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Literature Review of Energy Management in Combined Heat and Power Systems Based on High-Temperature Proton Exchange Membrane Fuel Cells for Residential Comfort Applications

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Abstract: Combined heat and power technologies represent an efficient way to ensure energy efficiency, as they promote usage of both electrical and thermal energy, something not done by most traditional energy sources, especially in residential environments. In this context, high-temperature proton exchange membrane fuel cells allow the implementation of combined heat and power systems. Additionally, in this environment, fuel cells are more efficient and less polluting than their traditional counterparts. We present a literature review of energy management in residential systems based on this type of fuel cell. In addition, we classify and detail the current state of fuel cell technologies, paying special attention to their characteristics, mathematical modelling and control, as well as combined heat and power systems and energy management strategies.

Keywords: energy management; combined heat and power; fuel cells

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1. Introduction

Potential energy shortages and issues caused by climate change are among the first problems nowadays, as various international institutions highlight [1,2]. For instance, a recent increase of 2.5% in primary energy consumption has been reported [3,4]. These studies also highlight the last decade's increase in coal consumption up to a maximum of 29.9% of the world's primary energy, corresponding to the year 2012 [3]. Simultaneously, consequences of natural disasters that led to Fukushima's nuclear power plant accident forced the Japanese government to move away from nuclear energy, reducing its dependence by 89% (6.9% around the world) [4,5]. Knowing that coal-fired power plants are able to reach efficiencies up to 41% [3], reducing heat waste appears as a key goal to envisage in the immediate future, both from a technological and economical viewpoint.

In reaction to this, political authorities are being forced to look for alternatives that deal with waste energy management during operation. In the case of residential applications, energy consumption represents 27% of the electrical energy and 38% of the thermal energy consumed globally [3]. The specific usage of this energy varies between countries. Some examples of residential energy usage can be seen in Figure 1.

In this state of events, what is called "green hydrogen" [6,7], consisting of using hydrogen as fuel, represents a sustainable solution to replace traditional energy sources in their applications. This hydrogen is produced using electrolysers able to split water into hydrogen and oxygen. These electrolysers need electrical energy to operate, so this should also come from sustainable energy sources such as solar panels, thus forming a cycle between solar panel, electrolyser and hydrogen fuel cells for residential applications [8].

Fuel cells are seen as a possible solution to replace traditional energy sources in many applications of this kind [6]. This is because, apart from generating electrical energy, as is their supposed role, high-temperature fuel cell technologies release heat during their operation, which can be used for heating [4,7–10]. Systems using this heat released for practical applications are known as combined heat and power (CHP) systems, and represent an option to lead with energy waste and increase efficiency [11]. Among different CHP systems, fuel cells are seen as a tool for helping reshape the global energy system [12]. This kind of system has been proven to be reliable in the long term from a technological and economical perspective in analyses such as the one carried out in [8]. The present article focuses on high-temperature proton exchange membrane fuel cells (HT-PEMFC) and, specifically, the chemical and physical characteristics and technological issues specific to them.

The present literature review starts with an explanation of different fuel cell technologies and their differences, advantages and drawbacks (Section 2). After this, the physical characteristics of PEMFC fuel cells are presented (Section 3), and different mathematical models available in the literature are classified (Section 3.1). Afterwards, control strategies for this kind of systems are classified (Section 3.2), and degradation phenomena described in the literature are explained (Section 3.3). Finally, CHP applications including HT-PEMFC are presented (Section 4), and we comment on different energy management strategies tackled by various authors (Section 5).

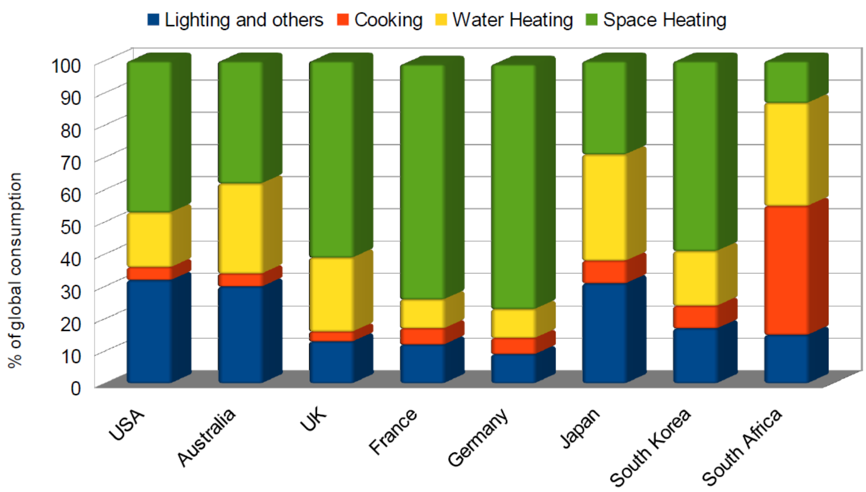

Figure 1. Energy used in residential environments in several countries [3].

2. Fuel Cell Technologies

A fuel cell (FC) is defined [13] as "an electrochemical converter which continuously converts the chemical energy from a fuel and an oxidant into electrical energy, heat and other reaction products". Both fuel and oxidant are continuously supplied and being consumed during the process. There exist different fuel cell technologies, classified according to their components, chemical reaction and operation temperature [13]. Each of these have different advantages and drawbacks that make them suitable for specific applications, and can be stationary or non-stationary depending on the case. Table 1 summarises different fuel cell technologies and their characteristics:

Regarding their applications, fuel cell technologies such as DMFC, AFC and other low-temperature technologies such as LT-PEMFC are useful for non-stationary applications such as vehicles, portable devices and others. In the case of non-stationary applications such as vehicles, in which fuel cells are used together with battery systems to replace traditional engines, only electrical energy is used, and heat is not used inside the car, so it needs to be dissipated. For this reason, LT-PEMFCs are a preferable technology, as higher temperatures could cause problems in mechanical elements involved in vehicle operation. Additionally, LT-PEMFCs are better for vehicles, as they are more prepared for fast start–stop operation, as start-up is easier when the operation temperature needed is lower and thus easier to achieve. On the other hand, high-temperature fuel cell technologies are mainly used for stationary applications where heat can be used for combined heat and power (CHP). These include industrial usages of MCFC or SOFC and residential usages such as those based on HT-PEMFC. This last application in housing facilities is the one explored and described in the following sections, focusing on HT-PEMFC modelling, residential CHP systems in particular and energy management strategies.

Table 1. Fuel cell technologies and their characteristics.

Type	Electrolyte	Temp. (°C)	Fuel	Advantages	Problems
Polymeric (PEMFC)	Polymeric membrane	30–100 (LT) 120–200 (HT)	H_2	- Fast start-up - Solid electrolyte	- Pure H_2 needed - Expensive catalyst
Direct Methanol (DMFC)	Polymeric membrane	30–100	CH_3OH	- Liquid fuel - No reforming step for fuel	- Slow reaction - Fuel crossover from anode to cathode
Alkaline (AFC)	KOH (liquid)	65–220	KOH	- Better current response (fast cathodic reaction)	- Reactants must be removed
Phosphoric Acid (PAFC)	H_3PO_4	150–220	H_2	- High efficiency with heat cogeneration	- Low power and current - Expensive catalysts
Molten Carbonate (MCFC)	Carbonates (Li, Na, K)	600–1000	H_2	- Better conductivity - High current density	- Slow start-up - Material problems
Solid Oxide (SOFC)	(Zr, Y) O_2	600–1000	H_2	- Solid electrolyte - Low cost material	- Material problems - Corrosion of metal

3. Proton Exchange Membrane Fuel Cells

In the case of PEMFCs, several cells are usually assembled together to form a fuel cell stack, simply known as a fuel cell, which consists of different layers. These are presented as follows, and the whole process is depicted in Figure 2:

- **Anode:** corresponding to the left part of Figure 2. Fuel in the shape of gas goes through these pores to reach the interface with the electrolyte, responsible for conducting ions and the place where fuel oxidises; electrons move across an external circuit from anode to cathode.
- **Cathode:** corresponding to the right part of Figure 2. The oxidant goes through cathode's pores to the electrolyte interface, where reduction takes place.
- **Membrane:** constituting an electrolyte, at the centre of Figure 2, it is responsible for conducting ions between electrodes.
- **Bipolar plates:** place where the anode and cathode channels are located, responsible for conveying electrons and reactants to the electrodes, as well as evacuating their excess and the reaction products. Heat released by the system needs to be handled adequately with additional devices.

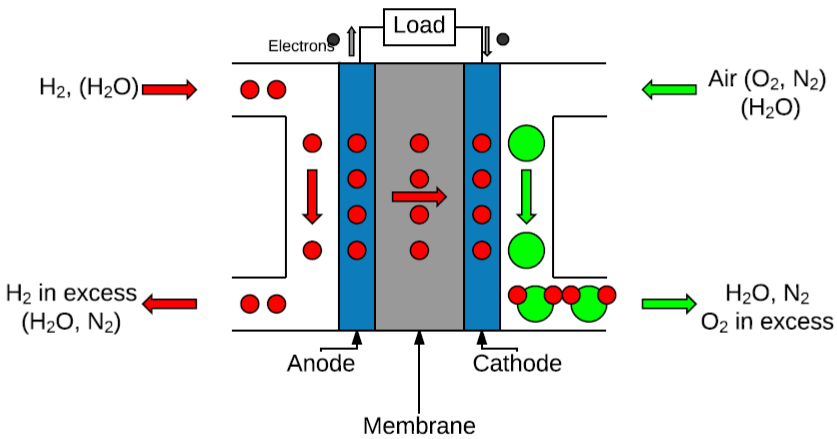

Figure 2. Fuel cell scheme.

These layers are sealed using silicon to prevent fluid leakages to form what is known as a fuel cell stack.

Pure hydrogen (H_2) is needed in the anode for a PEMFC reaction, and air, as it is mainly composed of nitrogen and oxygen, can be directly fed into the cathode to supply oxygen. As nitrogen is inert, that is, it does not react with other chemical species involved in the reaction, it is not depicted in the fuel cell cathode channel. This nitrogen simply circulates along the cathode channel and goes out unperturbed. Air is usually used instead of pure oxygen since it is easily available without any extra processing. Hydrogen oxidation occurs at the anode to produce protons (H^+) that are forced across the membrane connecting the anode and cathode. At the same time, the cathode receives electrons assembled by the mentioned bipolar plates. The reaction is accelerated using a catalyst such as platinum, whose active area is a key value to improve the process. This electrochemical active surface area (ECSA) should be increased and is one of the first elements to be degraded, as active parts are easily damaged or catalyst particles are lost during operation. Finally, it is at the cathode where protons and oxygen combine to generate water, as seen in Figure 2. Chemical redox half-reactions corresponding to this process are [13]:

$$H_2 \longrightarrow 2H^+ + 2e^-$$
$$\tfrac{1}{2}O_2 + 2e^- + 2H^+ \longrightarrow H_2O.$$

These half-reactions have been obtained using the balancing method consisting of taking both species, hydrogen and oxygen, and balancing the stoichiometry of both mass and charge adding protons H^+, water molecules H_2O and electrons e^-. This makes both the reactions in the anode and cathode explicit. A similar procedure could be done by splitting H_2O into OH^- and H^+. As a result of this process, electrical and thermal energy, as well as water, are produced. If process losses are neglected, the reversible Nernst potential V^N is defined as presented in [13]:

$$V^N = -\frac{\Delta g_f^0}{2F} + \frac{R \cdot T}{2F} \ln\left(\frac{P_{H_2} P_{O_2}^{\frac{1}{2}}}{P_{H_2O}}\right), \tag{1}$$

where $\Delta g_f^0 = -228.59$ kJ/mol is the Gibbs free energy to form a mole of vapour water, $R = 8.31$ J/(K mol) is the ideal gas constant, $F = 96485.34$ C/mol is Faraday's constant, T is the temperature, P_{H_2} is hydrogen's partial pressure, P_{O_2} is oxygen's partial pressure, and P_{H_2O} is water vapour's pressure.

In terms of heat released by the fuel cell during its operation, there are several phenomena contributing to it [14]:

- Half reactions shown above have an entropy variation related to heat.
- The electrochemical reaction itself releases heat during its activation.
- Gas diffusion layers in the fuel cell, responsible for conveying gases from the anode to the catalyst layer, undergo processes of sorption and desorption, contributing or diminishing heat released, depending on the case.
- Heat is released in the electrical part of the system by the Joule effect.
- Water phase-change in the gas diffusion layer, in the case of low-temperature fuel cells, absorbs heat from the cell.

The global redox reaction is exothermic, meaning it releases heat Q_r. This heat is connected to the reaction's entropy variation ΔS with the following relation:

$$Q_r = T\Delta S. \tag{2}$$

ΔS is calculated using formation entropies characteristic of each substance, i.e., hydrogen, water, oxygen and nitrogen. The relation between hydrogen flow and electrical current, I, is directly proportional, so identifying a similar relation between current and released heat is also desired. However, in real applications, fuel cells present voltage drop in comparison with Nernst reverse voltage V_N, be it with or without load. This decrease mainly increases losses in the cell, causing problems in the short and long run. Related issues are described as follows:

- Redox reactions need an activation energy to start, especially important in low-current scenarios.
- Ion transport across the membrane and electrodes involve ohmic resistance, neglected in the case of bipolar plates.
- There is a drop in voltage due to matter transport through porous electrodes, specifically the gas diffusion layer. This phenomenon is especially harsh at high currents and is related to current density j, which is a function of current I and the electrode area A:

$$j = \frac{I}{A}. \tag{3}$$

A single cell voltage can be defined as:

$$V_{cell} = V^N - \eta^a_{act} - \eta^c_{act} - \eta_{ohm} - \eta^a_{conc} - \eta^c_{conc}, \tag{4}$$

where:

- V^N is the Nernst reversible potential;
- η^a_{act} and η^c_{act} is the voltage drop provoked by activation at the anodic and cathodic electrodes, respectively;
- η^a_{ohm} is the voltage caused by ohmic resistance;
- η^a_{conc} and η^c_{conc} are the voltage drop due to matter transport at the anodic and cathodic electrode, respectively, also known as concentration losses.

As mentioned before, in real applications, the voltage provided by a single cell is too low to be useful (less than 1 V). For this reason, it is common to arrange several cells in N-cell stack terminals. The number of layers selected is, consequently, adapted to the specific application, depending on the voltage desired, space available for the fuel cell and other implementation issues. The resulting voltage of the whole stack must be defined accordingly, as seen in Equation (5):

$$V_{stack} = \sum_{1}^{N} V^i_{cell} \tag{5}$$

Typical values for the nominal current density of the whole stack are between 0.5 and 1 A/cm^2, with a corresponding mean cell voltage around 0.7 V. The residual power obtained by Joule's effect as well as process heat represents 37.5% of the output energy released (30% of the energy supplied by the fuel can be reused for the CHP system) [3].

In order to characterise PEMFC performance, a polarisation curve is defined [13], relating PEMFC voltage to current density. This polarisation curve changes depending on the operation temperature. When current is low, activation losses dominate (activation zone in Figure 3), concentration losses are most significant when current is high (concentration zone in Figure 3), and ohmic losses are predominant at intermediate currents (ohmic zone in Figure 3). Activation and concentration losses force an asymptotic tendency in the curve. An example of a polarisation curve for a HT-PEMFC is depicted in Figure 3, with current corresponding to a stack of 20 cells and an area of 1 cm^2 operating at a temperature of 127 °C . The same is done for the electrical and thermal power generated by a fuel cell, as seen in Figure 4, where the same three zones corresponding to different losses (activation, ohmic and concentration) are also depicted.

Differences between low-temperature PEM fuel cells (LT-PEMFC) and their high-temperature counterparts (HT-PEMFC) are mainly related to their operation temperature. While the former operate at 60–80 °C, the latter work between 120 °C and 200 °C [13]. Advantages and drawbacks of these technologies are:

- Generation of liquid water in LT-PEMFCs causes problems when managing this water and its distribution along the system. In LT-PEMFCs, membrane humidity should be kept within limits for proper operation. This humidity should not be too low, as a dry membrane does not work properly, but neither should it be too high, as this can lead to membrane flooding. This is not a problem in the case of HT-PEMFCs, as temperatures above water's boiling point turns the water into vapour, and membrane operation is not as restrictive as in LT-PEMFCs [15,16].

- The electrochemical reaction at the cathode side is slowed in LT-PEMFCs. This may cause cathode overpotential, responsible for cell voltage losses [13].
- A high concentrations of carbon monoxide (CO, above 10 ppm) reduces performance, as it causes platinum poisoning (platinum being used as an electro-catalyst). Although platinum poisoning cannot be completely eliminated, this risk is substantially reduced in the case of HT-PEMFC, as higher temperatures (above 140 °C) allow higher CO tolerance. This is because higher temperatures catalyse the chemical reaction between CO and water vapour to form CO_2 and hydrogen [3].
- Pure hydrogen is required for both LT-PEMFCs and HT-PEMFCs, but HT-PEMFCs are more tolerant to impurities, which may reduce the production cost of the global system [13,15].
- Higher temperatures cause changes in charge and transfer as resistance is reduced. Consequently, the efficiency of the kinetic reaction increases, thus enhancing global fuel cell efficiency [13,16]. Additionally, higher temperatures make heat released easier to be used for practical applications.

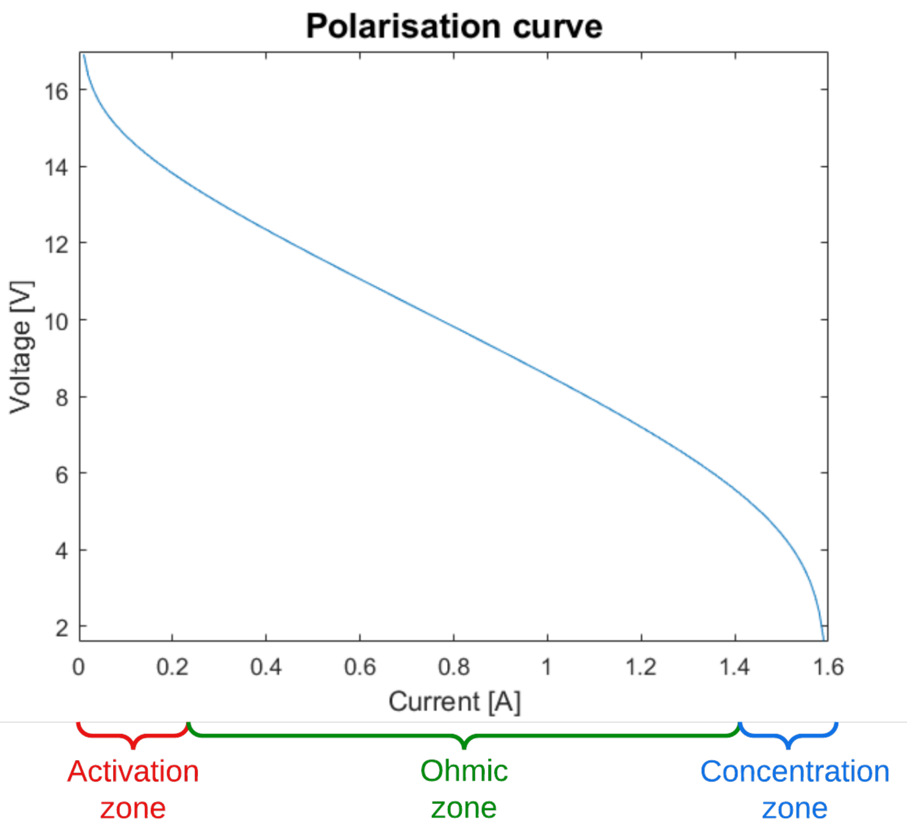

Figure 3. Polarisation curve of an HT-PEMFC (20 cells, area of 1 cm^2 and temperature of 127 °C).

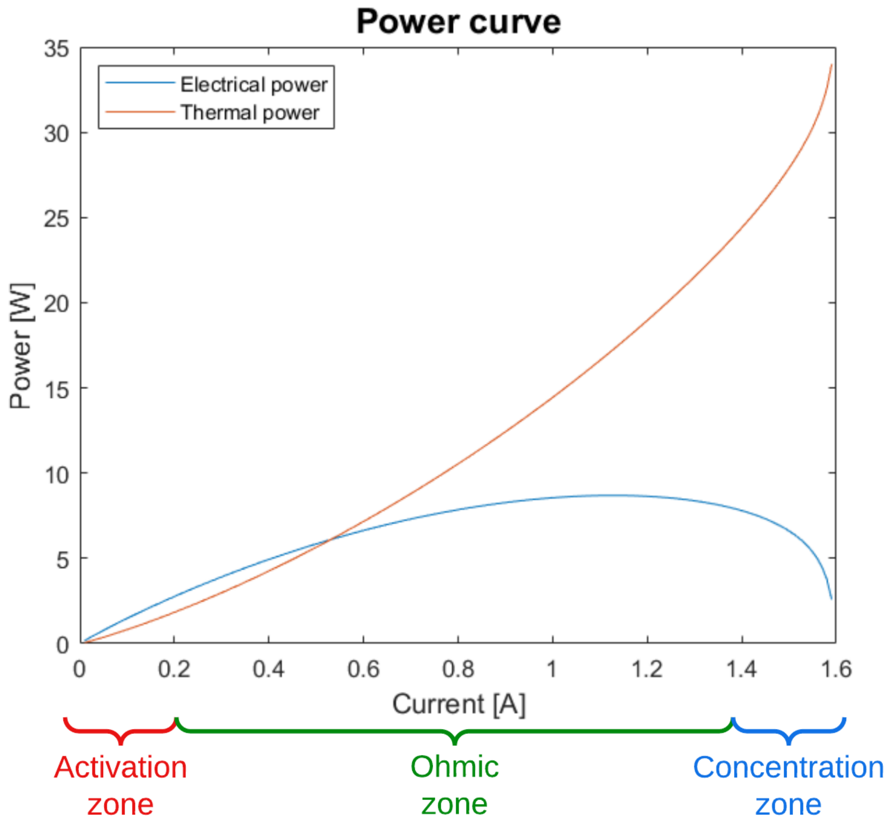

Figure 4. Electrical and thermal power curves of a HT-PEMFC (20 cells, area of 1 cm^2 and temperature of 127 °C).

3.1. Proton Exchange Membrane Fuel Cell Models

In the scientific literature, several ways of modelling can be found. Each type of model is suitable to specific applications and approaches [16,17]. Some approaches move towards concentrated parameters [6,18] in order to simplify the formulation and make the resulting simulation of the system less demanding from a computational point of view. Another advantage of this kind of model is their clarity when analysing the results to prove their reliability. However, this simplicity can lead to errors when too many interactions and dependencies between some system variables are neglected, and due to their lack of resemblance to the original system's geometry.

Another way of modelling is by using the original physical equations of fluid dynamics, diffusion and heat transfer [19–21]. These equations in their differential form include derivatives that make the system variables depend on both spatial (typically x, y, z) and temporal conditions for each part of the geometry and point in time. Therefore, partial differential equations (PDE) are used to determine fuel cell system variable evolution. These models are more precise but may become too complex when detailed phenomena are included. This complexity needs to be simplified accordingly for simulation. For this reason, the number of dimensions is occasionally reduced to two [22,23] or one [24,25]. Due to this fact, the complexity of the system may resemble that of a concentrated-parameter model, which is why certain authors propose three-dimensional models [18,21]. Reducing model dimensions can reduce the reliability of the results, but in certain cases, the obtained results are reliable and easily computed. Therefore, simple models are suitable for the presented study, and a simplified model can therefore be easily used for simulation and especially control design and implementation.

This article focuses specifically on high-temperature proton exchange membrane fuel cells. As mentioned previously, use of this kind of cell has recently been focused more on stationary applications. Non-stationary usages are usually the target of low-temperature fuel cells, even though some automotive applications using HT-PEMFCs are being studied. Unlike LT-PEMFCs, HT-PEMFCs do not produce liquid water (it evaporates). For this reason, gas transport models using stationary Navier–Stokes equations [19,21] or Darcy's law [26] are considered. There exists a trade-off between the reliability of model results and their usefulness when trying to implement control strategies. Another fuel cell technology operating at high temperatures is SOFCs, but their really high operation temperatures (600–1000 °C) make them impractical for implementation in housing facilities due to start and stop issues, high sensitivity to temperature gradients, and the heat exhaustion devices needed to get rid of extra heat released by them. This makes this kind of fuel cells more appropriate for industrial environments and manufacturing where CHP is needed for the process. Summarising, the current research in the field of PEMFCs and their modelling techniques can be summarised as seen in Table 2.

Table 2. PEMFC models and characteristics.

	Characteristics	Concentrated Parameter Models	PDE Models	Experimental Studies	HT Models	LT Models	1D Models	2D and 1D+1D Models	3D Models
PEMFC models	[15], [16], [26], [27], [28], [29], [30], [31],	[6], [24], [32], [33], [34]	[16], [17], [19], [20], [21], [22], [23], [25], [26], [35]	[19], [21], [33], [35]	[6], [16], [17], [21], [22], [23], [33],	[19], [20], [24], [25], [26], [32], [35]	[6], [24], [25], [33], [34], [35]	[22], [23], [26]	[16], [17], [19], [21]
PEMFC annex systems models	[6], [15], [27], [31], [36]	[6], [34]		[31], [37]	[6], [15], [27], [31], [36], [37]		[6], [34]		
CHP systems	[4], [6], [38], [39], [40],	[6], [11], [40]			[6], [11], [38], [39], [40], [41]		[6], [11], [40]		

3.2. Proton Exchange Membrane Fuel Cell Control Strategies

When using HT-PEMFC, there are several variables that can be controlled. Selecting one variable over another for control depends on the specific application, meaning that not all variables can be controlled at the same time. Some of the variables that can be selected as control variables are the following:

- **Operating temperature:** to prevent excess damage to the cell materials and to meet the required output heat.
- **Fuel cell stack voltage or fuel cell stack current:** to match the electrical demand required from the fuel cell. If voltage is fixed, current is consequently fixed, as the polarisation curve establishes a direct relation between them. Similarly, if current is chosen as the control variable, voltage follows its behaviour. Choosing current instead of voltage has the advantage of establishing a direct link with hydrogen flow, as they are directly related, while voltage control is done from an electrical point of view through voltage converters.
- **Input gases:** the amount of each gas injected, as well as their pressure and humidity, influence the stoichiometry and initial reaction conditions. These flows can be controlled to match a particular reactant balance.

There exist several proposed control strategies for PEMFC, the most relevant of which are presented in Table 3.

Table 3. Control strategies for PEMFC systems.

	State Feedback Control	Nonlinear Plant Control	Linearised Plant Control	Predictive Control	PID Controllers	LPV	Neural Network Control
PEMFC	[26]	[42], [43], [44], [45]	[46], [47], [48], [49]	[45], [47], [49], [50],	[46], [49]	[42], [43]	[49], [51],
PEMFC annex systems		[42], [43], [44]	[46], [47]	[47]	[46]	[42], [43]	
CHP systems		[44]					

When considering suitable control strategies for HT-PEMFC, the first step is to define the control objectives. In this case, low-level control must be applied to adjust the fuel cell's variables, and high-level supervisory control ensures system efficiency and reduces fuel cell degradation. Regarding low-level control strategies, some authors propose the well-known proportional, integral and derivative (PID) controllers [46,49], which are easier to design in linear systems but difficult to tune in the case of nonlinear systems such as fuel cells. PID controllers are better designed for linear systems around selected operating points over nonlinear ones, which implies that the system must be linearised, and some information may be lost in the process.

Another option used in certain PEMFC systems is linear parameter-varying (LPV) control [42,43], which is based on considering different operation points of a nonlinear system and working with its linearised version around these points. Several operation modes may be defined so that the state–space representation is linear and time-invariant around the selected operation point. A range of operation points need to be selected based on real physical states of the PEMFC system obtained from the literature or from simulations using multiphysics software such as Comsol®. The information obtained from the literature or from other simulations can provide knowledge regarding the range of operation of system variables. Once this range of operation is known, equilibrium points can be found to solve the system of equations around this operation zone. Afterwards, this system needs to be linearised accordingly to be controlled around each of these equilibrium points. This kind of control is presented as a way of dealing with nonlinear systems such as those resulting from the Navier–Stokes equations or Darcy's law for gas transport in HT-PEMFCs.

Finally, there exist other alternatives in HT-PEMFC control, for instance, adaptive control based on neural networks [49,51]. This control technique is much more complex than the others found in the literature, and may be an option depending on the system requirements.

3.3. Proton Exchange Membrane Fuel Cell Degradation

One of the main challenges nowadays in the field of PEMFC is the study of their degradation—not only its effects but also its causes and prevention and/or mitigation strategies. Degradation is one of the objectives tackled by control strategies such as those presented in the previous section, as fuel cell systems are easily degraded, and certain control strategies can help mitigate some of these phenomena. Degradation in PEMFCs can be caused as follows:

- **Chemical and mechanical membrane degradation:** damage to the membrane affecting the subsequent proton exchange [52].
- **Starvation:** when the stoichiometry of the reactants (hydrogen and oxygen) is insufficient for the reaction to take place.
- **Thermal degradation:** material degradation caused by excessive exposure to heat [13].
- **Catalyst carbon corrosion:** carbon structure of the catalyst is damaged [53].
- **Catalytic layer separation:** loss of contact between the layers, impeding a proper chemical reaction [54].

- **Platinum agglomeration and dissolution:** loss of active area of platinum in the catalyst, thus reducing its effect [53].
- **Catalyst poisoning:** loss of effectiveness of the catalyst due to excessive contact with carbon monoxide (CO) [13].
- **Hydrophobic losses in the gas diffusion layer (GDL):** transport problems of gases through the porous environment [53].

According to these criteria, the current literature regarding PEMFC degradation is classified in Table 4.

Table 4. PEMFC degradation mechanisms.

	Chemical and Mechanical Membrane Degradation	Thermal Degradation	Catalyst Carbon Corrosion	Catalytic Layer Separation	Platinum Agglomeration and Dissolution	Catalyst Poisoning	Hydrophobic Losses in the GDL
HT-PEMFC	[13], [52], [54], [55], [56], [57], [58]	[13], [52], [53], [56], [57], [58], [59]	[13], [52], [54], [55], [56], [57]	[52], [54]	[13], [52], [53], [54], [57]	[13], [54]	[55]
LT-PEMFC	[13], [59], [60], [61], [62], [63], [64], [65], [66], [67], [68], [69]	[59], [60], [65], [69]	[13], [61], [66], [67], [68], [69], [70], [71], [72], [73]	[63], [64], [68]	[13], [61], [62], [63], [64], [66], [67], [68], [69], [70], [71], [73]	[13], [62], [63], [69]	[59], [61], [62], [66], [67], [69], [73], [74]

There are some differences in the phenomena causing degradation in LT-PEMFCs vs. HT-PEMFCs. For instance, as can be seen in the literature [13,52], thermal degradation is much more important in HT-PEMFCs. The majority of references to PEMFC degradation focus on stress tests and other experiments that try to emulate real degradation under operating conditions. However, for this article, when trying to mitigate degradation, it is important to select ways of mitigating it from the exterior of the system. This is why variables able to affect degradation must be chosen so that they are accessible externally by control systems without interrupting internal physical phenomena by introducing internal sensors and/or actuators that could affect operation. These variables affecting PEMFC degradation need to be weighted according to their contributions to cell degradation. Certain references include mathematical relationships between electrochemical active surface area (ECSA) and fuel cell voltage [61], but these are scarce. Online parameter estimation algorithms can also be used to monitor the degradation of fuel cells [75–79].

Among these degradation phenomena, those that are controllable need to be addressed by this article. A relationship between externally controllable variables such as cell voltage, electrical current, temperature or gas flow and the internal phenomena aforementioned needs to be established. An analogous degradation index has been used for battery systems [80], even though the physical phenomena involved are completely different. There exist different kinds of degradation models for battery systems, depending on the approach adopted:

- **One-dimensional electrochemical model:** based on theoretical electrochemical equations. Degradation phenomena are modelled according to physical laws representing degradation phenomena described, so that they can be mitigated [53,61,67,81].
- **Semi-empirical degradation model:** based on theoretical regression models to be fitted with parameters experimentally. Experimental data are used to find simple correlations, which is much more direct than the ones codified by physical degradation models. These correlations can be used to directly act against degradation by modifying easily accessible variables, which is not easy for internal variables involved in degradation mechanisms [82,83].
- **Empirical degradation model:** based directly on experimental results to fit a certain model. These models offer direct relations between external variables able to

be manipulated and degradation, but lose physical understanding of the process studied [66,71].

These degradation models are used to establish relations between accessible and controllable variables such as fuel cell voltage, current, gas pressure and external temperature vs. internal variables affecting degradation. Once models are able to link these two sets of variables, internal and external, controllable external variables and their contributions to degradation mitigation can be identified.

4. Micro CHP Applications

HT-PEMFC-based CHP systems are among the multiple applications in which fuel cells are being used nowadays [3,84]. Fuel cells can be used for low-power and high-power electrical applications (from hundreds of mW to MW) [3]. A global FC-based CHP system includes the following elements (Figure 5) [85]:

- **Fuel cell stack:** an array of fuel cells dimensioned depending on the power required, with characteristics described above.
- **Hydrogen tank:** supplies pure hydrogen to the fuel cell. This hydrogen can come from an electrolyser, which splits water into hydrogen and oxygen [7], or from natural gas reformation, which is less environmentally friendly [34].
- **Heat exchanger:** HT-PEMFC heat needs to be processed with a cooling system in many applications, but is used in the case of CHP systems. For this reason, a heat exchanger is required to convey and adapt the temperature of an external fluid that acts as a medium to transfer this heat to use it for thermal demands, although some applications use equivalent systems based on air exchange [86].
- **Power conditioning system:** converts DC current generated by the fuel cell stack into the adequate shape, be it DC or AC (specifying its voltage levels). Different converters need to be designed for different parts of the system.
- **Battery systems:** used to save electrical energy during periods of low use for future demand. Storage of this extra energy mitigates problems caused by sudden demand in future periods, preventing overwork in the fuel cell that could contribute to fast degradation.
- **Water storage tanks:** has an equivalent role to the one corresponding to battery systems, but with the goal of storing hot water to be used later for thermal demands. Due to the fact that fuel cells generate both electrical and thermal energy simultaneously, it is quite typical that high electrical demands produce extra heat that can be stored. The opposite case is also possible, when high thermal demand is needed despite low electrical demand.

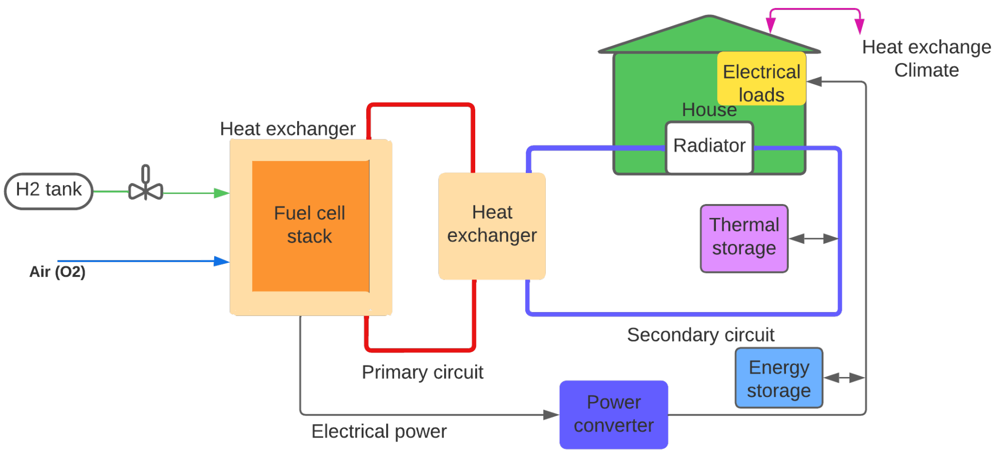

Figure 5. CHP system diagram.

There are technologies available to integrate the fuel cell, heat recovery unit, heat exchanger, control units and connections. A device like this has been obtained in the PACE project [87]. This fuel cell CHP device for residential and commercial applications has the following elements:

- Fuel cell stack with insulation;
- Heat exchanger;
- Desulphuriser;
- Controls and inverter.

The main problem with CHP systems similar to the PACE project ([87]) is that both electrical and thermal demands need to be satisfied at all times, while thermal and electrical storage systems are used to mitigate sudden changes in fuel cell operation, thus reducing fuel cell degradation and satisfying continuous operation of the global system. For this reason, different energy management strategies have been studied to deal with all these different objectives in parallel. These strategies need simple but reliable mathematical models of all elements of the CHP system [7], as detailed models based on fluid dynamics, such as the one in [88], are too cumbersome for control and optimisation purposes; thus, straightforward electrochemical equations are preferred for large-scale CHP applications such as the one studied.

In cases when fuel cell performance is poor due to the degradation problems already mentioned, external elements of the CHP system, such as storage elements or the electrical heating system, need to perform additional work. This also should be controlled by the energy management system. In extreme circumstances when storage systems and heating are insufficient, a connection to the traditional electrical grid is needed. Additionally, higher temperatures in PEMFCs increase both thermal and electrical energy production, but also increase fuel cell degradation. Both energy production and degradation need to be taken into consideration in the energy management procedure, so a trade-off must be made. All these issues must be assessed by the energy management strategy selected for the CHP system.

5. Energy Management Control Algorithms for Housing Facilities

More specifically, this article focuses on controlling CHP housing facilities, aiming at comfort and efficiency of global energy consumption. A CHP system is controlled at two levels (Figure 6):

- **Local controllers:** control devices such as the fuel cell stack, thermal storage and electrical battery systems. Ensures stability and proper operation of each device.
- **Supervisory control:** computes and provides system variable values so that electrical and thermal demand at all times are fulfilled. Among all devices involved in the CHP system, some need to be prioritised depending on certain defined objectives. These can be related to efficiency, environmental reasons, mitigating degradation, etc. Figure 6 shows systems controlled and variables provided by the supervisory control: fuel cell, water storage elements and battery systems, as previously presented in Figure 5. Additionally, external elements such as electrical grid connections, thermal energy generated via electrical devices and thermal energy released as waste are depicted. The variables that govern these elements are those that activate or disable them.

Several studies have been carried out to improve different areas of the CHP system [89]. Along this line, the following research topics have been explored:

- CHP housing systems and their mathematical models;
- Algorithms for CHP energy management.

Regarding mathematical models, the field of CHP systems for housing facilities has been widely studied by many authors [12,90–92]. As mentioned before, heat released by fuel cells needs to be used to increase the global energy efficiency of the system, thus contributing to more-autonomous housing facilities. To accomplish this, mathematical characterisation of the parts of the system are needed for control purposes. In most cases, different elements of the CHP system are designed as a result of simple energy balances, as housing applications do not require high accuracy in terms of chemical and thermal processes [7,93]. The energy management problem consists of ensuring autonomy of the FC-based CHP system, as it is a sustainable alternative to current energy sources, while promoting global efficiency and mitigating fuel cell degradation. The global control scheme in a CHP plant is seen in Figure 7. Fuel-cell input gas flow is controlled, as well as its temperature after the heat exchanger deals with the heat released by the fuel cell. Consequently, heat released is used to heat water in the thermal accumulator, which is used to guarantee comfort and match thermal demand. On the other hand, electrical energy produced is used to charge the battery (via electrical converters), which is used to supply electrical energy in cases when the fuel cell would need to work too suddenly. Finally, in case it is needed, a connection to the electrical grid is provided for safety reasons. To implement control, a multiobjective problem with the following objectives expressed as mathematical functions is defined:

- **Fuel cell current:** this must be the main electrical source, instead of grid or other traditional sources, to satisfy demand. However, its variation should also be smooth to prevent degradation, as start–stop reduces fuel cell lifespan. As a consequence, two objectives arise: maximise fuel cell current while reducing current variation.
- **Battery state of charge (SOC):** batteries must be used to store excess electrical energy during periods of low demand. However, the battery's state of charge must be kept between limits to avoid degradation.
- **Water tank temperature:** thermal energy must be used to heat the water tank, so that hot water can be used later to match thermal demand. This value should be below water's boiling temperature and should be quite stable to be ready when needed.
- **Security connections:** connection to the grid must be used only when needed, avoiding fast switching between fuel cell, battery and grid. Only in extreme cases and for concretely isolated iterations should this connection be enabled. The same should happen for security connection enablement, such as generating thermal energy via an electric space heater or releasing extra heat produced by the fuel cell to the environment. Both cases should be limited to exceptional occasions.

Regarding control algorithms, several options have been studied for residential CHP energy systems:

- Rule-based models;
- Recursive methods;
- Model predictive control (MPC).

Figure 6. Control scheme for the CHP system.

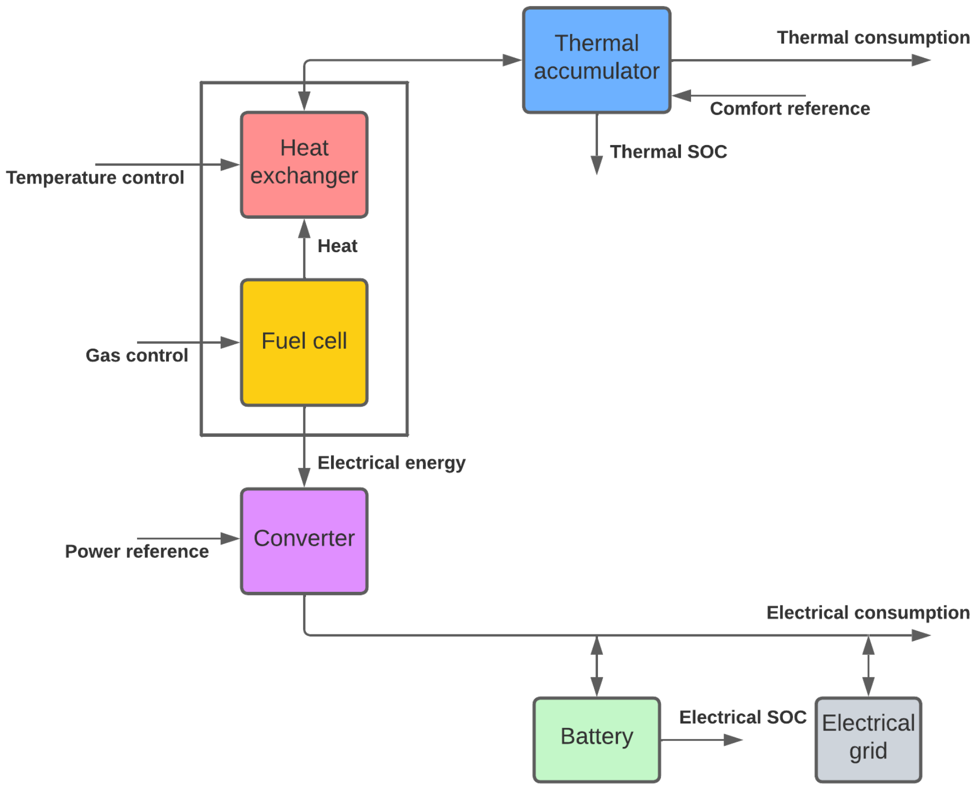

Figure 7. CHP plant and its controlled elements.

5.1. Rule-Based Models

One option studied nowadays is the use of rule-based models [90]; these are based on optimisation, but with a different formulation to compute CHP variables such as power generated to match both electrical and thermal demands. The method presented in [90] consists of a two-stage model aimed at following specific trajectories while reducing computational effort, thus making it suitable for both test-bench applications and embedded systems. Another method using Markov decision methods to apply deep reinforcement learning to manage house energy is presented in [94]. This method is reliable, as it ensures good trajectory matching, but it is highly demanding computationally. Finally, another case is presented in [7], which follows a logic chart to establish the different state of all CHP elements in the system. This ensures certain tracking of variables and system states.

5.2. Recursive Methods

Other energy management methods are based on recursive calculations [92,93]. In [92], a forecasting unit is added to a test-bench to match energy demand in a real CHP system. This is verified in a real experimental platform, and the operation of each CHP element is monitored. In [93], voltage and power of the CHP system are computed and compared to certain initial values, and local controllers are adjusted after each iteration in order for the system to match the target values.

5.3. Model Predictive Control

Model predictive control is a popular control technique for energy management systems in many different fields [95–98]. MPC has also been used in residential CHP applications in its different versions, either linear [12,91,99,100] or nonlinear [101,102]. Several studies aiming to improve performance via better prediction have been carried out [89,103]. The ability to optimise with constraints while introducing prediction is highly valued for planning demand and trying to guarantee efficiency in advance.

MPC is a way of governing CHP systems, as its algorithm is able to anticipate system evolution, more specifically, its tendency based on prediction of the future. Electrical and thermal demands have similar behaviours from one year to the next during a specific day or season. However, some variations are always present throughout the day, when a minute-to-minute analysis is done. This is why the system must be resilient and adapt to variations around the predicted tendencies. The MPC algorithm has an input–output structure as shown in Figure 8:

- **Objective function:** formed by a set of subfunctions to be minimised, such as fuel cell current and its variation, battery and water tank fluctuations, and energy exchanged with the grid or the environment. These subfunctions need to be multiplied by weight functions so that they can be added and form the global objective function to be minimised. These weight functions need to be selected so that some objectives are prioritised above others.
- **Variables:** system variables include fuel cell current and variables governing activation and deactivation of the battery, water accumulator, grid connection and environment connection. Electrical and thermal demands are included as system disturbances. Disturbance variables must be predicted so that the MPC can compute future scenarios, even though they cannot be predicted exactly (Figure 9).
- **Constraints:** these include upper and lower bounds for electrical current, battery state of charge, water accumulator temperature and others. Additionally, the system equations need to be imposed as a constraint.
- **Prediction horizon:** optimisation is based on the system model and variables evaluated at the current time-step iteration, but it also anticipates future evolution of these variables. For this reason, a certain number of iterations in advance are predicted so that disturbances and other variables are simulated, preparing the system trajectory for what is to come (Figure 9). The control horizon (H_u) and prediction horizon (H_p) move every time the iteration k advances, predicting an extra step while computing real values for the ones already completed. This ensures reliability and robustness when trying to fulfil electrical and thermal demands.

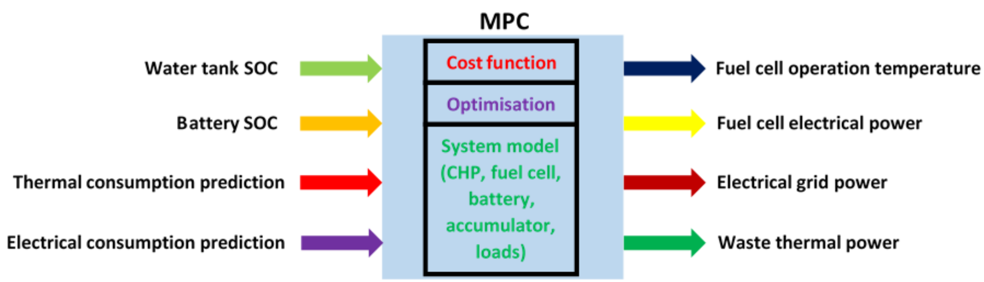

Figure 8. MPC scheme with variables and mathematical components.

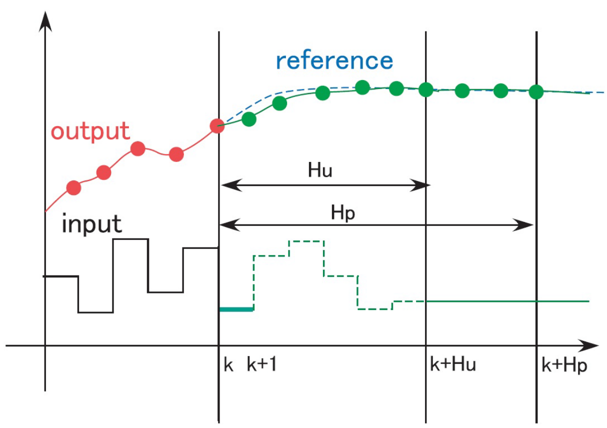

Figure 9. MPC variables, disturbances and prediction horizon.

Authors define prediction differently depending on the reliability of the information they have about future system behaviour and its predictability in general. For example, Ref. [104] tracks prediction error in the state of charge of batteries in an energy system so that this prediction can be improved in future scenarios. In [105], the effect of prediction uncertainty in an MPC-based energy management system is studied.

Multiobjective Problem Analysis Using Pareto Fronts

When dealing with multiple objectives at the same time, weighting functions need to be defined so that some objectives are prioritised above others. To guarantee weighting functions that correspond to optimal function, studies based on Pareto fronts have been published [106–109]. In HT-PEMFC-CHP systems specifically, several target objectives are presented. Among these objectives, some of them need to be prioritised, such as promoting the fuel cell as the main energy source; mitigating fuel cell degradation via small current variation; and low switching between energy sources, preventing grid or extra thermal system activation every few iterations. For this reason, objectives such as these are selected, and a Pareto front is calculated to find the weight functions corresponding to each objective. These objectives and weight functions are used to build the MPC objective function [110,111].

An energy management strategy for a CHP system composed of different renewable systems, storage elements and heating elements is presented in [106]. This strategy uses Pareto optimality for efficient and less-polluting operation in a multi-objective optimisation problem, connecting the CHP system to the grid when necessary. A similar approach is presented in [107], also prioritising efficiency and low emissions but using an epsilon-constraint technique to solve the multiobjective problem, and selecting a solution from among all Pareto optimals via fuzzy decision making.

In [108], an island renewable energy system is controlled under harsh weather conditions by performing a Pareto optimisation problem and a sensitivity analysis. Finally, selection between Pareto optimal solutions in residential energy systems is used in [109], with a goal similar to that of the following references.

In the specific case of energy models and microgrids, approximation of Pareto fronts to select weighting functions are the object of study in [110,111]. The aforementioned epsilon-constraint method is also used in [111], which aims to obtain a payoff table with points included in the Pareto front. The Pareto front is approximated online with a filter, selecting the important points to form the structure of this trade-off surface and discarding redundant points throughout the process. Once the final points approximating the Pareto front are found, this trade-off surface can be used to find a good combination of objective functions so that none of them is ignored completely. These algorithms are applied to systems such as renewable-based microgrids [111] in order to prioritise the typical objectives of energy efficiency and environmental, security and socioeconomic issues.

A similar approach is presented in [110]. However, their strategy is more flexible and tackles large-scale energy applications, focusing on reducing computational effort when applying the Pareto strategy in the multi-optimisation problem. This strategy is based on building a set of clusters with points obtained in the optimisation process along time. The procedure followed in the decision process is:

1. A set of clusters of points is defined successively based on the solutions of the optimisation problem;
2. For each specific configuration, values are assigned to each cluster;
3. The average of every cluster is obtained, and a curve representative of the cluster is defined;
4. For each configuration, the centroid profile is calculated;
5. This profile's values are sorted, creating sorted means and classifying them by the order in which they appear in the original curve;
6. Values are sorted according to the order established by the cluster's representative curve.

Once this is done, Pareto fronts can be computed, paying attention for low time and computing efforts. This algorithm is applied to different energy systems such as a self-sufficient building model and a prospective European network.

When implementing the multiobjective problem with the selected weight functions, all objectives are applied, but by contributing to the global optimum in a way that the global set of objectives is taken into consideration. Some of these objectives are prioritised, but none of them is completely discarded. Their contribution to the global optimum is taken into consideration after the Pareto front has been calculated. This ensures good fulfilment of objectives while, at least to some extent, not affecting others. In the case of CHP systems based on HT-PEMFCs, objectives of efficiency, maximum use of fuel cell instead of other energy alternatives, and fuel cell degradation mitigation using storage systems to reduce sudden changes in fuel cell operation are among the objectives to be combined, and Pareto front analysis guarantees that all of these factors contribute to the global results [110,111].

6. Conclusions

In this article, a literature review of proton exchange membrane fuel cells for CHP systems and their energy management techniques was presented. First of all, the state-of-the-art of PEM fuel cells and their physical characteristics and applications were presented. Following this, the different modelling approaches available to integrate them into CHP systems were detailed, as well as local control alternatives for these models. Afterwards, degradation mechanisms studied by several authors, and their mitigation strategies were classified, focusing on differences between high- and low-temperature PEM fuel cells. Following, the characteristics of a residential CHP system including an HT-PEMFC were explained, including elements involved in the global CHP system aiming to provide electrical and thermal management to satisfy both demand types. Finally, several energy management algorithms explored by different authors were detailed, and their differences were summarised. These techniques include decision and recursive methods and model predictive control approaches, with special attention paid to MPC tuning strategies based on Pareto fronts published in the literature.

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Abbreviations

The following abbreviations are used in this manuscript:

HT	High-temperature
LT	Low-temperature
PEM	Proton exchange membrane
FC	Fuel cell
PEMFC	Proton exchange membrane fuel cell
HT-PEMFC	High-temperature proton exchange membrane fuel cell

LT-PEMFC	Low-temperature proton exchange membrane fuel cell
DMFC	Direct methanol fuel cell
AFC	Alkaline fuel cell
PAFC	Phosphoric acid fuel cell
MCFC	Molten carbonate fuel cell
SOFC	Solid oxide fuel cell
CHP	Combined heat and power
ECSA	Electrochemical active surface area
SOC	State of charge of a battery or other storage element
MPC	Model predictive control

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