Renewable and Sustainable Energy Reviews 82 (2018) 126–155

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review of energy management strategies for renewable hybrid energy systems with hydrogen backup

F.J. Vivas*, A. De las Heras, F. Segura, J.M. Andújar

Grupo de Investigación de Control y Robótica TEP-192, Departamento de Ingeniería Electrónica, de Sistemas Informáticos y Automática, Escuela Técnica Superior de Ingeniería, Universidad de Huelva, Spain

ARTICLE INFO

Keywords:
State of art revision
Energy management strategy
Hybrid renewable power systems
Hydrogen backup

ABSTRACT

Hybrid systems are presented as a viable, safe and effective solution to minimize the associated problems of the dependence on renewable energies with the environmental resources. In this way different renewable systems such as photovoltaic, wind, hydrogen and so on, can work together to configure hybrid renewable systems. However, to make them work properly in a holistic way by creating synergies among them is not an easy task. Recently hydrogen technology has appeared as a promising technology to hybridize renewable energy systems, since it allows the generation (by electrolyzers) and storage of hydrogen when there is a surplus of energy in the system, and at a later time (e.g. when there are insufficient renewable resources available) using the stored hydrogen to generate electrical energy by fuel cells. The choice of a correct energy management strategy should guarantee an optimum performance of the whole hybrid renewable system; therefore, it is necessary to know the most important criteria in order to define a management strategy that ensures the best solution from a technical and economic point of view. This paper presents a critical review and analysis of different energy management strategies for hybrid renewable systems based on hydrogen backup. In the same way, a review is also presented of the most important technical and economic optimization criteria, as well as problems and solutions studied in the scientific literature.

1. Introduction

With the advancement of civilization and evolution of technology, energy demand has become a basic issue for the development of a society today. The usual ways to address this demand today are based mostly on resources such as fossil or nuclear fuels [1–3], which have a negative impact on the environment, either contributing with greenhouse gases, or by production of radioactive or inert solid waste. For this reason, every day the need to migrate to more environmentally responsible energy production models becomes more evident.

Together with the above, due to the high-energy requirement, it is necessary to look for generation models to ensure maximum system performance, minimizing the use of resources, cost and thus the environmental impact. In recent decades, the use of distributed generation has emerged as a viable and safe solution to increase electrical system performance, reducing the distance between generation and demand [4,5].

The incorporation of renewable energies is a non-polluting solution for a distributed generation, allowing different generation points in the geography of a country, region or even district, as well as providing a viable alternative from a technical and economic point of view for isolated generation applications [6–9]. Among the main renewable energy sources for distributed generation, we can find photovoltaic panels, small and medium wind turbines, micro-hydro turbines, biomass and biogas [27]. The electricity production by hydropower, biomass and biogas need a constant supply of fuel and resources, which would imply a major economic commitment to such a sector and there are a lot of pollutant emissions in the case of the last two technologies; so they would not be suitable for small outlets in homes, small business systems etc. By contrast, wind and solar sources can be more suitable and they are nonpolluting [27]. This is why most applications choose these sources to implement hybrid systems based on renewable energies. The wind resource, despite being available throughout the day, has a high randomness and large variations in the short term, so it is not a reliable source for supplying a load [8]. On the other hand, although the solar resource is more predictable and suffers less pronounced variations, there can be no solar production during the night or at dawn or nightfall, so production is minimized due to the reduced amount of incident radiation, resulting in an energy deficit [28].

Despite the benefits of renewable energy, there are associated problems with each technology, such as dependence on environmental resources, high cost, etc. To minimize the negative impact of these

* Corresponding author.

http://dx.doi.org/10.1016/j.rser.2017.09.014
Received 26 April 2016; Received in revised form 20 August 2017; Accepted 2 September 2017
Available online 17 September 2017
1364-0321/

Nomenclature

BAT	Battery
CHP	Combined Heat and Power (cogeneration)
DOD	Depth Of Discharge
ELEC	Electrolyzer
FC	Fuel Cell
LPSP	Loss of Power Supply Probability
MH	Metal Hydride
MPPT	Maximum Power Point Tracker
MT	Micro Turbine
PV	Photovoltaic source
SC	Supercapacitor
SOC	State Of Charge
UC	Ultracapacitor
WT	Wind Turbine

disadvantages, hybrid systems are presented as a viable, safe and effective solution [10–16].

The use of hybrid systems with different generation sources is an acceptable solution to cover the deficiencies of the different elements, but a backup system is necessary for an optimal power supply [5,15]. Nowadays for small and medium scale, energy is stored mostly in batteries and, for specific applications, in supercapacitors. For larger scale storage, potential energy is used with hydro pumping in swamps. Because wind and solar resources have a stochastic behavior, and the supply of the load profile is the main objective of generation systems, the use of energy storage systems is necessary to ensure the demand is reached and the stability of the supply system [28]. In the short term, energy storage systems have the primary function of supporting excess/deficiency of energy, and guaranteeing system security and power supply when the load changes [1]. In contrast, in the long term, energy storage systems have the function of providing the demand for a long period when the generation is not sufficient to maintain the load [1].

Traditionally, batteries and more recently supercapacitors have been used as short-term energy storage systems. Supercapacitors have a better dynamic behavior than batteries, so they can respond to demand shocks and supply energy almost immediately [29]. Moreover, their lifetime is very high with a safe operation without emission of harmful gases [29]. Despite all these advantages, their low capacity restricts their use. In contrast, batteries are elements with worse dynamic response, and a limited lifetime based on the number of charge/discharge cycles. Additionally, batteries may suffer deterioration and during normal operation can produce harmful gases [30]. The fact that the batteries have gained greater prominence is mainly because of their high load capacity and the ability to support a higher density of discharge current in amplitude and time. These features ensure greater security in the system response, since batteries can withstand longer defects and deficiencies in generation and dynamic changes in demand.

The long-term energy storage systems have always been based on non-renewable energy sources, such as diesel generators. These generators require high maintenance cost and produce sound and environmental pollution.

Recently, the use of hydrogen technology is presented to have a future value [15,17]. The use of hydrogen as a fuel in fuel cells is showing its strengths compared to diesel systems. Fuel cells have higher performance, lower maintenance and no emissions. Because hydrogen is an energy vector and it can be produced renewably, it is ideal for use as renewable energy storage [18,19]. The use of hydrogen as an energy vector absorbs excess energy during generation and produce energy in stages of energy deficit [14]. This alternative decreases battery size and increases system performance by taking advantage of energy surplus. Despite the benefits of using hydrogen, it is true that greater control, security and associated equipment for proper operation is necessary [15].

The energy transformation based on electricity-hydrogen-electricity relation is a starting point for new models of energy storage for example: power to gas [20–27].

In order to ensure proper operation of hybrid systems based on renewable energy, guaranteeing the demand and increasing the system performance, it is necessary to use energy management strategies [6,28–30]. The goals of these strategies will determine the behavior of the system, so it is very important to define a proper management strategy. Therefore, this paper undertakes a review of different energy management systems on hybrid power systems based on renewable energies, with the use of hydrogen as an energy vector. Section 2 includes a review and a classification of the most common topologies studied in the scientific literature. In Section 3, a review of the main techno-economic criteria for designing energy management strategies is done. In Section 4 solutions adopted in the literature are presented. Section 5 reviews and analyses different strategies used in the scientific literature. Finally, Discussion and Conclusions are compiled in Sections 6 and 7 respectively.

2. Configuration of hybrid renewable systems

Hybrid systems can be classified in different ways; the most common are those which distinguish the different systems depending on their connection to the grid; as well as the method of integration of elements inside the system.

2.1. Classification according to grid connection

Hybrid generation equipment can be classified according to their stand-alone or grid connected operation. The use of one or another

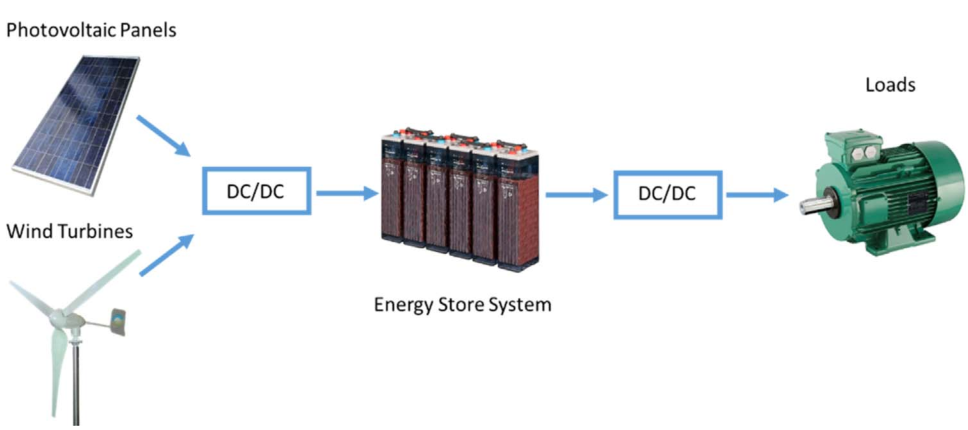

Fig. 1. Example of isolated topology.

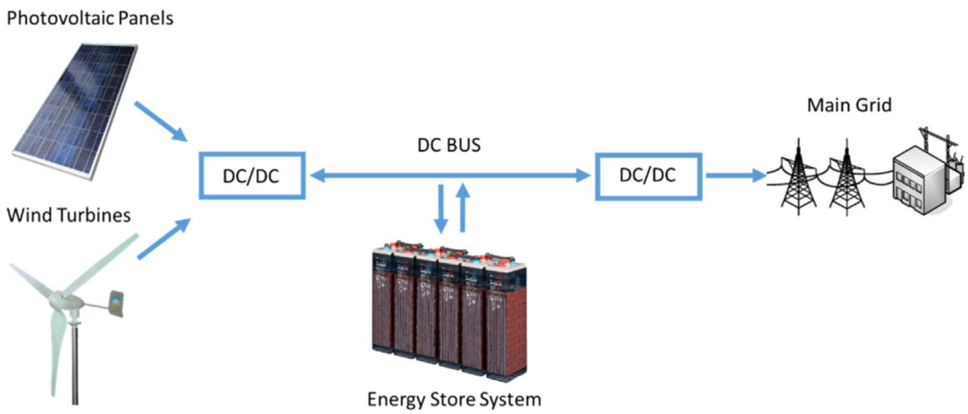

Fig. 2. Example of grid connected topology.

Table 1
Configuration and topology summary.

Ref.	Topology	Integration method
[2,3,19,30–45]	Grid connected	DC Bus
[5,8–12,28,29,46–93]	Isolated	DC Bus
[94–96]	Isolated	AC Bus
[97]	Isolated	Hybrid Bus

topology is mainly determined by the application and financial cost.

2.1.1. Isolated systems

In this topology, the system is isolated from the grid, so it is responsible for ensuring load demand at all times. The problems associated with this configuration are related to reliability and performance. Using a fully insulated system can endanger the security of the energy provided, due to the limited number of resources available. Similarly, the energy excess is a problem, and so it must be discarded, reducing system performance. For these reasons, this configuration has only technical and economic viability in applications where it is impossible or very expensive access to the grid connection. An example of isolated topology is presented in Fig. 1.

2.1.2. On-grid systems

In this configuration, the system is connected to the grid. This connection ensures demand is provided for in energy deficit situations, and increases system performance to take advantage of the energy excess for sale and distribution in the energy market. The use of this type of topology leads to new production models and energy management strategies based on consumption and distributed generation in small, medium or large scale. An example of a grid-connected configuration is presented in Fig. 2.

2.2. Classification by integration method

This type of classification distinguishes the system depending on the nature of the internal interconnection bus. The function of this bus is to create a physical link between all the elements, so generation and consumption is through the conditions imposed on the bus. Depending on the nature of the bus, we can distinguish between DC, AC or hybrid types. A summary table depending on grid connection and integration method is presented in Table 1.

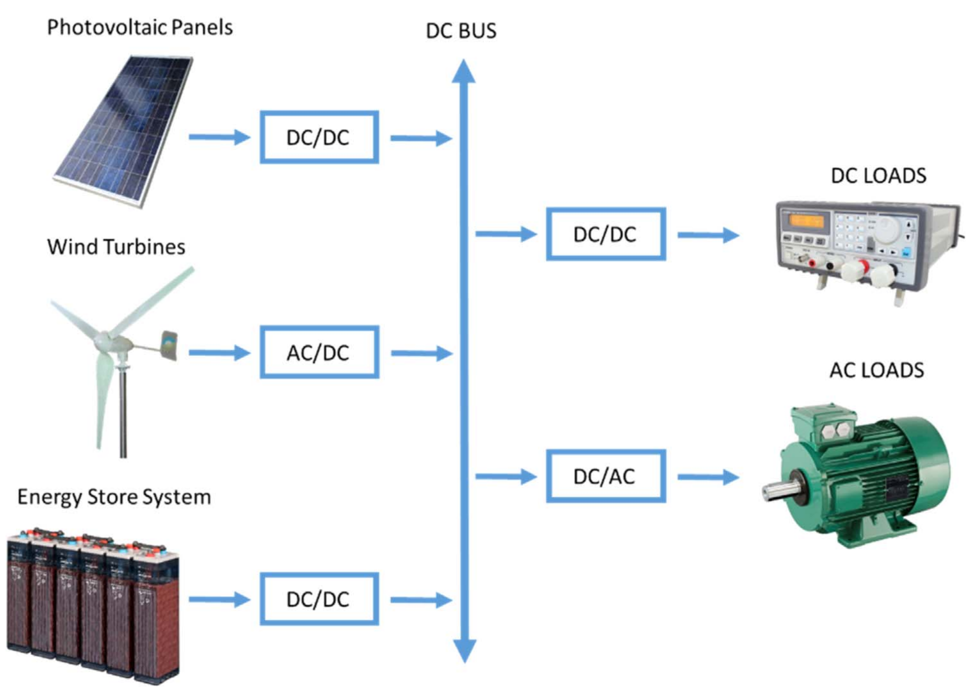

Fig. 3. Example of DC bus.

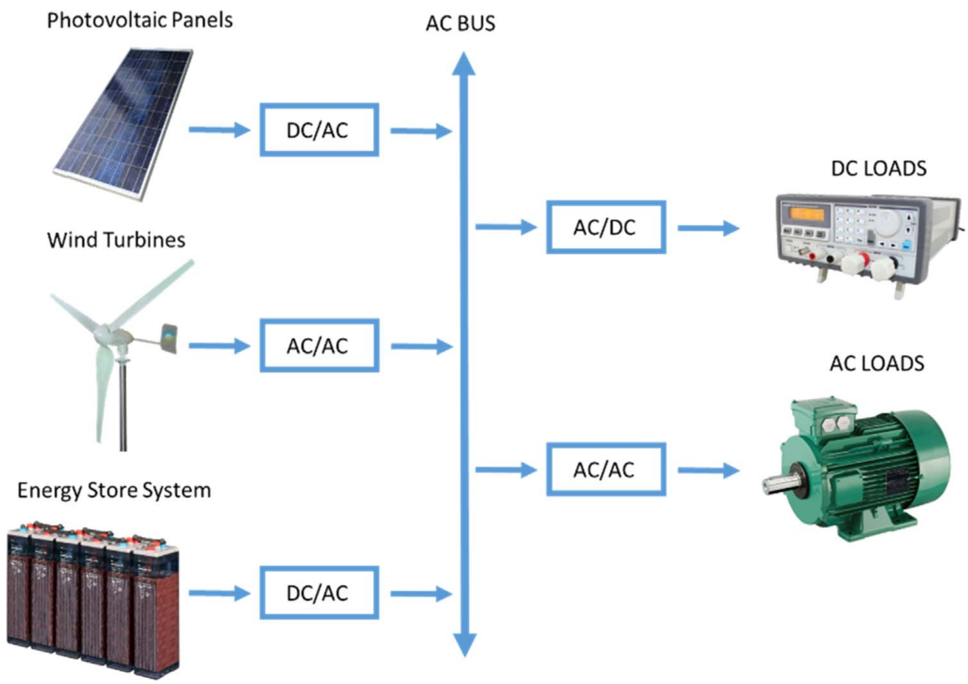

Fig. 4. Example of AC bus.

2.2.1. DC Bus

These buses are commonly used in low power applications because of a number of technical advantages that facilitate its use. Among these advantages, we can highlight their reduced losses and simplicity of use, avoiding technical problems related to power quality [1]. As a disadvantage, this configuration requires a larger number of conversion elements, because most of the loads must be supplied with AC. An example of topology based on a DC bus is presented in Fig. 3.

2.2.2. AC bus

AC buses are widely used in applications of medium and high production, due to the technical simplicity of operating at higher voltages than in DC, reducing internal losses of the system. The disadvantages of this configuration can often endanger the stability or integrity of the system. The main disadvantage is the need for elements for power quality correction [1]. It is increasingly common to find inductive and electronic loads that reduce the power factor and include harmonics respectively. A reduced power factor and high number of harmonics can damage the different generators, and requires the use of filtering and compensation elements, increasing the complexity and cost of the system. An example of AC bus-based configuration is presented in Fig. 4.

2.2.3. Hybrid bus

This configuration makes use of both buses (DC and AC) interconnecting generators and consumption which have the same nature. The principal advantage of this configuration is the reduction of power converters. As the main drawback of the system, it must be emphasized that the control is more complex, operating on two different networks, ensuring the balance of power at all times. An example of topology based on Hybrid bus is presented in Fig. 5.

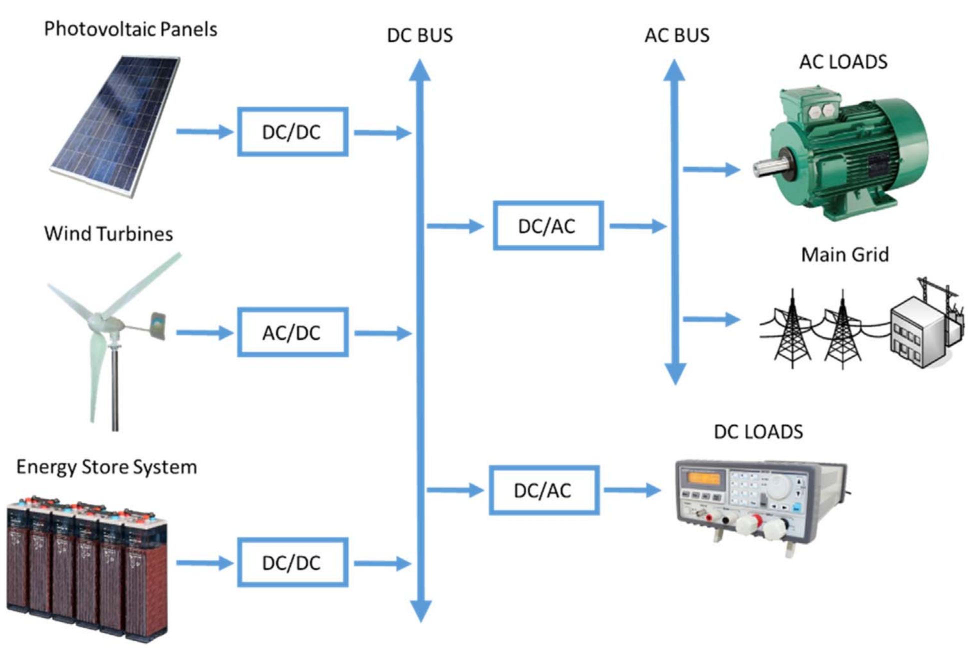

Fig. 5. Example of Hybrid bus.

2.3. Classification by integrated elements

The different integrated elements inside the hybrid system will define the generation, the energy storage system, or the demand. Next, the most common solutions adopted in the scientific literature are presented.

2.3.1. Generation

In case of generation, the most common solutions integrate renewable energy sources such as solar panels, wind turbines or hydro turbines. The use of solar panels guarantees generation during sun hours with an acceptable prediction margin. Wind turbines have a stochastic behavior so it provokes an unpredictable generation so the optimal use of the rest of the elements is necessary to guarantee the power balance. On the other hand, the wind generation is available during the entire day, intensified during the night. Wind turbines require special emplacement and environmental conditions, and therefore they are less used. According to the above, the hybridization of solar panel and wind turbines is considered an acceptable solution to generate energy from renewable sources.

In grid-connected topologies, the grid could be considered another generator if the renewable generation and energy storage system is not enough to guarantee the power balance.

2.3.2. Energy storage system

Batteries and/or supercapacitors seem to be the most important storage systems used in small applications. This solution permits the voltage stabilization of the internal DC bus, absorbing the transients during generation or load changes. Batteries and to a lesser extent supercapacitors represent the short-term storage system, and they are conceived as the main element of the system, whose parameters will define the operation of the other energy storage systems.

According to the goal of this paper, the hydrogen storage system is studied and evaluated in all the reviewed literature. This solution is a medium-long term storage system that is used to supply the demand when renewable generation and short-term storage systems are not enough. The main elements that compose the system are a fuel cell and hydrogen storage. The use of an electrolyzer or a reformer process (depending on application) is also extended and permits the utilization of excess energy to generate hydrogen and thus close the hydrogen energy cycle.

Other non-renewable storage systems are also used as the last resort to ensure demand. The most common solution is the use of diesel generators that are a synonym of pollution and fossil fuel consumption.

2.3.3. Demand

The demand will depend on the application in which the hybrid renewable system will be used. Desalinization processes, isolated telecommunication stations, distributed generation or residential uses are examples of different applications.

Finally, according to grid connection, the grid could be considered as another demand when it is necessary to guarantee the power balance during energy excess situations or when the purpose of the system is the energy injection to the national/regional/local energy system.

A summary based on all the previous classifications is shown in Table 1. Additionally, Appendix A includes an extended table where topology and integration methods, as well as constituent elements are also detailed for each reference.

2.4. Configurations review

Attending to the previous classifications and attending to different configurations and topologies, a brief analysis is performed bellow.

2.4.1. Single generation and single storage system

Configurations with DC bus and single generation which use only hydrogen storage systems are studied in these references: [10,38,39,63,67,73,85]. From the previous works in [10] and [38] an isolated and grid connected topology respectively use wind turbine as a renewable generator. Fuel cells represent the unique hydrogen backup system. Electrolyzers are included in isolated topologies in [63,67,73] and [39]. Solar panels are used as the main generator in [63] and [73], meanwhile in [67] and [39] the wind turbine replaces them.

2.4.2. Single generation and hybrid storage system

Configurations which include single generation, modeled by solar panels; and batteries and fuel cells/hydrogen as hybrid storage systems are presented in [5,31–33,48,49] and [40]. In [5,48,49] isolated applications are studied meanwhile grid connected topologies are studied in [31–33] and [40].

Electrolyzers are included in [9,41,50,64,65,71,77,80,83,91,92]. From previous configurations, only [9] and [41] present wind turbines as the only generator system. From the grid connection point of view, all the previous configurations except [41] present an isolated topology.

Finally, [83] presents an isolated application in which micro turbines are the main generator of the system, while batteries and fuel cells represent the hybrid storage system.

2.4.3. Hybrid generation and single storage system

In [2,34], and [36] a grid connected application based on DC bus integrates a hybrid generation composed of solar panels and wind turbines as main generators, and fuel cells/hydrogen as a unique storage system. On the other hand, [68] presents the same integrated elements in an isolated topology. Electrolyzers are included in the previous configurations in [8,19,29,37,43,60,66,69,70,84,88,94,95,97]; from which, [19,37,66,94] and [88] are developed in an isolated topology. A diesel generator is also included in an isolated application in [90].

Finally, from the integration method point of view, exceptions studied in [97] and [95] present a hybrid DC/AC and AC bus which are used respectively to integrate all the elements inside the hybrid system.

2.4.4. Hybrid generation and hybrid storage system

Isolated configurations which use solar panels and wind turbines as hybrid renewable generation, and batteries and fuel cells as hybrid storage systems are studied in [11,12,52,72] and [74]. In these configurations, hybrid generation and storage systems are used to solve the disadvantages of each technology taking advantage of the other ones. Hydrogen generation by electrolyzer is not considered in these applications.

The use of complete hybrid generation and hybrid storage systems under a DC bus in isolated application is presented in [28,30,32,46,51–59,61,62,75,76,78,79,81,82,86,87]. The use of hybrid generation is based on solar panels and wind turbines. On the other hand, the energy storage system is composed of batteries as a short-term storage solution, and fuel cells and electrolyzers as the hydrogen storage system. In these applications, electrolyzers take advantage of energy excess to produce hydrogen by electrolysis process. AC bus is used only in [96]. The same integrated elements are used on grid connected application in [3,30,35,42,44,45,93].

Finally, isolated configurations which also include diesel generators as long-term storage system are studied in [28,52,57,82,87,89,96].

3. Techno-economic criteria

To develop an energy management strategy in a hybrid renewable energy system it is necessary to take into account technical and economic criteria. These parameters will help to design a correct energy control, increasing the system performance. A description of the most important technical and economic criteria will be made below.

3.1. Technical criteria

Technical criteria are those that refer to the proper functioning of the equipment, in order to increase performance and reduce their degradation during normal system operation. A summary of technical considerations is presented in Table 2. The highlights to consider are presented below.

3.1.1. Solar & Wind sources

- MPPT techniques: The use of these techniques allow maximum performance and production for an environmental resource at a particular time [2,46].
- Wind turbine as main generator: Configurations that use wind turbines as the main generator can cause more changes in generation, so it will provoke an increased use of batteries and high number of start/stop cycles for electrolyzers and fuel cells. The use of solar panels and wind turbines enables a more consistent production during the day and takes advantage of the maximum wind resources overnight. With this topology, the use of energy storage equipment will be reduced and allows maximization of the environmental energy resources.

3.1.2. Battery

Short-medium term energy storage elements like batteries, can increase the system security under changes in consumption or production, and also during startups or shutdowns of the long-term storage equipment which has a slower dynamic [98–100]. In the same way, batteries will supply energy during energy deficit situations, allowing the reduction of hydrogen utilization, and therefore reduction in fuel cell and electrolyzer degradation by use.

- Battery discharge: The battery degradation is highly influenced by its own use. The use of high discharge depths may accelerate the battery deterioration, reducing its lifetime [101]. For lead acid batteries, a suitable sizing is one that estimates a running mode of operation around 20–30% of the DOD. Optimum replacement is determined when the maximum capacity of the battery has fallen to 80% of the initial nominal capacity [102].
- Battery charge: The charging process is crucial to operate the batteries safely and effectively [103–108]. There are different charging protocols depending on the battery technology and the desired charging rate. Despite this, a number of considerations need to be taken into account. The use of high charge currents can damage the cells and thus produce accelerated aging by corrosion [103–108]. Fast charging protocols require high voltages and high current, and therefore provoke an inefficient charge process, which can cause overcharge if it is not controlled. In spite of the above, the charge efficiency is very high even under fast charging processes.
  On the other hand, a slow charging process allows a safer and more efficient charge but it will cost some hours or even days [103–108]. Therefore, these charge processes would not be appropriate in hybrid systems whose generation is based on solar panels, because it will depend on weather conditions. In addition, a low voltage charge process can cause sulfation due to a low electrolyte renewal rate.
  Additionally, it is necessary to consider other factors such as the imbalance of charge between batteries, typical in series connection. In the long term, this problem can cause large voltage deviations between batteries causing non-homogeneous charging [107,108].
- Battery maintenance: The use of batteries requires basic maintenance principally to ensure correct operation and an increase in its lifetime. The main problem is related to self-discharge which causes capacity losses and even sulfation in case of long periods of inactivity [107,108].

3.1.3. Hydrogen resource

The proper use of hydrogen resources will increase the system performance in situations of excess or deficit of energy. In the case of using metal hydride tanks as storage technology, a proper management during the process of charge and discharge will be interesting to ensure a correct use.

- Hydrogen storage: Hydrogen storage systems are a safer solution which permits high energy density, high lifetime and a recharge time lower than that required by the batteries.
- Electrolyzer operation: Hydrogen based technology as electrolyzers and fuel cells has a proportional degradation with the number of start-stop cycles, as well as operating time [109,110]. An electrolyzer operating at low power can cause difference in pressures between the anode and cathode side, resulting in a flow of reagents from one electrode to another (crossover), obtaining products with low purity [111–113]. Similarly, operating at high powers causes a very high gas production, resulting in an accumulation of bubbles at the electrodes. This fact implies the reduction of the bonding surface between them and the electrolyte, increasing the electrical resistance and therefore reducing the performance [114–116]. Then the power operation will result from a combination between these previous processes.

Table 2
Summary of technical criteria.

 			
Solar and wind based topology allow maximization of energy resources MPPT improve power generation Production depends on weather conditions	Batteries improve system security Reduce fuel cell and electrolyzer operation time, and therefore operation degradation Lifetime depends on DOD	Start-stop cycles in electrolyzers produce deterioration Low/High electrolysis power provokes low puricity and low efficiency respectively	Start-stop cycles and load changes in fuel cells produce deterioration Operation in ohmic region improves efficiency Power converter operation can cause deterioration

- Fuel cell operation: Fuel cells suffer deterioration in start-stop cycles and load changes [117]. During the processes of startup and shutdown, over voltages appear due to reverse current between cathode and anode in the presence of air in one of the electrodes. This problem causes the oxidation of carbon (CO_2) in the bipolar plates, decreasing catalyst surface due to platinum-CO_2 reactions, resulting in increasing of mass transport losses [118–126]. In case of load changes, a non-uniform temperature distribution can appear over the membrane and the catalyst surface, which may cause similar problems as start-stop cycles [17,118,121,123]. Finally, the use of fuel cells at very low and very high power causes a low performance operation. For this reason, the operation of fuel cells typically takes place in the ohmic operation zone [9].

Thus, the use of fuel cells as well as the operating point should be chosen taking into account the above restrictions.

- Effect of power converters over the fuel cell: The use of power converters can also have a negative influence on the degradation of fuel cells. The high operating frequencies can be filtered by the internal dynamics of the stack on the model of double capacitance [127]. Low frequencies, switching or harmonics between 0.1 and 100 Hz cannot be filtered, and so produce negative effects as discussed for load changes [126–130].

3.2. Economic criteria

The economic criteria are those that focus their efforts on economic decisions, trying to give a system response economically viable to compete with traditional systems. A summary of economic criteria is presented in Table 3. Main issues to consider when choosing generation and storage systems are presented below.

3.2.1. Solar & wind sources

The use of generators based on solar and wind energy, ensures long operating life and low operating and maintenance costs compared to other renewable technologies [1,131]. The use of renewable energy systems can impact discounts on energy invoices as well as facilitate the market entry of new methods of consumption, as a net balance system [132].

3.2.2. Energy management strategy

The use of a proper energy management strategy which takes into account the technical criteria presented in the previous section, will increase the lifetime of elements, and reduce replacement and operating and maintenance costs [133].

3.2.3. Battery

The use of short-term storage systems like batteries increases system security against the use of elements with slower dynamics such as fuel cells and electrolyzers [47–49]. A secure system is that which ensures critical loads at all times, minimizing damage and penalty cost by power failure situations.

In the same way, batteries present a more economical solution with respect to hydrogen storage systems.

3.2.4. Hydrogen resource

The use of hydrogen-based storage compared to fossil fuel based technologies such as diesel generators, allows the production of electricity with higher performance, low emission and reduced operating and maintenance costs [1,13,131].

– Electrolyzer:
  PEM electrolyzers today constitute a promising technology but it is already under investigation. The reduced lifetime and the higher overall cost of this type of electrolyzer, are the main reason why alkaline electrolyzers are widely used, becoming a more competitive, safer and well known option for hydrogen production technologies [112,114,116].
  The use of electrolyzers in isolated configurations increases system performance because they use energy excess to produce hydrogen.
– Fuel cell

The use of fuel cells will provide a faster response, working at lower temperatures than other technologies on the market [121,134,135]. This will enable a faster response under dynamic changes in demand or generation, reducing problems associated with the lack of power in heavy load situations.

4. Techno-economic solutions

In order to optimize the energy management strategy based on the criteria presented in the previous sections, the scientific literature includes different technical and economic solutions for the operation of the most vulnerable elements of the system, such as batteries and hydrogen-based elements for production and consumption as electrolyzers

Table 3
Summary of economic criteria.

					
Solar and wind syste s today have a good lifetime nd low maint nance and opera ion cost Help to introduce ne energy models		Bat eries help to ensure demand a all times, red cing penalty cost	Alkaline electrolyzer echnology is we l known Reduced initial ost with respect to o her technologi s Improve sys em erformance ab orbing energy exc ss	EM fuel cells rovide faster res onse to ensure demand Hi her efficiency t an traditional e ergy sources	Proper e ergy management strategy can reduce verall cost

Table 4
Summary of techno-economic solutions.

			
The se of a DC Bus acilitates the system config ration Sup rcapacitors for ower factor correctio Use f grid to ensure ower balance	Direct con ection of batteries to DC Bus Current/Volt ge charge modes Hysteresis operation mode	Minimum ower electrolyzer o eration Variable power onditions	U e of a modular uel cell system peration in Ohm c zone se of filters to r duce switching effects

and fuel cells respectively. A summary of techno-economic solutions is presented in Table 4. The main solutions proposed in the literature are described below.

4.1. System configuration

- The use of a DC bus provides a simple way to control the energy exchange between the elements, avoiding power quality problems and power factor correction. In the same way, it can reduce the number of devices needed to adapt the generation, because most generators produce in DC currents [1].
- In case of a grid-connected system, the use of supercapacitors allows the correction of the power factor by injecting reactive power into the internal bus [31].
- The use of the grid will help to ensure the power balance, and supply the demand or absorb energy in case of deficit/excess energy situations respectively.

4.2. Batteries

- Battery connection: Direct connection of batteries to the internal bus will save bidirectional converters. On the other hand, a more comprehensive power control is necessary in order to resolve the problem with DC bus voltage variation, and to protect batteries against excessive discharge or overcurrent situations [136]. The use of power converters will increase system cost but it allows different charge modes to protect batteries.
- Battery operation: In case of charging situations for batteries, the use of current mode will allow faster charges for low SOC. On the other hand, in case of high SOC, the voltage mode will protect the battery with a slower charge mode in which current will be imposed by battery voltage [50,137]. The use of a reduced depth of discharge will extend the lifetime of the battery [98,101,102,138].
- Hysteresis Band: The use of hysteresis based on the battery SOC will determine the start or stop conditions of fuel cell and electrolyzer. These strategies will reduce the number of operating cycles, and therefore increase the lifetime of the elements by minimizing their degradation [18,19,51–59,133]. Strategies with appropriate hysteresis bandwidths will increase the system performance, avoiding the overuse the batteries, and reducing start and stop cycles for electrolyzer and fuel cell [51,57].

4.3. Hydrogen resource

- Electrolyzer operation: Strategies which impose a minimum operating power for the electrolyzer, allow the operation in a high efficiency area, and high purity production [18,47,50,111–113]. The use of electrolyzers under variable power conditions can increase the hydrogen production [54,133].
- Fuel cell configuration: The use of a modular fuel cell system will help to increase the safety system response, just as it may be adapted to the demand in the proper way, regarding the use of a single fuel cell with high nominal power [29].
- Fuel cell operation: Fuel cells always operate in the ohmic zone, ensuring high performance and low degradation [9]. Similarly, the operation at constant power will reduce problems related to dynamic changes in the demand and damage associated [118,121,123].
- Power converter switching: The implementation of active or passive filters reduces the effect of switching of power converters for frequencies between 1 and 120 Hz [60,127,128].

5. Energy management strategies

To operate, integrate and interconnect several devices in a generation system, ensuring safe operating regime and fulfilling the goals, a control system to manage the energy is necessary. A proper energy management strategy enables the system to supply the demand, increase the lifetime of the elements, reduce operating costs and therefore maximize system performance, providing a technically and economically feasible option. The aims of the different management strategies influence the behavior of the system. Most of the works found in the scientific literature present simulated strategies for hybrid systems, in order to maintain the demand, obviating technical and economic optimization criteria and multiple problems associated with real systems, such as degradation of hydrogen equipment or a correct management energy vector. Next, a review of the different strategies used in the scientific literature can be found, analyzing the different objectives used in each one. A summary and description of all works studied in this section is presented in Appendix B-E according to the four strategies studied bellow.

5.1. Strategies in which the objective is to the ensure the demand

The main objective of this type of strategy is to satisfy the demand, and for that it bases its control algorithm mainly on three design criteria: power balance, state of charge of the batteries and hydrogen stock, depending on the elements which integrate the system (see Table 5). These design variables establish the operating limits of major energy storage systems, such as batteries to short-term storage, and fuel cells and electrolyzers to long-term storage.

The main advantage of this strategy is the simplicity in design and control, governed mainly by algorithms based on simple flow chart diagrams. In the same way, sizing applications that include this strategy

Table 5
Summary of strategies which objective is to ensure demand.

Ref.	Optimization objectives	Design constrains	Control Algorithm
[2,5,8–12,29,32–34,41,46,48,49,61–63,65–69,72,73,88–92,94,97]	Ensure Demand Sizing	Power balance SOC H_2 Stock	Flow Chart
[31]	Ensure Demand	Power balance Battery Voltage H_2 Stock	Linear Programming
[55]	Ensure Demand	Power balance SOC H_2 Stock	Model Predictive Control
[64]	Ensure Demand	Power balance SOC H_2 Stock	Fuzzy Logic
[70][71]	Ensure Demand Sizing	Power balance SOC H_2 Stock	Pareto Optimal Solution
[35]	Ensure Demand	Power balance SOC H_2 Stock	Flow Chart & ANFIS

are also simplified. On the other hand, the non-use of optimization parameters based on equipment degradation, modes of operation or operating costs of the system, causes a non-optimal solution from a technical and economic point of view.

A summary scheme of the main characteristics of this strategy and a review of the optimization objectives, design constrains and control algorithm is presented in Fig. 6 and Table 5 respectively.

The operating priority is shared by almost all reviewed works, [9,11,12,32,33,35,41,46,48,49,55,61,62,65,71–73,88,90–92], and they give to the short-term storage system the responsibility for absorbing transients and stabilizing the power balance between a maximum and minimum state of charge. From these values, the fuel cell and electrolyzer will operate for the cases of excessive deficit or excess of energy respectively. The use of short-term storage systems implies having an element capable of dumping certain deviations in the power balance, and therefore limiting the use of the hydrogen storage system against situations of high excess or energy deficit. All this results in a lower degradation of these elements and therefore an increase in the useful lifetime of the system, to the detriment of the batteries.

There are other works whose strategies differ from the previous one. These other ones lack short-term storage elements, and therefore the SOC of the batteries/SC is not a design parameter. For example, in [2,8,29,34,63,66–70,89,90,94,97] the start/stop conditions of the hydrogen storage system will be determined by the value and sign of the power balance. This solution causes a high number of starts and stops of the fuel cell and electrolyzer, and consequently reduces the useful lifetime due to associated degradation.

With respect to the hydrogen-based energy storage system, the topologies studied in [8,9,29,35,41,46,55,65–67,69,72,73,88–92,94,97] have a hydrogen generating element, which allows the increase of the performance of the system by taking advantage of the excess energy and converting it into hydrogen. This hydrogen can be used by the fuel cell when it was necessary.

In the case of isolated topologies such as those presented in [5,8–12,29,35,46,48,49,55,61–63,65–68,73,88–92,94,97], the energy generation which cannot be stored by the energy storage systems is discarded through dumping loads. This fact implies a reduction in the operating performance of the system. Conversely, in case of excessive deficit, a prioritization of loads is necessary and in extreme cases, it is also necessary to disconnect the demand. This type of topology allows an operation strategy highly conditioned by the system sizing, and therefore the satisfaction of the demand can be put at risk.

On the other hand, in grid-connected topologies, the grid is an active element of the system and it allows maintaining the power balance

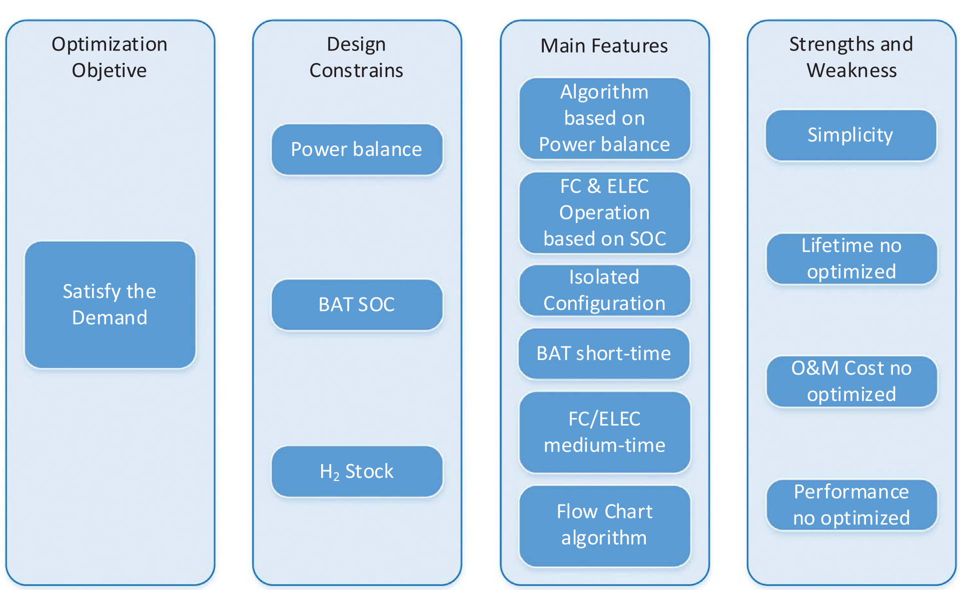

Fig. 6. Main characteristics of strategies for which objective is to ensure demand.

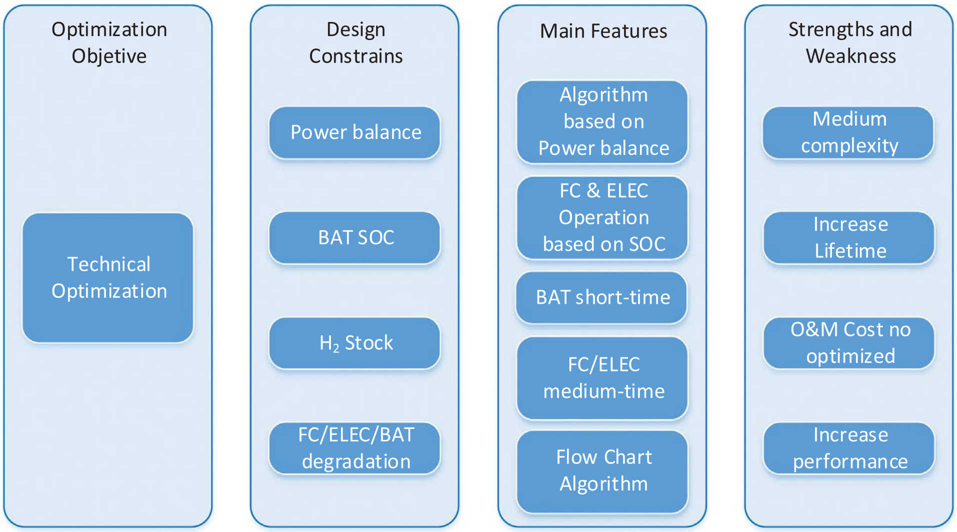

Fig. 7. Main characteristics of strategies whose objectives include technical decision factor.

by absorbing or supplying energy when the hydrogen stock is over its respective operating limits. In these topologies, such as those studied in [2,31–35,41], the excess or deficit of energy is corrected by the injection or purchase of energy from the grid. These topologies allow higher flexibility in the strategy and, also guarantee demand under any energetic situation.

Finally, based on the control algorithm, Flow Chart algorithm is the most extended solution, while other optimization algorithms are also used to calculate the reference power of the hydrogen energy system regarding the design constrains. As an example, Linear Programming in [31], Model Predictive Control in [55], Fuzzy Logic in [64], Pareto algorithm in [70] and [71] or Adaptative Neuro Fuzzy Inference System in [35]. The problem associated with these control algorithms is the need for accurate models of the overall system, demand and weather resources.

5.2. Strategies whose objectives include technical decision factor

These strategies, as well as ensuring demand at all times, take into account technical criteria in order to ensure the proper use of the equipment. The main target of these strategies is to reduce the degradation of the equipment more susceptible during operation of the system. These elements are battery, electrolyzer and fuel cell. The solutions adopted in the literature are diverse and depend on the main goal of the study. In order to perform the control algorithm, power balance, state of charge of the storage system and degradation parameters are defined as design constrains.

The main advantages of these strategies are their medium complexity design and control, and the good results in terms of system performance and/or lifetime, depending on the optimization objective. On the other hand, economic parameters are not taken into account, so the system response is not optimized.

A summary scheme of the main characteristics of this strategy and a review of the optimization objectives, design constrains and control algorithm is presented in Fig. 7 and Table 6 respectively.

As for the previous case, the most common solutions integrate short-term storage systems, and therefore, they will operate in first instance to absorb or supply energy when it is necessary. The use of long-term storage system based on hydrogen backup will operate when the maximum or minimum operating limits of batteries are reached. In the

Table 6
Summary of strategies whose objectives include technical decision factor.

Ref.	Optimization objectives	Design constrains	Control Algorithm
[19]	Ensure Demand Increase Lifetime	Power balance	Model Predictive Control
[30,47,50–,56–58,60,74,76,95]	Ensure Demand Increase Performance Increase Lifetime	Power balance SOC H_2 Stock	Flow Chart
[36]	Ensure Demand Stability	Power balance SC Energy function	Differential Flatness Based Control
[75]	Ensure Demand Maximize H_2 generation	Power balance SOC	Linear Programming
[77]	Ensure Demand Maximize H_2 generation Minimize Battery use	Power balance SOC	Fuzzy Logic
[78]	Ensure Demand Increase Lifetime	Power balance Load Forecast	Dynamic Real-Time Optimization
[79]	Ensure Demand Increase Lifetime	Power balance SOC	Fuzzy Logic
[80]	Ensure Demand Increase Lifetime	Power balance SOC H_2 Stock Weather Forecast	Flow Chart
[81]	Ensure Demand Increase Lifetime	Power balance SOC H_2 Stock	Artificial Neural Network Controller

case of isolated topology, the use of dumping loads and demand prioritizing are the most common solutions to solve the energy excess or high deficit of energy situations. On the other hand, in the case of grid connected topologies, the grid will absorb or supply energy when the energy storage system is over its operation limits. An example of application of these strategies are presented in [19,30,47,50–54,56–58,60,74,80,95].

Other works define the priority and the power reference of the elements based on the solution of different algorithms which have taken into account diverse parameters. Examples of that are studied in [36,75–79,81].

The main differences between these strategies and the ones studied in the previous section are based on the restrictions imposed to the operation points of the energy storage system to assure the different objectives, increase the system lifetime or increase the system performance.

In order to increase the system lifetime, different solutions are adopted to reduce the degradation caused by start/stop cycles of electrolyzers and fuel cells. [53][54][56][57][58] use a strategy based on hysteresis operation mode, which are defined by the predefined values of battery SOC. Despite being an important improvement from the point of view of degradation, the hysteresis bandwidth is fixed and modeled by a simple flow chart. For this reason, there is room for improvement in the storage system utilization.

In the same way, [19,52,79,80] use weather and demand prediction in order to determine if the use of hydrogen storage system in the next iteration step is necessary, reducing unnecessary start/stop cycles. To implement the control law, flow chart algorithm is used in [52] and [80], while [19] and [79] use Model Predictive Control and Fuzzy Logic respectively. According to above, the reliability of the strategy will depend on accurate forecast and reliable system models to perform a correct operation, and therefore the system performance will be conditioned by the accuracy of the models used.

Finally, [81] proposes a strategy in which Artificial Neural Network Controller is used to define the power reference of the hydrogen storage system in order to maintain the battery SOC in a fixed point. This strategy will increase the battery lifetime at expense of an intensive use of the fuel cell and electrolyzer. The system operating and maintenance cost in this strategy will be huge because of the higher degradation on the hydrogen storage system.

With the objective to increase the system performance, three solutions are adopted.

The first one tries to guarantee high purity products from electrolysis process. To get this target, in [30,47,51,95] a simple strategy based on flow chart and imposed minimum power to start up the electrolyzer is used. This constraint helps to solve degradation problems associated with the fuel contamination on fuel cells. On the other hand, higher utilization of batteries will be required to assure the minimum power of the electrolyzer in the case of a low power balance.

The second solution implemented in [74] modifies the fuel cell power in order to operate always in its maximum efficiency point. This strategy causes the fuel cell generation to not be synchronized with the energy requirements, and therefore implies a higher use of batteries and even start/stop cycles.

The last solution has the goal to maximize the hydrogen production. To get it, an optimization problem is defined in [75,77,78], and solved by different optimization algorithms: Linear Programming, Fuzzy Logic and Dynamic Real-Time Optimization Algorithm. The non-use of lifetime constraints could provoke high degradation of the energy storage system, so this strategy does not get an optimal solution.

5.3. Strategies whose objectives include economic decision factor

These strategies include an economic analysis in addition to a guarantee of the power balance. These economic parameters will help to determine an optimal solution from an economic point of view. In many cases, this optimal solution does not determine a favorable operation for equipment due to not having enough technical criteria to avoid problems associated with different operating regimes. These strategies have potential applications on sizing and long-term analysis.

The main advantage of these strategies is the optimal system response from an economic point of view. On the other hand, complex optimization algorithms are used, so it increases the complexity in real applications. In the same way, the reliability of the model to define the cost function is crucial to get the best performance. Finally, technical parameters are not taken into account, so the system lifetime might not be optimized.

A summary scheme of the main characteristics of this strategy and a review of the optimization objectives, design constrains and control algorithm is presented in the Fig. 8 and Table 7 respectively.

The solutions adopted in the literature are based on the use of different cost functions associated with the charge or discharge of the elements, which determine an optimization problem. Different algorithms are used to calculate the solution of the optimization problem. These determine the priority and the power reference of each element which guarantees the most economical utilization of the energy storage system during each integration period. As happened in previous cases, the solution implemented in extreme cases of high excess or energy deficit will depend on the topology.

The main difference between the consulted references is the optimization algorithm used to minimize the cost function (see Table 7). In the case of grid-connected applications, the interaction between grid and hybrid system is also taken into account. For this reason, the losses or benefits when buying or selling energy from the grid are taken into account as well.

5.4. Strategies whose objectives include technical and economic decision factors

Finally, this kind of strategy seeks to increase system performance,

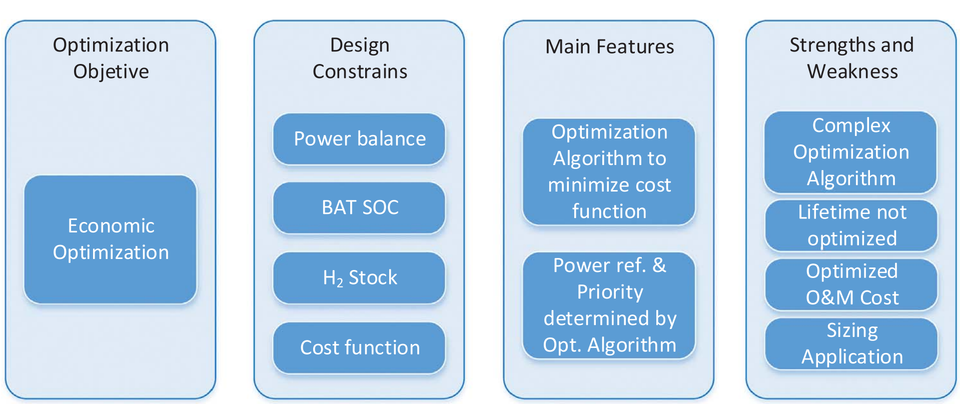

Fig. 8. Main characteristics of strategies whose objectives include economic decision factor.

Table 7
Summary of strategies whose objectives include economic decision factor.

Ref.	Optimization objectives	Design constrains	Control Algorithm
[3]	Ensure Demand Cost reduction	Power balance Cost function	Model Predictive Control
[28]	Ensure Demand Cost reduction	Power balance Cost function	Flow Chart & Genetic Algorithm
[82]	Ensure Demand Cost reduction	Power balance SOC Cost function LPSP CO_2 emissions	Fuzzy Logic & Differential Evolution Algorithm
[96]	Ensure Demand Cost reduction	Power balance SOC H_2 Stock Cost function Weather Forecast	Mixed-Integer Linear Programming
[83]	Ensure Demand Cost reduction	Power balance SOC H_2 Stock Cost function	Flow Chart
[37]	Ensure Demand Cost reduction	Power balance Cost function	Receding Horizon Optimization Algorithm
[38]	Ensure Demand Cost reduction	Power balance Cost function	Genetic Algorithm
[39]	Ensure Demand Cost reduction	Power balance Cost function	Receding Horizon Optimization Algorithm
[84]	Ensure Demand Cost reduction	Power balance Cost function	Gravitational Search Algorithm
[85]	Ensure Demand Cost reduction	Power balance Cost function Load Forecast	Particle Modified Swarm Optimization Algorithm
[40]	Ensure Demand Cost reduction	Power balance Cost function Load Forecast	Adaptive Model Predictive Control
[42]	Ensure Demand Cost reduction	Power balance SOC Cost function Weather Forecast	Fuzzy Logic
[43]	Ensure Demand Cost reduction	Power balance SOC H_2 Stock Cost function	Interior Search Algorithm

based on the proper supply to demand. Technical and economic criteria are taken into account to increase equipment life and reduce maintenance costs. This strategy has an optimal solution for a technical and economic point of view, compared to traditional generation alternative systems. The solutions adopted in the literature are based on nonlinear optimization problems, using cost and equipment depreciation

Table 8
Summary of strategies whose objectives include technical and economic decision factor.

Ref.	Optimization objectives	Design constrains	Control Algorithm
[59]	Ensure Demand Cost reduction Increase Lifetime	Power balance SOC H_2 Stock Cost function	Flow Chart
[86]	Ensure Demand Cost reduction Increase Lifetime	Power balance SOC H_2 Stock Cost function	Fuzzy Logic
[87]	Ensure Demand Cost reduction Increase Lifetime	Power balance SOC	Particle Swarm Optimization Algorithm
[44]	Ensure Demand Cost reduction Increase Lifetime Increase Performance	Power balance SOC H_2 Stock	Particle Swarm Optimization Algorithm
[93]	Ensure Demand Cost reduction Increase Lifetime	Power balance SOC H_2 Stock Cost function Degradation function	Flow Chart & Linear Programming
[45]	Ensure Demand Cost reduction Increase Lifetime Increase Performance	Power balance SOC H_2 Stock Cost function	Flow Chart

integrated in a multi-objective function. The solution of this problem by various techniques, determines the reference power supplied by each element in each iteration, ensuring the power balance with optimal system performance. Finally, as the previous cases, the solution implemented in extreme cases of high excess or energy deficit will depend on the topology.

The main advantage of these strategies is the optimal system response from a technical and economic point of view. Lifetime and performance parameters are taken into account to define the cost function. On the other hand, complex optimization algorithms are used, so it increases the complexity to develop real applications.

A summary scheme of the main characteristics of this strategy and a review of the optimization objectives, design constrains and control algorithms is presented in the Fig. 9 and Table 8 respectively.

The main difference between the proposed strategies is based on the technical constraints, and also the optimization algorithm used to solve the nonlinear optimization problem.

In [44,86,93] Fuzzy Logic, Particle Swarm Optimization Algorithm and Linear Programming are used respectively to solve the multi-objective problem. The cost function includes lifetime parameters of each

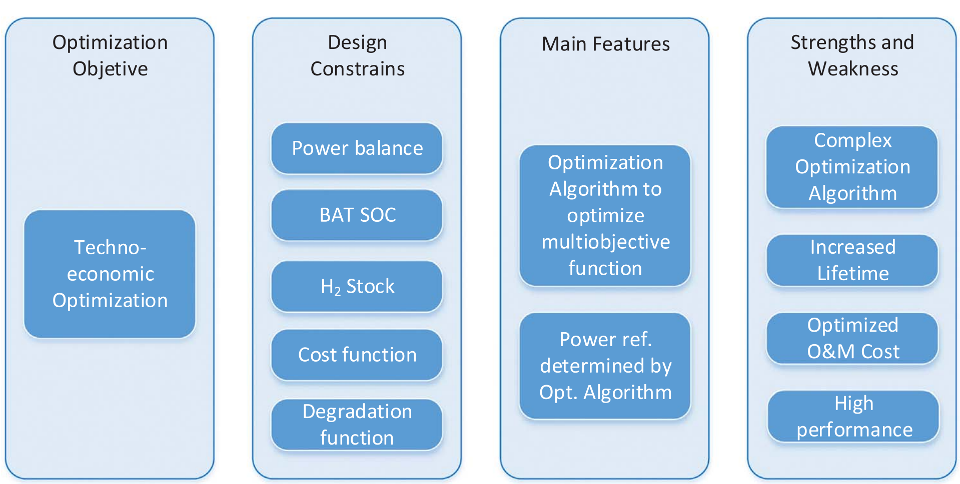

Fig. 9. Main characteristics of strategies whose objectives include technical and economic decision factor.

element and also the associated degradation cost. The priority and the power reference of each element are based on the response of the optimization problem.

In [87] a work is presented in which three different objectives are optimized with the use of Particle Swarm Optimization Algorithm. These objectives will define three different cost functions depending on the objective to minimize operation and maintenance cost, increase system efficiency or increase system lifetime.

In [59] the cost associated with the degradation process is included in the cost function. The priority of the energy storage system is based on the energy reserves of each storage system and the associated accumulated degradation cost.

Finally, [45] presents different cases and strategies based on a flow chart diagram in which different optimization objectives are studied. The short-term storage system is the core of the decision, and the start/stop conditions and power reference of the fuel cell and electrolyzer will depend on hysteresis operation mode and the optimization objective. Cost reduction, hydrogen maximization and system performance are the three main objectives studied in this work.

6. Discussion

Based on the structure of the paper and attending to all the issues developed in it, the Discussion Section will be classified in each of the topics analyzed along the manuscript.

6.1. Topologies and configurations

The chosen configuration, the topology and the elements which compose the system, will determine the operation and performance of it, (see Table 1 and Appendix A). The main problem to be solved in this area is the correct management of the energy in situations of excess and energy deficit, due to the stochastic production of the main sources of renewable generation.

Isolated topologies present problems related to low performance and low security to supply the demand. To solve the last problem it is common to oversize the storage equipment, increasing the investment cost. In the same way, in case of excess energy, the surplus energy must be discarded and therefore reduces the performance of the system.

Grid connected topologies allow the grid to be included as an active part of the system, and therefore optimize the system during excess or deficit of energy.

According to the energy storage system studied in Section 2.3, the use of batteries as a short-term storage element allows reduction of costs and the degradation related to the operation of the hydrogen storage systems. In addition to the above, simplicity, high efficiency and modularity help with the integration of these technologies. On the other hand, the charging process must be controlled and requires high charging time, caused mainly by the seasonality in photovoltaic or wind generation. All this has repercussions in a more complex system and the use of batteries with higher capacity.

Similarly, the use of hydrogen-based storage systems ensures a high energy density solution to guarantee a constant response against low state of charge of batteries, as well as a solution to evacuate the excess of energy in isolated systems. In addition to the above, it is presented as a clean and low maintenance system compared to traditional diesel systems. On the other hand, the complexity, the cost of these systems and their reduced useful lifetime, determine the need of a proper energy management strategy.

The use of hybrid storage systems will reduce the sizing of both technologies, as well as provide a more economical, simpler and more viable solution to the problem of energy storage.

The sizing criteria of these hybrid systems should respond to technical and economic criteria, as well as the topology used. Due to the above, grid-connected systems allow a cost reduction in batteries thanks to the reduction of its capacity. The stock of hydrogen can also be reduced because the grid can supply energy during low SOC situations. In the same way, during charging process, the grid can evacuate energy, so the hydrogen generator power could also be decreased.

In isolated applications, to guarantee the demand is the priority of the system, so a more comprehensive sizing process should be carried out in order to calculate the optimal storage capacity of the two storage systems. The maximum battery DOD, environmental conditions, demand profile as well as the cost of the different elements, will determine an optimization problem that requires a more exhaustive analysis.

6.2. Optimization objectives

The optimization objectives analyzed in Section 3, Tables 2, 3 will determine the performance and complexity of the system operation. Similarly, system configuration can limit the scope of these objectives.

The main objective of any generation system must be to satisfy the demand, so additional objectives will be determined by the possible options that the configuration and topology of the system allows. For example, isolated systems which only have a storage system based on batteries or hydrogen will not be able to implement other objectives than to guarantee the power balance at any moment.

The inclusion of new elements will allow including a degree of freedom on the decisions of the system against excess or deficit energy situations. The system response can be optimized according to technical and/or economic criteria, such as the operation of the system with a maximum performance or a minimum cost or a minimum degradation. Those works which integrate both criteria will allow an optimal performance of the system.

The study of new optimization objectives will allow renewable energy systems to be more competitive from a technical and economic point of view, thus encouraging the use of environmentally friendly technologies.

6.3. Techno-economic parameters

The technical and economic parameters are the baseline to define management strategies to fulfill different optimization objectives.

These parameters will largely depend on the topology and configuration used, as they will determine the advantages and disadvantages of the different technologies as well as the minimum criteria for a safe and efficient operation.

Taking into account the most used configurations, as has been studied in Section 4, Table 4 the most important parameters to guarantee the primary objective of satisfying the demand are the power balance, the batteries SOC and the available hydrogen stock. In the same way, in order to optimize system response, other criteria may be taken into account to meet secondary optimization objectives, such as equipment degradation, battery charging processes, the modularization of the fuel cell and the operation and maintenance cost.

The inclusion of new technical and economic parameters will allow a more secure and efficient management of the system, although more complex energy management strategies will be necessary.

6.4. Energy management strategies

The different energy management strategies are based on the achievement of different optimization objectives, based on different technical and economic criteria. These strategies are intended to define the energy flows during the normal operation of the system, and therefore to determine which equipment must operate and its power reference.

Depending on the optimization objectives and the topology and configuration of the system, the strategy can be more or less complex, requiring the use of more or less complex optimization algorithms.

In view of the classification of strategies according to their objectives, the simplest strategies are those in which the objective is to satisfy the demand, (see Fig. 6, Table 5 and Appendix B). For that, it bases its control algorithm mainly on three design criteria: power balance, state of charge of the batteries and hydrogen stock, depending on the elements that integrate the system. These design variables establish the operating limits of major energy storage systems, such as batteries to short-term storage, and fuel cell and electrolyzer to long-term storage. From the point of view of system performance, these strategies do not optimize the use of equipment or operating costs, so they are recommended for systems with a very simple configuration such as isolated topology with a single energy storage system.

Strategies that take into account technical criteria, try to improve the system response with respect to the previous strategies, and a more complex configuration allows their implementation. The main target of these strategies is to reduce the degradation of the equipment more susceptible during operation of the system. These elements are battery, electrolyzer and fuel cell. The solutions adopted in the literature are diverse and depend on the main goal to study. In order to perform the control algorithm, power balance, state of charge of the storage system and degradation parameters are defined as design constrains. Other objectives that can integrate these strategies are increasing the useful lifetime, increasing the efficiency of a certain element, increasing the hydrogen production, etc. Depending on the previous objectives, the implemented solutions are different including hysteresis operation mode, minimum power condition for electrolyzer, or fixed operation power in the case of fuel cells, (see Fig. 7, Table 6 and Appendix C). These strategies are shown as an incomplete solution, due to the need for more competitive systems from an economic point of view.

On the other hand, strategies that only take into account economic criteria provide a solution that tries to minimize a cost function, and for this purpose, they use optimization algorithms which determine the priority and reference power of the elements, (see Fig. 8, Table 7 and Appendix D). This type of strategy increases complexity by introducing a more complex algorithm, so its implementation in real systems will require a large computational capacity of the control system. Although there is an apparent cost reduction with respect to the previous strategy, it is an incomplete analysis, since it does not take into account operation costs associated with certain operation modes, such as start and stop cycles of the fuel cell and electrolyzer.

Finally, we can find strategies which incorporate both criteria, technical and economic, in order to optimize the response of the system. These strategies are complex and consider a cost function that includes degradation parameters associated with each piece of equipment. Technical and economic criteria are examined to increase equipment life and reduce maintenance costs. This strategy has an optimal solution for a technical and economic point of view, compared to traditional generation alternative systems.

The solution of this problem by various techniques, determines the reference power supplied by each element in each iteration, ensuring the power balance with optimal system performance. This multi-objective problem requires a complex optimization algorithm, so it presents an added difficulty to be implemented in a real system, (see Fig. 9, Table 8 and Appendix E). Conversely, these types of strategies use the advantages of the elements to mitigate the effects of the main drawbacks. That is, despite the fact that complex optimization algorithms are required these strategies guarantee higher lifetime and better performance of the whole system at time that reduced cost.

7. Conclusions

In this paper, a thorough review of the energy management strategies for renewable hybrid energy systems with hydrogen backup has been carried out. It classifies and analyzes both the topologies of the systems as the criteria and techno-economic solutions until reaching the energy management strategies. In addition, the work is completed with an exhaustive discussion based on the obtained results.

Every day it becomes more evident that there is a need to migrate from a centralized electric model to a distributed model. Distribution systems based on fossil fuels require importing resources and producing pollution. Migration models based on renewable energies will allow generation of a low level of emissions and less dependence on oil.

Despite the benefits of renewable energy, there are problems related to each renewable source and associated technology, such as dependence on environmental resources, high cost, etc. To minimize the negative impact of these technologies, hybrid systems are presented as a viable, safe and effective solution. With them, the use of hydrogen technology is presented as a future value, mainly due to the high performance of the elements, and the possibility of energy storage in the form of hydrogen as an energy vector.

In order to ensure a proper operation mode of hybrid systems based on renewable energy, guaranteeing demand and increasing system performance, it is necessary to use energy management strategies. The objectives of these strategies will determine the behavior of the system, so it is very important to define a proper management strategy. The study of new technologies based on a technical-economic analysis is a key factor to make the hybrid system competitive.

For this reason, this paper has presented a comprehensive review and analysis of different energy management strategies for hybrid renewable systems based on hydrogen backup. For this purpose, the first step has been to classify hybrid systems in different ways. The most common are those which distinguish the different systems depending on their connection to the grid as well as the method of integration of elements inside the system.

Next, attending to the importance of developing an energy management strategy in a hybrid renewable energy system, technical and economic criteria have been described throughout. These parameters will help to design a correct energy control, increasing the system performance.

Once the technical and economic criteria have been studied, an analysis about the solutions found in the scientific literature is presented. In order to optimize the energy management strategy based on the chosen criteria, the literature includes different solutions for the operation of the most vulnerable elements of the system, such as batteries and hydrogen-based elements for production and consumption as electrolyzers and fuel cells respectively.

Finally, a review of the different strategies used in the scientific literature can be found, analyzing the different objectives used in each one. A summary and description of all works studied in this section has been presented in Appendix B–E according to the four strategies studied above. Moreover, benefits and problems associated with these systems are defined. The revision includes an analysis of the main characteristics, highlighting the strengths and weaknesses of each case. According to the latter, we can conclude that the most common strategies only try to satisfy demand, and in spite of their simplicity, show an inefficient behavior. Strategies that include technical and economic criteria are presented as the most efficient and secure, while they require more complex algorithms that are difficult to implement in a real control system.

Based on the study done and according to the results, it is necessary to continue advancing in the development of algorithms and multi-objective strategies that allow their application in real systems, permitting a more widespread use in distributed energy applications. Winning the bet on renewable hybrid energy systems with hydrogen backup depends fundamentally on this.

Appendix A

Ref.	Topology	Integration method	Integrated Elements
[2]	Grid connected	DC Bus	PV-WT-FC
[3]	Grid connected	DC Bus	PV-WT-BAT-FC-ELEC
[5]	Isolated	DC Bus	PV-FC-BAT
[8]	Isolated	DC Bus	PV-WT- FC-ELEC
[9]	Isolated	DC Bus	WT-BAT-FC-ELEC
[10]	Isolated	DC Bus	WT-FC-SC
[11]	Isolated	DC Bus	PV-WT-BAT-FC
[12]	Isolated	DC Bus	PV-WT-BAT-FC
[19]	Grid connected	DC Bus	PV-WT-FC-ELEC
[28]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[29]	Isolated	DC Bus	PV-WT-FC-ELEC
[30]	Grid connected	DC Bus	PV-WT-BAT-FC-ELEC-CHP
[46]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-SC
[47]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[48]	Isolated	DC Bus	PV-BAT-FC-SC
[49]	Isolated	DC Bus	PV-BAT-FC
[31]	Grid connected	DC Bus	PV-BAT-FC-SC
[50]	Isolated	DC Bus	PV-BAT-FC-ELEC
[51]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[52]	Isolated	DC Bus	PV-WT-BAT-FC
[53]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[54]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[55]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[56]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[57]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[58]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[59]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[60]	Isolated	DC Bus	PV-WT-FC-ELEC-SC
[32]	Grid connected	DC Bus	PV-BAT-FC
[33]	Grid connected	DC Bus	PV-BAT-FC
[61]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[62]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[63]	Isolated	DC Bus	PV-FC-ELEC
[64]	Isolated	DC Bus	PV-BAT-FC-ELEC
[65]	Isolated	DC Bus	PV-BAT-FC-ELEC
[66]	Isolated	DC Bus	PV-WT-FC-ELEC
[94]	Isolated	AC Bus	PV-WT-FC-ELEC
[67]	Isolated	DC Bus	WT-FC-ELEC
[97]	Isolated	Hybrid Bus	PV-WT-FC-ELEC
[68]	Isolated	DC Bus	PV-WT-FC
[69]	Isolated	DC Bus	PV-WT-FC-ELEC
[34]	Grid connected	DC Bus	PV-WT-FC
[70]	Isolated	DC Bus	PV-WT-FC-ELEC
[71]	Isolated	DC Bus	PV-BAT-FC-ELEC
[72]	Isolated	DC Bus	PV-WT-BAT-FC
[73]	Isolated	DC Bus	PV-FC-ELE C-SC
[35]	Grid connected	DC Bus	PV-WT-BAT-FC-ELEC
[74]	Isolated	DC Bus	PV-WT-BAT-FC
[36]	Grid connected	DC Bus	PV-WT-FC-SC
[75]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[76]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[77]	Isolated	DC Bus	PV-BAT-FC-ELEC
[95]	Isolated	AC Bus	PV-WT-FC-ELEC-SC
[78]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[79]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[80]	Isolated	DC Bus	PV-BAT-FC-ELEC
[81]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[82]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[96]	Isolated	AC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[83]	Isolated	DC Bus	PV-BAT-FC-ELEC
[37]	Grid connected	DC Bus	PV-WT-FC-ELEC

[38]	Grid connected	DC Bus	WT-FC
[39]	Grid connected	DC Bus	WT-FC-ELEC-CHP
[84]	Isolated	DC Bus	PV-WT-FC-ELEC
[85]	Isolated	DC Bus	MT-BAT-FC
[40]	Grid connected	DC Bus	PV-BAT-FC
[86]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC
[87]	Isolated	DC Bus	PV-WT-BAT-FC-ELEC-DIESEL
[88]	Isolated	DC Bus	PV,WT,FC,ELEC,BAT,DIESEL
[89]	Isolated	DC Bus	PV,WT,FC,ELEC
[41]	Grid connected	DC Bus	WT,BAT,FC,ELEC
[90]	Isolated	DC Bus	PV,WT,FC,ELEC,DIESEL
[91]	Isolated	DC Bus	PV, BAT,FC,ELEC
[92]	Isolated	DC Bus	PV,BAT,FC,ELEC
[42]	Grid connected	DC bus	PV,WT, BAT,FC,ELEC
[43]	Grid connected	DC bus	PV,WT,FC,ELEC
[44]	Grid connected	DC bus	PV,WT, BAT,FC,ELEC
[93]	Isolated	DC bus	PV,WT, BAT,FC,ELEC
[45]	Grid connected	DC bus	PV,WT, BAT,FC,ELEC

Appendix B

Ref	Elements of the hybrid system / Application	Optimization objectives	Design constraints	Outcome
Strategies which objective is to ensure the demand				
[2]	PV, WT, FC On-grid application DC bus Simulated	Ensure demand	Power balance	Strategy to ensure demand. Wind and solar generators are presented as the main sources of energy. In the case of excess energy, it is sold to the grid; the energy deficit is supplied by fuel cell or grid. It focuses mainly on the design of algorithms to control power converters, in order to interconnect the different elements and to establish the optimum operating point of each one.
[5]	PV, FC, BAT Isolated application DC bus Simulation results	Ensure demand	Power balance	A micro grid with solar source as the main generator. In the case of energy deficit, battery or fuel cell may supply demand. In the case of excess energy, batteries charge with constant current to a maximum value, after which the energy will be discarded by dumping load. The main objective is the study of different control algorithms for power converters, in order to ensure optimum operating point for generators.
[8]	PV, WT, FC, ELEC Isolated application DC bus Simulated	Ensure demand	Power balance	Strategy to ensure the power balance. The main generators are wind and solar sources. The excess energy is absorbed by the electrolyzer while energy deficit is supplied by the fuel cell. This work focuses on the design of control algorithms for power converters, which allow interconnection of generators and loads and operate all elements at optimum operating points.
[9]	WT, FC, ELEC, BAT Isolated application DC bus Simulated	Ensure demand	Power balance, SOC, FC power points, Wind forecast	The strategy presented is based on wind and demand forecast. For a known forecast, a study is performed based on the stock of energy stored in hydrogen tanks and batteries, determining the maximum acceptable load, including prioritizing if it is not possible to assure it. The operation of different elements is based on different operating points of the battery SOC. The optimal system response will depend on the accuracy of the forecast.
[10]	WT, FC, SC Isolated application DC bus Simulated	Ensure demand	Power balance, DC and SC energy	The strategy is based on keeping the DC bus energy, in order to ensure demand at all times. Wind generators and fuel cells are presented as the main generators of the system. In case of deficit/excess energy situations, the supercapacitor will supply or absorb energy to ensure energy stability in the bus. To calculate the reference power of the supercapacitor, the problem is based on state variables models, which are represented by the DC bus and supercapacitor energy. The resolution of the different trajectories of the state variables will be solved by a flatness based control.

[11]	PV, WT, FC, BAT, BIOETHANOL REFORMER Isolated application DC bus Simulated	Ensure demand	Power balance, SOC	The strategy presented tries to ensure the demand and to maximize the use of hydrogen obtained from a bioethanol reforming process. Wind and solar sources are the basic generators of the system. The battery is presented as the main backup element of the system, and hence the SOC is the most important decision parameter. In the case of excess energy, batteries assume the system load. In the opposite case, batteries and fuel cells with the bioethanol reformer will provide the necessary energy. This is an example of hydrogen resource use for chemical industry application.
[12]	PV, WT, FC, BAT Isolated application DC bus Simulation results	Ensure demand	Power balance	Simple strategy for an isolated application. The main generators are determined by wind and solar sources. In the case of excess energy, batteries will absorb it until their maximum capacity and then it will be discarded. In the case of energy deficit, batteries in the first instance and subsequently fuel cells will supply the needed energy to keep the power balance.
[29]	PV, WT, FC, ELEC Isolated application DC bus Simulated	Ensure demand	Power balance	The management strategy used is simple, wind and solar are presented as main generators of the system. In the case of excess energy, it will be converted into hydrogen by electrolysis. In the case of energy deficit, a fuel cell stack is used according to the rated power of each one. This system provides a security response to supply the load, ensuring demand in situations of excessive deterioration of any fuel cell, as well as a proportionate response to demand at all times.
[46]	PV, WT, FC, ELEC, BAT, UC Isolated application DC bus Simulated	Ensure demand	Power balance, SOC	In this application all the systems used in renewable energy generation are presented. Solar and wind are used as the main generators, while the other elements will be used to ensure the power balance. The use of batteries and supercapacitors is reduced to respond against transients, supporting the other elements with slower dynamics. In the case of excess energy, these fast response elements will absorb the energy until they reach their maximum SOC, and then the electrolyzer will absorb the excess energy. In the opposite situation, they are discharged to the minimum SOC, and then the fuel cell will supply the energy still necessary. The paper makes a study of different control algorithms for power converters in order to ensure optimum operating point for each element.
[48]	PV, FC, SC, BAT Isolated application DC bus Simulation results	Ensure demand	Power balance, DC bus voltage	The bus voltage is the main decision parameter for energy management. The batteries will determine bus voltage. The use of supercapacitors and fuel cells is limited to situations of temporary or peak demand and excessive energy deficits respectively.
[49]	PV, BAT, FC Isolated application DC bus Simulation results	Ensure demand	Power balance, DC bus voltage, Active and reactive power	Micro grid in which the main generator is the solar source, delegating fuel cells to supply energy in deficit situations and batteries to absorb energy and respond against transients. The main goal of this study is to control each element, so it focuses on PWM techniques using fuzzy logic to maintain stable bus voltage and supplying the active and reactive power demanded by the load.
[31]	PV, FC, SC, BAT On-grid application DC bus Empirical results	Ensure demand	Battery voltage	The strategy is based solely on observing the battery voltage and compares it with certain preset limits. The battery voltage will determine the energy situation, so this parameter is presented as the main decision variable of the system. The power balance is kept at all times with the main source (solar) and battery. If the battery level reaches its minimum reference voltage, the fuel cell is activated at its maximum operating point. In case the battery reaches its maximum value, supercapacitors and the grid will absorb the excess energy. The objective of using the battery voltage as an element of study, obviates SOC based methods, therefore current measurement which can produce medium and long-term integration errors.
[55]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand	Power balance, SOC, stock H2	A strategy based on power balance, battery SOC and hydrogen stock is presented to compute the operating points of the different elements. The charge or discharge priority is given as result of calculating the remaining energy storage, prioritizing

				hydrogen stock. In the case of excess energy, the energy will be sent first to the electrolyzer, and then to battery. In the case of energy deficit, stored resources will be evaluated again, prioritizing hydrogen stock. In the case of equality of resources, a proportional charge/discharge operation will take place. The tool used in this case to determine the operating points of each element would be the Model Predictive Control, and it is based on a linear model of the system and hysteresis band for battery SOC and hydrogen stock. The solution of the algorithm will define the power reference of each element at all times.
[32]	PV, FC, BAT On-grid application DC bus Empirical results	Ensure demand	Power balance, SOC	This paper studies a power source application for a telecommunications antenna; therefore, the system's target is to supply the demand as long as possible. In this application, a solar source is the main generator of the system. Batteries respond in situations of excess or deficit of energy, in order to ensure the power balance at all times. Finally, in case of low battery SOC and energy deficit situations, fuel cells will supply the demand.
[33]	PV, FC, BAT On-grid application DC bus Simulated and empirical results	Ensure demand	Power balance, DC bus voltage, cost function	This work aims to increase economic and technical performance of the whole system. In this application, the solar source is the main generator, while the battery and the fuel cell are used as short and medium-long term storage elements respectively. The performance of the battery and the fuel cell depends on the SOC and hydrogen stock in the system. In this case, the battery SOC is related to the bus voltage, so the battery is the main element of the system. Finally, different simulations are presented for different allowed battery depths of discharge, and different fuel cell operating points. The results are intended to find an optimal sizing rather than to demonstrate the correct operation of the proposed strategy.
[61]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulated	Ensure demand	Power balance	The proposed strategy aims to ensure demand. The main energy sources will be represented by solar and wind generators, and the power balance will determine the power operation points of the other elements. Negative balances will cause the operation of fuel cell; positive balance operation will cause electrolyzer start condition. The battery function is limited to respond against transients during switching of the other components, so it does not require high capacity. In situations of overproduction, energy will be discarded by dumping load.
[62]	PV, WT, FC, ELEC, BAT Isolated application DC bus Empirical results	Ensure demand	Power balance, stock H_2	This paper presents a strategy that guarantees power balance with fuel cell and electrolyzer in case the hydrogen stock permits it. Solar and wind are the main generators of the system, while the use of electrolyzer and fuel cell are determined for excess and deficit energy situation respectively. The batteries will only be used to respond to transients while fuel cell or electrolyzer are under switching operation, ensuring system stability. This is an empirical application, so a detailed study of sensors and conditioning equipment is performed.
[63]	PV, FC, ELEC Isolated application DC bus Simulated	Ensure demand	Power balance, Weather & load forecast	The strategy target is to ensure the power balance. It uses predictive models for solar generation. The excess/deficit energy will be absorbed/supplied by electrolyzer and fuel cell respectively.
[64]	PV, FC, BAT, ELEC Isolated application DC bus Simulation results	Ensure demand	Power balance, SOC, stock H_2	Domestic application in which solar power is entirely used for the production of hydrogen by an electrolyzer. Batteries and fuel cells supply demand according to the SOC of the first and the level of hydrogen stored. Priority in discharge situation will be given for that element which has a greater amount of stored energy. The use of fuzzy logic will help the task of decision and determination of the optimum levels of charge or discharge of each element.
[65]	PV, FC, BAT, WASTEWATER Isolated application DC bus Simulation results	Ensure demand, Sizing, Cost	Power balance, SOC	Specific application of a hybrid renewable system and hydrogen recovery using wastewater plant. The management strategy is very simple and is based on batteries SOC. In the case of excess energy, batteries absorb the surplus energy. In case batteries reach the minimum SOC; the fuel cell with the

				hydrogen produced at the wastewater plant will maintain energy demand. Finally, an analysis is performed to verify the performance and safety of the system for the particular application.
[66]	PV, WT, FC, ELEC Isolated application DC bus Simulation results	Ensure demand, sizing	Power balance	Work oriented to optimal sizing strategy. In this case, wind and solar sources are main generators, while the fuel cell and electrolyzer should respond for deficit or excess energy respectively. To calculate the optimal sizing functions, equipment costs, performance features as LPSP and physical constraints associated with each element have been taken into account. An algorithm based on swarm intelligence determines the optimal configuration of each of the elements.
[94]	PV, WT, FC, ELEC Isolated application DC & AC bus Simulation results	Ensure demand, sizing	Power balance	The proposed strategy ignores short-term storage elements, so the management strategy is simpler. The main generators are wind and solar sources, while electrolyzers and fuel cells will absorb or supply energy depending on power balance. The aim of this work is to find an optimal sizing strategy.
[67]	WT, FC, ELEC, SYNC CAPACITOR Isolated application DC bus Simulation results	Ensure demand	Power balance	A very simple system in which wind turbines are the main generators. The electrolyzer and fuel cell will respond to energy excess/deficit respectively. In this application a synchronous condenser is reserved for the use of reactive compensation.
[97]	PV, WT, FC, ELEC,MHIDRO Isolated application AC bus Simulation results	Ensure demand, sizing	Power balance	The strategy used in this work is very simple and aims to ensure the power balance. A Particle Swarm Optimization algorithm is also presented for optimal sizing. The main sources of energy in this application are wind, solar and micro hydro. The hydrogen elements will ensure the power balance by consumption or energy production when necessary.
[68]	PV, WT, FC Isolated application DC bus Simulation results	Ensure demand	Power balance, DC bus voltage, Active and reactive power	In this application there is no short-term storage element, so the excess energy is discarded. Primary sources are solar and wind generators, delegating fuel cell response to energy deficit. The work focuses on the system control in order to ensure constant bus voltage, power factor correction and removal of any harmonics. Techniques for PWM control using fuzzy logic are studied.
[69]	PV, WT, FC, ELEC Isolated application DC bus Simulation results	Ensure demand, sizing	Power balance	An isolated application for a desalination plant is presented. The primary energy is obtained with solar and wind sources. In case of excess production, energy can be stored as hydrogen for later use in a fuel cell. The aim of this paper is the correct sizing of the system.
[34]	PV, WT, FC On-grid application DC bus Simulation results	Ensure demand	Power balance	This work is focused on the study of the control of power converters in the system. However, a management strategy is also presented. The primary generators are wind and solar sources, delegating the fuel cell the task of supplying energy in situations of energy deficit. In cases of excess energy or excessive deficit, the grid may act as a further element of the system, in order to ensure the power balance at all times.
[70]	PV, WT, FC, ELEC Isolated application DC bus Simulation results	Ensure demand, sizing	Power balance	This work is focused on a sizing algorithm using three-dimensional Pareto Optimal Solution, which will determine the optimum solution for a multi-objective problem. In this case, a management strategy for the system is also presented. In this application, wind and solar sources represent the main generators while the electrolyzer and fuel cells will absorb or supply energy respectively to ensure the power balance at every moment.
[71]	PV, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand	Power balance, SOC	Authors present three different strategies for energy management based on solar panels as the main generator in the system, and battery SOC as the most important decision parameter. The operations of the three strategies are very similar: the battery state of charge determines the start and stop conditions for the electrolyzer and the fuel cell. The differences between strategies reside in the power operation point of each element. In the first one, the power of each device will vary adapted at all times to the system demand. In the second strategy, the batteries will support fuel cells in case of low hydrogen stock. Finally, in the third strategy, all the equipment will operate at rated power; the battery will support the system:

				absorbing by fuel cell the excess produced energy or supplying the deficit energy for the rated operation of the electrolyzer. A comparison of the three strategies is not presented because the main goal of the system is the sizing and not the energy control.
[72]	PV, WT, FC, BAT Isolated application DC bus Experimental results	Ensure demand	Power balance, SOC	Strategy applied to a domestic application. The battery SOC will determine the start and stop conditions for the fuel cell. For other situations, the battery maintains the power balance. As a special feature, the use of a small starter battery in parallel with the fuel cell will absorb transients and avoid dynamic start/stop cycles.
[73]	PV, FC, ELEC, UC Isolated application DC bus Simulation results	Ensure demand	Power balance, SOC (UC,H2)	This paper proposes a simple strategy that uses short-term storage based on supercapacitors to solve problems of stability and transients. In the present application, a solar source is the main generator. The fuel cells are used as the main element to supply energy in case of deficit. In the case of excess energy, supercapacitors and then electrolyzers will absorb it. The remaining energy will be discarded through a dumping charge.
[35]	PV, WT, FC, ELEC, BAT On-grid application DC bus Simulation results	Ensure demand	Power balance, SOC, stock H2	The strategy is based on determining the amount of energy stored/generated by the energy storage equipment, in order to ensure the power balance among the main generators (wind and solar) and demand. To determine these variables, authors use a model based on adaptive neuro-fuzzy inference system (ANFIS) control, whose input variable values are the hydrogen stock, battery SOC and the net power at every moment. The result of the ANFIS method determines the optimum power reference for the battery. Depending on the sign of the power balance, the power reference of electrolyzer and fuel cell will be calculated according to the difference between net and battery power. A final study compares the results of the proposed strategy with another strategy based on state diagrams control, providing greater energy production and better efficiency.
[88]	PV,WT,FC,ELEC,BAT,DIESEL Isolated application DC bus	Ensure demand	Power balance, SOC, H_2 stock	Simple strategy. Solar Panels and Wind Turbines are the primary generators. The batteries will absorb or supply energy in short term. In the long term, fuel cell and electrolyzer will supply/absorb energy respectively. The use of Diesel generator is relegated to high deficit of energy.
[89]	WT,PV,FC,ELEC Isolated application DC bus	Ensure demand	Power balance, H2 stock, Water demand	This paper shows an application for water pumping. Solar panels and Wind Turbines will supply energy as much as possible, and the excess of energy will be used to produce Hydrogen or store water. In case of deficit of energy, the fuel cell will supply the demand. Finally, if necessary, the storage water can be used to supply the demand. A water limitation will occur when there is not enough energy to maintain the water flow rate.
[41]	WT,FC,BAT,ELEC On-grid application DC bus	Ensure demand, Voltage stability	Power balance, SOC, H_2 stock	In this paper, a simple on-grid application is presented. The battery is the main element of the system, absorbing or supplying energy during transients. Fuel cell and electrolyzer will operate to absorb or supply energy excess/deficit respectively. The use of grid is relegated to maintain the power balance when the hydrogen based system is not capable of it.
[90]	PV,WT,FC,ELEC,DIESEL, DUMPING LOAD Isolated application DC bus	Ensure demand	Power balance, H_2 stock	Solar panels and Wind turbines will supply energy depending on weather conditions. Fuel cell and electrolyzer will supply or absorb energy during deficit/excess situations respectively. In case of high hydrogen storage, the excess energy will be discarded by dumping load. In case of low hydrogen stock, a diesel generator will ensure power balance.
[91]	PV,ELEC,BAT,FC Isolated application DC bus	Ensure demand	Power balance, SOC, H_2 stock	Solar panel is the main generator of the system. Battery will absorb or supply energy in first instance, until it reaches its operation limits. Fuel cell will supply energy in case of energy deficit. On the other hand, electrolyzer will absorb the excess of energy. The authors use two battery banks which will alternate their operation in order to reduce cycled degradation.
[92]	PV,BAT,FC,ELEC Isolated application DC bus	Ensure demand	Power balance, SOC, H_2 stock	The paper presents a comparative between diesel and renewable solutions for a radio station application. The solar panels will supply energy as much as possible. The battery is

				the main element of the system, absorbing or supplying energy while it operates between predefined SOC limits. The use of fuel cell and electrolyzer is indicated when batteries are not capable of ensuring demand or power balance.

Appendix C

Ref.	Elements of the hybrid system / Application	Optimization objectives	Design constraints	Outcome
Strategies whose objectives include technical decision factor				
[19]	PV, WT, FC, ELEC On-grid application DC bus Simulated	Ensure demand, increase equipment lifetime	Power balance	The strategy uses a predictive control to minimize the degradation processes of the electrolyzer and fuel cell due to dynamic start/stop cycles. The main generators are wind and solar sources and the electrolyzer and fuel cell will ensure power balance in situations of excess/deficit energy respectively. In case of high or low production, the grid can act as a generator or load to support the system at all times assuring certain operating conditions such as minimum input power for the electrolyzer.
[30]	PV, WT, CHP, FC, ELEC, BAT On-grid application DC bus Simulated and empirical results	Ensure demand, improve performance	Power balance, SOC, SOC (H2)	Authors present a grid-connected system for a domestic application. The proposed strategy depends on the battery SOC and hydrogen stock available, therefore the use of each element will depend on them. The battery is presented as the most important element, supplying or absorbing energy under certain operating limits given for charge conditions. The maximum and minimum SOC will determine the start/stop conditions of the other components (electrolyzer and fuel cell). The use of minimum power conditions for the ignition of the electrolyzer and maximum depths of discharge for batteries are included in the energy management, in order to reduce degradation and increase the performance of elements. Finally, in case of high deficit/excess of energy, the grid can act as generator or load, increasing system security.
[74]	PV, WT, FC, BAT Isolated application DC bus Simulation results	Ensure demand, power quality, fuel cell efficiency	Power balance, Active and Reactive power	The goals of this work are to operate the fuel cell stack at its maximum efficiency operation point, while controlling the power factor. Although the work is mainly focused on control algorithms for power converters, an energy management strategy is proposed. This strategy is based on the use of solar and wind sources as main generators, while the fuel cell will operate against any energy deficit. The use of battery will be limited to absorb energy transients, excess energy and keep the fuel cell on its maximum efficiency power point, absorbing or giving power when necessary.
[36]	PV, WT, FC, SC On-grid application DC bus Experimental	Ensure demand, Stability	Power balance, SC energy function	Authors develop a control law and a nonlinear problem which aims to ensure the power balance. In this application, the wind and solar sources are the main generators of the system. To determine the contribution of the other elements, the power reference values depend on the sign of the power balance and the amount of available energy inside the storage systems. The response of the nonlinear optimization problem will be based on differential flatness-based control.
[47]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase performance	Power balance, SOC	In this paper, three strategies whose core decision is the batteries SOC are presented. The solar and wind sources are the main generators. The maximum and minimum values of the battery SOC will determine the start and stop conditions for the electrolyzer and fuel cell. The difference between the three strategies is given by the use of batteries for excess energy. In the first one, the electrolyzer will start if it reaches a minimum operating power, while batteries will assume the excess energy. In the second strategy, the batteries will

				support the electrolyzer to achieve a minimum power value. In the third and final strategy, the batteries will be disconnected to avoid overcharging them. Finally, authors present two sensitivity analyses based on the minimum battery SOC, and the use of a fixed and variable operating power for the fuel cell. Results determine that reducing the minimum SOC would increase the use of batteries and decrease the use of fuel cells. In case of a variable operating point of the fuel cell, the hydrogen consumption will be lower, adjusting it at all times to the required demand.
[50]	PV, FC, BAT, ELEC Isolated application DC bus Simulated	Ensure demand, improve performance, Battery management	Power balance, SOC, stock H_2	The target of the proposed management strategy is to keep power balance all times. The use of solar energy is considered to be the main generator of the system. Batteries assume the main role of the system, responding against situations of excess/deficit energy. Its SOC will determine the start/stop conditions for the electrolyzer and fuel cell. Two different controls for battery operation are studied depending on their SOC. First, the current control is used for fast charging in low SOC and the voltage control to protect the batteries at high charging conditions. When there is high excess energy, the solar generation will be limited and it will be used for hydrogen generation in order to absorb excess energy. The fuel cell will be used to supply demand and neutralize the power balance.
[51]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime	Power balance, SOC	In this paper, the proposed strategy is based on hysteresis band operation determined for battery SOC. Hysteresis limits will determine the start/stop conditions for the electrolyzer and fuel cell. The aim of this work is to increase the useful lifetime of elements by reducing the degradation associated with dynamic operation. Additionally, the effect of using a minimum power for the electrolyzer to ensure optimum performance is studied. In order to reach the last target, two simulations of two different strategies are presented; the first one prevents electrolyzer operation while the excess energy is lower than the minimum power point, and the second one uses batteries to reach it. The result shows increased hydrogen production in the second strategy; increasing the overall system performance, with greater use of batteries. Finally, a parametric analysis based on the hysteresis bandwidth determines how it affects the battery lifetime as well as the use of other elements inside the system.
[52]	PV, WT, FC, BAT Isolated application DC bus Simulation results	Ensure demand, improve lifetime	Power balance, Weather forecast, SOC	Authors propose a strategy based on demand and production forecast in less than a two minute range. With the result of the forecast and the current state of the system, it will determine the actions required, allowing the charge/discharge of the batteries, or the start/stop conditions of the fuel cell and the reference power for each element. The use of this strategy will determine the efficiency of the fuel cell operation, and avoid unnecessary start/stop cycles thus reducing the degradation.
[53]	PV, WT, FC, ELEC, BAT, DIESEL Isolated application DC bus Simulation results	Ensure demand, improve lifetime	Power balance, SOC	In this paper the authors propose a study of a strategy based on hysteresis operation depending on maximum and minimum battery SOC. These levels determine the start and stop conditions of the fuel cell and electrolyzer. The use of hysteresis with minimum power conditions for the electrolyzer, tries to reduce degradation of the elements, and thus increases system lifetime. The use of diesel equipment will only operate in situations of high-energy deficit.
[54]	PV, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime	Power balance, SOC	The work presents a solution for degradation problems studied for fuel cells and electrolyzers. It implements a strategy based on hysteresis band operation for battery SOC. This strategy will determine the start/stop conditions of the electrolyzer and fuel cell. The strategy is based on the use of solar resources as the primary generator and a battery as a last resort. The excess/deficit energy is absorbed primarily by the battery if the SOC is within its operating limits, and

				then by the electrolyzer or fuel cell, depending on the energy situation. Besides the above, the fuel cell will operate in a fixed mode to avoid power transients operation and associated problems. Finally, the use of the electrolyzer in fixed or variable power mode is realized, determining that the variable operation mode is more efficient. This strategy shows many possible solutions to increase the lifetime of equipment, and thereby reduce costs and avoid malfunctions associated with incorrect operation of the system.
[56]	PV, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime	Power balance, SOC	In this paper, a proposed management strategy based on hysteresis operation depending on battery SOC is presented. This parameter will define the start/stop conditions of the electrolyzer and fuel cell. The target of the strategy is to reduce the size of the batteries and avoid extra degradation due to overuse. To achieve this, authors resolve to establish a battery range in which the system will operate in normal situations. In the case of high battery charge or discharge situations, the electrolyzer and fuel cell will be used at full power to bring the battery to the safe hysteresis band. In any situation, batteries will perform in the first instance to absorb or transfer the necessary energy to ensure the power balance. If that is not enough, the electrolyzer and fuel cell energy will support according to need.
[57]	PV, WT, FC, ELEC, BAT, DIESEL Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime, sizing	Power balance, SOC	In this paper, the strategy is based on the hysteresis band of battery SOC, which determines the start/stop conditions of the electrolyzer and fuel cell. The purpose of hysteresis is therefore to reduce the number of power cycles, avoiding the degradation associated with them. Besides operation with hysteresis, minimum power values for the electrolyzer and fuel cell are used in order to assure the optimal performance. If the minimum power of the electrolyzer is not reached, batteries will supply the remaining power. If the power operation of the fuel cells exceeds the energy deficit, batteries will absorb the excess energy. In extreme cases, the use of diesel equipment can supply the energy deficit necessary to ensure the power balance. Finally, a study of sizing based on a multi-objective problem is presented.
[58]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime, sizing	Power balance, SOC	Authors present a simulation tool to study different scenarios in which solar and wind are the main generators. The simulator has a strategy based on the hysteresis band of the battery SOC. The maximum and minimum SOC will determine the start and stop conditions for the electrolyzer and fuel cell. There is no requirement to determine the operating point of the elements inside the system, so the energy excess or deficit will be absorbed or supplied by the battery, electrolyzer or fuel cell just based on power balance. Finally, a genetic algorithm is used to solve the multi-objective sizing problem which takes into account the costs and lifetime of each element.
[60]	WT, FC, ELEC, SC Isolated application DC bus Simulation results	Ensure demand, improve lifetime	Power balance	The work proposes a strategy that takes into account the deterioration of fuel cells due to the influence of high frequency switching. The proposed strategy is simple; wind is the main generator and uses supercapacitors to support the system during transients or load changes. The use of the electrolyzer and fuel cell are only justified to absorb or supply energy when supercapacitors are at their maximum or minimum charge respectively. The use of different low pass filters will help to reduce the problems associated with the switching of power converters over the fuel cell.
[75]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulated	Ensure demand, maximize Hydrogen production	Power balance, SOC	This study is based on three different strategies that differ in the method of using the excess energy. All the proposed strategies share the use of solar and wind sources as main generators and the rest of equipment as energy storage elements. The start/stop condition of the fuel cell and electrolyzer depends on the battery SOC. In the first strategy, the battery assists in the production of hydrogen with the

				main generators. The target of this strategy is to maximize the hydrogen production. In the second strategy, the electrolyzer will not be used, and therefore the battery will assume the full energy excess in order to increase the temporal response of the battery. Finally, the third strategy has a compromise between maximizing the production of hydrogen and maintaining an optimal battery SOC. The battery and electrolyzer will absorb the energy excess, while the deficit will be provided by battery and fuel cell, without specifying any priority.
[76]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, lifetime	Power balance, SOC, stock H2	This strategy aims to ensure the demand and increase the lifetime of the elements. In order to get it, authors present an analysis between two alternative strategies, depending on the priority of charge/discharge energy. In the present application, the main generators are wind and solar sources. The remaining elements form part of the energy storage system. The decision variables of the system will be the battery SOC and the hydrogen stock. The priority to charge or discharge energy is based on the stored energy inside the different elements. In case of equal resources, the element with the lowest deterioration accumulated by its operation will be responsible for guaranteeing the power balance.
[77]	PV, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, maximize Hydrogen production, minimize battery usage	Power balance, SOC	The strategy has the target to ensure demand, increase hydrogen production, and minimize the use of batteries. To get it, batteries will operate in a narrow range of SOC, limiting their use to respond only against transients or short-term demands. In order to maximize the production of hydrogen, the electrolyzer will absorb the excess energy more often than batteries, while fuel cells will supply the energy deficit. Authors use a system based on fuzzy logic to decide which part of energy excess or deficit will be supplied/absorbed by the batteries, the electrolyzer or the fuel cell.
[95]	PV, WT, FC, ELEC, UC Isolated application AC bus Simulation results	Ensure demand, increase life time	Power balance, SOC (UC)	The implemented strategy has the target of guaranteeing the demand and increasing equipment lifetime, reducing transients and start/stop cycles for the electrolyzer and fuel cell. To solve the above problems, the electrolyzer will operate at different steps of continuous power, with a minimum starting power in order to avoid transients and associated deterioration. Fuel cells only come into operation when the supercapacitors SOC is lower than a defined set level. Finally, any short-term disruption will be absorbed by the supercapacitors, whose SOC should remain within safe operating ranges. The operation point of each device may be obtained at any time through the power balance equations.
[78]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, increase equipment lifetime	Power balance, Load and Resources estimation	An active strategy based on demand and production forecasts is presented. The use of forecast and the current battery SOC will determine a multi-objective function, designed to maximize hydrogen production and reduce start/stop cycles of the electrolyzer and fuel cell. The response to the algorithm will determine which element will absorb or supply energy at its rated power. Finally, to solve the nonlinear problem, the use of algorithms based on dynamic real-time optimization is performed.
[79]	PV, WT, FC, BAT, ELEC Isolated application DC bus Simulation results	Ensure demand, improve lifetime	Power balance, SOC	In this paper, fuzzy logic is used to implement a management strategy that will avoid unnecessary start/stop cycles, with the consequent degradation reduction. The decision parameters of this strategy will be the battery SOC and generation/demand forecast, which will determine the start or stop conditions of the electrolyzer and fuel cell. The use of fuzzy logic allows application of an algorithm which determines the operation point of the different elements, based on the previous parameters.
[80]	PV, FC, ELEC, BAT Isolated application DC bus	Ensure demand, improve lifetime	Power balance, SOC, stock H_2, Weather forecast	In this strategy, the solar source is the main generator of the system. The battery SOC and hydrogen stock represent the main decision parameters of the system, as well as the result

	Simulation and empirical results			of generation and demand forecasts. In the first instance, the battery will operate between preset maximum and minimum values, which determine the start and stop conditions of the electrolyzer and fuel cell. In order to increase the lifetime, reducing degradation of hydrogen elements, three different energy management strategies will be considered. The first one is based on ensuring minimum operating power to the electrolyzer with the discharge of battery if necessary. The second one refers to the operating point of the fuel cells. In order to operate the fuel cell in the maximum efficiency range, minimum and maximum power will be determined in order to get it. Finally, the third one is used to reduce the number of start/stop cycles of the elements and is based on the use of equipment in standby mode if the forecasting determines an imminent use of them.
[81]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, battery lifetime	Power balance, SOC, stock H_2	For this strategy, an artificial neural network controller is used in order to supply demand and preserve the battery SOC within preset limits. The main generators are represented by wind and solar sources, while the other elements are used for energy storage. In normal operation, the battery usages will respond against transient situations and start/stop cycles of the other elements. The strategy tries to maintain a battery SOC around 70%, so in the case of excess/deficit energy situations, the electrolyzer and fuel cell must respond to get it. Finally, the use of the algorithm is justified to determine the operating point of each element when excess/deficit energy situations occur while the battery is discharged or hydrogen stock is too low respectively.

Appendix D

Ref.	Elements of the hybrid system / Application	Optimization objectives	Design constraints	Outcome
Strategies whose objectives include economic decision factor				
[3]	PV, FC, BAT, ELEC On-grid application DC bus Experimental	Ensure demand, cost reduction	Power balance, cost function	The presented strategy attempts to ensure power balance at all times, by operating the system at the operation point that ensures the lowest value of the system-grid cost function. The technique uses an algorithm based on Model Predictive Control and a demand and generation forecast. This algorithm determines the operation points of the battery, fuel cell, and electrolyzer. During system operation, the purchase/sales price of grid energy is calculated at every moment, so the grid is an important element to consider for energy management.
[28]	PV, WT, MH, FC, ELEC, BAT, DIESEL Isolated application DC bus Simulated	Ensure demand, cost reduction	Power balance, cost function	This paper aims to ensure proper power supply to the load, optimizing operating costs. Authors present a cost function associated with the use of energy storage devices, such as batteries, electrolyzers, fuel cells or diesel generators. The use of physical constraints, current system status, and expected lifetime would determine a nonlinear optimization problem, which would be solved by genetic algorithms. The result determines at each time the cost of each element and the optimum operating point. The option to charge or discharge the system will be based on the element that keeps the lowest operation cost, within the range of optimal power for each one.
[82]	PV, WT, FC, ELEC, BAT, DIESEL Isolated application DC bus Simulation results	Ensure demand, cost reduction, sizing	Power balance, cost function, LPSP, CO_2 emissions, SOC	Authors present a strategy that aims to reduce costs, emissions, and ensure the power balance. The authors present some expressions which model each target depending on various parameters such as LPSP, CO_2 emissions, battery SOC, cost function... etc. Fuzzy logic and a differential evolution algorithm are used to solve the multi-objective problem. The result of this algorithm is the reference power for each of the elements in the

				different energy situations, giving priority to the use of batteries and renewable energy generators before diesel operation. In general, this is a sizing algorithm.
[96]	PV, WT, FC, ELEC, BAT, DIESEL Isolated application AC bus Simulation results	Ensure demand, cost reduction	Power balance, weather prediction, cost function, SOC, stock H_2	The aim of this study is to compare the proposed strategy regarding other strategies based on the battery SOC as the most important decision parameter. The presented strategy in the first instance is based on the generation and demand forecast, which is the input parameter to the decision algorithm. Considering the outcome of the previous forecast, the current state of the system (battery SOC and hydrogen stock) and the degradation, operation, maintenance and replacement costs, it will determine the reference power of each element. The operation will take place at each iteration by a linear simplified system model, in order to avoid heavy algorithms. The result of the comparison between strategies is the improvement in cost reduction, compared to traditional strategies, but the need for very accurate models and high processing capacity of the control system.
[83]	PV, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, cost reduction	Power balance, SOC, stock hydrogen, cost function	The management strategy is based on hydrogen stock and batteries SOC. Depending on the previous decision parameters, it will determine the batteries charge/discharge and the start/stop conditions of the electrolyzer and fuel cell, prioritizing the element with higher energy stored. In case both parameters are equal, an economic decision factor represented by a cost function, determines the element with the lowest cost to charge or discharge inside the system.
[37]	PV, WT, FC, CHLOR-ALKALI PROCESS On-grid application DC bus Simulation results	Ensure demand, cost reduction	Power balance, cost function	This work is based on a particular application of the chemical production of chlorine. In the chemical process to obtain the product, hydrogen gas is generated, which can be stored for future use and conversion into electrical energy. The strategy is based on calculating the operation points of the fuel cell and the chlorine production system, with the target of minimizing operation costs, taking into account the benefits of injecting or buying power from the grid. A receding horizon optimization algorithm is used to solve the optimization problem.
[38]	WT, FC On-grid application DC bus Simulation results	Ensure demand, cost reduction	Power balance, cost function	The presented work studies the combination of wind power and a fuel cell to produce electricity and heat in a domestic application. Some expressions are presented to estimate the operation and maintenance costs of the use of the fuel cell or the grid. A genetic algorithm in any case allows calculating the cheaper option and determining the reference power of each element to support wind generation.
[39]	WT, FC, ELEC, HYDRAULIC GENERATOR, PUMP On-grid application DC bus Simulation results	Ensure demand, Cost reduction	Power balance, cost function	An application for a specific production model is presented. In this case, the main power generation is given by the wind source. In case of excess of energy, the system proposes two options. The first one proposes the conversion to hydrogen through electrolysis process; the second one uses a pumping station for water storage at high altitude. In the case of energy deficit situations, the required energy can be obtained through the production of electricity using fuel cells, or by generating electricity in a hydraulic plant. The most economically viable option will act at all times. The target strategy therefore is to maximize the wind resource, allowing the energy storage and subsequent use in the most economical way possible.
[84]	PV, WT, FC, ELEC Isolated application DC bus Simulation results	Ensure demand, cost reduction	Power balance, cost function	The target of this work is the optimal energy management from the economic point of view for a residential application. In order to get it, a cost function associated with energy production of each element is presented. The use of different physical constraints together with the previous cost functions will identify a nonlinear optimization problem. The problem will be solved with the use of gravitational search algorithms. The result is the reference power of each element, which assures the lowest production costs for system operation.
[85]	MT, FC, BAT Isolated application DC bus Simulation results	Ensure demand, cost reduction	Power balance, demand prediction, cost function	In this paper, a multi-objective function is presented to calculate the reference power of each element inside the system, knowing the costs associated with each item and demand forecasts for the next 24 h. The problem will be solved by an adaptive particle

				modified swarm optimization algorithm, which determines the energy delivered by each element according to the obtained estimator.
[40]	PV, FC, ELEC On-grid application DC bus Simulation results	Ensure demand, cost reduction	Power balance, weather prediction, cost function	In this paper a grid-connected system is studied in which solar energy is presented as the main generator. Authors present a function to model the operating costs of each element and power sale/purchase cost from the grid. The demand and solar generation forecast and the cost function, represent the input variables of an optimization algorithm, whose response will be calculated by adaptive model predictive control. The result of the optimization algorithm determines the elements' operating points for the most economical option, maintaining a minimum level of hydrogen in the energy storage system.
[42]	PV,WT,BAT,ELEC,FC On-grid application DC bus Simulation results	Ensure demand, cost reduction	Power balance, SOC, weather prediction, cost function	In this paper, a cost function is used to determine the power reference of grid, fuel cell and electrolyzer in order to minimize overall electricity cost. Battery SOC, power balance and a weather and demand forecast are used as input parameters of the optimization algorithm. The battery is used to absorb the transients during the generation and demand. The grid is another active element of the system.
[43]	WT,PV,FC,ELEC On-grid application DC bus	Ensure demand, cost reduction	Power balance, H_2 stock, cost function	A multi-objective function is developed to minimize the operation and maintenance cost of the system. The result of the optimization algorithm is the power reference of the grid, fuel cell and electrolyzer. The fuel cell will supply energy in case of energy deficit, while the electrolyzer will absorb energy during energy excess situations. The grid will operate as another active element inside the hybrid system.

Appendix E

Ref.	Elements of the hybrid system / Application	Optimization objectives	Design constraints	Outcome
Strategies whose objectives include technical and economic decision factor				
[59]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, cost reduction, Increase Lifetime	Power balance, SOC, stock H2, cost and life function	The presented strategy is based on hydrogen stock and battery SOC. The main generators of the system are wind and solar sources, while the other devices are part of the energy storage system. The charge or discharge of any element inside the system will depend on which element has the highest or lowest amount of energy stored respectively. In the case of equality of resources, a technical-economic factor will decide which element will supply or absorb the necessary energy to guarantee the power balance. This factor will be represented by a cost function, which integrates the cost associated with the degradation accumulated by the operating time.
[86]	PV, WT, FC, ELEC, BAT Isolated application DC bus Simulation results	Ensure demand, cost reduction, improve lifetime	Power balance, SOC, H_2 stock, cost function	In this paper, two targets are studied: reducing costs and increasing elements lifetimes at the same time. In the application, wind and solar sources are the main generators. To calculate the priority of each element, a multipurpose optimization problem is studied. Fuzzy logic will be used to calculate which element will be responsible for absorbing or supplying energy and its power reference. The inputs of the algorithm are represented by some cost expressions associated with each element, as well as estimation of the remaining lifetime and the current state of the energy of storage equipment.
[87]	PV, WT, FC, ELEC, BAT, DIESEL Isolated application DC bus	Ensure demand, improve lifetime, cost reduction	Power balance, SOC	Authors present three different strategies for different purposes in order to demonstrate the correct operation of the particle swarm optimization algorithm for solving nonlinear optimization problems. The response of the

	Simulation results			algorithm for different configurations is the reference power of the different elements, depending on the different targets: minimizing costs, increasing efficiency and equipment lifetime. Really, there is no priority in the use of the different elements, so this priority will be determined by the result of each algorithm calculation for each application.
[44]	PV,WT,FC,ELEC, BAT On-grid application DC bus Simulation results	Ensure demand, improve lifetime, cost reduction, improve performance	Power balance, SOC, H_2 stock	A multi-objective function based on degradation, performance and cost parameters is optimized in order to guarantee the optimal system response. The power reference of the fuel cell and electrolyzer will be defined by the optimization solution. Batteries are the core of the hybrid system and they will absorb or supply energy while they operate between prefixed states of charge limits. The fuel cell and electrolyzer will operate under high energy deficit or energy excess situations according to their optimal operation point. The grid will operate as a demand or generator depending on the sign of the power balance.
[93]	PV,WT,FC,ELEC,BAT Isolated application DC bus	Ensure demand, improve lifetime, cost reduction, improve performance	Power balance, SOC, H_2 stock, cost function, degradation function	This paper presents a multi-objective degradation-cost function which is minimized with an optimization algorithm. The result of the optimization is the power reference of the fuel cell, battery, and electrolyzer depending on state of charge of the battery and hydrogen stock. The hysteresis operation mode fixes the start/stop conditions of the electrolyzer and fuel cell.
[45]	PV,WT,FC,ELEC,BAT On-grid application DC bus Experimental	Ensure demand, improve lifetime, cost reduction, improve performance	Power balance, SOC, H_2 stock, cost function, performance function	In this work, authors studied the behavior of a hybrid system based on different strategies which integrate hysteresis operation mode. These strategies define different operation points for the fuel cell, electrolyzer, and battery, in order to show the response of the system under different goals, maximizing hydrogen production, increasing system performance, and the cases of rated operation mode for the three previous elements. The results of different strategies are compared based on technical and economic parameters to get the optimal solution. Advantages and disadvantages of the different configurations are also studied.

References

[1] Chauhan A, Saini RP. A review on Integrated Renewable Energy System based power generation for stand-alone applications: configurations, storage options, sizing methodologies and control. Renew Sustain Energy Rev 2014;38:99–120.

[2] Ahmed NA. On-grid hybrid wind/photovoltaic/fuel cell energy system. In: proceedings of the 10th international power & energy conference (IPEC), Ho Chi Minh City; 2012, p. 104–9. doi: http://dx.doi.org/10.1109/ASSCC.2012.6523247.

[3] Bordons C, García-Torres F, Valverde L. Gestión Óptima De La Energía En Microrredes Con Generación Renovable. Rev Iberoam Automática Inf Ind RIAI 2015;12(2):117–32.

[4] IEA (International Energy Agency. Renewable Energy Outlook, World Energy Outlook 2013; 2013, p. 197–232.

[5] Sun XSX, Lian ZLZ, Wang BWB, Li XLX. A Hybrid renewable DC microgrid voltage control, In: Proceedings of IEEE 6th international power electron. motion control conference, vol. 3; 2009. p. 725–9.

[6] Semaoui S, Hadj Arab a, Bacha S, Azoui B. The new strategy of energy management for a photovoltaic system without extra intended for remote-housing. Sol Energy 2013;94:71–85.

[7] Robitaille M, Agbossou K, and Doumbia ML. Modeling of an islanding protection method for a hybrid renewable distributed generator. In: Proceedings of IEEE Canadian conference on electrical and computer engineering, vol. 2005, no. May; 2005. p. 1485–9.

[8] Li X, Jiao X, and Wang L. Coordinated power control of wind-{PV}-fuel cell for hybrid distributed generation systems. In: SICE annual conference (SICE), 2013 Proceedings of ; 2013, p. 150–5.

[9] Osman Haruni a, Negnevitsky M, Haque ME, Gargoom A. A novel operation and control strategy for a standalone hybrid renewable power system. IEEE Trans Sustain Energy 2013;4(2):402–13.

[10] Tégani I, Aboubou A, Ayad MY, Becherif M, Bahri M. Power flow management in WT/FC/SC hybrid system using flatness based control. In: Proceedings of 3rd international symposium on environment-friendly energies and applications. EFEA; 2014.

[11] Feroldi D, Degliuomini LN, Basualdo M. Energy management of a hybrid system based on wind–solar power sources and bioethanol. Chem Eng Res Des 2013;91(8):1440–55.

[12] Mbarek E, Belhadj J, Le BP, Tunis B. Photovoltaic Wind hybrid system integrating a Permanent Exchange Membrane Fuel Cell (PEMFC). In: Proceedings of international multi-conference on systems, signals and devices; 2009, no. 1, 2009, p. 1–6.

[13] Fathima AH, Palanisamy K. Optimization in microgrids with hybrid energy systems – a review. Renew Sustain Energy Rev 2015;45:431–46.

[14] Vasallo MJ, Bravo JM, Andújar JM. Optimal sizing for UPS systems based on batteries and/or fuel cell. Appl Energy 2013;105:170–81.

[15] Segura F, Durán E, Andújar JM. Design, building and testing of a stand alone fuel cell hybrid system. J Power Sources 2009;193(1):276–84.

[16] Vasallo MJ, Andújar JM, García C, Brey JJ. A methodology for sizing backup fuel-cell/battery hybrid power systems. IEEE Trans Ind Electron 2010;57(6):1964–75.

[17] Segura F, Andújar JM. Step by step development of a real fuel cell system. Design, implementation, control and monitoring. Int J Hydrog Energy 2015;0:1–13.

[18] Valverde L, Ali D, and Gordo R. "A technical evaluation of Wind-Hydrogen (WH) demonstr ration projects in Europe. In: Proceedings of power engineering, energy and electrical drives (POWERENG), 2013 fourth international conference on, no. May; 2013. p. 13–7.

[19] Trifkovic M, Sheikhzadeh M, Nigim K, Daoutidis P. Modeling and control of a renewable hybrid energy system with hydrogen storage. IEEE Trans Control Syst Technol 2013;22(1). [1–1].

[20] Baumann C, Schuster R, Moser A. Economic potential of power-to-gas energy storages. In: Proceedings of international conference european energy market (EEM); 2013.

[21] Moskalenko N, Lombardi P, Komarnicki P. Multi-criteria optimization for determining installation locations for the power-to-gas technologies. In: IEEE PES General Meeting|Conference & Exposition, National Harbor, MD; 2014, p. 1–5. doi: http://dx.doi.org/10.1109/PESGM.2014.6939362.

[22] Clegg S, Mancarella P. Integrated modeling and assessment of the operational impact of power-to-gas (P2G) on electrical and gas transmission networks. IEEE Trans Sustain Energy 2015;6(4):1234–44.

[23] Belderbos A, Delarue E, D'haeseleer W. Possible role of power-to-gas in future energy systems. In: proceedings of the 12th International Conference on the European Energy Market (EEM), Lisbon; 2015, p. 1–5. doi: http://dx.doi.org/10.1109/EEM.2015.7216744.
[24] Heymann F, Bessa R. Power-to-gas potential assessment of Portugal under special consideration of LCOE. In: Proceedings of IEEE Eindh Power; 2015.
[25] Heinisch V. Effects of power-to-gas on power systems: a case study of Denmark. In: Proceedings of IEEE Eindh PowerTech; 2015, p.1–6.
[26] Alkano D, Kuiper I, Scherpen JMA. Distributed MPC for Power-to-Gas facilities embedded in the energy grids. In: European Control Conference (ECC), Linz; 2015, p. 1474–9. doi: http://dx.doi.org/10.1109/ECC.2015.7330747.
[27] Diaz I, Mendaza DC, Bhattarai BP, Optimal sizing and placement of power-to-gas systems in future active distribution networks. In: Proceedings of innovative smart grid technologies - Asia (ISGT ASIA); 2015 IEEE.
[28] Dufo-López R, Bernal-Agustín JL, Contreras J. Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage. Renew Energy 2007;32(7):1102–26.
[29] El-Shatter TF, Eskander MN, El-Hagry MT. Energy flow and management of a hybrid wind/PV/fuel cell generation system. Energy Convers Manag 2006;47(9–10):1264–80.
[30] Baumann L, Boggasch E, Rylatt M, Wright A. Energy flow management of a hybrid renewable energy system with hydrogen, In: Proceedings of innovative technologies for an efficient and reliable electricity supply (CITRES), IEEE Conference on; 2010, p. 78–5.
[31] Karami N, Moubayed N, Outbib R. Energy management for a PEMFC-PV hybrid system. Energy Convers Manag 2014;82:154–68.
[32] Kato N, Kurozumi K, Susuld N, Muroyama S. Hybrid power-supply system composed of photovoltaic and fuel-cell systems. In: proceedings of the twenty-third International Telecommunications Energy Conference INTELEC 2001, Edinburgh, UK; 2001, p. 631–5. doi: http://dx.doi.org/10.1049/cp:20010663.
[33] Bruni G, Cordiner S, Galeotti M, Mulone V, Nobile M, Rocco V. Control strategy influence on the efficiency of a hybrid photovoltaic-battery-fuel cell system distributed generation system for domestic applications. Energy Procedia 2014;45:237–46.
[34] Das D, Esmaili R, Xu L, Nichols D. An optimal design of a grid connected hybrid wind/photovoltaic/fuel cell system for distributed energy production. In: Proceedings of IEEE industrial electronics society, IECON 2005. 31st annual conference; 2005. p. 2499–504.
[35] García P, García CA, Fernández LM, Llorens F, Jurado F. ANFIS-based control of a grid-connected hybrid system integrating renewable energies, hydrogen and batteries. IEEE Trans Ind Inform 2014;10(2):1107–17.
[36] Thounthong P, Sikkabut S, Mungporn P, Sethakul P, Pierfederici S, Davat B. Differential flatness based-control of fuel cell/photovoltaic/wind turbine/supercapacitor hybrid power plant, In: Proceedings of the 4th international conference clean electrical power, Renewable Energy Resources Impact, ICCE; 2013, p. 298–305.
[37] Wang X, Tong C, Palazoglu A, El-farra NH. Energy Management for the chlor-alkali process with hybrid renewable energy generation using receding horizon optimization. In: Proceedings of the 53rd IEEE conference on decision and control; 2014, p. 4838—43.
[38] Talebian ME, Sobhani S, Borzooi A. New hybrid system of fuel cell power plant and wind turbine for household consumption. In: proceedings of the 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul; 2013, p. 1–6. doi: http://dx.doi.org/10.1109/EPECS.2013.6713074.
[39] Dagdougui H, Minciardi R, Ouammi A, Robba M, Sacile R. A dynamic decision model for the real-time control of hybrid renewable energy production systems. IEEE Syst J 2010;4(3):323–33. http://dx.doi.org/10.1109/JSYST.2010.2059150. Sept.
[40] Zervas PL, Sarimveis H, Palyvos J a, Markatos NCG. "Model-based optimal control of a hybrid power generation system consisting of photovoltaic arrays and fuel cells. J Power Sources 2008;181(2):327–38.
[41] Kamal T, Hassan SZ, Li Hui, Mumtaz S, Khan L. Energy management and control of grid-connected wind/fuel cell/battery Hybrid Renewable Energy System. In: International Conference on Intelligent Systems Engineering (ICISE), Islamabad; 2016, p. 161–6. doi: http://dx.doi.org/10.1109/INTELSE.2016.7475114.
[42] Athari MH, Ardehali MM. Operational performance of energy storage as function of electricity prices for on-grid hybrid renewable energy system by optimized fuzzy logic controller. Renew Energy 2016;85:890–902.
[43] Rouholamini M, Mohammadian M. Heuristic-based power management of a grid-connected hybrid energy system combined with hydrogen storage. Renew Energy 2016;96:354–65.
[44] Fernandez-Ramírez LM, Garcıa-Tribiño P, Gil-mena AJ, Llorens-iborra F, Jurado F, García-V-azquez CA. Optimized operation combining costs, efficiency and lifetime of a hybrid renewable energy system with energy storage by battery and hydrogen in grid-connected applications. Int J Hydrog Energy 2016;41:23132–44.
[45] Valverde L, Pino F, Rosa F. Definition, analysis and experimental investigation of operaion modes in hydrogen-renewable-based power plants incorporating hybrid energy storage. Energy Convers Manag 2016;113:290–311.
[46] Bizon N, Oproescu M, Raceanu M. Efficient energy control strategies for a standalone renewable/fuel cell hybrid power source. Energy Convers Manag 2015;90:93–110.
[47] Ipsakis D, Voutetakis S, Seferlis P, Stergiopoulos F, Elmasides C. Power management strategies for a stand-alone power system using renewable energy sources and hydrogen storage. Int J Hydrog Energy 2009;34(16):7081–95.
[48] Samson GT, Undeland TM, Ulleberg O, Vie PJS. Optimal load sharing strategy in a hybrid power system based on PV/fuel cell/battery/supercapacitor, In: Proceedings of IEEE international conference on clean electrical power, no. 2027; 2009, p. 141–6.
[49] Mohammadi M, Nafar M. Fuzzy sliding-mode based control (FSMC) approach of hybrid micro-grid in power distribution systems. Int J Electr Power Energy Syst 2013;51:232–42.
[50] Dash V, Bajpai P. Power management control strategy for a stand-alone solar photovoltaic-fuel cell–battery hybrid system. Sustain Energy Technol Assess 2015;9:68–80.
[51] Ipsakis D, Voutetakis S, Seferlis P, Stergiopoulos F, Papadopoulou S, Elmasides C. The effect of the hysteresis band on power management strategies in a stand-alone power system. Energy 2008;33(10):1537–50.
[52] Brka A, Kothapalli G, Al-Abdeli YM. Predictive power management strategies for stand-alone hydrogen systems: lab-scale validation. Int J Hydrog Energy 2015;40(32):9907–16.
[53] Ziogou C, Ipsakis D, Elmasides C, Stergiopoulos F, Papadopoulou S, Seferlis P, Voutetakis S. Automation infrastructure and operation control strategy in a stand-alone power system based on renewable energy sources. J Power Sources 2011;196(22):9488–99.
[54] ZHOU K. Optimal energy management strategy and system sizing method for stand-alone photovoltaic-hydrogen systems. Int J Hydrog Energy 2008;33(2):477–89.
[55] Torreglosa JP, García P, Fernández LM, Jurado F. Energy dispatching based on predictive controller of an off-grid wind turbine/photovoltaic/hydrogen/battery hybrid system. Renew Energy 2015;74:326–36.
[56] Tesfahunegn SG, Ulleberg Ø, Vie PJS, Undeland TM. Optimal shifting of Photovoltaic and load fluctuations from fuel cell and electrolyzer to lead acid battery in a Photovoltaic/hydrogen standalone power system for improved performance and life time. J Power Sources 2011;196(23):10401–14.
[57] Giannakoudis G, Papadopoulos AI, Seferlis P, Voutetakis S. Optimum design and operation under uncertainty of power systems using renewable energy sources and hydrogen storage. Int J Hydrog Energy 2010;35(3):872–91.
[58] Carapellucci R, Giordano L. Modeling and optimization of an energy generation island based on renewable technologies and hydrogen storage systems. Int J Hydrog Energy 2012;37(3):2081–93.
[59] Torreglosa JP, García P, Fernández LM, Jurado F. Hierarchical energy management system for stand-alone hybrid system based on generation costs and cascade control. Energy Convers Manag 2014;77:514–26.
[60] More JJ, Puleston PF, Kunusch C, Fantova MA. Development and implementation of a supervisor strategy and sliding mode control setup for fuel-cell-based hybrid generation Systems. IEEE Trans Energy Convers 2015;30(1):218–25.
[61] Wang C, Nehrir MH. Power management of a stand-alone wind/photovoltaic/fuel cell energy system. IEEE Trans Energy Convers 2008;23(3):957–67.
[62] Calderón M, Calderón aJ, Ramiro a, González JF. Automatic management of energy flows of a stand-alone renewable energy supply with hydrogen support. Int J Hydrog Energy 2010;35(6):2226–35.
[63] Hatti M, Meharrar a, Tioursi M. Power management strategy in the alternative energy photovoltaic/PEM fuel cell hybrid system. Renew Sustain Energy Rev 2011;15(9):5104–10.
[64] Stewart EM, Lutz AE, Schoenung S, Chiesa M, Keller JO, Fletcher J, Ault G, McDonald J, Cruden A. Modeling, analysis and control system development for the Italian hydrogen house. Int J Hydrog Energy 2009;34(4):1638–46.
[65] Wu W, Christiana VI, Chen S-A, Hwang J-J. Design and techno-economic optimization of a stand-alone PV (photovoltaic)/FC (fuel cell)/battery hybrid power system connected to a wastewater-to-hydrogen processor. Energy 2015;84:462–72.
[66] Sanchez VM, Chavez-Ramirez AU, Duron-Torres SM, Hernandez J, Arriaga LG, Ramirez JM. Techno-economical optimization based on swarm intelligence algorithm for a stand-alone wind-photovoltaic-hydrogen power system at south-east region of Mexico. Int J Hydrog Energy 2014;39(29):16646–55.
[67] Mendis N, Sayeef S, Muttaqi KM, Perera S. Hydrogen energy storage for a permanent magnet wind turbine generator based autonomous hybrid power system. In: Proceedings of power and energy society general meeting, IEEE; 2011. p. 1–7.
[68] Eid A. Utility integration of PV-wind-fuel cell hybrid distributed generation systems under variable load demands. Int J Electr Power Energy Syst 2014;62:689–99.
[69] Chedid R, El Khoury H. Design of a hybrid wind-PV-fuel cell system for powering a desalination plant. In: Proceedings of power engineering society general meeting, IEEE PES; 2007. p. 1–6.
[70] Baghaee HR, Gharehpetian GB, Kaviani aK Three dimensional Pareto optimal solution to design a hybrid stand-alone Wind/PV generation system with hydrogen energy storage using multi-objective particle swarm optimization. In: Proceedings of second Iranian conference on renewable energy and distributed generation; 2012. p. 1–6.
[71] Behzadi MS, Niasati M. Comparative performance analysis of a hybrid PV/FC/battery stand-alone system using different power management strategies and sizing approaches. Int J Hydrog Energy 2015;40(1):538–48.
[72] Eroglu M, Dursun E, Sevencan S, Song J, Yazici S, Kilic O. A mobile renewable house using PV/wind/fuel cell hybrid power system. Int J Hydrog Energy 2011;36(13):7985–92.
[73] Uzunoglu M, Onar OC, Alam MS. Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. Renew Energy 2009;34(3):509–20.
[74] Hussain EK, Member S, Bingham CM, Stone D, Hybrid stand-alone renewable energy system with high fuel-cell efficiency and unity power factor. In :Proceedings of IEEE PES conference on innovative smart grid technologies – Middle East (ISGT Middle East); 2011. p. 1–6.
[75] Dursun E, Kilic O. Comparative evaluation of different power management strategies of a stand-alone PV/Wind/PEMFC hybrid power system. Int J Electr Power Energy Syst 2012;34(1):81–9.
[76] García P, Torreglosa JP, Fernández LM, Jurado F. Improving long-term operation of power sources in off-grid hybrid systems based on renewable energy, hydrogen and battery. J Power Sources 2014;265:149–59.
[77] Zhang F, Thanapalan K, Procter A, Carr S, Maddy J, Premier G. Power management control for off-grid solar hydrogen production and utilisation system. Int J Hydrog Energy 2013;38(11):4334–41.
[78] Trifkovic M, Marvin WA, Sheikhzadehy M, Daoutidis P. Dynamic real-time

optimization and control of a hybrid energy system. In: European Control Conference (ECC), Zurich; 2013, p. 2669–74.
[79] Cano MH, Kelouwani S, Agbossou K, Dubé Y. Power management system for off-grid hydrogen production based on uncertainty. Int J Hydrog Energy 2015;40(23):7260–72.
[80] Miland H, Ulleberg Ø. Testing of a small-scale stand-alone power system based on solar energy and hydrogen. Sol Energy 2012;86(1):666–80.
[81] Yumurtaci R. Role of energy management in hybrid renewable energy systems: casecase study based analysis considering varying seasonal conditions. Turk J Electr Eng Comput Sci 2013;21(4):1077–91.
[82] Abedi S, Alimardani A, Gharehpetian GB, Riahy GH, Hosseinian SH. A comprehensive method for optimal power management and design of hybrid RES-based autonomous energy systems. Renew Sustain Energy Rev 2012;16(3):1577–87.
[83] Castañeda M, Cano A, Jurado F, Sánchez H, Fernández LM. Sizing optimization, dynamic modeling and energy management strategies of a stand-alone PV/hydrogen/battery-based hybrid system. Int J Hydrog Energy 2013;38(10):3830–45.
[84] Rouholamini M, Mohammadian M. Energy management of a grid-tied residential-scale hybrid renewable generation system incorporating fuel cell and electrolyzer. Energy Build 2015;102:406–16.
[85] Moghaddam AA, Seifi A, Niknam T, Alizadeh Pahlavani MR. "Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source. Energy 2011;36(11):6490–507.
[86] García P, Torreglosa JP, Fernández LM, Jurado F. Optimal energy management system for stand-alone wind turbine/photovoltaic/hydrogen/battery hybrid system with supervisory control based on fuzzy logic. Int J Hydrog Energy 2013;38(33):14146–58.
[87] García-Triviño P, Llorens-Iborra F, García-Vázquez CA, Gil-Mena AJ, Fernández-Ramírez LM, Jurado F. Long-term optimization based on PSO of a grid-connected renewable energy/battery/hydrogen hybrid system. Int J Hydrog Energy 2014;39(21):10805–16.
[88] Cozzolino R, Tribioli L, Bella G. Power management of a hybrid renewable system for artificial islands: a case study. Energy 2016;106:774–89.
[89] Smaoui M, Krichen L. Control, energy management and performance evaluation of desalination unit based renewable energies using a graphical user interface. Energy 2016;114:1187–206. ISSN 0360-5442 http://dx.doi.org/10.1016/j.energy.2016.08.051.
[90] Achour D, Chaib A, Kesraoui M. Power control and load management of an isolated hybrid energy system, In: Proceedings of 7th international renewable energy congress (IREC); 2016.
[91] Miron C, Christov N. Energy management of photovoltaic systems using fuel cells. In: Proceedings of the 20th international conference on system theory, control and computing; 2016.
[92] Cordiner S, Mulone V, Giordani A, Savino M, Tomarchio G, Malkow T, Tsotridis G, Pilenga A, Karlsen ML, Jensen J. Fuel cell based hybrid renewable energy systems for off-grid telecom stations: data analysis from on field demonstration tests q. Appl Energy 2016.
[93] Torreglosa JP, García-triviño P, Fernández-ramirez LM, Jurado F. Control based on techno-economic optimization of renewable hybrid energy system for stand-alone applications. Exp Syst App 2016;51:59–75. ISSN 0957-4174 http://dx.doi.org/10.1016/j.eswa.2015.12.038.
[94] Zahedi A. Technical analysis of an electric power system consisting of solar PV energy, wind power, and hydrogen fuel cell. In: Proceedings of Australasian universities power engineering; 2007, p. 1–5.
[95] Patsios C, Antonakopoulos M, Chaniotis A, and Kladas A. Control and analysis of a hybrid renewable energy-based power system,. In: Proceedings of XIX international conference electrical machines, ICEM; 2010, p. 1–6.
[96] Cau G, Cocco D, Petrollese M, Knudsen Kær S, Milan C. Energy management strategy based on short-term generation scheduling for a renewable microgrid using a hydrogen storage system. Energy Convers Manag 2014;87:820–31.
[97] Ri YB, and Cell DMH. "Optimal design and performance evaluation of," no. Iconce; 2014. p. 89–93.
[98] Ng KS, Moo CS, Lin YC, Hsieh YC. Investigation on intermittent discharging for lead-acid batteries, In: Proceedings of IEEE power electronics, Special Conference; 2008, pp. 4683–8.
[99] Guinot B, Champel B, Montignac F, Lemaire E, Vannucci D, Sailler S, Bultel Y. Techno-economic study of a PV-hydrogen-battery hybrid system for off-grid power supply: impact of performances' ageing on optimal system sizing and competitiveness. Int J Hydrog Energy 2015;40(1):623–32.
[100] Segura F, Andújar JM, Tomé JM. "Solutions to power management based on voltage and current control methods applied to fuel cell hybrid systems. In: Proceedings of international conference on biosciences (BIOSCIENCESWORLD); 2010. p. 99–105.
[101] Dufo-López R, Lujano-Rojas JM, Bernal-Agustín JL. Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems. Appl Energy 2014;115:242–53.
[102] Crossland AF, Anuta OH, Wade NS. A socio-technical approach to increasing the battery lifetime of off-grid photovoltaic systems applied to a case study in Rwanda. Renew Energy 2015;83:30–40.
[103] Koutroulis E, Kalaitzakis K, Novel battery charging regulation system for photovoltaic applications, p. 191–7.
[104] Andrade AMSS, Mattos E, Gamba CO, Schuch L, Martins MLS. Design and implementation of PV power zeta converters for battery charger applications. In: Proceedings of energy conversion congress and exposition (ECCE), IEEE; 2015. p. 3135–42.
[105] Lee CS, Lin HC, and Lai S, "Development of fast large lead-acid battery charging system using multi-state strategy," vol. 2; 2013. no. 2, p. 56–65.
[106] Horkos PG, Yammine E, Karami N. "Review on different charging techniques of lead- acid batteries. In: Proceedings of technological advances in electrical, electronics and computer engineering (TAEECE), third international conference on; 2015. p. 27–32.
[107] Linden TB, David, Reddy. Handbook of batteries. McGraw-Hil; 2002.
[108] Linden D, Reddy TB, *HANDBOOK OF BATTERIES*.
[109] Chen H, Pei P, Song M. Lifetime prediction and the economic lifetime of proton exchange membrane fuel cells. Appl Energy 2015;142:154–63.
[110] Little M, Thomson M, Infield D. Electrical integration of renewable energy into stand-alone power supplies incorporating hydrogen storage. Int J Hydrog Energy 2007;32(10–11):1582–8.
[111] Leng Y, Chen G, Mendoza AJ, Tighe TB, Hickner M a, Wang CY. Solid-state water electrolysis with an alkaline membrane. J Am Chem Soc 2012;134(22):9054–7.
[112] Rashid MM, Al Mesfer MK, Naseem H, Danish M. Hydrogen production by water electrolysis: a review of alkaline water electrolysis, PEM water electrolysis and high temperature water electrolysis. Int J Eng Adv Technol 2015;4(3):80–93.
[113] Dutton aG, Bleijs J aM, Dienhart H, Falchetta M, Hug W, Prischich D, Ruddell aJ. Experience in the design, sizing, economics, and implementation of autonomous wind-powered hydrogen production systems. Int J Hydrog Energy 2000;25:705–22.
[114] Symes D, Al-Duri B, Bujalski W, Dhir a. Cost-effective design of the alkaline electrolyser for enhanced electrochemical performance and reduced electrode degradation. Int J Low-Carbon Technol 2013. [vol. -, no. -, p. -].
[115] Santos DMF, Sequeira CAC. Revisão. vol 36, no. 8; 2013. p. 1176–93.
[116] Zeng K, Zhang D. Recent progress in alkaline water electrolysis for hydrogen production and applications. Prog Energy Combust Sci 2010;36(3):307–26.
[117] Calderón A, González I, Calderón M, Segura F, Andújar J. A new, scalable and low cost multi-channel monitoring system for polymer electrolyte fuel cells. Sensors 2016;16(3):349.
[118] Jourdan Mohammed, Mounir H, Marjani AEl. Compilation of factors affecting durability of proton exchange membrane fuel cell (PEMFC), In: Proceedings of international renewable and sustainable energy conference; 2014. pp. 542–7.
[119] Janssen GJM, Sitters EF, Pfrang a. Proton-exchange-membrane fuel cells durability evaluated by load-on/off cycling. J Power Sources 2009;191:501–9.
[120] Kannan A, Kabza A, Scholta J. Long term testing of start–stop cycles on high temperature PEM fuel cell stack. J Power Sources 2015;277:312–6.
[121] Borup RL, Davey JR, Garzon FH, Wood DL, Inbody M a. PEM fuel cell electrocatalyst durability measurements. J Power Sources 2006;163(1):76–81.
[122] Bae SJ, Kim S-J, Park JI, Park CW, Lee J-H, Song I, Lee N, Kim K-B, Park J-Y. Lifetime prediction of a polymer electrolyte membrane fuel cell via an accelerated startup–shutdown cycle test. Int J Hydrog Energy 2012;37(12):9775–81.
[123] Yu Y, Li H, Wang H, Yuan X-Z, Wang G, Pan M. A review on performance degradation of proton exchange membrane fuel cells during startup and shutdown processes: causes, consequences, and mitigation strategies. J Power Sources 2012;205:10–23.
[124] Oyarce A, Zakrisson E, Ivity M, Lagergren C, Ofstad AB, Bodén A, Lindbergh G. Comparing shut-down strategies for proton exchange membrane fuel cells. J Power Sources 2014;254:232–40.
[125] Lin R, Cui X, Shan J, Técher L, Xiong F, Zhang Q. Investigating the effect of start-up and shut-down cycles on the performance of the proton exchange membrane fuel cell by segmented cell technology. Int J Hydrog Energy 2015;40(43):14952–62.
[126] Uno M, Tanaka K. Pt/C catalyst degradation in proton exchange membrane fuel cells due to high-frequency potential cycling induced by switching power converters. J Power Sources 2011;196(23):9884–9.
[127] Fontes G, Turpin C, Saisset R, Meynard T, Astier S. Interactions between fuel cells and power converters Influence of current harmonics on a fuel cell stack, In: Proceedings of IEEE transactions on power electronics, special conference., vol. 6, no. 2; 2004, p. 4729–35.
[128] Hoshi H, Aisaka Y, Control Method of Multiple Power Converter to Reduce Deterioration of Fuel Cells.
[129] Changrong L, Jih-Sheng L. Low frequency current ripple reduction technique with active control in a fuel cell power system with inverter load. Power Electron IEEE Trans 2007;22(4):1429–36.
[130] Choi W, Howze JW, Enjeti P. Development of an equivalent circuit model of a fuel cell to evaluate the effects of interter ripple current. J Power Sources 2006;158(C):1324–32.
[131] Upadhyay S, Sharma MP. A review on configurations, control and sizing methodologies of hybrid energy systems. Renew Sustain Energy Rev 2014;38:47–63.
[132] de E EyTG. Ministerio de Industrial, Plan Nacional De Acción De Eficiencia Energética 2014–2020; 2014 p. 1–156.
[133] Ulleberg Ø. The importance of control strategies in PV–hydrogen systems. Sol Energy 2004;76(1–3):323–9.
[134] Kim J, Kim M, Kang T, Sohn YJ, Song T, Choi KH. Degradation modeling and operational optimization for improving the lifetime of high-temperature PEM (proton exchange membrane) fuel cells. Energy 2014;66:41–9.
[135] Jouin M, Gouriveau R, Hissel D, Jouin M, Gouriveau R, Hissel D. Remaining useful life estimates of a PEM fuel cell stack by including characterization-induced disturbances in a particle filter model. Noureddine Zerhouni To cite this version; 2014.
[136] Segura F, Andújar JM. Power management based on sliding control applied to fuel cell systems: a further step towards the hybrid control concept. Appl Energy 2012;99:213–25.
[137] Sacarisen SP, Parvereshi JJP, Improveq Lead-Acid Battery Management Techniques.
[138] Duryea S, Islam S, Lawrance W. A battery management system for stand-alone photovoltaic energy systems. Ind Appl Mag IEEE 2001;7:67–72.