	35.2 Nm^3 (2.95 kg)	–	200 bar and 350 bar HRS	Low (6 Nm^3 at 6 bar and medium (35 Nm^3 at 200 bar) pressure, MH (24 Nm^3) (5.5 kg)	–	Pressure, MH	–	2 x MH 7.2 Nm^3 (1.2 kg)
Electrolyzer-to-Fuel Cell ratio	2.0	–	1.0	–	–	–	1.2	5.8	1.05	–	2.4
Electrolyzer-to-Total power ratio	0.6	–	0.08	–	–	0.07	0.3	0.5	0.4	–	0.6

demand between generators, warehouses and connection with the supplier) [86]; Universidad de Valencia base its strategy in peer-to-peer communication network with a structured decentralized architecture, allowing a higher scalability, robustness, flexibility, and efficiency of the communication system of microgrids [87]; LABDER make use of a heuristic controller; and CEDER-CIEMAT developed a robust decentralized agent-based approach for energy management of its microgrid. On the other hand, IREC [55] and Instituto Tecnológico de la Energía [48] make use of both centralized and decentralized control strategies.

Finally, in the advanced level, Universidad de Navarra [39] uses a control strategy based on energy management algorithms that make use of future demand predictions using a retarded mean average; whereas, INTA, Hylab, and CNH2 microgrids, stand out in the assessment of different advanced control techniques such as fuzzy control and model predictive control (MPC). In particular, INTA has developed a fuzzy logic EMS whose rules include both technical and economic criteria so that it can be capable of satisfy the power demanded, while reducing the electricity invoice [62]; CNH2 has designed some optimal economic schedules using MPC applied to hydrogen based microgrids [88] or to a network of microgrids [89]; Hylab microgrid has been used to assess control strategies based on MPC, such as stochastic MPC [90] or multicriteria optimal operation [91].

It seems clear that the tendency in microgrid control studies is to develop advanced control strategies such as MPC or fuzzy logic, since their use points to a higher efficiency and economic savings in microgrid operation. In addition, the implementation of decentralized control strategies using peer-to-peer communication systems, that show interesting results in simulation, has to be tested more in experimental microgrids to confirm them. Also, it is important to start creating norms and standards about security operation of microgrids, interconnection between microgrids and protection against cyber-attacks. Initial considerations on the protection differentiating between AC and DC grids can be seen in Refs. [92,93]. A review of actual standards, norms and recommendations for cyber security in microgrids can be consulted in Ref. [94].

A summary of which microgrid incorporates each of the control systems and their advantages and disadvantages can be seen in Tables 4 and 5.

Table 4
Main control strategies used in Spanish microgrids.

Microgrid	Regulatory Only	Centralized	Decentralized	MPC	Optimization
1	–	–	–	YES	YES
2	–	–	–	YES	YES
3	–	–	–	YES	YES
4	–	–	–	–	YES
5	–	–	YES	–	–
6	–	–	YES	–	–
7	–	YES	–	–	–
8	YES	–	–	–	–
9	YES	–	–	–	–
10	–	YES	–	–	–
11	–	YES	–	–	–
12	YES	–	–	–	–
13	–	YES	YES	–	–
14	–	–	–	–	YES
15	–	–	YES	–	–
16	–	YES	YES	–	–
17	YES	–	–	–	–
18	–	YES	–	–	–
19	–	–	–	YES	YES
20	–	–	YES	–	–
21	YES	–	–	–	–
22	–	–	YES	–	–
23	YES	–	–	–	–

Table 5
Advantages and disadvantages of the main control strategies used in Spanish microgrids.

Control Strategy	Advantages	Disadvantages
Regulatory Only	- Allow a secure and stable operation - Low computational time	- Not optimal operation
Centralized	- One controller capable of managing all facility subsystems	- High computational time - Low robustness and flexibility
Decentralized	- High robustness and flexibility	- Dependency on the communication system
MPC	- Allow a better energy management based on predictions of the energy sources or demands	- Require good predictions - High computational time
Optimization	- Allow a more efficient energy management in technical or economic aspects	- High computational time

5. Conclusions

Nowadays, major challenges in smart-grids go through the development of strong regulations that must be able to lay the foundations for a new system energy that defines a roadmap according to the scenarios proposed, which can protect both clients or owners of micro networks, as well as those who cannot have access to it, define new remuneration and tax plans and establish the processes necessary to access these facilities, as well as a framework that regulates the interconnections between micro networks and the central network, in economic, technological and social, and that seeks to establish operating protocols, both in terms of normal and emergency regimen. Regulation of the energy transition should be possible in parallel with the development of technology and be not an obstacle, but a driver that defines the rights and obligations to be respected and fulfilled by all parties involved in this process of renewal.

Spanish smart-grids laboratories are strongly betting for green hydrogen as energy vector, integrating electrolyzer and fuel cells along with the traditional generation (photovoltaic panels and wind turbines) and storage (batteries) systems. This development is being supported by the Spanish Government through its Hydrogen Roadmap. Still, energy storage is one of the main issues renewable energy has to face due to its intermittency.

Also, power quality and reliability must be ensured, as well as operational security. In this sense, energy management systems are implementing more precise and sophisticated control strategies that allow to safely operate not only smart grids, isolated or connected to the main grid, but also lumps of smart grids that implement different technologies.

The technological objectives of all Spanish microgrids have been focused on the integration of renewable energy and different energy storage systems to supply electrical demands, in a reliable and safe way, delving into the optimal modes of operation and control techniques, determining the most favorable storage systems for the short and long term and the durability of the equipment. The technological challenges to be achieved in the coming years for full integration of microgrids in the electricity system are focused on adapting the regulations and legislation to accommodate them, promoting actions of economic support and financing for this type of systems, reducing the costs of storage systems and increasing its durability, and a need for standardization and homogenization of design and dimensioning criteria depending on the type of demand.

All these issues have to be thoroughly investigated to ensure a quick and smooth energy transition from fossil fuel-based system to renewable energy.

Credit author statement

G. M. Cabello González: Conceptualization, Investigation, Formal analysis, Data curation, Writing – original draft. Sergio J. Navas: Conceptualization, Formal analysis, Writing – original draft, Project administration. I.M. Vázquez: Data curation, Formal analysis. A. Iranzo: Writing – review & editing, Supervision. F. J. Pino: Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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