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Research

Energy Management Systems for Microgrids: Evolution and Challenges within the Framework of the Energy Transition

Sistemas de gestión de energía para microrredes: evolución y desafíos en el marco de la transición energética

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Abstract

Context: Microgrids have been gaining space and credibility in terms of research and real applications. Tech- nological maturity and new regulations have allowed these types of systems to position themselves as a real alternative to increase the coverage of the energy service and improve its quality. One of the biggest challenges of microgrids is the management of resources and their synchronization with conventional grids. In order to overcome the inconvenience of synchronizing and managing the components of a microgrid, research on management systems has been conducted, which usually consist of a set of modules and control strategies that manage the available resources. However, these studies have not reached unanimity on the best method to perform these tasks, which is why it is necessary to perform a systematic collection of information and clearly define the state of research in energy systems management for this type of network.
Method: Based on the above, a systematic mapping was carried out in this article, wherein a significant number of papers that have contributed to this area were compiled. Taxonomies were generated based on the nature of the variables collected. These variables correspond to the data or information that enters and/or leaves the microgrid management system, such as meteorological variables, power, priority loads, intelligent loads, economic, operating states, and binary outputs.
Conclusions: It was observed that, despite the advances in studying different techniques and strategies microgird control and management, other factors that may affect performance have not been covered in a relevant way, such as the nature of variables and microgrid topology, among others.

Keywords: microgrid, management system, input and output variables

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Resumen

Contexto: Las microrredes eléctricas han venido ganando espacio y credibilidad a nivel de investigación y aplicaciones reales. La madurez tecnológica y las nuevas regulaciones han permitido que este tipo de sistemas se posicionen como una alternativa real para aumentar la cobertura del servicio de energía y mejorar su calidad. Uno de los mayores retos de las microrredes es la gestión de los recursos y su sincronización con la red convencional. Con el fin de superar el inconveniente de sincronizar y gestionar los componentes de la microrred, se ha investigado sobre sistemas de gestión, los cuales normalmente consisten en un conjunto de módulos y estrategias de control que administran los recursos disponibles. Sin embargo, estas investigaciones no han llegado a una unanimidad sobre el mejor método para realizar estas tareas, por lo cual se hace necesario realizar una recopilación sistemática de información y definir claramente el estado de la investigación en gestión de sistemas de energía para este tipo de redes.
Método: Con base en lo anterior, en este artículo se realizó un mapeo sistemático, donde se recopiló un importante número de artículos que han aportado a este campo. Se generaron taxonomías basadas en la naturaleza de las variables que se recopilaron. Dichas variables corresponden a los datos o información que entran y/o salen del sistema de gestión de la microrred, tales como variables meteorológicas, potencia, cargas prioritarias, cargas inteligentes, económicas, estados de operación y salidas binarias.
Conclusiones: Se observa que, a pesar de los avances en el estudio de las diferentes técnicas y estrategias de control y gestión de microrredes, no se han cubierto de forma relevante otros factores que pueden afectar al rendimiento, como la naturaleza de las variables y la topología de la microrred, entre otros.

Palabras clave: microrred, sistema de gestión, variables de entrada y salida

Table of contents

1. Introduction

Since the emergence of microgrids, the incidence of renewable energies in the energy landscape has increased (1). A microgrid consists of the interconnection of loads of different nature, communication systems, metering, control, and distributed energy sources. This system can operate in standalone mode and connect with other microgrids or the main power grid (1, 2). A microgrid has the following sections: a physical plant where the distributed energy components are located (generation and storage elements, load groups, flexible loads, smart loads, and protection and connection elements); a control section, which governs the components of the physical plant and may be centralized (the management system controls the microgrid as a single entity) or decentralized (the control of each component is independent); and a management section, where the flow of energy depends on data from inside and outside the microgrid, according to specific objectives (3) (Fig. 1). Microgrids have become more relevant due to changes in regulatory aspects (4) and the cost reduction of different components (5). These characteristics have also led to increased research aimed at solving various problems associated with these systems (6), particularly focusing on the development of a good energy management system (EMS) (7).

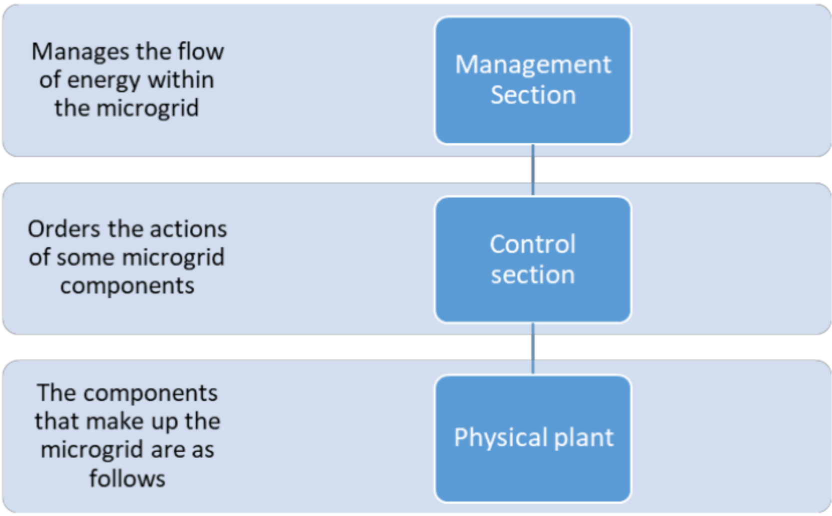


Figure 1. Microgrid sections

The first publications on microgrids date back to the early 2000s (8), which could be counted by the dozen. Nowadays, publications amount to approximately 1.500 articles per year (9). A wide variety of factors affect microgrids, such as generation, energy demand, storage status, and the cost of energy, without omitting any regulations that apply. These factors must be synchronized and managed in order to ensure the most efficient operation (10, 11). To this effect, a microgrid must have a suitable local generation system that allows it to operate in any scenario (desired and undesired) (12).

Different approaches have studied the problems associated with energy resource management (13), (14). A variety of research works focus on microgrid control methods and configurations (15), management system functionalities (16), architectures and the components to be controlled (17), and input and output variables. Different objectives and factors influence microgrid energy flow (18). However, these works have not reached unanimity on these aspects. Therefore, a systematic compilation of these works is necessary, in addition to a clear definition of the state of research on EMS for this type of grid.

This paper presents a descriptive review of the factors involved in the management system of a microgrid, such as input and output variables, topology configurations, and the control method and strategy. This review seeks to be a reference tool that will be available for all those interested in working on microgrid energy management to find a compendium of the main components in this type of system.

The structure of this paper is as follows: Section 2 presents the concept of a microgrid management system; Section 3 explains the variables involved in a microgrid management system; Section 4 presents them; and Section 5 provides some conclusions based on the collected information.

2. Microgrid management systems

In IEC 61970, the International Electrotechnical Commission defines a management system in electrical environments as ”a computer program comprising a software platform that provides basic support services and a set of applications providing the functionality necessary for the efficient operation of electrical generation and transmission facilities to ensure adequate security of power supply at minimum cost" (19). A microgrid management system generally consists of modules such as energy resource distribution and load forecasting systems, human-machine interfaces, and supervisory control and data acquisition (SCADA) systems, which ensure the efficient implementation of decision-making strategies by sending orders to generation, storage, and load unit components (20). The management system performs various functions, such as monitoring, analyzing, and forecasting power generation from distributed energy resources, load consumption, energy market prices, auxiliary markets, and meteorological factors. These functions help the management system improve the microgrid’s performance while compensating for its limitations (21).

Management systems implement one of two control strategies: centralized and decentralized. In the centralized one, a central controller accumulates information from the energy resources distribution and load forecasting modules, such as meteorological and energy data and user consumption patterns, among others. These data enter the SCADA module, which determines the energy programming of the microgrid and sends orders to the local controller, which is in charge of executing them in the different components of the microgrid (15). In contrast, in the decentralized control strategy, the central microgrid controller sends and receives all information from the local controllers of the microgrid components in real time. Each local controller proposes a current and future order to the central controller of the microgrid, and the central controller determines the most beneficial scheduling and delivers it to the local controllers. The latter may disagree with the current operation and may continue negotiating until global and local objectives are achieved (22).

With the integration of renewable energy resources, storage systems, electric vehicles, and demand response, the objectives of microgrid management systems have diversified, *e.g.*, scheduling distributed energy resources and loads, minimizing system losses and outages, controlling the intermittency and volatility of renewable energy resources, and achieving economical, sustainable, and reliable operation for the microgrid (16).

3. Variables involved in a microgrid management system

Unlike traditional power systems, in a microgrid, it is possible to evaluate multiple variables thanks to the installation of smart meters and a better knowledge of the system's operation. These variables can be inputs or outputs of the management system.

3.1. Management system inputs

Different works focused on implementing EMS (23–26) show the diverse use of input variables and different alternatives in decision-making.

The input variables can be divided into three categories:

- External variables
- Internal variables
- Economic variables

External variables

The external inputs of the microgrid are related to the factors that influence energy generation and are usually of a meteorological nature. They change with respect to the type of renewable energy used.

For photovoltaic energy, the relevant variables are

- Solar irradiance
- Environment temperature
- Effective hours of sunlight

For wind energy, there is

- Wind speed
- Air density
- Rotor area or surface area in contact with the air

The external variables can be subdivided into two new categories:

- Meteorological
- Generation system power

Meteorological

In (28–32), the authors use solar irradiance, temperature, and wind speed as external variables of a meteorological nature. Uncertainty prediction methods establish the variable values to obtain an approximation of the microgrid's energy and ability to supply the demand of its loads. Although these references share these common aspects, they implement different architectures, generation systems, strategies, and control methods (16). Although there is a difference in generation sources, the treatment of information and the obtention methods are similar. A general review of this subject is presented in Table I.

Table I. External meteorological variables

Ref.	Year	Management techniques	External variables	Microgrid architecture	Control strategy	Microgrid generation
(27)	2016	Integer and mixed linear programming	Wind speed, solar irradiance, temperature	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generators, grid connection
(28)	2016	Mixed linear programming	Solar irradiance, hydrogen flux, temperature	Grid-connected mode	Centralized	Fuel cells, photovoltaics, grid connection
(29)	2016	Mixed linear programming	Solar irradiation, water flow, temperature	Grid-connected mode	Centralized	Photovoltaics, geothermal, thermal energy storage, grid connection
(30)	2014	Mixed linear programming	Solar irradiance, wind speed	Islanded mode	Centralized	Photovoltaic, wind power
(31)	2013	Dynamic programming	Wind speed, temperature	Grid-connected mode	Centralized	Wind power, grid connection
(32)	2016	Genetic algorithm	Solar irradiance, wind speed, photovoltaic and wind power forecasting	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generator, grid connection
(33)	2015	Swarm optimization	Solar irradiance, wind speed, photovoltaic and wind energy prediction	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(34)	2016	Ant colony optimization	Solar irradiation, wind speed, photovoltaic and wind power forecasting	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(35)	2014	Gravitational search algorithm	Solar irradiation, wind speed	Islanded mode	Centralized	Photovoltaic, wind power, micro gas turbine
(36)	2017	Fuzzy logic	Wind speed, solar irradiation, temperature, photovoltaic and wind energy forecasting	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(37)	2011	Fuzzy logic	Temperature, solar irradiation, wind speed, photovoltaic, wind energy output power	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, grid connection
(38)	2016	Multi-agent system	Wind speed, solar irradiance, temperature, etc.	Islanded mode	Decentralized	Photovoltaic, wind power
(39)	2017	Multi-agent system	Solar irradiance, temperature	Grid-connected mode	Decentralized	Fuel cells, photovoltaic, wind power, grid connection

The most relevant meteorological variables are solar irradiance, temperature, and wind speed. Fig. 2 shows the use percentage of these variables. Irradiance is the most frequently mentioned due to the technological advances for measuring it and the availability of official information in some countries. Methods based on artificial intelligence have led the field by predicting behavior and due to their ability to use large volumes of data to estimate the generation potential.

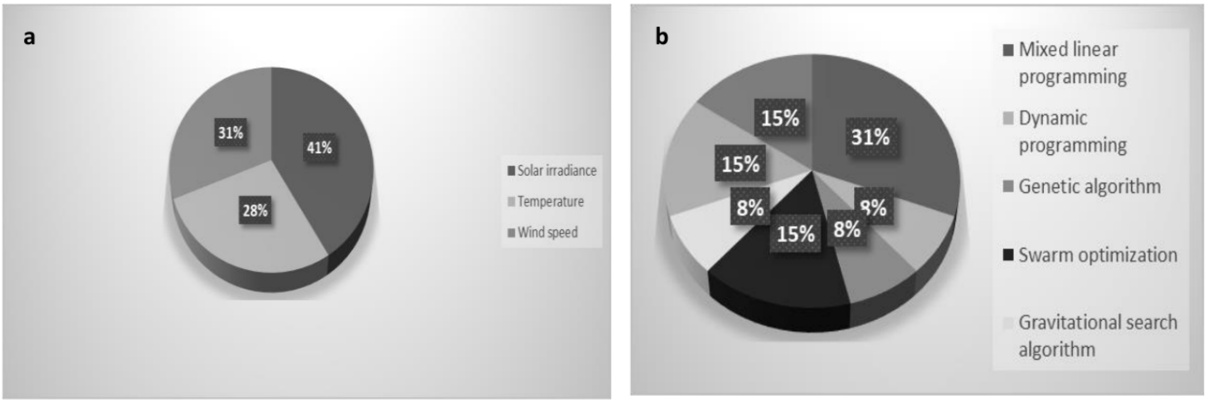


Figure 2. a) Relevant meteorological variables, b) management techniques relevant to meteorological variables

Generation system power

In several works (18,40–46), the variables used by the management system involve the output power of the generation systems in order to determine the maximum power that can be supplied via historic data or by directly measuring the output power. Hence, they only consider the result of the microgrid's energy generation (Table **II**).

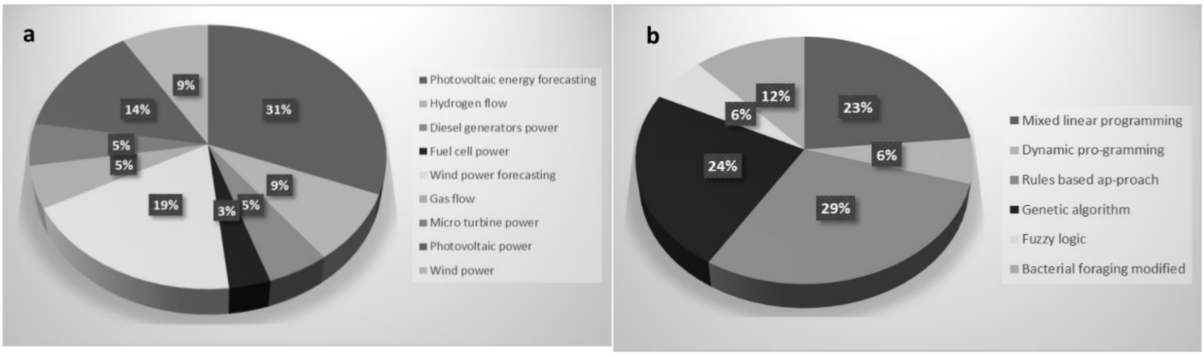


Figure 3. a) Relevant power generation system variables, b) relevant management techniques regarding the power variables of generation systems

Internal variables

The information handled by the internal variables is electrical. Within this category the following groups can be mentioned:

- The state of charge and capacity of the storage system
- The state of charge of an electric vehicle

Table II. External variables associated with generation system power

Ref.	Year	Management techniques	External variables	Microgrid architecture	Control strategy	Microgrid generation
(40)	2014	Mixed linear programming	Maximum solar power available, maximum wind power available	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(42)	2017	Mixed linear programming	Photovoltaic power, diesel generator power	Islanded mode	Centralized	Photovoltaic, diesel generators
(47)	2017	Mixed linear programming	Photovoltaic power, photovoltaic energy generation	Grid-connected mode	Centralized	Photovoltaic, grid-connected
(41)	2011	Mixed non-linear programming	Photovoltaic and wind power	Grid-connected mode	Centralized	Micro gas turbines, fuel cells, wind power, photovoltaics, grid connections
(43)	2017	Dynamic programming	Photovoltaic power, diesel generators power	Islanded mode	Centralized	Diesel generators, photovoltaic
(44)	2016	Rule-based approach	Prediction of photovoltaic power, fuel cell power, hydrogen flow	Grid-connected mode	Centralized	Photovoltaic, fuel cell, grid connection
(48)	2011	Rule-based approach	Prediction of photovoltaic power, micro turbine power, gas flow	Grid-connected mode	Centralized	Photovoltaic, micro gas turbine, grid connection
(46)	2015	Rule-based approach in a load-bearing state	Prediction of photovoltaic and wind power, micro turbine power, gas flow	Grid-connected mode	Centralized	Photovoltaic, wind power, micro turbine gas, grid connection
(18)	2015	Rule-based approach in a load-bearing state	Photovoltaic and wind power forecasting	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(49)	2013	Rule-based approach	Photovoltaic power	Grid-connected mode	Centralized	Photovoltaic, grid connection
(23)	2016	Genetic algorithm	Prediction of photovoltaic and wind power generation	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, micro gas turbine, grid connection
(26)	2016	Genetic algorithm	Load demand forecasting, photovoltaic generation forecasting	Islanded mode	Centralized	Photovoltaic, diesel generators
(50)	2017	Genetic algorithms	Photovoltaic and wind power	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(20)	2011	Coded genetic array algorithm	Photovoltaic energy prediction	Grid-connected mode	Centralized	Photovoltaic, grid connection
(51)	2016	Differential evolution	Photovoltaic and wind power forecasting	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(52)	2012	A self-adaptive gravitational search algorithm	Photovoltaic and wind power	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(53)	2013	Bacterial foraging modified	Photovoltaic and wind power forecasting, fuel cost, hydrogen flow	Grid-connected mode	Centralized	Photovoltaic, wind, fuel cells, grid connection
(54)	2014	Bacterial foraging modified	Wind power forecasting, gas flow, installed power of gas microturbines	Grid-connected mode	Centralized	Wind, gas microturbines, grid connection
(55)	2012	Fuzzy logic	Prediction of photovoltaic and wind power generation, hydrogen flow	Grid-connected mode	Centralized	Photovoltaic, wind, fuel cells, grid connection

- The power output of the generation or prediction
- The frequency of the generated power
- Load demand, smart loads, and flexible loads

There are two subcategories:

- Priority loads
- Controllable loads

Priority loads

Within this category, (27,28,42,43,48), and (56) control variables that are inherent to the mi- crogrid. There are loads with a degree of priority, as the network is operated via a management system with a hierarchy of consumption. This system prioritizes the supply of loads with a higher value regard- ing decision-making (Table **III**).

The most relevant variables used in this category are shown in Fig. **4**.

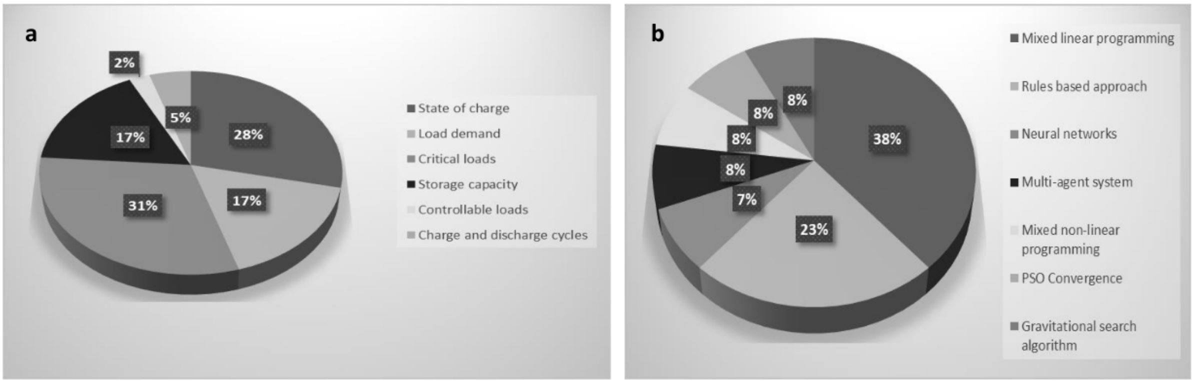


Figure 4. a) Relevant variables of priority loads, b) relevant management techniques for priority load variables

Controllable loads

In (10, 48, 50–52), the implementation of controllable or intelligent loads that help to prevent the network from overloading or destabilizing also facilitates communication with the management system. This configuration allows the EMS to adjust the power supplied or the actions to be taken from a predetermined range of parameters. Thus, the loads can operate partially, preserving their primary functions (Table **IV**).

Economic variables

The economic variables of the microgrid are mainly related to its operation and maintenance costs, *e.g.*,

- The cost of operation (maintenance and start-up)
- Energy purchase price
- Energy sale price

This financial information is usually obtained through energy sales exchanges (61) and has two sub-

Table III. Internal variables for priority loads

Ref.	Year	Management techniques	Internal variables	Microgrid architecture	Control strategy	Microgrid generation
(27)	2016	Integer and mixed linear programming	Battery status, charging capacity, priority, interruptible or switchable loads	Grid-connected mode	Centralized	Photovoltaic, wind, diesel generators, grid connection
(56)	2015	Mixed linear programming	Priority and non-priority loads, battery status, charging capacity	Grid-connected mode	Centralized	Micro gas turbines, fuel cells, grid connection
(28)	2016	Mixed linear programming	Battery status, storage capacity, priority, and non-priority loads	Grid-connected mode	Centralized	Fuel cells, photovoltaic, grid connection
(40)	2014	Mixed linear programming	Several charging points, EV charging capacity, EV charging status, charging and discharging efficiency, critical loads, adjustable loads, and network capacity	Grid-connected mode	Centralized	Photovoltaic, wind, grid connection
(42)	2017	Mixed linear programming	Battery charge factor, nominal discharge time, storage capacity, critical and non-critical loads, charge and discharge cycles	Islanded mode	Centralized	Photovoltaic, diesel generators
(41)	2011	Mixed non-linear programming	Load status of the core system, critical and non-critical loads, and set points for active and reactive power	Grid-connected mode	Centralized	Micro gas turbines, fuel cells, wind, photovoltaic, grid connection
(48)	2011	Ruler-based approach	Load forecasting, critical loads, controllable loads, battery state of charge, ultracapacitor state of charge	Grid-connected mode	Centralized	Photovoltaic, micro gas turbine, grid connection
(46)	2015	Rule-based approach in the load state	Load forecasting, critical loads, controllable loads, battery state of charge, and ultracapacitor state of charge	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(18)	2015	Rule-based approach in the load state	Critical loads, controllable loads, state of charge batteries.	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection.
(57)	2016	PSO Convergence	Battery state of charge, load demand, critical loads	Islanded mode	Centralized	Photovoltaic, wind power, diesel generator
(35)	2014	Gravitational search algorithm	Battery state of charge, load demand, critical loads	Islanded mode	Centralized	Photovoltaic, wind power, micro gas turbine
(58)	2016	Neural networks	Load status, storage capacity, load demand, load shedding, critical loads	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, diesel generators, grid connection
(38)	2016	Multi-agent system	Load demand, critical loads, state of charge, storage capacity	Islanded mode	Decentralized	Photovoltaic, wind power

Table IV. Internal variables for controllable loads

Ref.	Year	Management techniques	Internal variables	Microgrid architecture	Control strategy	Microgrid generation
(44)	2016	Rule-based approach	Battery state of charge, load profile, variable loads, reference system	Grid-connected mode	Centralized	Photovoltaic, fuel cell, grid connection
(48)	2011	Rule-based approach	Load forecasting, critical loads, controllable loads, battery state of charge, ultracapacitor state of charge, energy price	Grid-connected mode	Centralized	Photovoltaic, micro gas turbine, grid connection
(49)	2013	Rule-based approach	Load demand, controllable loads, battery state of charge	Grid-connected mode	Centralized	Photovoltaic, grid connection
(50)	2017	Genetic algorithms	Battery state of charge, load demand, controllable loads	Grid-connected mode	Centralized	Photovoltaic, wind power, co-connection to the grid
(20)	2011	Genetic algorithms	Load demand, controllable loads, battery state of charge	Grid-connected mode	Centralized	Photovoltaic, grid connection
(51)	2016	Differential evolution	Load demand, controllable loads, battery state of charge	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(34)	2016	Ant colony optimization	Load demand, battery charging status, controllable loads	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(59)	2017	Fuzzy logic	Load demand, controllable loads, storage capacity, battery state of charge	Connected to the grid and other microgrids	Centralized	Photovoltaic, wind power, grid-connected, other microgrids
(39)	2017	Multi-agent system	Load demand, controllable loads, battery state of charge, storage capacity	Grid-connected mode	Decentralized	Fuel cells, photovoltaic, wind power, grid connection
(60)	2015	Multi-agent system	Load demand, controllable loads, battery state of charge, storage capacity	Grid-connected mode	Decentralized	Photovoltaic, wind power, fuel cells, grid connection

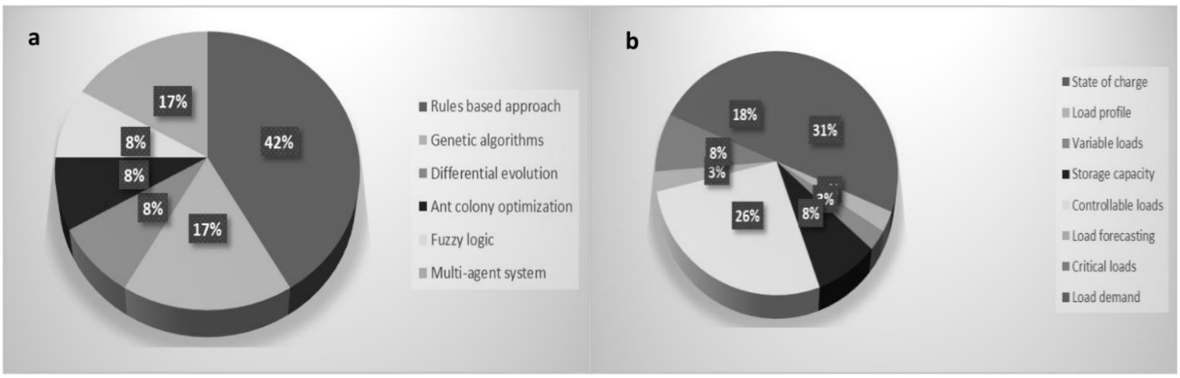


Figure 5. a) Relevant variables of controllable loads, b) relevant management techniques for controllable load variables

categories:

1. Energy value
2. Cost of generation

Table V. Internal variables for controllable loads

Ref.	Year	Management techniques	Economic variables	Microgrid architecture	Control strategy	Microgrid generation
(27)	2016	Integer and mixed linear programming	Fuel cost, generator maintenance cost, power cost, energy price	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generators, grid connection
(56)	2015	Mixed linear programming	Fuel cost, generator maintenance cost, power cost, energy price	Grid-connected mode	Centralized	Micro gas turbines, fuel cells, grid connection
(32)	2016	Genetic algorithm	Energy price, fuel cost	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generator, grid connection
(29)	2015	Mixed linear programming	Energy price	Grid-connected mode	Centralized	Photovoltaic, geothermal, thermal energy storage, grid connection
(40)	2014	Mixed linear programming	Battery wear cost, energy price	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(31)	2013	Dynamic programming	Energy price	Grid-connected mode	Centralized	Wind power, grid connection
(48)	2011	Rule-based approach	Energy price	Grid-connected mode	Centralized	Photovoltaic, micro gas turbine, grid connection
(46)	2015	Rule-based approach in the load state	Energy price	Grid-connected mode	Centralized	Photovoltaic, wind, micro gas turbine, grid connection
(23)	2016	Genetic algorithms	Energy sales and purchase price, operating costs	Grid-connected mode	Centralized	Photovoltaic, wind, fuel cells, micro gas turbine, grid connection
(50)	2017	Memory-based genetic algorithms	Energy prices, operating costs	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(34)	2016	Ant colony optimization	Energy prices, operating costs	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(53)	2013	Modified bacterial foraging	Energy price, fuel cost	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, grid connection
(36)	2017	Fuzzy logic	Energy price	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(55)	2012	Fuzzy logic	Operating and maintenance costs, energy prices	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, grid connection

(58)	2016	Neural networks	Fuel price, energy price	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, diesel generators, grid connection
(39)	2017	Multi-agent system	Energy sales and purchase price, maintenance, operating costs	Grid-connected mode	Decentralized	Fuel cells, photovoltaic, wind power, grid connection
(60)	2015	Multi-agent system	Energy price, maintenance, operating costs	Grid-connected mode	Decentralized	Photovoltaic, wind power, fuel cells, grid connection
(62)	2016	Game theory	Energy sales and purchase price, operating cost	Grid-connected mode	Decentralized	Photovoltaic, fuel cells, grid connection
(63)	2013	Game theory	Operating costs, energy prices	Grid-connected mode	Decentralized	Photovoltaic, wind power, micro gas turbine, grid connection
(39)	2017	Multi-agent system	Energy sales and purchase price, maintenance, operating costs	Grid-connected mode	Decentralized	Fuel cells, photovoltaic, wind power, grid connection
(60)	2015	Multi-agent system	Energy price, maintenance, operating costs	Grid-connected mode	Decentralized	Photovoltaic, wind power, fuel cells, grid connection
(62)	2016	Game theory	Energy sales and purchase price, operating costs	Grid-connected mode	Decentralized	Photovoltaic, fuel cells, grid connection

Energy value

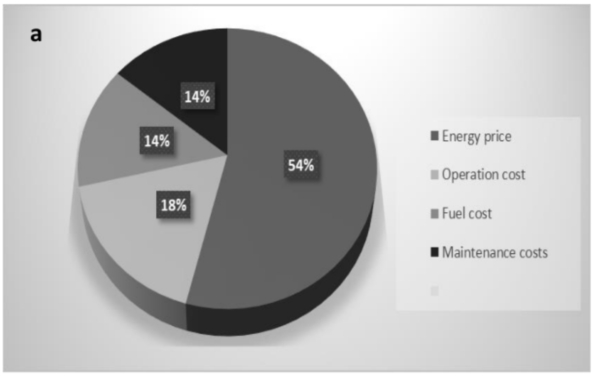
As per (29,30,33,46), and (**?**), this category has associated operating costs and values, with particular emphasis on the energy price. The energy value generated can be similar to the energy price for the time during which the microgrid operates autonomously. This results in a saving that justifies the resources spent, contributing to the viability of the microgrid's implementation (Table **V**).

The most relevant variables used in this category are shown in Fig. **6**.

Cost of generation

In (26, 30, 42), and (43), factors such as the fuel or generation cost, the operating costs, and the maintenance costs of the microgrid take on greater relevance. The price of energy supplied by the conventional power grid is not considered by these authors, as the microgrid operates in islanded mode (Table **VI**).

The most relevant variables used in this category are shown in Fig. **7**.



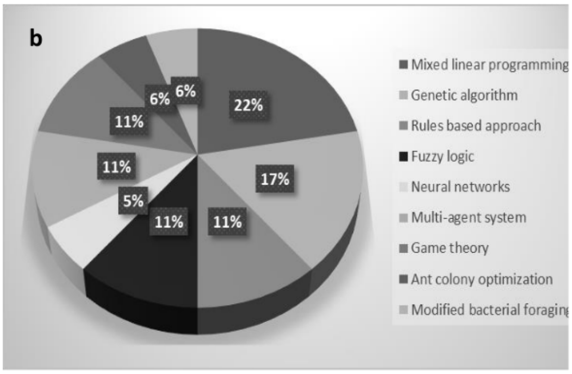


Figure 6. a) Economic variables regarding energy value, b) relevant management techniques regarding energy value

Table VI. Economic variables regarding the cost of generation

Ref.	Year	Management techniques	Economic variables	Microgrid architecture	Control strategy	Microgrid generation
(42)	2017	Mixed linear programming	Fuel price	Islanded mode	Centralized	Photovoltaic, diesel generators
(30)	2017	Mixed linear programming	Cost of components, operating costs	Islanded mode	Centralized	Photovoltaic, wind power
(43)	2017	Dynamic programming	Fuel price	Islanded mode	Centralized	Diesel generators, photovoltaic
(26)	2016	Genetic algorithms	Fuel price	Islanded mode	Centralized	Photovoltaic, diesel generators
(57)	2016	PSO Convergence	Fuel price	Islanded mode	Centralized	Photovoltaic, wind power, diesel generator
(35)	2014	Gravitational search algorithm	Fuel price	Islanded mode	Centralized	Photovoltaic, wind power, micro gas turbine
(38)	2016	Multi-agent system	Maintenance cost, generation cost	Islanded mode	Decentralized	Photovoltaic, wind power
(64)	2013	Multi-agent system	Maintenance cost, generation cost	Connected to other microgrids	Decentralized	Photovoltaic, connection to other microgrids

3.2. Management system outputs

A management system's output is the instruction or orders that the system executes to fulfill an objective. These instructions influence the routing of the energy flow and the operation or shutdown of components.

The outputs of the management system can be divided into two categories:

A. Preset operating status

B. Binary decisions

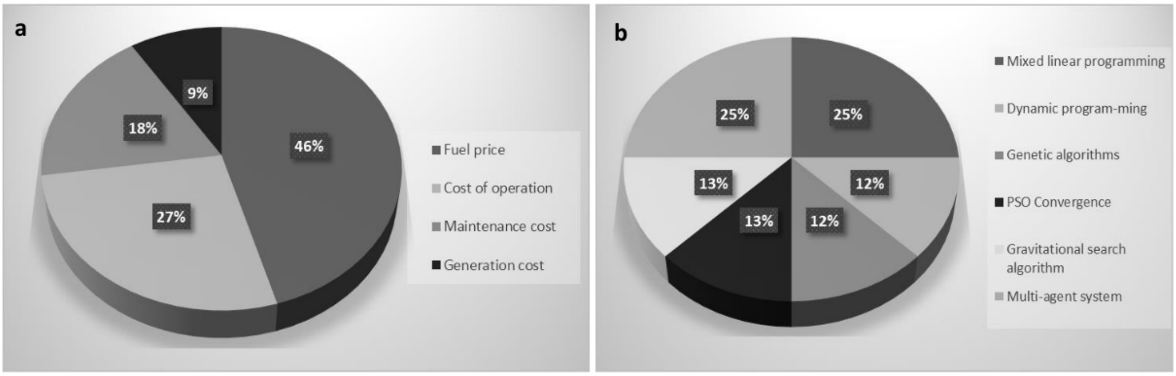


Figure 7. a) Economic variables regarding the cost of generation, b) relevant management techniques for economic variables regarding the cost of generation

A. Preset operating status

(28, 41–43), and (48) propose, as outputs of their management systems, pre-defined scenarios that are activated when the microgrid parameters reach previously defined values. These scenarios focus on directing the energy flow to meet a specific objective, maintaining the microgrid in islanded mode, feeding the storage components, or reducing the demand of the loads, among others (Table **VII**)

Table VII. Preset operating status

Ref.	**Year**	**Management techniques**	**Preset operating status**	**Microgrid architecture**	**Control strategy**	**Microgrid generation**
(28)	2017	Mixed linear programming	Continuous operation mode, power-sharing mode	Grid-connected mode	Centralized	Fuel cells, photovoltaic, grid connection
(40)	2014	Mixed linear programming	Power-sharing mode, connection status at the EV charging point	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(42)	2017	Mixed linear programming	Scenarios: charging and consumption of diesel generators, charging and consumption of solar panels, energy from batteries	Islanded mode	Centralized	Photovoltaic, diesel generators

(41)	2011	Mixed non-linear programming	Load switching, load shedding scenario, grid connection scenario, grid disconnection scenario	Grid-connected mode	Centralized	Micro gas turbines, fuel cells, wind power, photovoltaic, grid connection
(65)	2016	Non-linear programming	Cell charging scenario, EV charging, grid connection scenario, grid disconnection scenario	Grid-connected mode	Centralized	Fuel cell, photovoltaic, grid connection
(48)	2011	Rule-based approach	Load switching, load mode, mains connection -disconnection	Grid-connected mode	Centralized	Photovoltaic, micro gas turbine, connection to the main grid
(46)	2015	Rule-based approach in the load state	Load switching, load mode, mains connection-disconnection	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(18)	2015	Rule-based approach in the load state	Load switching, load mode, mains connection-disconnection	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(49)	2013	Rule-based approach	Charging mode, grid connection-disconnection, load disconnection, load connection scenario, panel consumption	Grid-connected mode	Centralized	Photovoltaic, connection to the grid
(23)	2016	Genetic algorithms	Grid connection-disconnection, control of generation sources	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, micro gas turbine, grid connection
(50)	2017	Memory-based genetic algorithms	Grid connection-disconnection, generation source control, load mode	Grid-connected mode	Centralized	Photovoltaic, wind, grid connection
(20)	2011	Genetic algorithm	Demand control response, battery charge-discharge, import-export to the grid, control of generation sources	Grid-connected mode	Centralized	Photovoltaic, grid connection
(32)	2016	Genetic algorithm	Demand control response, battery charge-discharge, EV charging, import-export to the grid, generation source control.	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generator, grid connection.
(33)	2015	Swarm optimization	Renewable energy generation scenario, grid connection scenario, supply, load scenario	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection

(51)	2016	Differential evolution	Demand control response, battery charge-discharge, import-export to the grid, control of generation sources	Grid-connected mode	Centralized	Photovoltaic, wind power, micro gas turbine, grid connection
(52)	2012	A self-adaptive gravitational search algorithm	Import-export to the grid, demand control response, battery charge-discharge	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(53)	2012	Modified bacterial foraging	State of charge, load switching, generation source control, import-export to the grid	Grid-connected mode	Centralized	Photovoltaic, wind power, fuel cells, grid connection
(54)	2014	Modified bacterial foraging	Load status, load switching, import-export to the grid	Grid-connected mode	Centralized	Wind power, micro gas turbine, grid connection
(36)	2017	Fuzzy logic	Demand control response, state of charge, import-export to the grid	Grid-connected mode	Centralized	Photovoltaic, wind power, grid connection
(38)	2016	Multi-agent system	Consumption hierarchy, demand control response, state of charge	Islanded mode	Decentralized	Photovoltaic, wind power
(63)	2013	Game theory	Control response, demand response, import-export to the grid, state of charge	Grid-connected mode	Decentralized	Photovoltaic, wind power, micro gas turbine, grid connection

The most relevant variables used in this category are shown in Fig. 8.

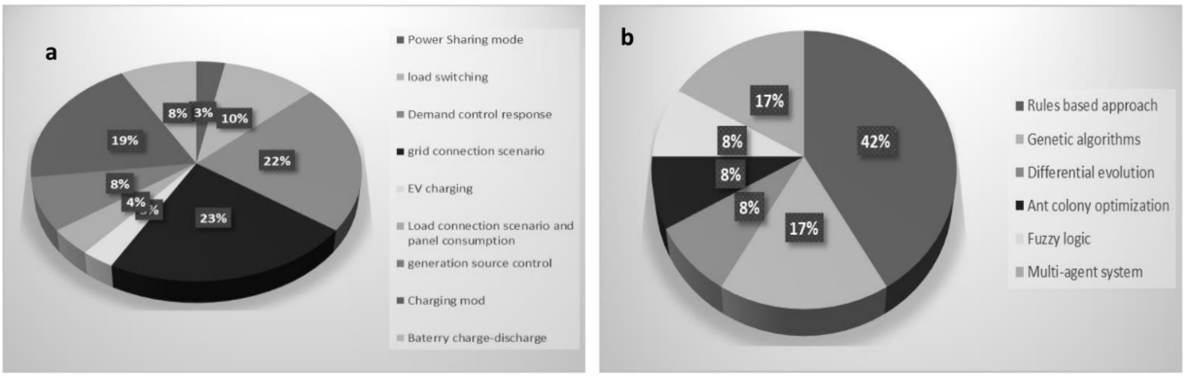


Figure 8. a) Output variables for the preset operating status, b) relevant management techniques regarding the output variables for the preset operating status

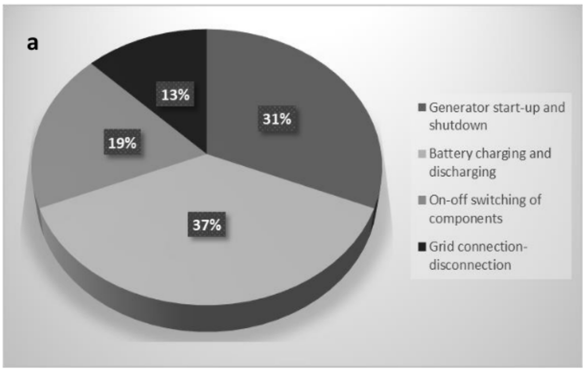
B. Binary decisions

In (26, 27, 30), and (43), the management systems' outputs correspond to the connection or disconnection of microgrid elements, as well as to the flow of energy (Table VIII).

Table VIII. Binary decisions

Ref.	Year	Management techniques	Binary decisions	Microgrid architecture	Control strategy	Microgrid generation
(27)	2016	Integer and mixed linear programming	Load disconnection, partial load supply, generator start-up, grid connection-disconnection, battery discharge-charge	Grid-connected mode	Centralized	Photovoltaic, wind power, diesel generators, grid connection
(30)	2017	Mixed linear programming	Charging-discharging of batteries, photovoltaic energy consumption and load, wind energy consumption and load	Islanded mode	Centralized	Photovoltaic, wind power
(31)	2013	Dynamic programming	On-off switching of components, heat flow, grid connection-disconnection, storage system charging-discharging	Grid-connected mode	Centralized	Wind power, grid connection
(26)	2016	Genetic algorithms	Generator start-up and shutdown, battery charging and discharging	Islanded mode	Centralized	Photovoltaic, diesel generators
(43)	2017	Dynamic programming	Charging-discharging of batteries, connection-disconnection of diesel generators	Islanded mode	Centralized	Diesel generators, photovoltaic
(57)	2016	PSO convergence	Charging-discharging of batteries, connection-disconnection of diesel generators	Islanded mode	Centralized	Photovoltaic, wind power, diesel generator

The most relevant variables used in this category are shown in Fig. 9.



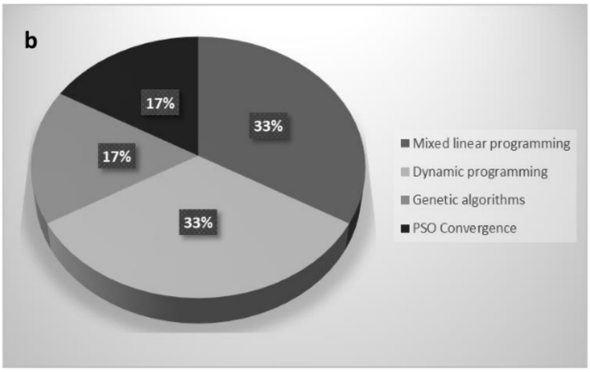


Figure 9. a) Binary output variables, b) relevant management techniques for binary output variables

4. Analysis

This systematic review shows the importance of microgrid components and their influence on the data to be considered by the management system. The importance is primarily evident in the type of generation of the microgrid, where solar irradiance is the most relevant input of the external category. The meteorological subsection, which pertains to more than 40 % of the papers studied, shows a more effective implementation in microgrids that have photovoltaic generation sources. The same trend is visible in the category of external variables related to generation power, where photovoltaic power prediction is the most recurrent, with 31 % of the papers studied. This also applies to the category of external variables, with wind speed being the second most relevant meteorological variable (31 %). Similarly, for generation power, wind energy prediction variable is present in 19 % of the papers studied, which contrasts with the implementation of microgrids that use fossil fuels as generation sources, (5 %). This can be better seen in Fig. 10a. These results show a clear trend regarding the implementation of renewable energies in microgrids.

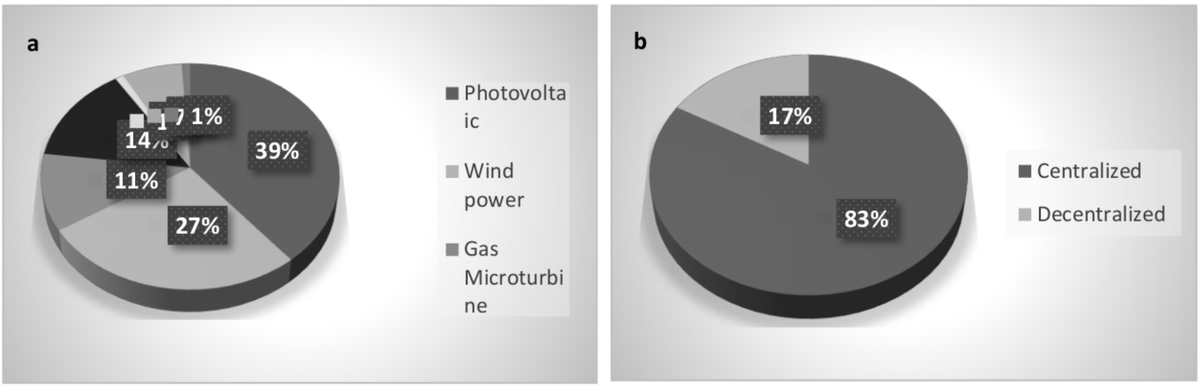


Figure 10. a) Microgrid generation in the reviewed papers, b) microgrid control strategies in the reviewed papers

Although some microgrid components influence the data used by the EMS, there is no significant impact. The methods for collecting and processing data are so varied that they do not reflect a significant statistical difference in the inputs and outputs of the management system. On the other hand, a more effective implementation of centralized control strategies is noticeable, which is present in 83 % of the papers studied (Fig. 10b). A meticulous analysis of the papers' year of publication shows a trend towards decentralized control strategies. This may be due to the fact that these strategies are more flexible and ensure a better fulfillment of the objectives, although the computational effort and resources required are more significant (16). The control techniques implemented by the management systems of the studied papers are so varied that they do not represent a significant statistical difference, as seen in Fig. 11a.

The inputs follow the needs of the management system modules and the specific components of the microgrid. This need is evident since more than 90 % of the papers studied implement some type of storage system, mainly batteries, whose state of charge and storage capacity are used for monitoring. The other variables in this category depend more on the type of loads that the microgrid must supply. The economic variables depend primarily on the microgrid architecture, as they are directly related to

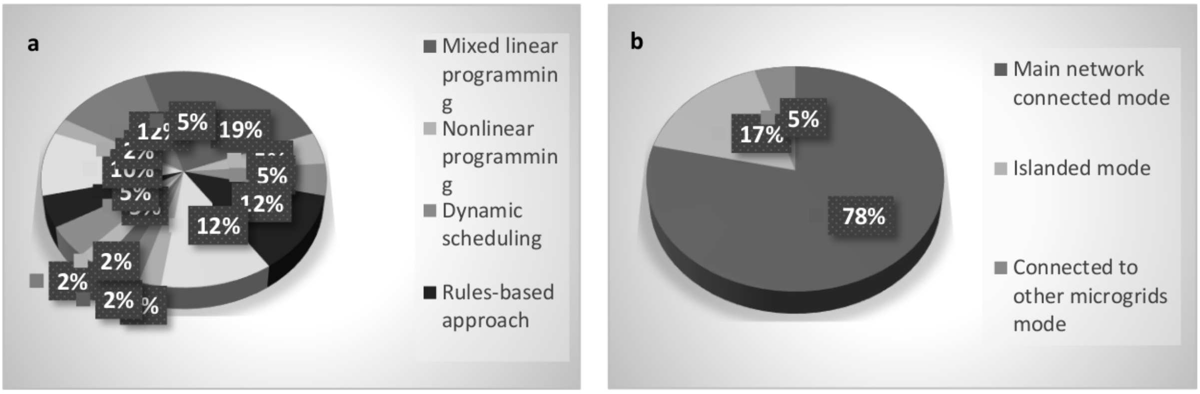


Figure 11. a) Microgrid control strategies in the reviewed papers, b) microgrid architecture in the reviewed papers

the connection to the main grid or other microgrids. If the microgrid is islanded, the economic variables focus on the costs of operation and the fuel prices, given that diesel generators or similar resources are used to guarantee a constant flow of energy. The connection with the primary grid entails a focus on the energy sales price and the operating costs. This type of architecture is the most used in the analyzed papers (78 %) (Fig. 11b).

The output variables do not show any direct relationship with the EMS modules studied when compared to the input variables. The outputs depend more on how the author wants decision-making to take place, *e.g.*, by having binary decisions involving the connection or disconnection of microgrid components. Decisions on the generation and autonomy of the microgrid are the most implemented when compared to those aimed at managing the demand.

5. Conclusions

This review article started with a brief description of the management systems applied to microgrids, in order to determine the functions they should perform. With these definitions, the data to be collected and its associated variables were determined, which would be the input for a correct EMS performance. With these variables as a basis, an analysis of their properties was conducted. The variables that shared properties were grouped into categories while considering the functions for which they provide information. In light of the above, this article proposes a taxonomy for the input and output variables of a microgrid management system.

Progress has been made in microgrid management using different control and management techniques and strategies, evaluating their pros and cons. However, it is relevant to consider other factors that may affect performance, such as the nature of the variables and the topology of the microgrid, among others.

It is important to know the variables that serve as the inputs and outputs of management systems in order to ensure a good microgrid performance. In this vein, this paper helps those interested in delving into the implementation of these systems. The proposed taxonomy could serve as a guide to perform the conceptual and basic engineering of projects in this sector.

Given that most of the papers studied used simulation environments, it is also necessary to test management systems in real-world scenarios to evaluate their effects and performance.

6. Author contributions

These are contributions of each author according to the CRedit taxonomy:

- **Carlos Santiago Vidal Martínez:** Writing – original draft
- **Maximiliano Lopéz Bueno:** Writing – review and editing
- **Juan Fernando Flórez Marulanda:** Writing – review and editing
- **Álvaro René Restrepo Garcés:** Writing – review and editing

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