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# A Review of the State of the Art of Industrial Microgrids Based on Renewable Energy

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**Abstract:** Electric microgrids based mainly on renewable energies have seen a big expansion in recent years due to the great advantages they present against fossil fuels. Nowadays different governments are becoming aware of the use of environmentally friendly energies, so progressive investment has been granted to the consumers in Spain. Many microgrids have been installed in both connected and isolated circumstances, and this fact brings new challenges regarding the technical and economic points of view. This study aims to delve into electrical microgrids based on renewable energies applied in industrial facilities through a review of the literature associated with the study of general microgrids. It later focuses on the relationships between renewable energies and industrial environments. A brief reference is made to the use of energy storage systems in industrial installations depicting the most used systems. This paper presents a review of the state of the art of microgrids from distributed energy resources technologies to industrial microgrids optimization, with the primary objective of providing insight on current trends and directions in research and further identifying areas in need of further development.

**Keywords:** microgrids; distributed generation; photovoltaic; wind; energy storage system; renewable energy

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## 1. Introduction

In order to start researching industrial microgrids (MGs), it is necessary to review previous works, as there are advantages and issues that this new technology can bring. Many studies about MGs have been released during the last decade, resulting in a widespread abundance of information and papers from several researchers, pointing to a new changing scenario from COx emitting energy sources to environmentally friendly "green" renewable energy sources. It should be noted that in applications using renewable energies, the use of energy storage systems (ESS) has been implemented with the aim of improving the reliability of the system to avoid the intermittent nature of energy generation [1–3]. Most of these ESS use lithium-ion batteries and sodium–sulfur batteries having high power and energy densities and high efficiency. Many industrial activities are gradually giving an opportunity to this type of MG system of renewable energy (RE) with EES. For some part of this work, grey literature obtained from renowned research laboratories has been analyzed and reviewed.

From a few years ago until today, the general trend of large industrial electrical energy consumers has been to access reliable electrical energy locally, sell power during surplus generation or peak grid price time periods, and buy power in case of cheap electricity prices. From the year 2019 Spain has released the administrative procedures to ease its RE market [4]. Royal Decree 244/2019 is the official Spanish law that regulates the administrative, technical, and economic conditions related to the self-consumption of electrical energy. The text shows a new self-computation type definition based on the surplus or not of the installation. Regarding the aforementioned, in [5], Rosales et al. proposed a stable legal framework design aimed at implementing and allowing an electricity self-consumption system.

In the scientific literature, it is possible to find a large number of research papers exploring the microgrid concept, installation, optimization, economic, and/or environmental impacts of it with its use of renewable energy.

However, the potential repercussions that sensitive load conditions of the industrial environment have on the feasibility of the microgrid have not been given the same attention. From a deeper survey of grey literature [1,6–48] related to the topic addressed here, it was possible to find that—even though there is a great deal of different approaches—this paper undoubtedly contributes to the pool of existing knowledge by giving a focused perspective. From this line of analysis, a much clearer insight of microgrid repercussions on the industries is gained.

The rest of the paper is presented as follows: Section 2 provides Materials and Methods; Section 3 addresses the theoretical framework of the study, where MGs and their classifications and configurations related to industrial applications are explained. Moreover, research on the relationship between the MGs and RE is addressed. Mostly, the section looks at two main kinds of REs, wind and PV, and shows some industrial MGs examples that have been carried out today. Section 4 addresses the discussion and results obtained from this review. Finally, Section 5 shows the conclusions, where it is said that further investigation must be developed aimed at improving the use of RE in industries, as well as future possible investigation trends.

Thus, the purpose and main contribution of this study of the state of the art is to define the state of the theoretical development within the subject, to later serve as a conceptual basis for other investigations.

## 2. Materials and Methods

To give documentary strength to this review, it was necessary in the first instance to consult more than 130 scientific publications and/or grey literature in the field of microgrids. While not absolute, it is a representative sample of the state of art of the subject under study. Once the scientific/grey literature was reviewed, the articles were divided into three main subjects: Microgrid/Microgrid Optimization, ESS, and industrial Microgrids. Qualitative and comprehensive research has been performed searching on different online databases, such as Web of Science, Science Direct, IEEE Xplore, Scopus, and Berkley Lab. Information has been extracted, analyzed, and synthesized to get the relevant ideas and conclusions. References have been introduced in a timeline. This review is based on three main phases: (1) Planning and design, (2) Management and analysis, and (3) Formalization and elaboration.

The goal of this paper is to present a review of the state of the art of industrial MGs based on RE.

## 3. Theoretical Framework

### *3.1. Definitions of Distributed Generation and Microgrid*

Ackermann et al. [49] presented a discussion of the relevant aspect of distributed generation (DG) and provide a definition that understands the DG as an electric power source connected directly to the distribution network or on the customer side of the meter.

Robert et al. [50] reported the benefits of introducing distributed energy resources (DERs) within an industrial site, detailing the factory design, its electrical system, the loads, and the micro-turbines used. Viral et al. [51] describe the concept as an electric source connected directly to the network or to the customer site and indicates that a hybrid of two or more optimization techniques would yield a more efficient and reliable optimal solution. Table 1 shows the different ratings of DG according to the authors:

**Table 1.** Ratings of distributed generation. Source: adapted from [51].

| Categories | Ratings |
|---|---|
| Micro-distributed generation | ~1 W < 5 kW |
| Small distributed generation | 5 kW < 5 MW |
| Medium distributed generation | 5 MW < 50 MW |
| Large distributed generation | 50 MW < 300 MW |

Richard E. Brown et al. [42] described some advantages and disadvantages of DG compared to Central Generation:

Advantages

- No distribution requirements.
- Reduced interruptions.
- Short lead times for procurement and installation.
- Available in modular units.

Disadvantages

- Higher energy costs.
- Less load diversity requires increased peak capacity.
- Requires redundancy for equivalent reliability.
- May require a utility connection for backup power.
- May require a utility connection for load following.

A review of the future direction of IEEE 1457 and IEEE 1457.1 standards is addressed by Basso et al. [12], providing the closer development of the documents. IEEE 1457 Standard addresses interoperability and associated interface aspects and establishes the base of the interconnection of DERs.

DERs has changed the passive distribution system to an active network, where lot of challenges are arising according to Ullah et al. [52]. Future research directions regarding the DGs installations are shown below:

- Planning and sizing.
- Grid Synchronization.
- Frequency and voltage regulation.
- Stability and protection.
- Power quality.

In the existing studies, the interconnection issues of DG are another big trend that should be investigated. Today, the use of RE are increasing constantly, and the number of MGs that use RE are increasing, so DGs plays a very important role here.

Development in power electronics, control and communication has been the key pillars for the increment of MG systems through the improvement of design and operation techniques according to Piagi et al. [38]. Several definitions of the MG concept have been described from the very early research and studies of DERs. First trials of installations of MG date back to the 1980s [53]. Chris et al. [54] define an MG as a cluster of electrical sources, storage systems, and loads that utilize as primary energy source fossil fuels or RE as PV, wind, biomass, wave, hydroelectric, and more. Microgrids are intended to be installed to reach the on-site demand generations for any application. Owen et al. [8] define an MG as a semiautonomous grouping of power-generating sources located closer to the consumption application points. Lasseter et al. [55] define the CERTS MG concept as an aggregation of loads and micro-sources operating as a single system providing both power and heat, and the required flexibility through a power electronic control system. This fact allows the CERTS MG to provide reliability and security as a single controlled unit. In [53] the concept of the MG is defined by Kueffner et al. as a discrete electricity system based on renewable and traditional energy sources and storage with energy management systems (EMS) in smart buildings. In the definition of MG, there is no universally accepted minimum or maximum size. In [26], Kaushal et al. define the concept of MG as a group of DERs and loads interconnected between them within the electrical boundaries acting as a single control unit connected to the main utility grid.

Microgrid Topologies and Configurations

There are several studies that address the different topologies, sizes, and configurations of microgrids. An MG can operate both connected and disconnected from the main grid. MGs can be classified based on the characteristics of the distribution line (AC or DC). Several authors, such as Alsaidan et al. [56], discuss that there are two main types of microgrids in terms of grid connection: grid-tied and isolated microgrids. The first one is connected through the PCC meanwhile the second one is used to supply remote areas' demand for electricity. Different MGs models are proliferating based on some parameters such as voltage, geography, consumer preferences, and economic viability. Nevertheless, based on the different components that a microgrid can have, three main different configurations exist according to Soshinskaya et al. [57]: radial, ring, or mesh.

A radial grid configuration uses a mainline to which power consumers and generation are connected, so the current goes in one direction. Ring configuration is usually used while the current flows in more than one direction. Mesh grid configuration is used when some nodes are established, getting more benefits regarding the reachability of power for the consumers, but making some more other technical aspects such as protection, control, and operation more difficult.

### *3.2. Reviews of Microgrids*

The paper presented in [58] by Feng et al. reviews through some U.S. projects, the trends in the technology development of MG systems and control methods, and establishes a reference for research from the lessons learned during the expansion of this kind of power source. Work presented in [59] by Planas et al. provides a detailed study of AC and DC MGs and the main features of the components of both. Moreover, technical, economic, and regulatory issues are discussed here. A review of issues concerning MGs is presented in [37] by Parhizi et al., getting a general view of the MG integration in power systems. A state of the art review is presented by Kumar et al. [28] with different control strategies and key integration issues of REs within MGs. Work described by Delfino [60] focuses extendedly on MGs that can be representative for DER in a district grouped on a geographical basis over America, Europe, Asia, Africa, and Oceania. Mehta et al. [61] discuss the research in MGs based on small-signal, transient, and voltage stability. Soshinskaya et al. [57] identify the main problems of MGs grouped in main categories: technical, regulatory, financial, and stakeholder-based in thirteen cases of study. Figure 1 represents some main advantages of the use of MGs, as well as future trends to be researched.

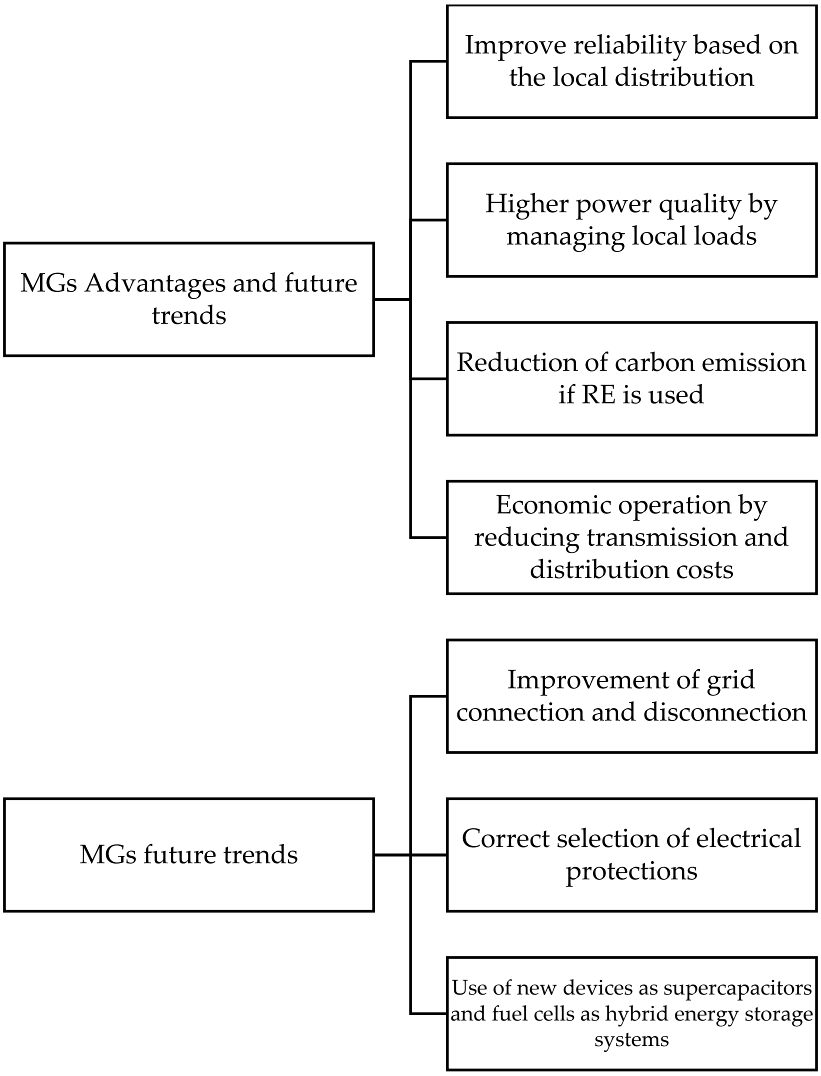


**Figure 1.** Main advantages of the use of MGs and future trends (source: own elaboration).

Sultana et al. [62] performed a review of the optimal allocation of DG regarding the power and energy loss minimization, voltage stability, and voltage profile improvement. However, the study does comment slightly on the allocation techniques in industrial environments using RE. An overview of aspects such as MG development, control and operation strategies and protection schemes are presented by Hassan et al. in [63]. Alam et al. [10] present a review of the state of the art for networked MGs. The main architecture, control, and EMS of networked MGs is pointed. The main potential benefits such as operational cost reduction and the improvement of the resiliency and the reliability of the system are discussed. Major challenges such as protection schemes, operation during emergency situations, and threats of cyber-attack are discussed and will need to be researched according to the authors. Olivares et al. in [35] presented a review of the state of the art related to the control in the MG. The authors define a three-level hierarchical structure, primary, secondary, and tertiary, and introduce main control systems for each one. Moreover, the ESS is identified as a key technology for the use of renewable sources, which introduces, at the same time, more challenges for the control systems regarding the effectiveness and reliability in MGs.

Others such as Boqtob et al. [64] reviewed the state of the art regarding the EMS for MGs. The paper discusses the integration of EMS into different MGs based on load type, optimization constraints, combined heat power, and electrical vehicles and reviews some optimization algorithms that can improve the overall EMS. A review of MGs through layer structures was presented by Carpintero-Rentería et al. in [65]. The authors classified the manuscript based on six different layers: policies and standards, business, climate conditions, infrastructure, communications, and operation and control. The latter is considered a key factor in the success of the electrical system, and it has been extendedly studied by authors based on IEEE 2030.7 Standards. Colmenar et al. [66] presented and evaluated a novel charging strategy aiming to increase penetration of RES by electric vehicles. According to the authors, in the 2050 context, electric power will be the main technology used in road transport, so the use of electric vehicles will increase the demand for electricity, and it will be needed new strategies for charging and avoiding problems in the main power grid supply.

Some other authors [28,35,38,61,67] addressed the different MGs control techniques in their research. Reliability and economical operation of the microgrid must be ensured. From a general point of view, MGs control techniques can be divided into two main groups: centralized and decentralized control techniques. Kumar et al. [28] separate the hierarchical control into three main groups: primary, secondary, and tertiary. The primary level controls power-sharing, local dynamics, voltage control, and current control. The secondary level controls power quality and grid synchronization. Finally, the tertiary level controls power flow and energy management.

### 3.3. Microgrids in the Industrial Environment

An industrial MG is a set of DERs where a common industrial process is located (manufacturing, refinery, transformation process, and desalinization) in addition to RE generation processes such as RE plants (CSP, PV, and wind) and which needs electric power to complete the industrial process. The industrial plants use large step changes in loads and sensitive loads, which could result in outages due to lack of power supply if the DERs are not properly sized and there is no adequate protection system nor an optimization and reliability program that provides the system with the necessary robustness.

A first approach to the benefits of introducing distributed resources within an industrial site can be found in the work presented by Robert et al. [50]. The work describes a fictional industry with multiple sensitive loads and analyses both steady and transient states, establishing the main micro-sources power setpoints (connected to the grid and in an islanded mode) and the load dispatch strategy. In [18], Derakhshandeh et al. propose a dynamic optimal power flow formulation for industrial MGs that includes security and factories constraints related to photovoltaic (PV) constraints based on DERs using combined heat power and PV generation systems with energy storage. The study concludes that introducing PV generation systems coupled with battery storage in industrial MGs has a positive effect on the scheduling solution and minimizes the overall cost of it. Moreover, the possibilities for the storage of electric energy to cover the power quality needs of industrial operations are also discussed by Kueck et al. [68].

The work addressed by Kaushal et al. [26] presents a framework for an AC MG combination, PV energy and wind energy as main DERs, testing an automatic generation control method for controlling the frequency and the voltage changes while loads shedding occurs. In [15], Cetinkaya et al. analyzed three aspects of a power system of a real refinery (TUPRAS-RAF/RUP) through SINCALTM software. The paper examines the decoupling from the grid and the voltage and frequency recoveries and continues with a study of the load shedding stages depending on the number of generators simulated. In [29] Lainfiesta et al. compare two simulated industrial MGs with the aim of studying the $CO_2$ emissions and total annual cost for both connected and non-connected facilities. The results show that the cost could rise while reducing the $CO_2$ emissions.

According to Zhe et al. [48], natural gas power generation and internal combustion engine technology are mostly used as DG main technologies, and wind energy and PV are widely used. Thangam et al. [69] reviewed and analyzed the diverse techniques associated with PV-based MGs (controllers, PV capacity, and inverter topologies) and focused on PV-based MG systems for better regulation of the maximum power point tracking (MPPT).

In [23], Heo et al. described an MG design using PV and ESS in both grid-connected and islanded mode operation. AC and DC connections in the MG were simulated for an active load and ESS, considering the phase synchronization and the power conditioning system that regulates the overall system. Rosales-Asensio et al. [70] propose a configuration for a desalination plant aimed at reducing the cost of water. The configuration is based on wind energy and battery systems. Colmenar-Santos et al. [71] review the possible repowering of the Spanish wind energy systems concerning their economical and profitable aspects. It shows a comparison study between the opportunities of installing new wind farms against the repowering of old ones maintaining the same energy conditions. Results obtained show the feasibility of repowering wind farms from a profitability point of view in Spain.

Choudhary et al. presented a review of the main solar PV trends and growth opportunities in [72]. The authors review goes from the background of solar PV, through some methods for reaching environmental sustainability, to some related future sustainable solutions. In [13], Bracco et al. presented a performance analysis of a PV plant connected to a low voltage MG. The authors obtained real data key parameters (net electricity production, solar radiation on the PV modules, final PV system yield, reference yield, performance ratio, and overall PV system global efficiency) from the plant for one year and later compared it with the performance obtained from a new one. Javid et al. [73] proposed a methodology for optimal sizing of a hybrid system for an industrial load located in Pakistan. They studied five simulated cases using HOMER software to achieve the best result regarding reliability and sustainability, analyzing whether such a hybrid option is a cost-effective solution or not. Gust et al. [74] established both proactive and reactive strategies under real-world conditions for an MG located in California. Using DER-CAM software, the authors conclude that proactive strategies perform better regarding the total costs, while reactive strategies perform better regarding one cost component. Blake et al. [75] introduced a model of an industrial MG and studied the costs and emissions associated with the use of different DERs (wind, combined heat power, and ESS) using, like many others, MATLAB software. The results presented confirm the reduction of costs and carbon emissions while using RE sources in the industrial environment. In [76] Horhoianu et al. presented an MG simulation of the oil industry using HOMER software. The paper shows an MG formed by a RE system (PV and wind) with an ESS and a cogeneration energy system. Results show that several factors and parameters need to be considered due to the number of design options available. In the work presented by Naderi et al. [77], industrial MG research is presented. The authors made a five scenarios simulation using HOMER software. CNC machines were considered as sensitive loads, and different components were used to set up the distribution resources generation such as fuel cell, electrolyzer, PV, wind turbines, a battery storage system (BESS), and a diesel power generator.

In Spain, some MGs facilities have been developed for several years since the government eased the administrative processing and fees related to implementing this kind of project. As a real example, it has been developing in La Graciosa Island (Canary Islands, Spain) an MG with BEES and ultracapacitors aimed at optimizing the distribution grid based on the implication of different stakeholders such as distribution companies, marketers, and final consumers, as well as to reduce investment and operational costs. In relation to the aforementioned, Sanz et al. in [78] analyzed the European policies and incentives and described the constraints to which Spain was subject. Colmenar et al. [79] discuss the implementation of installing a theoretical multi-effect distillation plant of 9000 $m^3$. It opens a new path for distillation plants regarding the use of MGs based on RE to feed the power equipment that can be used according to the configuration (use of EMS, Double Effect Absorption, Heat Pump technique, etc.) Polleux et al. [80] provide a review of the scientific literature from fossil engine thermodynamics to control system theory applied to industrial systems as new challenges of solar PV integration in industrial installations. Table 2 shows the category of industrial MGs, as well as the advantages, disadvantages, and applied techniques. Applied techniques can be applied for every kind of industrial MGs.

**Table 2.** Industrial microgrids types, advantages, disadvantages, and applied techniques (source: own elaboration).

| Industrial MG | Advantages | Disadvantages | Applied Techniques |
|---|---|---|---|
| Oil and Gas | Reduction of $CO_2$ emissions<br>Possibility of use of Hybrid Energy Storage Systems | Use of sensitive loads in instrumentation<br>Use of big loads<br>High costs | Improvement of reliability<br>Voltage and frequency control<br>Reduction of costs<br>HVDC protections techniques<br>Control optimization<br>Control of HESS<br>MGs size and location methods |
| Mining | MG can be fully islanded<br>Possibility of use of Hybrid Energy Storage Systems (HESS) | Use of big sensitive loads<br>Location of MG | |
| Chemical | Reduction of $CO_2$ emissions<br>Possibility of use of Hybrid Energy Storage Systems | Use of sensitive loads in instrumentation<br>Use of big loads<br>High costs | |
| Manufacturing | MG can be fully islanded<br>Possibility of use of Hybrid Energy Storage Systems (HESS) | Use of sensitive loads<br>Discontinuity in power consumption if grid-connected<br>High costs | |
| Energy Production | No use of big loads<br>Easy connection and disconnection of the main grid | Use of DC voltage for distribution<br>Use of sensitive loads | |

### *3.4. Microgrid Optimization*

Optimization in MGs has been already studied by many authors in different contexts, where mathematical models and technical constraints have a great impact on the results.

Mondal et al. [32] described a method for preventing the stalling phenomenon under large fluctuating load conditions in reciprocating an industry-based engine generator set. The work presents a smart load-shedding scheme using two natural gas gen-sets that manages the MG without hampering the overall islanded grid. Li et al. [81] present a dynamic energy scheduling strategy for industrial MGs using the RegPSO algorithm addressing an economic operation model for an MG with flexible loads using RE sources. Some models for sensitive loads are pointed at the reduction output fluctuation of the intermittent renewable generation and the total energy cost. The results concluded that it is possible to minimize the fuel cost and grid power purchasing expense and enhance the utilization of RE within the MG. Thangam et al. [69] present a brief analysis of PV based MG systems to get a better regulation of the maximum MPPT. In [34] various cases of study are presented by Nasr et al. integrating PV systems with spinning reserve constraints. The paper results demonstrate a significant fuel reduction in the new off-grid system. In [14], a simulation platform developed in MATLAB/Simulink environment is shown by Brissette et al. The aim of the simulation is to capture the behavior of an MG on different time scales. The development of a universal compensator in a radial type of MG with unbalanced DGs and loads is presented by Blake et al. [75] to improve the system operation performance.

An EMS was implemented in the Atacama Desert by Palma-Behnke et al. [36] for an MG composed of PV panels, wind turbines, diesel generators, and an ESS. Two days ahead, forecast and prediction for electric consumption was used based on a neural network model. The results of the EMS showed the economic benefit of the proposed unit commitment with a rolling horizon (UC-RH) in comparison with a standard unit commitment (UC). In [47], Wang et al. developed an MG control system using batteries to support a critical facility. In [11], Alfieri et al. performed research of the influence of the control of the reactive power exposing two different control strategies (Active Power Control and Active and Reactive Power Control) and demonstrating, through a simulation carried out in MATLAB/Simulink, the importance of the reactive power control at the point of common coupling (PCC) in an AC/DC hybrid MG. In [20], Fu et al. analyzed the performance and control of an MG in both islanded and grid-connected mode, as well as the location of an ESS based on a 25 kV IEEE 34 bus system. A review of distributed renewable generators (DRG) techniques to get the optimal location and sizing in power system environments is exposed in [82] by Tan et al. It studies DRG placement methods, summarized in Figure 2, aimed at reducing the power losses, improving voltage profiles, and finding the optimal size and location.

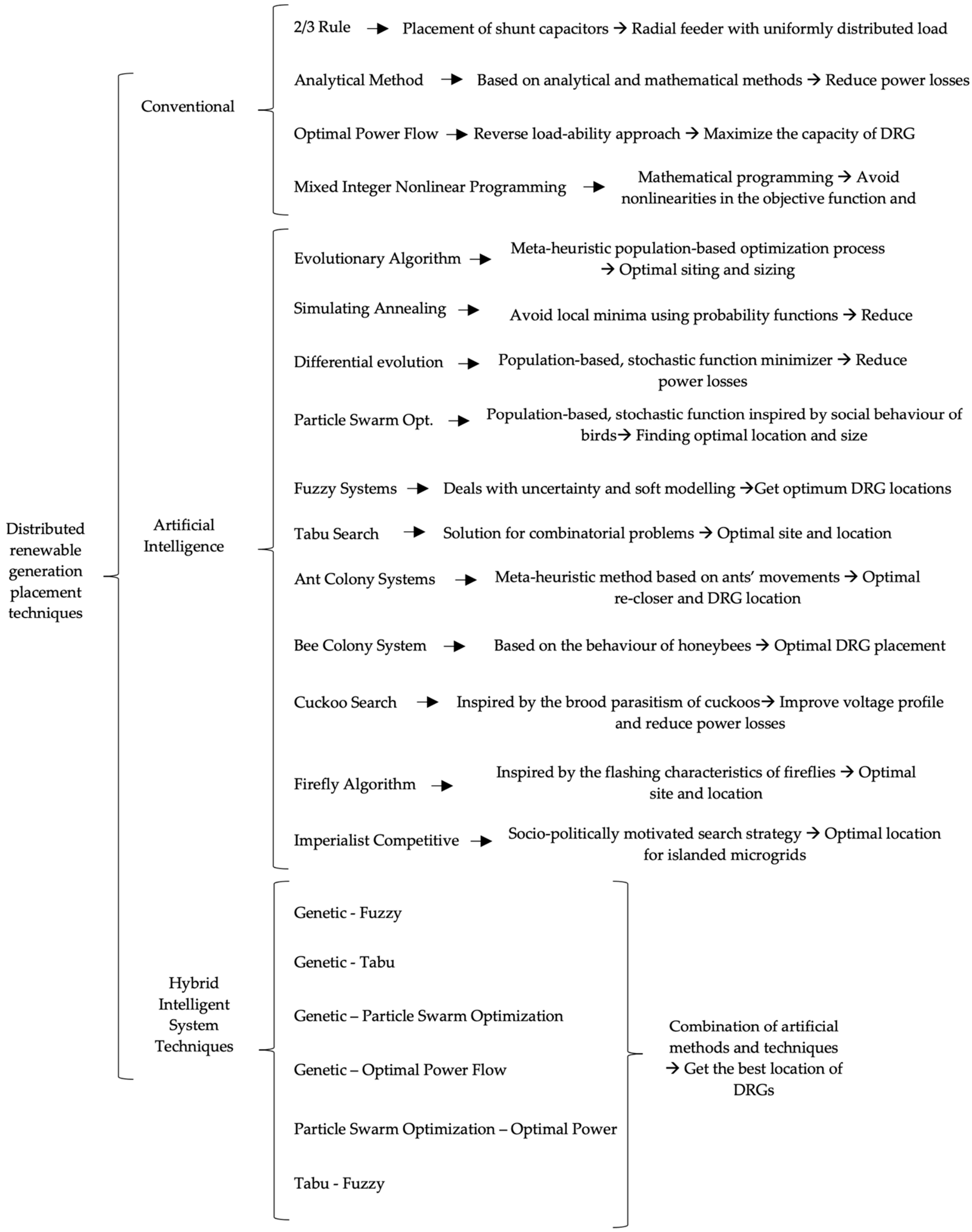


**Figure 2.** Optimization placement techniques for DRG. Adapted from [82].

Garde et al. [83] analyze an MG during islanded mode operation based on the master–slave configuration in the ATENEA MG (CENER-National Renewable Energy Centre of Spain). Some tests have been performed using both diesel generator and power electronics acting as the master of the installation in an islanded mode in load and no-load scenarios. Study results show a better performance in the islanded MG using the diesel generator as the master regarding the V-f control and total harmonic distortion (THD). In [84], Jeong et al. defined a power management algorithm for islanded DC MG operation to improve the reliability and the dynamic response using the DC bus voltage. The algorithm was simulated on a DC MG testbed for various scenarios. The use of adaptative dispatching energy storage and a standby diesel generator through a smart integrated centralized controller with adaptative control strategy is presented in [85] by Karimi et al. as a solution for sustaining an islanded MG. However, the authors do not implement the inverter DC to AC system while simulating the centralized controller. Wang et al. [86] proposed an energy management strategy (EMS) for networked MGs with high renewable penetration aimed at minimizing the costs related to the process. A review of DC protection strategies such as current protection systems, protection devices, grounding options, and protection principles and schemes is presented in [87] by Zhang et al., pointing that the lack of effective protection DC systems restricts the development and use of DC MGs. Many issues regarding the lack of new protection devices are present nowadays, so the coordinated strategy of control and protection could be more effective in the meantime.

De la Hoz et al. [88] developed a model to optimize the EMS on an LV MG, taking into account the Spanish self-consumption regulatory scheme. Results show that the elements belonging to the generation power line are forced to increase their participation in the energy supply while using the model based on the Spanish regulatory scheme. Parol et al. [89] presented two different strategies for power energy management for LV MG, controlling the active power generated in micro-sources with energy storage units and controlling the power generated in micro-sources with active power received by controllable loads. Moreover, a study of the optimization of the sizing of technical and economic battery energy storage sizing was prepared. The paper deals with the solutions of the optimization problem from a mathematical and algorithmic point of view. Chandra et al. [90] review different protection techniques, explaining protection systems and schemes for DC MGs. The article also addresses the DC MG design guidelines and the protection strategies based on the main protection parameters.

On the other hand, Patnaik et al. [91] presented a detailed analysis regarding the issues, challenges, and protective solutions to AC MGs protection. Due to the bi-directional electrical flow, control and protection of MGs are more challenging as compared to the conventional ones. Some issues have been discussed in the article, related to the existing MG protection and their traditional protective solution. Moreover, Chandra et al. [92] reviewed and analyzed some AC protection techniques, explaining the pros and cons of every technique: overcurrent protection, differential protection, under-voltage protection, distance protection, and communication systems.

Ramabhotla et al. [39] carried out a review of the reliability of MGs. The authors discussed the simulation techniques regarding the solutions and challenges for the MGs, controls strategies, and improvement methods. Tooryan et al. [93] used Particle Swarm Optimization to find the optimal size of DERs in a residential MG. The EMS considers various components such as PV, wind turbine, BESS, thermal ESS, fuel cells, and boilers as well as the uncertainties of using PV and wind turbines and the net present cost of the MG. The conclusions refer to the effectiveness of the proposed optimal design and energy management in a hybrid MG system while decreasing the cost of MG and $CO_2$ emissions. V. Arun Kumar et al. [28] proposed a model for the optimization of a hybrid MG with different loads using mixed-integer linear programming and attempted to get the optimal size of implicated DERs (PV, wind, biomass, diesel generator, and BESS) located in India. The authors tested the model in real situations and got a reduced levelized cost of energy and $CO_2$ emissions.

### 3.5. Energy Storage Systems

Solar PV and wind energy systems have introduced many technical issues from their early uses, such as power quality, reliability, safety, grid operation, and economics, among others [20]. Solar PV and wind energies are very uncertain due to the climatic variations that have an important impact on the power generation, so DGs cannot always provide satisfactory support to the power system. Poullikkas et al. [3] made a technical comparison of different kinds of batteries: lead-acid batteries, lithium-ion batteries, nickel-cadmium batteries, sodium-sulfur batteries, and flow batteries (vanadium redox and zinc-bromine batteries). Table 3 present the main battery technologies used in large scale applications, as well as the advantages and disadvantages of each technology. As indicated by Kueck et al. [68], to meet the electric power needs required from industrial operations, there are several possibilities for implementing ESS. The intrinsic kind of sources of RE provided by PV and wind energy systems produce a volatile and intermittent way of output power, and thus, these negative features impact directly the industrial consumer if non-EES are properly sized and installed according to the technical specifications. In [33], Mondal et al. analyzed the performance of an industrial MG to meet the ISO 8528-5 standard performance. Through an EES, it has avoided the frequency variations that were produced by two natural gas gen-sets, thus complying with the specifications prescribed in the standard. Hina Fathima et al. [94] make a study of the benefits of combining PV-wind hybrid in MGs, adding some simulations studies to evaluate the impact of PV and wind hybrid systems in case of transient disturbance scenario.

**Table 3.** Main battery technologies used in large-scale applications. Adapted from [3].

| Energy Storage System | Advantages | Disadvantages |
|---|---|---|
| Lead-acid batteries | Low power density and capital cost | Limited life cycle when deeply discharged |
| Lithium-ion batteries | High power and energy densities, high efficiency | High production cost, requires special charging circuit |
| Sodium–sulfur batteries | High power and energy densities, high efficiency | Production cost, safety concerns (addressed in design) |
| Flow batteries | High energy density, independent power and energy ratings | Low capacity |

Khadse et al. [27] proposed a design showing an MG based on both DC and AC buses with batteries as storage. Furthermore, a PV panel, battery, inverter, and DC load are connected to a DC bus. After physical implementation, results show correct behavior of the system using lead-acid batteries. A review of the Distributed Energy Storage (DES) integrating and sizing methods is presented in [56] by Alsaidan et al. The authors present a classification of the methods based on cost-basis and proposed a new generic sizing method based on the DES operation lifetime. El-Bidairi et al. [2] proposed a system frequency control based on the sizing of a battery energy storage system (BESS). It demonstrated that selecting the optimum BESS size reduces high-frequency power fluctuations. The study was based on two cases scenarios (not using BESS and using BESS). In [95], Bektas et al. revised more than 100 relevant articles related to the optimal energy management problems for industrial MGs. The authors carried out an intensive analysis of the papers and clustered them using self-organizing maps.

### 3.6. Hybrid Storage Systems: Supercapacitors and Fuel Cells

Hybrid Storage Systems (HESSs) present a big improvement regarding the technical and economic points of view. On one hand, a combination of batteries and supercapacitors showed better performance compared to other hybrid solutions. Authors such as M. Porru et al. [96] use HESSs based on supercapacitors to manage the frequency of the microgrid. Supercapacitors are characterized by much higher power density and better performance and present fast charge-discharge rates, longer life cycle, high power, and high energy density according to Olabi et al. [97]. The use of supercapacitors storage systems can be used to properly operate MGs in grid-connected and islanded modes of operation. On the other hand, fuel cells are perfect candidates for inclusion in HESSs due to their big potential for emission-free electricity generation. Hydrogen is a clean, non-toxic, and highly abundant renewable energy storage chemical, and therefore, a hydrogen fuel cell can provide peak-hour electricity when needed [98].

## 4. Discussion and Main Findings

Several studies of MGs have been released since the last decade. The utilization of electrical MGs based on renewable energies is becoming established in a general way. New challenges appear with this use. Many research works base their study on optimization both from a technical and an economic point of view. However, through this study, an emphasis is placed on possible future paths of research on MGs in industrial environments. Increasingly, the global trend of the stakeholders points to the use of renewable energies, so the implementation of MGs in industrial environments will become common in the medium and long term.

Results show that there are many research studies aimed at energy optimization but not too many focused on optimizing power supply and load demand simultaneously. More than 65% of the reviewed literature focuses on the optimization of several kinds of MGs, and not many studies focus on industrial MG and ESSs. MG reliability, feasibility, electrical protections, and optimization are the main working paths where researchers from all over the world are focusing their efforts. Industrial MGs are facilities where sensitive loads usually exist, and load shedding can be continuously present if the installed MG is not properly optimized and sized. Production cuts may appear if the MG is made up of isolated DG. To avoid these issues, the use of ESSs is increasing continuously. Figure 3 shows a summary of the trends and lines of study that could be addressed in future research articles. As shown in Figure 4, there is a clear lack of research regarding industrial MGs since the development of this kind of installation. The figure shows the number of articles related to the discipline of study based on a timeline.

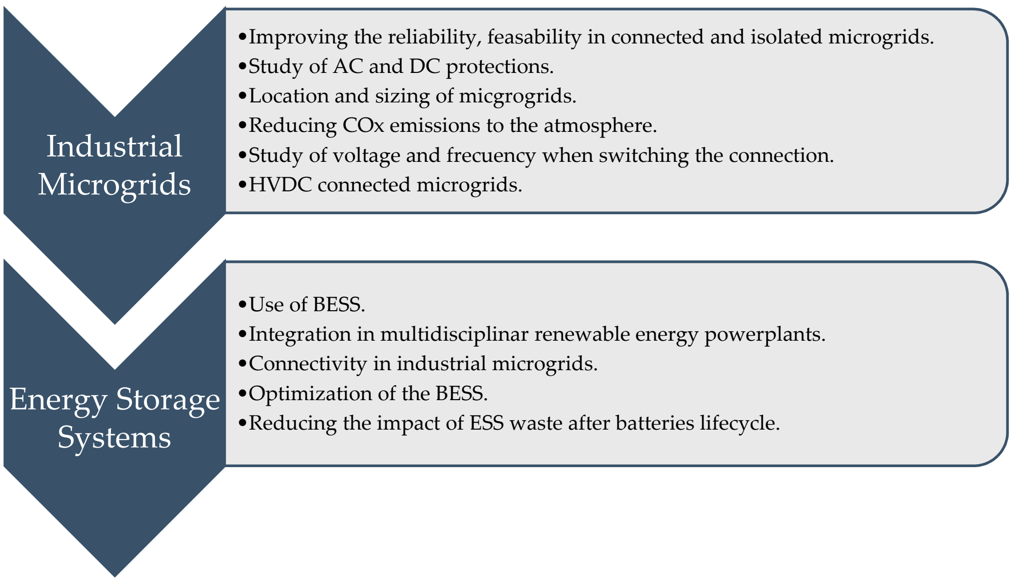


**Figure 3.** Possible trends and future research path regarding industrial MGs (source: own elaboration).

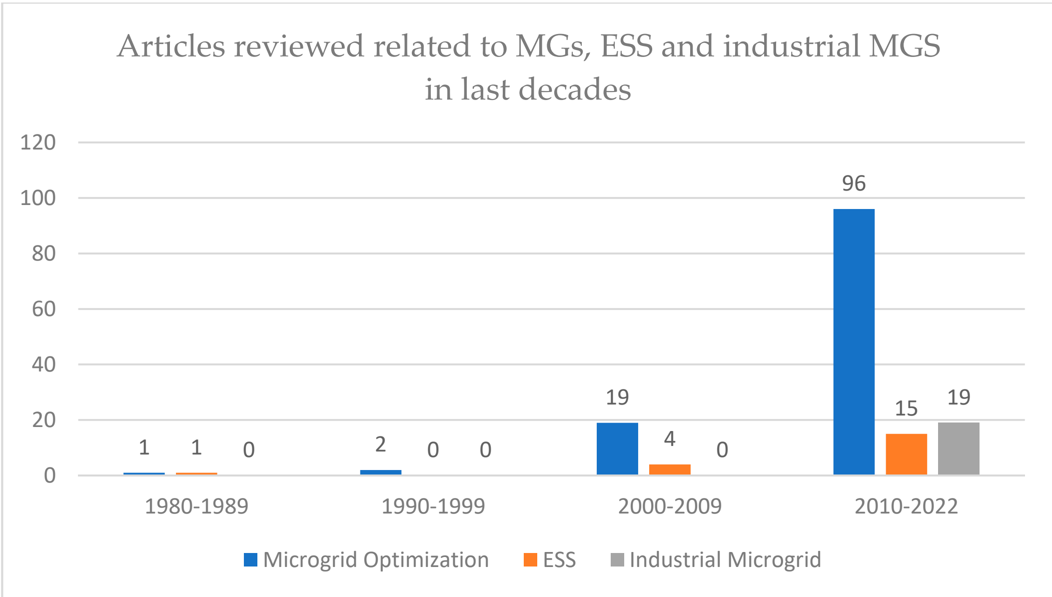


**Figure 4.** Articles reviewed and divided into MGs/MGs Optimization, ESS and Industrial MGs (source: own elaboration).

PV facilities in Spain have increased considerably from the year 2019 to the present. This fact involves the expected change for the self-consumption scheme and a high impact on the PV development. There are not so many studies regarding the research of the MGs using ESSs in industries although some important electrical equipment manufacturing companies arise today.

## 5. Conclusions

Renewable energies are increasing due to the drawbacks that fossil fuels present. Not so many studies address MG implementation in industrial environments. This paper provides a timely and comprehensive review of the state-of-the-art of industrial MGs based on renewable energies. There are many definitions of the term "microgrid". Today, this type of electrical installation is being implemented in the world since it presents numerous advantages such as the energy contribution it provides in isolated environments where the main network does not reach. In the past few years, governments have become increasingly aware that they must be more environmentally friendly and provide facilities at a global level to implement more electrical MGs based on RE. There are not many research studies regarding the use and application of electrical MGs in industrial environments, and many challenges remain to be investigated in relation to optimization systems, protections, and installation methods in industrial environments. Therefore, new research paths can be studied in relation to the above. A large part of the studies carried out on MGs does not consider the different sensitive loads that are present in industrial environments, so research could be aimed at this point. The use of BESS and HESS is not widespread yet in industrial environments, due in a certain way to the lack of awareness on the part of investors of the possibility of using this type of technology; therefore, a transition period is recommended to achieve positive results.

Some existing challenges for future research on industrial MGs are listed in Table 4.

**Table 4.** Research gaps and future trends of industrial MGs (source: own elaboration).

| Research Gaps and Future Trends | Recommendations |
|---|---|
| Optimization of control methods | Control methods, instrumentation, and computational techniques can be further improved for industrial MGs |
| Use of HVDC for energy distribution | HVDC recently became a common electrical voltage used for distribution in RE. New research can be carried out on HVDC regarding industrial MGs |
| Optimization of sizing and location of MGs | Sizing and location of MGs has been extensively studied, but not regarding industries. There is a lack of research regarding this topic |
| Control techniques for use of HESS | Control techniques should be researched in extension as new storage technologies arise. |
| Analysis of standards, codes, and regulations related to industrial MGs using RE | There is not a legal framework regarding industrial MGs, topologies, and configuration in Spain |

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