processes

MDPI

Review

A Comprehensive Review and Technical Guideline for Optimal Design and Operations of Fuel Cell-Based Cogeneration Systems

Farah Ramadhani [1], Mohd Azlan Hussain [1,*] and Hazlie Mokhlis [2]

[1] Chemical Engineering Department, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia; farahramadhani@siswa.um.edu.my
[2] Electrical Engineering Department, Faculty of Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia; hazli@um.edu.my
* Correspondence: mohd_azlan@um.edu.my

Received: 2 October 2019; Accepted: 10 December 2019; Published: 12 December 2019

Abstract: The need for energy is increasing from year to year and has to be fulfilled by developing innovations in energy generation systems. Cogeneration is one of the matured technologies in energy generation, which has been implemented since the last decade. Cogeneration is defined as energy generation unit that simultaneously produced electricity and heat from a single primary fuel source. Currently, the implementation of this system has been spread over the world for stationary and mobile power generation in residential, industrial and transportation uses. On the other hand, fuel cells as an emerging energy conversion device are potential prime movers for this cogeneration system due to its high heat production and flexibility in its fuel usage. Even though the fuel cell-based cogeneration system has been popularly implemented in research and commercialization sectors, the review regarding this technology is still limited. Focusing on the optimal design of the fuel cell-based cogeneration system, this study attempts to provide a comprehensive review, guideline and future prospects of this technology. With an up-to-date literature list, this review study becomes an important source for researchers who are interested in developing this system for future implementation.

Keywords: review; cogeneration; fuel cell; optimal design; guidelines

1. Introduction

The rapid increase of energy demand in conjunction with the depletion of oil and coal and the environmental threats to pollution over the world have led to an energy security issue. Researchers, scientists and engineers are making effort to find solutions by using more effective and efficient power generation systems or finding energy sources that are cleaner and renewable. The prospect in creating new technologies for energy generation purpose and utilizing cleaner energy sources have increased around the world by the commitment of countries to reduce their carbon emissions and to include the renewable energy sector into their energy plan [1,2].

In line with the development of energy generation systems, which are more efficient and reliable, the cogeneration system has played its role in power and heat production systems. The technology had been popular in 1977 using coal and oil as the fuels, but its prospect became more and more gloomy when the fuel price increased in 1980 [3]. However, this technology has gone back to be more popular in this last decade in line with the finding of new energy sources, which are renewable, cleaner and economically competitive. Currently, cogeneration systems can be derived not only using combustion engines or gas turbine but also employing fully renewable or semi-renewable energy sources such as photovoltaic thermal panels, Stirling engines and fuel cells.

Amongst the emerging technologies as the prime mover candidate for cogeneration systems, fuel cells are one of the most suitable devices that can generate electricity and heat continuously. Fuel cells act as an energy conversion device, which generates electricity from the thermodynamic and electrochemical reactions between hydrogen and oxygen. Along with the generated electricity from the fuel cells, they also generate heat, water and fewer carbon per kWh energy production compared to conventional combustion engines when using hydrocarbons as the fuel. The heat generated from the cell is potential to be used in the cogeneration system by producing hot water or converting it into cooling energy for room and water.

Based on its electrolyte technology and operating point, fuel cells have various types such as the proton exchange membrane fuel cell (PEMFC), direct methanol fuel cell (DMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC), microbial fuel cell (MFC) and solid oxide fuel cell (SOFC) [4–6]. Amongst them, PEMFC being the low temperature fuel cell and SOFC as the high-temperature fuel cell are most popular to be employed as the prime mover in cogeneration systems. Application of these fuel cell types is not limited for residential use but also for industrial, public facilities and transportations [7].

Even though fuel cells are promising as a prime mover in cogeneration systems, the technology is expensive and has a long payback period, which is not economically competitive compared to other prime movers [8]. The research and development of new materials, which are cheaper and flexible with various fuels are needed to be done to reduce the investment cost of the fuel cells. Furthermore, the optimal design of the fuel cell-based cogeneration system has been proven to reduce the total cost and carbon emission generated by the system [9]. The optimal design of the fuel cell-based cogeneration system is also effective in tackling the size issue of the system capacity that leads to the energy-waste problem.

There has been a rise in the research, development and review of the fuel cell-based cogeneration system from year to year. Arsalis et al. [10] did a comprehensive review of fuel cell-based power and heat generation system which focused on the technology and configuration of the system. The study concerned two fuel cell types (PEMFC and SOFC) as the prime mover technology for the studied cogeneration system along with the thermal management for the system. Milcarek et al. [11] gave a review for the fuel cell-based cogeneration system covering the fundamental aspect on the future prospect of this system for commercialization. The study focused on the application of the cogeneration system for residential use only. Other reviews of the cogeneration systems not only focused on the fuel cell as the prime mover but also other technologies such as gas turbine, combustion engines, Stirling engine and renewable energy devices [3,12,13]. It can be concluded that reviews of fuel cell-based cogeneration systems are still limited. From our knowledge, there is no review that focused on the optimal design of fuel cell-based cogeneration system and guideline to design an optimal system based on its applications, energy requirements and various specific criteria.

Therefore, this study attempts to provide a comprehensive review of fuel cell-based cogeneration systems including its theoretical and working principle, research, development, commercialization, current state of the system and on the optimal design of the system. This study also provides guidelines for designing an optimal cogeneration system by using the fuel cell as the prime mover with its future prospects. An up-to-date summary of previous studies conducted in the past 5 years has also been included to give an insight for researchers who are interested in further studying the fuel cell-based cogeneration systems.

2. Overview of Fuel Cells and Cogeneration Systems

2.1. Fuel Cells: Working Principle and Types

All fuel cells have two porous electrodes called anode and cathode, which are separated by a dense electrolyte layer. They have similar characteristics to a battery in converting chemical primary sources into electrical energy through electrochemical reactions. The reactions occurring between hydrogen, oxygen and other oxidizing agents generate heat and water as the by-products and electricity as the primary product. In general, hydrogen as fuel moves through the porous anode while the oxygen as the oxidant transport through the porous cathode. In the interface between the anode and cathode, the hydrogen breaks up to H^+ ions and two electrons, which are absorbed to the electrode surface and pass through an external circuit to create direct current power as explained in the literature [11]. At the same time, the oxygen molecule at the porous anode combines with the two electrons from the electrode to form O^{2-} ion, which diffuses to the electrolyte layer and reacts with H^+ ions to form water molecule.

The development of the electrolyte material enhances fuel cells to be fueled by other than pure hydrogen. Due to the high-cost of pure hydrogen, some fuel cells can be driven using hydrocarbon fuels. Hydrocarbons can be used via external reforming such as steam reforming or fuel combustion or via internal reforming on a catalyst layer with direct electro-oxidation [11]. Steam reforming is an endothermic reaction that reforms the hydrocarbon to hydrogen and syngas (CO). For several fuel cell types especially those that work at high temperature, the syngas can be used directly to form two electrons and carbon dioxide. Meanwhile, for low-temperature fuel cells, the gas must be processed into pure hydrogen through the water gas shift reaction where the syngas reacts to water to form pure hydrogen and carbon dioxide.

Fuel cells have also attracted much attention due to its environment friendly nature compared to the conventional generators, which generate harmful gases as by-products. According to Table 1, different types of fuel can be used to drive the fuel cells. Pure hydrogen is commonly used by low-temperature fuel cells such as alkaline fuel cell (AFC) and polymer electrolyte membrane fuel cell (PEMFC). The pure hydrogen itself can be produced from hydrocarbons, methanol or syngas. High-temperature types such as molten carbonate fuel cell (MCFC) and solid oxide fuel cell (SOFC) are more flexible in the use of the fuel. Furthermore, the fuel price can be competitive by using various types of hydrocarbon, biogas and natural gas.

Fuel cells can be categorized as pure renewable energy generation if pure hydrogen is used to drive the cells as they only produce water as the by-product [11]. However, the process of producing hydrogen, which mostly comes from the hydrocarbon reforming processes must be taken into consideration when calculating the life cycle assessment of the fuel cells. In several high-temperature fuel cells, the CO produced in the steam reforming process can be used directly and produces CO_2 as by-products along with water. However, compared to combustion engines, fuel cells are more environmentally friendly even though some small emissions of carbon and NOx may be produced during the reforming processes as much as having higher operating efficiency.

2.2. Cogeneration: System Components and Applications

In several applications, especially for offices and residential homes, electricity is not the sole energy required. Other energies such as heating and cooling water are also needed continuously [14]. However, most office and residential buildings utilized the separated system (SP) in generating electricity, heating and cooling energies to meet those requirements, which caused inefficiency in energy usage and significantly raises the energy cost. Therefore, an integrated system that can cover more than one energy demand is desired to enhance the system efficiency, energy utilization and cost, using what is called the cogeneration system.

Table 1. Comparison between different type of fuel cell [15–18].

Fuel Cell Type	PEMFC	AFC	DMFC	PAFC	MCFC	SOFC
Operating temp (°C)	30–100	90–100	50–100	160–220	600–700	500–1000
Electrical efficiency (%)	30–40	60	20–25	40–42	43–47	50–60
Energy conversion efficiency (heat and power) (%)	85–90	85	85	85–90	85	up to 90
Typical stack size	<1–100 kW	10–100 kW	Up to 1.5 kW	50–1000 kW (250 kW module typical)	<1–1000 kW (250 kW module typical)	5–3000 kW
Electrolyte	Solid polymeric membrane	Aqueous solution of potassium hydroxide soaked in a matrix	Solid organic polymer poly-perfluoro sulfonic acid	100% phosphoric acid stabilized in an alumina-based matrix	Li2CO3/K2CO3 materials stabilized in an alumina-based matrix	Solid, stabilized zirconia ceramic matrix with free oxide ions
Fuels	Hydrocarbons or methanol	Pure hydrogen	Methanol	Hydrogen from natural gas	Natural gas, biogas, others	Natural gas or propane, hydrocarbons or methanol
Operational life cycle	40,000–50,000 h (stationary) Up to 5000 h (mobile)	Up to 5000 h	10,000–20,000 h	Up to 40,000 h	Up to 15,000 h	Up to 40,000 h

Cogeneration system can be defined as the system that generates simultaneous power and heat from the same primary energy source [3]. The power generated includes mechanical, electrical or even fuel conversion chemically. On the other hand, the system also generates useful heat, which can be used for heating, cooling, distiller purposes or converted to electricity. Furthermore, cogeneration processes can produce three or more types of energy, which are called trigeneration and polygeneration system with additional components.

Cogeneration system consists of a single or hybrid energy source called the prime mover that generates one or two types of primary power simultaneously and consists of auxiliary components to recover the primary energy from the prime mover as depicted in Figure 1. In several applications, a cogeneration system is also equipped with storage devices such as hot water tank or battery. The storages are used to store excess energies generated by the system. By using this configuration, cogeneration can reach an efficiency of up to 80% compared to the single-power generation system [19].

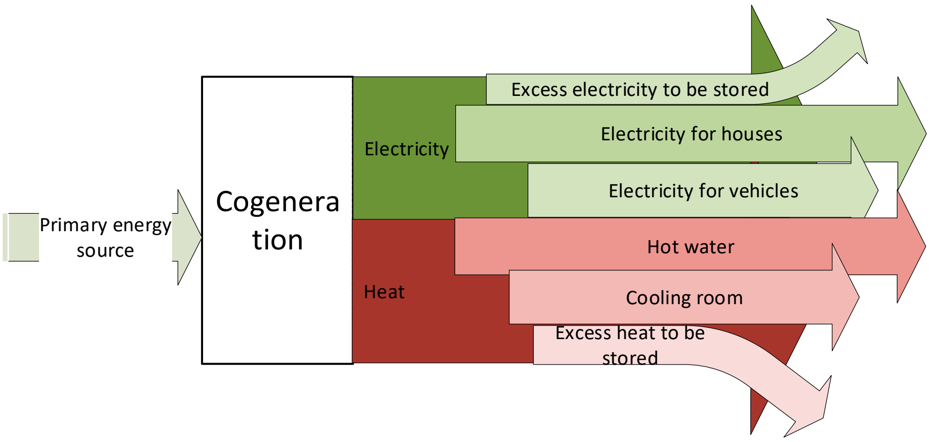

Figure 1. Cogeneration system layout.

Initially cogeneration system increased electricity generation by 58% in industrial plants [3] since the early century. However, due to economical, regulation and fuel availability issues, this system becomes less attractive for further development in the 1950s and accounted for only about 5% of the total electricity generation in the 1970s [3]. However, in the next few decades, implementation of cogeneration had been gaining attention again in line with the awareness of fuel depletion and environmental concern.

Combined heat and power (CHP) system is one of the most favorable types of cogeneration system, which generates electricity and heat. The CHP is efficient since it does not require additional fuels to produce heat power as in the separated system. The system was the first energy generation commercialized for residential applications, which had been successfully developed by several companies such as Hexis (Switzerland) and Ceres Power (UK), in partnership with British Gas and Ceramic Fuel Cells Ltd. (Australia) [20].

Currently, cogeneration systems have been designed and built for various other applications such as residential, industrial, public facilities and transportation. As the fuel cell is used as the prime mover, application for residential use as the stationary power system is more popular than others. In the industries, combinations of fuel cell fueled by biogas or syngas are also potential for waste-to-energy purposes in wastewater treatment (WWT) plant.

3. Current Developments of the Fuel Cell-Based Cogeneration Systems

The increased development of the fuel cell-based cogeneration system in the research and development sector as well as commercialization can be visualized by the rise of publications and commercial products in the last five years. Explanation of the current condition of the system development is discussed in these subsections below.

3.1. Research and Development Sector

Our review divides the research topics into three different types of fuel cell: polymer electrolyte membrane fuel cell (PEMFC), solid oxide fuel cell (SOFC) and other types of the fuel cell. The research and development of fuel cell-based cogenerations system as depicted in Figure 2 shows a positive trend in the past 10 years. It can be seen that both PEMFC and SOFC are the popular fuel cell implemented in cogeneration systems during that period.

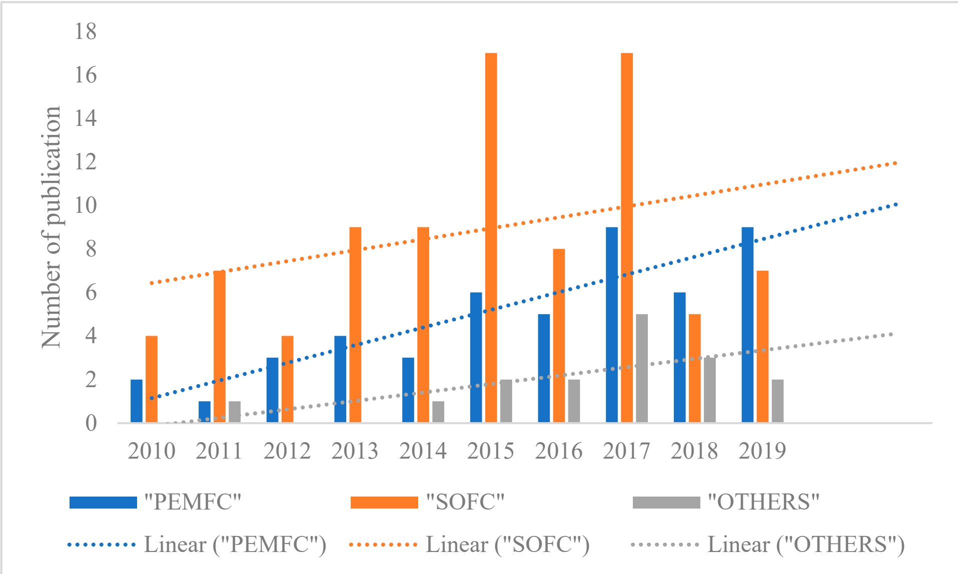

Figure 2. The research trends of the fuel cell-based cogeneration systems within the past 10 years.

Comparing these two, the applications involving PEMFC as the prime mover show a sharper increase as compared to the SOFC and others. One of the reasons is due to its flexibility of operation without any reforming and burning systems. The stability and load following capability of the PEMFC add more benefits to this type for small and mobile power generation. Moreover, further studies have developed the high-temperature proton membrane exchange fuel cell (HT-PEMFC), which can be more suitable for power and heat applications. The HT-PEMFC is seen to be popular and extensively developed since the past 5 years with 90% of system employment for CHP systems [21].

On the other hand, the increase of publication regarding SOFC-based cogeneration system is consistent from year to year. Not only developing the HT version of PEMC, but other studies also paid attention to the low-temperature solid oxide fuel cell (LT-SOFC). The LT-SOFC has been reported in several studies [22,23]. One of the reasons for decreasing the temperature is to reduce the material cost of the SOFC. The high temperature SOFC generates more heat and power but with increased cost in the electrolyte material as compared to the PEMFC. The high-temperature also causes the material to get cracked and degraded thus reducing the life cycle of the SOFC [24].

The other types of fuel cell such as PAFC, MCFC and DMFC have been reported in some studies [25–28]. The development of PAFC in Japan reported in [28] showed slow progress but promising for CHP systems in residential applications. However, not much attention has been given to further developments of other fuel cell types and this lack of study affects the progress of commercialization and their competitiveness in real applications.

3.2. Commercialization Sector

As a leader in this technology, Japan is pioneer in the development of fuel cells and cogeneration systems. As reported in the literature, the world's first residential proton exchange membrane fuel cell (PEMFC) CHP system in the Japanese market was built in 2009 [29]. It is planned that 5.3 million units of residential FC-CHP systems would be installed by 2030 to achieve Japan's Intended Nationally

Determined Contributions (INDC; a 26% reduction of total greenhouse gas (GHG) emissions by First Year (YF) 2030 compared with those in FY 2013) [30]. Furthermore, as Japan has succeeded to achieve GHG emission by 1270 $MtCO_2$/a in FY 2019, it has attained about 50% of the target of INDC [31].

In some of the European countries, the project H2home decentralized energy supply using hydrogen fuel cells is part of the HYPOS initiative (Hydrogen Power Storage and Solutions) [32]. In the building sector, proof of function has been provided in practice by the completed national project CALLUX (field test fuel cell for home ownership, 500 units in Germany) and the ongoing European project "Ene.Field" (which will deploy up to 1000 residential fuel cell micro-CHP installations across eleven key European countries). The European Commission set the greenhouse gas emissions and energy sustainability targets to be achieved by 2020: reducing by 20% the greenhouse gas emissions compared to 1990, reaching a share of 20% of renewable resources in the energy production and reducing by 20% the overall primary energy consumption compared to the projections made in 2007 [33].

Therefore, commercialization activities such as reducing the cost of the fuel cell system, increasing the electrical efficiency, increasing the energy efficiency in generating hydrogen, demonstrating the large-scale competitiveness of fuel cell and hydrogen technologies produced from primary renewable energy [34] will ensure that performance of the system fulfill the low-carbon economy target during this period up to 2050.

3.3. *Governmental Support*

In Japan, the promotion of SOFC micro CHP units involves an investment-based support scheme in the form of a capital grant. It reduces by half the initial cost of the generator, which is currently in use [35]. In Europe countries, a Feed-in Tariff scheme (price-based) was instead launched in 2010 in the United Kingdom (UK) where eligible generators are the micro-CHP units with a power output below 2 kW. The latter value has been chosen according to the cap given by the Feed-in Tariff actually adopted in the UK for 2 kW capacity for residential usage. Pellegrino et al. [35] studied the possible support by the UK governments in the fuel cell-based cogeneration system such as Capital grants, purchase and resale supports, Net metering support and two scenarios of feed-in-tariffs.

The United Nations Environmental Program has supported the Fuel cell installation with a total investment of $307.1 million in 2012, while the US Department of Energy (DOE) rolled out $9 million in grants to speed up the technology in June 2013 [34]. In China, the Ministry of Science and Technology of China, the Ministry of Finance of China, the Ministry of Industry and Information Technology of China and the National Development and Reform Commission of China have collaborated to develop new energy strategies by rolling out national grants focusing on fuel cells development and commercialization starting from 2012 [36]. Following this, other countries in Asia such as Malaysia has supported the utilization of renewable energy and development of hydrogen fuel cell through national grants given to universities [37] and feed-in-tariffs (FiT) scheme for residential applications [38,39].

4. Designing a Fuel Cell-Based Cogeneration System

Development of a better cogeneration system needs optimization of the overall system. Even though the cogeneration system is theoretically better than a separated system, the high-cost issue in the fuel cell development must be tackled by the proper design of the system. In optimizing the design, there are several steps to be followed as guidelines: modeling of the components, choosing the criteria for evaluation, evaluation of the system design, system control and management and optimization of the overall design. As depicted in Figure 3, these guidelines can be applied for any applications and system components to provide an optimal cogeneration system. The details of these steps will be explained in the subsections below.

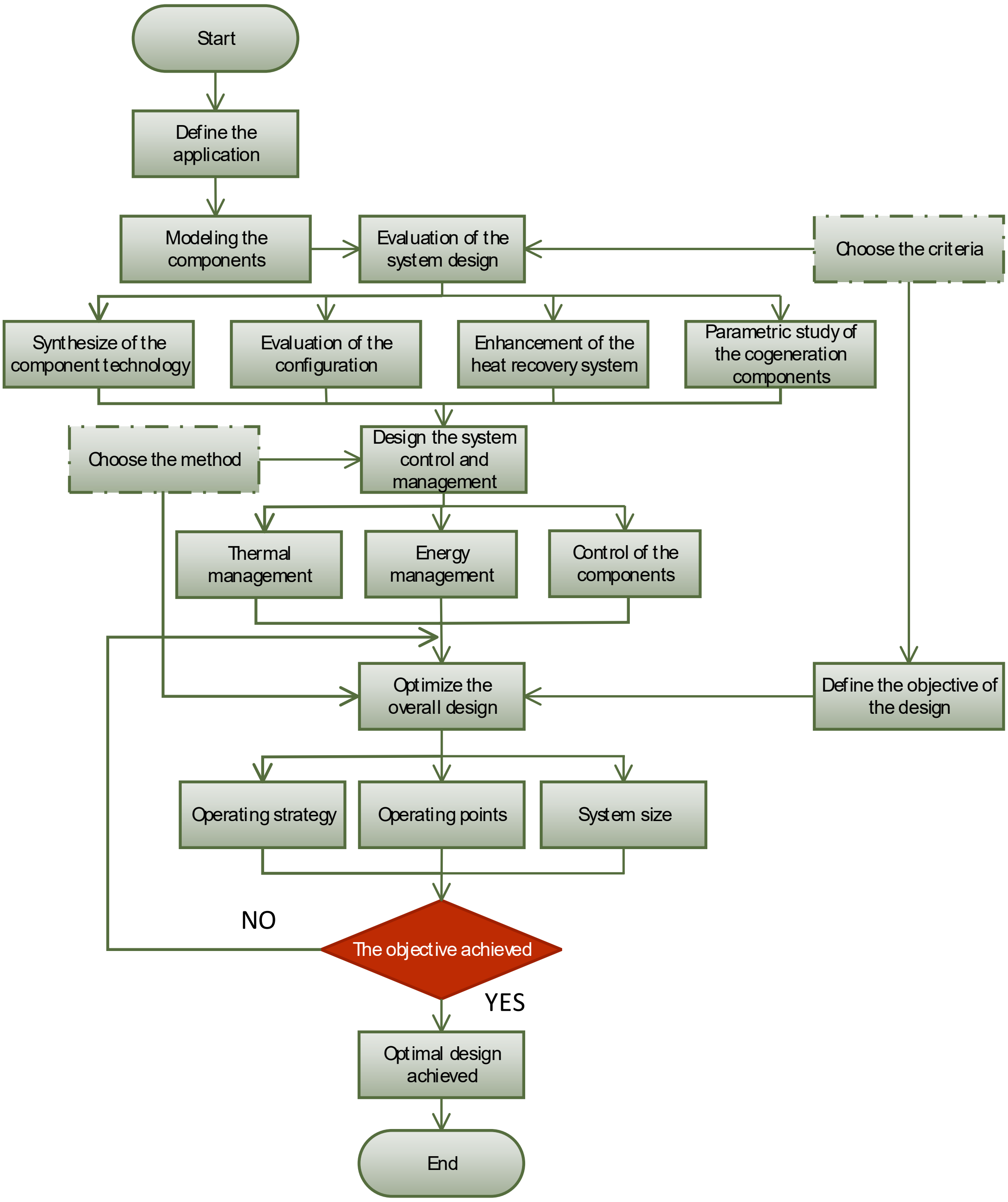

Figure 3. Guideline in designing an optimal cogeneration system with fuel cell as the prime mover.

4.1. *Modeling the Components*

In order to assess the performance of the cogeneration system, modeling the system components must be done first. The modeling part is always associated with the validation of the cogeneration component before going to be controlled and optimized. Most of the study focusing on the assessment of the cogeneration system built their system through mathematical modeling. With some assumptions and simplifications used, the model of components can validate the performance of the whole system. As a major prime mover of the cogeneration system, modeling of the fuel cell is vital to analyze the behavior of the component in generating power and heat for the cogeneration system.

In the modeling the cogeneration system, researchers have used several approaches such as 3D, 2D, 1D and even using 0D or black box predictions. Each approach is different in its complexity, accuracy and application. If the purpose is to achieve accuracy for detailed analysis, then the 3D approach is most suitable for the modeling approach. The mass, momentum and energy equations are presented in three dimensions with the heat transfer from the outer stack to surrounding surfaces [11]. This approach is mostly used for analyzing a single fuel cell where its geometry is appropriately discretized using the finite volume or finite difference method [11].

A 2D approach is simpler than the 3D approach because it neglects one dimension of fuel cell geometry and generates different models for different fuel cell geometries. However, the 1D approach is suitable for modeling of integrated fuel cells applications in a stack or combinations with other heating or cooling components in cogeneration systems. The 1D approach presents the fuel cell model in one direction for the variations of fuel cell temperature, pressure, concentration and other thermodynamic phenomena and material properties. In the literature, black box prediction models are also frequently used for analysis, control, management, evaluation and optimization studies in an integrated fuel cell-based system such as cogeneration.

Due to the complexity in integrating more than two components and applying adjusted operating strategies and sizes, the detailed fuel cell model must be simplified with a consequence in the reduction of accuracy. In order to enhance the accuracy of the model, most of the studies consider fuel cells as the prime mover in a cogeneration system and for more advanced systems, which include real experimental data from the literature to validate the cell model [39–42]. One example is that conducted by Asensio [43] that predicted the PEMFC system for optimal energy management using a black box model, and applied the adaptive neural network (ANN) combined with a 3D lookup table to predict the hydrogen consumed and output power of PEMFC in the cogeneration system.

4.2. Choosing the Criteria for Evaluation

While designing a cogeneration system, one, two or more criteria are used as the objective of the design. Based on the literature, criteria based on energy, economics and environmental are commonly used in the cogeneration design for evaluation of different configurations, parameter analysis, energy management and optimization of the system. In some studies, criteria used for the design is not limited to single criteria but also multi-criteria such as energy-environmental, exergoeconomic or eco-environmental parameters. The multi-criteria parameters are used to assess the system to deal with more than one criterion to be satisfied.

From the technical aspect, many studies in the literature commonly used efficiency of the system as the criterion [44,45]. Other studies use primary energy saving (PES) or primary energy consumption (PEC) as the energy criteria [25,46]. The values of the PES or PEC are obtained by subtracting the amount of primary energy or fuel used in the reference system (usually using a separated system) with the proposed cogeneration system. Besides using energy output and energy efficiency as the criteria, many studies in the literature focused on the second law of thermodynamics by using exergy as the criterion. Exergy is the available energy, which can be used from the consumption of primary energy including power and heat. The concept of exergy is more viable and practical in the cogeneration system since not only electric power is considered but also heating and cooling demands. Several studies in the literature also used exergy and efficiency as the criteria for the system performance achieved [45,47,48]. From the criteria, exergy destruction can also be used to indicate which part of the cogeneration components affects the system performance.

From the economical aspect, criteria such as energy cost, net present cost, payback period and total costs of the system are used in the cogeneration design. For the investment of the system and analysis of the system viability, the payback period is commonly used as the criterion. Some scenarios involving subsidiary from the government, tax reduction, net metering to feed-in-tariffs as incentives were studied to make the system more economically competitive compared to the conventional separated system (CSS) [35].

Environmental aspects have also been taken into account in achieving a cleaner environment and reducing the pollution caused by the energy sector. The older energy generation technologies using non-renewable sources have created negative impacts to the environment, thus the developments in the new emerging technologies are essential to achieve the sustainability of the energy. Reduction of carbon emission and other harmful gases are also other criteria, which are used in the cogeneration design. Furthermore, life cycle analysis (LCA) is also used to analyze the impact of the technology used in the cogeneration system to the environment, which is comprehensive since it covers all aspects from system production to system operation.

4.3. Evaluation of the System Design

Evaluations of the system consisting of system synthesis and assessment are important to analyze the actual performance of cogeneration systems. Evaluation and synthesis of the system include its configurations, prime mover types, heating/cooling devices, storages and other auxiliary components in the cogeneration system. Synthesis of the system defines the acceptability of each component in a cogeneration system in improving the performance of the system. System synthesis for cogeneration system has been made using the P-graph Fuzzy approach [49], TOPSIS [50] and MILP [51]. On the other hand, evaluation of the system can be performed by a parametric study to analyze the operating points of the components [27,40,45]. Furthermore, some modifications in the heat recovery system and system operation have also been done by [25,52]. Regarding the implementation of the cogeneration system, other studies compared the system for different climate conditions, places, and demand profiles [41,53,54].

Several works as reported in the literature, used a conventional separated system (CSS) and compared it with the proposed cogeneration [39,55,56]. The CSS uses different primary energy sources to provide electricity, cooling or heating for the users. Electric power is commonly provided from the national grid while heating or hot water is generated from a fuel driven boiler. Several studies found that the fuel cell-based cogeneration system is more promising to reduce primary energy consumption, energy cost and carbon emission generated by the system compared to the CSS [55,57,58].

4.4. System Control and Management

System operation in a cogeneration system plays an important role in reducing unused wasted energy that is generated by the prime mover and other components where, optimal energy management is able to reduce primary energy consumptions and operation costs. The operating strategies, which have been reported in the literature involve control and management for the prime mover, heating/cooling devices, storages and also dispatch mechanisms between cogeneration components in satisfying the load demands.

As the prime mover, a fuel cell can generate electricity and heat as long as the fuel is injected into the cell. However, the fluctuations in demand, fuel costs and other varying conditions affect the operation of the fuel cell. Therefore, fuel control is one of the options to optimize the utilization of the fuel depending on the power and heat required by the demands. Moreover, high-temperature fuel cells such as the SOFC and PAFC are very sensitive to the temperature shock caused by the high fluctuation of temperature during the operation. It needs thermal management to avoid material cracking and increase the life cycle of the cell.

Some energy management approaches related to energy storage control or demand control have also produced a better and efficient cogeneration system. The controls are also capable of reducing components capacity, thus reducing the investment and operational costs. The energy management approach in relation to storage control can also improve the reliability of the system, preventing system blackout and utilizing excess power generated from the supply side.

4.5. Optimization of the Overall Design

As the last step in designing the cogeneration systems, optimization approach can be conducted based on the fulfilled objectives. Optimization for the cogeneration system involves optimal operating strategy (OOS), optimal operating parameters (OOP) and optimal size of the cogeneration components

(OS). These three design objectives are significant variables in increasing the overall performance of the cogeneration system.

In designing the operating strategies, several system operations need an optimization approach to find the best strategy in their cogeneration designs. Scheduling and dispatching the energy from the cogeneration components to the demand side involve many combinations that have to be examined. In order to fulfill one or more objectives, a combined operating strategy can be the better choice. Therefore, the role of optimization in this case is to find the best operating strategy to be applied with the specific objectives as the requirement.

In terms of the operating parameters, optimization of those parameters can improve the performance of the cogeneration components in reducing the fuel usage, decreasing its costs or generating less carbon emission. As the prime mover, fuel cell parameters such as temperature, hydrogen flow, steam to carbon ratio and pressure can be optimized to improve the flexibility in its operation and reducing its primary energy consumption. Meanwhile, other component parameters for generating hot water, cooling or hydrogen can also be used to reduce the costs of the components and increase the value of the cogeneration system.

Several studies in the literature have also focused on optimizing the size of the various components of the cogeneration system [38,59,60]. From these studies, comparisons of various configurations on the cogeneration performance is essential to avoid oversizing or under sizing of the system for the specific energy demand and applications.

5. Summary of the Gathered Literature in the Past 5 Years

As presented in Table 2, the publication summary shows an intense increase in research and development for fuel cell-based cogeneration system in the last 5 years. There are several important summaries to be extracted from the Table. Firstly, PEMFCs and SOFCs are still the popular fuel cells for cogeneration systems and will be further developed for use in cogeneration systems. In the future, steady-state and linear models are mostly used for the modeling process of the system. On the other hand, studies that concern in the model prediction are limited although the predicted models have some advantages in simplifying the mathematical equations used in the modeling process and closer to the real performance when using real experimental data as the reference. A few numbers of study that focused on the control and energy management strategy was reported from the literature.

Furthermore, the topics that studied the hybrid configurations between fuel cell and renewable energy devices are also limited. Most of the studies found in the literature used the fuel cell as the sole prime mover in the cogeneration system. Only several studies combined between two types of fuel cell [25,26,28,57,61,62] and the combinations between the fuel cell and other energy conversion devices such as photovoltaic, electrolyzer, thermoelectric and batteries as the storage were reported in [46,63–65].

In terms of its applications and designed scenario, most of the cogeneration systems were implemented for residential and building sectors while the use in the transportation sector and mobile power generation have not been found. Furthermore, the number of studies that implemented the cogeneration system for providing other than power and heat (example treated water, cooling, hydrogen, oxygen, etc.) is still limited. It can also be seen that very few of the studies consider the external support from the society or impacts of the cogeneration on the society as the feasibility study and only a few studies included government support as the assessment scenario [19,38] in the design of the cogeneration system.

Table 2. Summary of studies in fuel cells-based cogeneration system design in the past 5 years (2015–2019).

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Wakui et al. [25]	SOFC, PEFC	Residential	NL-Quasi steady state	RTC using MILP	4 cases of operation	-	PEC (TCN)
Sarabchi et al. [66]	PEMFC (HT)	-	Steady state, EES	-	√	MO	Energy and exergy efficiencies (TCN), specific costing (ECO), MSE_{CO_2} (ENV)
Nalbant et al. [45]	PEMFC (HT)	-	Steady state, EES	-	Parameter analysis	-	Energy and exergy efficiencies (TCN),
Luo and Fong [52]	SOFC	-	2D dynamic		Configurations of bottoming cycle	-	Efficiency, PI, CR (TCN)
Löbberding and Madlener [67]	PEMFC	Residential	Steady state simulation	EO and HO operations	Economic analysis	-	NPV(ECO) and competitiveness
Kwan et al. [46]	PEMFC-TED	-	Steady state simulation	EMS with mode decision	-	-	PEC efficiency (TCN)
Jung et al. [53]	SOFC	Residential	TRNSYS	Thermal load following	Weather cons. and surplus elect.	-	PEC (TCN), OC & PP (ECO), CO_2E (ENV)
Jin et al. [68]	PEMFC	-	Quantitative model	-	Configurations of extraction	-	COP (TCN)
Huang et al. [69]	FC	Residential	MINLP	PLR, Scheduling	-	PSO-SQP for scheduling	COE (ECO)
Guo et al. [40]	PEMFC (HT)	-	1D isothermal model	-	Parametric studies	-	DL, Humidity, Heat loss, heat coefficient,
Marcoberardino et al. [41]	PEMFC	Residential	Aspen plus	-	Different configurations and scenarios	-	ES (ECO)
Cinti et al. [44]	SOFC	-	Cycle tempo	-	Effect of hythane as fuel	-	Efficiency, EI (TCN)

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	**Control/Management**	**Evaluation of System**	**Optimization**	
Bachmann et al. [70]	PEMFC and SOFC	Residential	Environmental model	-	4 Technologies of CHP	-	LCA, LCIA (ENV)
Roshandel et al. [71]	SOFC	Residential	Steady state	√	4 hybrid systems	MO	LCOE (ECO), CO_2E (ENV)
Romdhane et al. [72]	PEMFC	Residential	Steady state using MATLAB	Heat-led Electric-led	√	-	EFF-PES- (TCN), CO_2E (ENV)
Facci et al. [54]	PEMFC	Buildings	Dynamic, AspenPlus	Cost and PEC minimizations	5 buildings, 5 climate conditions	-	PEC (TCN), COE-PBP (ECO)
Yoda et al. [73]	SOFC	Residential	-	-	Real system of CHP	-	EFF-DRB (TCN), Cost reduction (ECO)
Wakui et al. [25]	SOFC and PEFC	Residential	MILP	Scheduling using MILP, operation control under receding horizon	4 types of fuel cell and 4 storages	-	PEC (TCN), DRN
Baldi et al. [59]	SOFC and PEMFC	Residential	Linear model	-	-	Sizing using MILP	Efficiency (TCN), Investment cost (ECO)
Wu et al. [27]	PAFC-TEG	-	Steady state model	-	Parametric study of T, P, m, K, c1 and c2	-	Current and power densities, efficiency (TCN)
Spazzafumo [74]	MCFC and SOFC	-	AspenOne	-	Evaluation of pressure composition	-	Efficiency (TCN)
Perna et al. [75]	SOFC	-	Numerical model using AspenPlus	-	Evaluation of GT pressure and S/C	-	Power and efficiency (TCN)
Ozawa and Kudoh [30]	PEMFC and SOFC	Residential	Linear model	OOP with MILP	Evaluation based on energy demand types	-	NPC (ECO), GHG emission (ENV)

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Herrmann et al. [32]	PEMFC	Residential	TRNSYS	-	Evaluation of CHP configurations	-	Primary energy, efficiency, usable energy (TCN), total cost (ECO), CO_2 Emissions
Mamaghani et al. [60]	PEMFC (HT)	-	Steady state model	-	-	MO using Pareto frontier GA	Thermal power and net power output, net electrical and thermal efficiency (TCN)
Giarolla et al. [76]	SOFC	Industrial (WWT)	MILP model	-	Evaluation of 3 scenarios and 5 configurations of the system	OOP using GAMS and CPLEX solver	LCOE (ECO)
Marcoberardino et al. [77]	PEMFC	Residential	Energy balance	-	Evaluation of system configuration	-	Target cost (ECO) LCA (ENV)
Chitsaz et al. [78]	SOFC	-	Steady state using MATLAB	-	Evaluation between 2 configurations	Optimal value of design parameters (MO)	Exergy efficiency (TCN), CO_2 gas emission (ENV)
Budak and Devrim [79]	PEMFC (LT and HT)	-	Experimental study	-	Performance test of two PEMFC types	-	SPT (ECO)
Asensio et al. [43]	PEMFC	-	Prediction model using ANN and 3D lookup table	-	-	-	Hydrogen flowrate and efficiency (TCN)
Aki et al. [28]	PEFC	Residential	MILP model	EMS prediction and OOP	-	-	Energy cost (ECO), PEC (TCN), CO_2E (ENV)

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Wakui et al. [25]	PEFC and SOFC	Residential	MILP model	Energy demand prediction using SVR	-	OOP scheduling	Energy cost (ECO), PEC (TCN), CO_2E (ENV)
Vialetto et al. [58]	SOFC	Residential and transportation	Linear model	Three operating strategies	Comparison between 3 systems	-	PES (TCN), EAC (ECO)
Tanaka et al. [80]	SOFC	Academic institution	Linear model	On-off control	Evaluation of system configuration	-	PES (TCN)
Mehr et al. [81]	SOFC	Industrial (WWT)	Steady state model	-	Evaluation of system configuration	-	Efficiency, ANGR (TCN) LCOE, PBT, NPV (ECO)
Kupecki et al. [82]	SOFC	-	Aspen HYSYS and Experimental data	-	Parametric study	-	Efficiency, output power (TCN)
Karami et al. [83]	PEMFC	Residential	Energy balance model	EMS with scheduling	-	OOP using CCA	OC (ECO)
Hosseinpour et al. [48]	SOFC	-	EES	-	Parametric study (j, Ti, CR, εr)	OOP using DSM	Energy and exergy efficiency (TCN)
Mejia et al. [84]	SOFC	Residential	Experimental data	-	Evaluation of 3 configuration cases	-	Grid imported, peak power (TCN), Total cost (ECO), GHG emission (ENV)
Hajabdollahi et al. [85]	SOFC	Residential	Energy balance	-	-	OOP using MOGA	Exergy efficiency (TCN), TCR (ECO)
Mamaghani et al. [86]	PEMFC (HT)	-	1D steady state model	-	-	OOP using MOGA	Electrical efficiency, thermal generation, electrical power generation

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Eveloy et al. [87]	SOFC	Industrial (Desalination plant)	Aspen plus and FORTRAN	-	Evaluation of system	OOP using GA and TOPSIS	Exergy efficiency (TCN), TCR (ECO)
Anyenya et al. [88]	SOFC	Industrial (in situ oil shale)	Aspen plus	-	Parametric study	-	Electric power, stack temperature, HE ratio, efficiency (TCN)
Zhang et al. [89]	SOFC	-	Steady state	-	Parametric study	-	Efficiency, power density (TCN)
Reyhani et al. [90]	SOFC	Industrial (MED)	Steady state using MATLAB	-	Evaluation of configuration	MO using GA	Exergy efficiency (TCN), ACS (ECO)
Pohl et al. [91]	PEMFC (HT)	Residential	Linear model	Heat-driven, on-off switch	Evaluation of system performance	-	PES, Degree of coverage (TCN)
Misra et al. [92]	FC	Residential	Steady state using HOMER	-	Evaluation of the system performance	-	NPC (ECO)
Khani et al. [42]	SOFC	-	Steady state model using EES	-	-	OOP in MO using GA MATLAB	Exergy efficiency (TCN), SUCP (ECO)
Khani et al. [93]	SOFC	-	Steady state model using EES	-	Evaluation of the configurations	OOP in MO using GA MATLAB	Exergy efficiency, exergy destruction (TCN), SUCP (ECO)
Isa et al. [38]	PEMFC	Hospital	Steady state using HOMER	-	Evaluation of the configurations	Size optimization	Energy allocation (TCN) LCOE, TNPC, LCC, and salvage cost (ECO), CO_2E (ENV)
Hassanzadeh et al. [55]	SOFC	Residential	Energy and exergy balance	-	Evaluation of the system configurations	MO	Power and production, exergy destruction (TCN)

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Mamaghani et al. [21]	PEMFC (HT)	-	1D steady state model	-	Evaluation of the system conditions	OOP in MO using GA	Net electrical efficiency (TCN), TCC (ECO)
Fong and Lee [94]	SOFC	Residential	Dynamic, TRNSYS	-	Parametric study	-	PEC (TCN), PP (ECO), CO_2E (ENV)
Assaf and Shabani [95]	PEMFC	Residential	Dynamic, TRNSYS	-	Evaluation of the system configurations	Size optimization using DSM	Power and heat generation (TCN), NPC (ECO)
Windeknecht and Tzscheutschler [96]	SOFC	Residential	SimulationX	-	Evaluation of the system configurations	-	PEC (TCN), ATC (ECO)
Vialetto and Rokni [97]	SOFC	Residential	DNA	Electric equivalent load (EEL)	Evaluation of the system configurations	-	PES (TCN), NPV, PP (ECO)
Ullah et al. [98]	SOFC	-	Experimental data	-	Parametric study	-	Output power and efficiency (TCN)
Shariatzadeh et al. [99]	SOFC-SOEC	Solar chimney	Steady state	-	-	OOP and size using GA (SO)	Total cost (ECO)
Pellegrino et al. [35]	SOFC	Residential	Linear model	Continuous, modulations, controlled output	Evaluation of the system conditions	Size optimization using direct search	PP, total retail cost (ECO)
Napoli et al. [61]	SOFC and PEMFC	Residential	Linear model	Modulation strategies	Evaluation of the system conditions	-	PES (TCN), NPV (ECO)
Liso et al. [100]	SOFC	Single house	Steady state	-	Evaluation based on fuel types	Tank sizing	Heat recovery (TCN)
Kupecki et al. [101]	SOFC	-	Steady state and experimental models	-	Parametric study	-	Electrical efficiency (TCN)

Table 2. *Cont.*

Authors	Prime Mover	Application	Designing Parts				Criteria Used
			Modeling	Control/Management	Evaluation of System	Optimization	
Ham et al. [102]	PEMFC	Residential	Steady state and empirical data (black box)	-	Evaluation of system performance	-	Net output power, Net heat power (TCN)
Elmer et al. [103]	SOFC	Single home	Real experimental data	-	Eco-environmental assessment	-	CO_2E (ENV), Cost reduction (ECO)
Cappa et al. [104]	PEMFC	Residential	Steady state	Thermal tracking	Evaluation of the system configurations	OOC using dynamic programming	PEC (TCN), NPV (ECO)
Canelli et al. [105]	PEMFC	House and office	Dynamic, TRNSYS	Load sharing	Evaluation of system configurations	-	PES (TCN), Operational cost reduction (ECO), CO_2eq (ENV)
Borji et al. [106]	SOFC	-	1D model	-	Parametric study	OOP using NSGA	Output power and efficiency (TCN)
Arsalis et al. [107]	PEMFC	Residential	1D model	-	Evaluation of system configurations	OOP and size using EES	System efficiency (TCN) LCC (ECO)
Antonucci et al. [108]	SOFC	Residential	Steady state and experimental data	Thermal standby and electric standby	Evaluation of system configurations	-	PES (TCN), Specific costs (ECO)
Akikur et al. [39]	RSOFC	Single house	Steady state	PV-SOSE, SOFC and PV-SOFC modes	Evaluation of system configurations	Sizing using DSM	Efficiency (TCN) COE, PP (ECO), CO_2E (ENV)

6. Future Directions of Fuel Cells Application in Energy Generation Systems

Based on the current status of fuel cell developments in cogeneration systems and the review done, several promising directions for future developments of the system can be obtained. In terms of the research topic regarding the optimum system, the study that involves monitoring and predictions aspects are potential in the design of optimal cogeneration system. The monitoring and predictions are not only conducted for the cogeneration components, but also for the demand profiles and the operation of the system. These topics could increase the value of the optimum system since the data collected is not based on the assumptions but real experimental data. Predicted system components and the demands also simplify the analysis of the system performance and lessen the complexity in the interactions between the cogeneration components since no mathematical model is used.

In line with the monitoring and prediction of the system, experimental studies involving the real fuel cell-based cogeneration system is valuable to analyze the durability of the system. A couple of studies that have implemented the cogeneration system for a real implementation can be used as references [109,110]. Since the PEMFC and SOFC are well known as the prime mover in cogeneration systems, the finding of its commercialized products is easier to obtain. However, finding the commercialized products for the other types of fuel cell is challenging, thus experimental studies regarding these other types of fuel cell is highly promising.

Moreover, the cost issue regarding fuel cell development can also be tackled by finding technologies for fuel reforming and using various types of fuel. Some studies have started to develop syngas and various hydrocarbons as fuels for driving the cogeneration system [75,90]. Other studies focused on the new materials of the electrolyte of the fuel cells to reduce the investment cost and increase the life cycle [111,112].

Besides using various types of fuel, the cogeneration performance can also be increased by finding technologies in optimizing electricity production from the fuel cells. Combination between fuel cells and other power generators as a hybrid prime mover is the key to doubling the electric power generation and reducing the size of the fuel cell. In terms of hybrid the cogeneration system with other energy conversion devices, several promising units such as solar rechargeable, thermoelectric, electrolyzer with solid oxide electrolysis cell and flow batteries can be coupled with the system to increase the fuel utilization and system capacity with valuable costs [27,63,113].

For system operations, energy management strategy combined with optimal operation parameters and system predictions seems important to be developed, which have shown good results in reducing primary energy consumption as well as its operating cost and carbon emission from the cogeneration system. The predictions in the demand can also tackle the energy loss issue and increase the reliability of the system.

Lastly, applications for waste-to-energy usage have huge potential for the further development of the fuel cell-based cogeneration system where these newly innovative systems can be economically competitive in the commercial and government sector.

7. Conclusions

Based on the scientific indicator that was presented in the research review, PEMFC and SOFC were the two well-known and most applied fuel cells among others. Current developments of those fuel cells show that they were more being widely used especially with further improvement of its material to increase its durability with higher temperature ranges. Furthermore, being one of the focuses of this study, a guideline to develop an optimal fuel cell cogeneration system was also presented. The guidelines start from the modeling of the components, assessment of the system design, designing the operating strategy and optimization of the overall design involving operating parameters and size of the components. Through the guidelines given, optimal design can be done comprehensively using different specific applications and criteria for the implementation of the cogeneration system. Numerous publications for the last five years can be a good point of reference to design an optimal cogeneration system with various approaches, objectives and applications. Those publications also indicated the various ways to increase system performance, reduce system cost and emissions of the systems and give more insight for the researchers and developers who are interested to work in this area in the future.

For power generation, fuel cell-based cogeneration system has a better future compared to the conventional heat engine-based technology. From this study it also can be seen that various hydrocarbon fuels have been utilized to replace the utilization of pure hydrogen as to reduce the fuel cost with various materials chosen to increase the temperature range and durability of the fuel cells. Application of cogeneration system can be explored widely not only for stationary but also for mobile power generation uses in the future.

Author Contributions: All authors have contributed to this research article. M.A.H. has contributed in conceptualization and editing, while H.M. has revised technical terms in this article. As the main author, F.R. has contributed in conceptualization, writing and editing processes.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations/Symbols

ACS	Annualized cost system
AFC	Alkaline fuel cell
ANGR	Annual natural gas reduction
ANN	Adaptive neural network
CCA	Colonial competitive algorithm
CHP	Combined heat and power
CO2E	Carbon dioxide emission
COP	Coefficient of performance
CR	Contribution ratio
CSS	Conventional separated system
DL	Doping level
DMFC	Direct methanol fuel cell
DRB	Durability
DSM	Direct search method
EAC	Estimated annual cost
ECO	Economic aspect
EES	Engineering equation solver
EFF	Efficiency
EI	Energy index
EMS	Energy management strategy
ENV	Environmental aspect
EO	Electric operation
ES	Energy saving
GHG	Greenhouse gas
HE	Heat-to-electric
HO	Heat operation
HT	High temperature
LCA	Life cycle analysis
LCIA	Life cycle integrated analysis
LCOE	Levelized cost of energy
LT	Low temperature
MCFC	Molten carbonate fuel cell
MED	Multi-effect distillation

MFC	Micro-bacterial fuel cell
MILP	Mixed integer linear programming
MINLP	Mixed integer non-linear programming
MO	Multi-objective
MOGA	Multi-objective genetic algorithm
MSE	Mass specific emission
NL	Nonlinear
NPC	Net present cost
NPV	Net present cost
OC	Operational cost
OOP	Optimal operating parameter
PAFC	Phosphoric acid fuel cell
PBT	Payback time
PEC	Primary energy consumption
PEMFC	Proton exchange membrane fuel cell
PES	Primary energy saving
PI	Performance index
PLR	Part load ratio
PP	Payback period
RTC	Real-time control
S/C	Steam to carbon ratio
SOFC	Solid oxide fuel cell
SP	Separated system
SPT	System payback time
SUCP	Sum of unit cost of products
SVR	Support vector regression
TCN	Technical aspect
TCR	Total cost rate
TED	Thermoelectric device
WWT	Wastewater treatment
T	Temperature
P	Pressure
m	Thermoelectric elements
K	Conductance
$c1$	Regenerative losses
$c2$	Heat-leakage losses
j	Current density
Ti	Inlet temperature of SOFC
εr	Regenerator effectiveness

References

1. Busu, M. The Role of Renewables in a Low-Carbon Society: Evidence from a Multivariate Panel Data Analysis at the EU Level. *Sustainability* **2019**, *11*, 5260. [CrossRef]
2. Zhao, W.; Zou, R.; Yuan, G.; Wang, H.; Tan, Z. Long-Term Cointegration Relationship between China's Wind Power Development and Carbon Emissions. *Sustainability* **2019**, *11*, 4625. [CrossRef]
3. Frangopoulos, C.A. Cogeneration Technologies, Optimisation and Implementation. In *Iet Energy Engineering*; The Institution of Engineering and Technology: London, UK, 2017; Volume 87.
4. Weng, G.-M.; Li, C.-Y.V.; Chan, K.-Y. Hydrogen battery using neutralization energy. *Nano Energy* **2018**, *53*, 240–244. [CrossRef]
5. Weng, G.-M.; Li, C.-Y.V.; Chan, K.-Y. An Acid–Base Battery with Oxygen Electrodes: A Laboratory Demonstration of Electrochemical Power Sources. *J. Chem. Educ.* **2019**, *96*, 1701–1706. [CrossRef]
6. Maffei, N.; Pelletier, L.; Charland, J.; McFarlan, A. An intermediate temperature direct ammonia fuel cell using a proton conducting electrolyte. *J. Power Sources* **2005**, *140*, 264–267. [CrossRef]

7. Kordesch, K.; Simader, G. *Fuel Cells and Their Applications*; Wiley-VCH: Weinheim, Germany, 1996.
8. Ramadhani, F.; Hussain, M.A.; Mokhlis, H.; Fazly, M.; Ali, J.M. Evaluation of solid oxide fuel cell based polygeneration system in residential areas integrating with electric charging and hydrogen fueling stations for vehicles. *Appl. Energy* **2019**, *238*, 1373–1388. [CrossRef]
9. Al Moussawi, H.; Fardoun, F.; Louahlia, H. Selection based on differences between cogeneration and trigeneration in various prime mover technologies. *Renew. Sustain. Energy Rev.* **2017**, *74*, 491–511. [CrossRef]
10. Arsalis, A. A comprehensive review of fuel cell-based micro-combined-heat-and-power systems. *Renew. Sustain. Energy Rev.* **2019**, *105*, 391–414. [CrossRef]
11. Milcarek, R.J.; Ahn, J.; Zhang, J. Review and analysis of fuel cell-based, micro-cogeneration for residential applications: Current state and future opportunities. *Sci. Technol. Built Environ.* **2017**, 1–20. [CrossRef]
12. Isa, N.M.; Tan, C.W.; Yatim, A.H.M. A comprehensive review of cogeneration system in a microgrid: A perspective from architecture and operating system. *Renew. Sustain. Energy Rev.* **2018**, *81*, 2236–2263. [CrossRef]
13. Murugan, S.; Horák, B. A review of micro combined heat and power systems for residential applications. *Renew. Sustain. Energy Rev.* **2016**, *64*, 144–162. [CrossRef]
14. Ahmadi, P. *Modeling, Analysis and Optimization of Integrated Energy Systems for Multigeneration Purposes*; University of Ontario Institute of Technology: Oshawa, ON, Canada, 2013.
15. Elmer, T. *A Novel SOFC Tri-Generation System for Building Applications*; University of Nottingham: Nottingham, UK, 2015.
16. Ellamla, H.R.; Staffell, I.; Bujlo, P.; Pollet, B.G.; Pasupathi, S. Current status of fuel cell based combined heat and power systems for residential sector. *J. Power Sources* **2015**, *293*, 312–328. [CrossRef]
17. US Department of Education. *(EERE), U.D.E.E.a.R.E., Ed.*; Energy Efficiency and Renewable Energy: Washington, DC, USA, 2007.
18. Kimiaie, N.; Wedlich, K.; Hehemann, M.; Lambertz, R.; Müller, M.; Korte, C.; Stolten, D. Results of a 20,000 h lifetime test of a 7 kW direct methanol fuel cell (DMFC) hybrid system–degradation of the DMFC stack and the energy storage. *Energy Environ. Sci.* **2014**, *7*, 3013–3025. [CrossRef]
19. Chen, J.M.P.; Ni, M. Economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong. *Energy Build.* **2014**, *75*, 160–169. [CrossRef]
20. Irvine, J.T.S.; Connor, P. *Solid Oxide Fuels Cells: Facts and Figures: Past Present and Future Perspectives for SOFC Technologies*; Springer: London, UK, 2012.
21. Haghighat Mamaghani, A.; Najafi, B.; Casalegno, A.; Rinaldi, F. Long-term economic analysis and optimization of an HT-PEM fuel cell based micro combined heat and power plant. *Appl. Therm. Eng.* **2016**, *99*, 1201–1211. [CrossRef]
22. Mosaffa, A.H.; Farshi, L.G. Thermodynamic and economic assessments of a novel CCHP cycle utilizing low-temperature heat sources for domestic applications. *Renew. Energy* **2018**, *120*, 134–150. [CrossRef]
23. Abdullah, T.; Liu, L. Simulation-based microstructural optimization of solid oxide fuel cell for low temperature operation. *Int. J. Hydrog. Energy* **2016**, *41*, 13632–13643. [CrossRef]
24. Ramadhani, F.; Hussain, M.A.; Mokhlis, H.; Hajimolana, S. Optimization strategies for Solid Oxide Fuel Cell (SOFC) application: A literature survey. *Renew. Sustain. Energy Rev.* **2017**, *76*, 460–484. [CrossRef]
25. Wakui, T.; Sawada, K.; Kawayoshi, H.; Yokoyama, R.; Iitaka, H.; Aki, H. Optimal operations management of residential energy supply networks with power and heat interchanges. *Energy Build.* **2017**, *151*, 167–186. [CrossRef]
26. Wakui, T.; Kawayoshi, H.; Yokoyama, R. Optimal structural design of residential power and heat supply devices in consideration of operational and capital recovery constraints. *Appl. Energy* **2016**, *163*, 118–133. [CrossRef]
27. Wu, M.; Zhang, H.; Zhao, J.; Wang, F.; Yuan, J. Performance analyzes of an integrated phosphoric acid fuel cell and thermoelectric device system for power and cooling cogeneration. *Int. J. Refrig.* **2018**, *89*, 61–69. [CrossRef]
28. Aki, H.; Wakui, T.; Yokoyama, R.; Sawada, K. Optimal management of multiple heat sources in a residential area by an energy management system. *Energy* **2018**, *153*, 1048–1060. [CrossRef]

29. Partners, E.-F. Accumulating Numbers of Residential Fuel Cell Ene-Farm Exceeded 200,000 Units. (In Japanese)
30. Ozawa, A.; Kudoh, Y. Performance of residential fuel-cell-combined heat and power systems for various household types in Japan. *Int. J. Hydrog. Energy* **2018**, *43*, 15412–15422. [CrossRef]
31. Climate Governance in Japan. Available online: https://climateactiontracker.org/countries/japan/ (accessed on 3 November 2019).
32. Herrmann, A.; Mädlow, A.; Krause, H. Key performance indicators evaluation of a domestic hydrogen fuel cell CHP. *Int. J. Hydrog. Energy* **2018**, *44*, 19061–19066. [CrossRef]
33. Commission, E. Europe 2020–EU-wide Headline Targets for Economic Growth. (n.d.) Available online: http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm (accessed on 23 June 2019).
34. Niakolas, D.K.; Daletou, M.; Neophytides, S.G.; Vayenas, C.G. Fuel cells are a commercially viable alternative for the production of "clean" energy. *Ambio* **2016**, *45*, S32–S37. [CrossRef]
35. Pellegrino, S.; Lanzini, A.; Leone, P. Techno-economic and policy requirements for the market-entry of the fuel cell micro-CHP system in the residential sector. *Appl. Energy* **2015**, *143*, 370–382. [CrossRef]
36. Lu, Y.; Cai, Y.; Souamy, L.; Song, X.; Zhang, L.; Wang, J. Solid oxide fuel cell technology for sustainable development in China: An over-view. *Int. J. Hydrog. Energy* **2018**, *43*, 12870–12891. [CrossRef]
37. Mohamed, W.A.N.W.; Atan, R.; Sin, Y.T. Current and possible future applications of hydrogen fuel cells in Malaysia. In Proceedings of the International Conference on Advances in Mechanical Engineering (ICAME), Kuala Lumpur, Malaysia, 24–25 June 2009.
38. Isa, N.M.; Das, H.S.; Tan, C.W.; Yatim, A.H.M.; Lau, K.Y. A techno-economic assessment of a combined heat and power photovoltaic/fuel cell/battery energy system in Malaysia hospital. *Energy* **2016**, *112*, 75–90. [CrossRef]
39. Akikur, R.K.; Saidur, R.; Ullah, K.R.; Hajimolana, S.A.; Ping, H.W.; Hussain, M.A. Economic feasibility analysis of a solar energy and solid oxide fuel cell-based cogeneration system in Malaysia. *Clean Technol. Environ. Policy* **2015**, *18*, 669–687. [CrossRef]
40. Guo, X.; Zhang, H.; Zhao, J.; Wang, F.; Wang, J.; Miao, H.; Yuan, J. Performance evaluation of an integrated high-temperature proton exchange membrane fuel cell and absorption cycle system for power and heating/cooling cogeneration. *Energy Convers. Manag.* **2019**, *181*, 292–301. [CrossRef]
41. Di Marcoberardino, G.; Chiarabaglio, L.; Manzolini, G.; Campanari, S. A Techno-economic comparison of micro-cogeneration systems based on polymer electrolyte membrane fuel cell for residential applications. *Appl. Energy* **2019**, *239*, 692–705. [CrossRef]
42. Khani, L.; Mehr, A.S.; Yari, M.; Mahmoudi, S.M.S. Multi-objective optimization of an indirectly integrated solid oxide fuel cell-gas turbine cogeneration system. *Int. J. Hydrog. Energy* **2016**, *41*, 21470–21488. [CrossRef]
43. Asensio, F.J.; San Martín, J.I.; Zamora, I.; Oñederra, O. Model for optimal management of the cooling system of a fuel cell-based combined heat and power system for developing optimization control strategies. *Appl. Energy* **2018**, *211*, 413–430. [CrossRef]
44. Cinti, G.; Bidini, G.; Hemmes, K. Comparison of the solid oxide fuel cell system for micro CHP using natural gas with a system using a mixture of natural gas and hydrogen. *Appl. Energy* **2019**, *238*, 69–77. [CrossRef]
45. Nalbant, Y.; Colpan, C.O.; Devrim, Y. Energy and exergy performance assessments of a high temperature-proton exchange membrane fuel cell based integrated cogeneration system. *Int. J. Hydrog. Energy* **2019**. [CrossRef]
46. Kwan, T.H.; Shen, Y.; Yao, Q. An energy management strategy for supplying combined heat and power by the fuel cell thermoelectric hybrid system. *Appl. Energy* **2019**, *251*. [CrossRef]
47. Nami, H.; Mahmoudi, S.M.S.; Nemati, A. Exergy, economic and environmental impact assessment and optimization of a novel cogeneration system including a gas turbine, a supercritical CO_2 and an organic Rankine cycle (GT-HRSG/SCO_2). *Appl. Therm. Eng.* **2017**, *110*, 1315–1330. [CrossRef]
48. Hosseinpour, J.; Sadeghi, M.; Chitsaz, A.; Ranjbar, F.; Rosen, M.A. Exergy assessment and optimization of a cogeneration system based on a solid oxide fuel cell integrated with a Stirling engine. *Energy Convers. Manag.* **2017**, *143*, 448–458. [CrossRef]
49. Aviso, K.B.; Tan, R.R. Fuzzy P-graph for optimal synthesis of cogeneration and trigeneration systems. *Energy* **2018**, *154*, 258–268. [CrossRef]

50. Cavallaro, F.; Zavadskas, E.K.; Raslanas, S. Evaluation of Combined Heat and Power (CHP) Systems Using Fuzzy Shannon Entropy and Fuzzy TOPSIS. *Sustainability* **2016**, *8*, 556. [CrossRef]
51. Frangopoulos, C. Effect of reliability considerations on the optimal synthesis, design and operation of a cogeneration system. *Energy* **2004**, *29*, 309–329. [CrossRef]
52. Luo, X.J.; Fong, K.F. Investigation on part-load performances of combined cooling and power system primed by solid oxide fuel cell with different bottoming cycles. *J. Power Sources* **2019**, *429*, 127–178. [CrossRef]
53. Jung, Y.; Kim, J.; Lee, H. Multi-criteria evaluation of medium-sized residential building with micro-CHP system in South Korea. *Energy Build.* **2019**, *193*, 201–215. [CrossRef]
54. Facci, A.L.; Ubertini, S. Analysis of a fuel cell combined heat and power plant under realistic smart management scenarios. *Appl. Energy* **2018**, *216*, 60–72. [CrossRef]
55. Hassanzadeh, H.; Farzad, M.A.; Safavinejad, A.; Agaebrahimi, M.R. Performance assessment of a SOFC cogeneration system for residential buildings located in eastern Iran. *Iran. J. Hydrog. Fuel Cell* **2016**, *2*, 81–97.
56. Vialetto, G.; Rokni, M. A New Cogeneration Residential System Based on Solid Oxide Fuel Cells for a Northern European Climate. In Proceedings of the Global Conference on Global Warming, Athens, Greece, 24–27 May 2015.
57. Wakui, T.; Yokoyama, R. Optimal structural design of residential cogeneration systems with battery based on improved solution method for mixed-integer linear programming. *Energy* **2015**, *84*, 106–120. [CrossRef]
58. Vialetto, G.; Noro, M.; Rokni, M. Combined micro-cogeneration and electric vehicle system for household application: An energy and economic analysis in a Northern European climate. *Int. J. Hydrog. Energy* **2017**, *42*, 10285–10297. [CrossRef]
59. Baldi, F.; Wang, L.; Pérez-Fortes, M.; Maréchal, F. A Cogeneration System Based on Solid Oxide and Proton Exchange Membrane Fuel Cells With Hybrid Storage for Off-Grid Applications. *Front. Energy Res.* **2019**, *6*. [CrossRef]
60. Haghighat Mamaghani, A.; Najafi, B.; Casalegno, A.; Rinaldi, F. Optimization of an HT-PEM fuel cell based residential micro combined heat and power system: A multi-objective approach. *J. Clean. Prod.* **2018**, *180*, 126–138. [CrossRef]
61. Napoli, R.; Gandiglio, M.; Lanzini, A.; Santarelli, M. Techno-economic analysis of PEMFC and SOFC micro-CHP fuel cell systems for the residential sector. *Energy Build.* **2015**, *103*, 131–146. [CrossRef]
62. Rabbani, A.; Rokni, M. Modeling and Analysis of Transport Processes and Efficiency of Combined SOFC and PEMFC Systems. *Energies* **2014**, *7*, 5502–5522. [CrossRef]
63. Agarwal, S.; Chourasiya, S.; Kumawat, R.K.; Palwalia, D.D.K. Performance Analysis of Standalone Hybrid PV- SOFC- BATTERY Generation System. *Natl. Conf. Renew. Energy Environ. (NCREE-2015)* **2015**, *2*, 49–53. [CrossRef]
64. Sadeghi, S.; Ameri, M. Multi-objective optimization of pv-sofc-gt-electrolyser hybrid system. *J. Renew. Energy Environ.* **2015**, *2*, 47–58.
65. Wu, S.; Zhang, H.; Ni, M. Performance assessment of a hybrid system integrating a molten carbonate fuel cell and a thermoelectric generator. *Energy* **2016**, *112*, 520–527. [CrossRef]
66. Sarabchi, N.; Mahmoudi, S.M.S.; Yari, M.; Farzi, A. Exergoeconomic analysis and optimization of a novel hybrid cogeneration system: High-temperature proton exchange membrane fuel cell/Kalina cycle, driven by solar energy. *Energy Convers. Manag.* **2019**, *190*, 14–33. [CrossRef]
67. Löbberding, L.; Madlener, R. Techno-economic analysis of micro fuel cell cogeneration and storage in Germany. *Appl. Energy* **2019**, *235*, 1603–1613. [CrossRef]
68. Jin, Y.; Sun, L.; Shen, J. Thermal economic analysis of hybrid open-cathode hydrogen fuel cell and heat pump cogeneration. *Int. J. Hydrog. Energy* **2019**, *44*, 29692–29699. [CrossRef]
69. Huang, Y.; Wang, W.; Hou, B. A hybrid algorithm for mixed integer nonlinear programming in residential energy management. *J. Clean. Prod.* **2019**, *226*, 940–948. [CrossRef]
70. Bachmann, T.M.; Carnicelli, F.; Preiss, P. Life cycle assessment of domestic fuel cell micro combined heat and power generation: Exploring influential factors. *Int. J. Hydrog. Energy* **2019**, *44*, 3891–3905. [CrossRef]
71. Roshandel, R.; Golzar, F.; Astaneh, M. Technical, economic and environmental optimization of combined heat and power systems based on solid oxide fuel cell for a greenhouse case study. *Energy Convers. Manag.* **2018**, *164*, 144–156. [CrossRef]
72. Romdhane, J.; Louahlia, H.; Marion, M. Dynamic modeling of an eco-neighborhood integrated micro-CHP based on PEMFC: Performance and economic analyses. *Energy Build.* **2018**, *166*, 93–108. [CrossRef]

73. Yoda, M.; Inoue, S.; Takuwa, T.; Yasuhara, K.; Suzuki, M. Development and Commercialization of New Residential SOFC CHP System. *Ecs Trans.* **2017**, *78*, 125–132. [CrossRef]
74. Spazzafumo, G. Cogeneration of power and substitute of natural gas using electrolytic hydrogen, biomass and high temperature fuel cells. *Int. J. Hydrog. Energy* **2018**, *43*, 11811–11819. [CrossRef]
75. Perna, A.; Minutillo, M.; Jannelli, E.; Cigolotti, V.; Nam, S.W.; Yoon, K.J. Performance assessment of a hybrid SOFC/MGT cogeneration power plant fed by syngas from a biomass down-draft gasifier. *Appl. Energy* **2018**, *227*, 80–91. [CrossRef]
76. Giarola, S.; Forte, O.; Lanzini, A.; Gandiglio, M.; Santarelli, M.; Hawkes, A. Techno-economic assessment of biogas-fed solid oxide fuel cell combined heat and power system at industrial scale. *Appl. Energy* **2018**, *211*, 689–704. [CrossRef]
77. Di Marcoberardino, G.; Manzolini, G.; Guignard, C.; Magaud, V. Optimization of a micro-CHP system based on polymer electrolyte membrane fuel cell and membrane reactor from economic and life cycle assessment point of view. *Chem. Eng. Process. Process Intensif.* **2018**, *131*, 70–83. [CrossRef]
78. Chitsaz, A.; Sadeghi, M.; Sadeghi, M.; Ghanbarloo, E. Exergoenvironmental comparison of internal reforming against external reforming in a cogeneration system based on solid oxide fuel cell using an evolutionary algorithm. *Energy* **2018**, *144*, 420–431. [CrossRef]
79. Budak, Y.; Devrim, Y. Investigation of micro-combined heat and power application of PEM fuel cell systems. *Energy Convers. Manag.* **2018**, *160*, 486–494. [CrossRef]
80. Tanaka, T.; Kamiko, H.; Akiba, K.; Ito, S.; Osaki, H.; Yashiro, M.; Inui, Y. Energetic analyses of installing SOFC co-generation systems with EV charging equipment in Japanese cafeteria. *Energy Convers. Manag.* **2017**, *153*, 435–445. [CrossRef]
81. Mehr, A.S.; Gandiglio, M.; MosayebNezhad, M.; Lanzini, A.; Mahmoudi, S.M.S.; Yari, M.; Santarelli, M. Solar-assisted integrated biogas solid oxide fuel cell (SOFC) installation in wastewater treatment plant: Energy and economic analysis. *Appl. Energy* **2017**, *191*, 620–638. [CrossRef]
82. Kupecki, J.; Skrzypkiewicz, M.; Wierzbicki, M.; Stepien, M. Experimental and numerical analysis of a serial connection of two SOFC stacks in a micro-CHP system fed by biogas. *Int. J. Hydrog. Energy* **2017**, *42*, 3487–3497. [CrossRef]
83. Karami, H.; Sanjari, M.J.; Gooi, H.B.; Gharehpetian, G.B.; Guerrero, J.M. Stochastic analysis of residential micro combined heat and power system. *Energy Convers. Manag.* **2017**, *138*, 190–198. [CrossRef]
84. Hormaza-Mejia, A.; Zhao, L.; Brouwer, J. SOFC Micro-CHP system with thermal energy storage in residential applications. In Proceedings of the ASME 2017 15th International Conference on Fuel Cell Science, Engineering and Technology FUELCELL2017, Charlotte, NC, USA, 26–30 June 2017; pp. 1–6.
85. Hajabdollahi, Z.; Fu, P.-F. Multi-objective based configuration optimization of SOFC-GT cogeneration plant. *Appl. Therm. Eng.* **2017**, *112*, 549–559. [CrossRef]
86. Haghighat Mamaghani, A.; Najafi, B.; Casalegno, A.; Rinaldi, F. Predictive modelling and adaptive long-term performance optimization of an HT-PEM fuel cell based micro combined heat and power (CHP) plant. *Appl. Energy* **2017**, *192*, 519–529. [CrossRef]
87. Eveloy, V.; Rodgers, P.; Al Alili, A. Multi-objective optimization of a pressurized solid oxide fuel cell–gas turbine hybrid system integrated with seawater reverse osmosis. *Energy* **2017**, *123*, 594–614. [CrossRef]
88. Anyenya, G.A.; Sullivan, N.P.; Braun, R.J. Modeling and simulation of a novel 4.5 kW e multi-stack solid-oxide fuel cell prototype assembly for combined heat and power. *Energy Convers. Manag.* **2017**, *140*, 247–259. [CrossRef]
89. Zhang, X.; Ni, M.; Dong, F.; He, W.; Chen, B.; Xu, H. Thermodynamic analysis and performance optimization of solid oxide fuel cell and refrigerator hybrid system based on H_2 and CO. *Appl. Therm. Eng.* **2016**, *108*, 347–352. [CrossRef]
90. Reyhani, H.A.; Meratizaman, M.; Ebrahimi, A.; Pourali, O.; Amidpour, M. Thermodynamic and economic optimization of SOFC-GT and its cogeneration opportunities using generated syngas from heavy fuel oil gasification. *Energy* **2016**, *107*, 141–164. [CrossRef]
91. Pohl, E.; Meier, P.; Maximini, M.; Schloß, J.v. Primary energy savings of a modular combined heat and power plant based on high temperature proton exchange membrane fuel cells. *Appl. Therm. Eng.* **2016**, *104*, 54–63. [CrossRef]

92. Misra, S.; Satyaprasad, G.; Mahapatra, S.S.; Mohanty, A.; Biswal, S.R.; Dora, A. Design of Fuel cell based Co-generation systems: An approach for battery less Solar PV system. *Int. Res. J. Eng. Technol.* **2016**, *3*, 47–50.
93. Khani, L.; Mahmoudi, S.M.S.; Chitsaz, A.; Rosen, M.A. Energy and exergoeconomic evaluation of a new power/cooling cogeneration system based on a solid oxide fuel cell. *Energy* **2016**, *94*, 64–77. [CrossRef]
94. Fong, K.F.; Lee, C.K. System analysis and appraisal of SOFC-primed micro cogeneration for residential application in subtropical region. *Energy Build.* **2016**, *128*, 819–826. [CrossRef]
95. Assaf, J.; Shabani, B. Transient simulation modelling and energy performance of a standalone solar-hydrogen combined heat and power system integrated with solar-thermal collectors. *Appl. Energy* **2016**, *178*, 66–77. [CrossRef]
96. Windeknecht, M.; Tzscheutschler, P. Optimization of the Heat Output of High Temperature Fuel Cell Micro-CHP in Single Family Homes. *Energy Procedia* **2015**, *78*, 2160–2165. [CrossRef]
97. Vialetto, G.; Rokni, M. Innovative household systems based on solid oxide fuel cells for a northern European climate. *Renew. Energy* **2015**, *78*, 146–156. [CrossRef]
98. Ullah, K.R.; Akikur, R.K.; Ping, H.W.; Saidur, R.; Hajimolana, S.A.; Hussain, M.A. An experimental investigation on a single tubular SOFC for renewable energy based cogeneration system. *Energy Convers. Manag.* **2015**, *94*, 139–149. [CrossRef]
99. Shariatzadeh, J.O.; Refahi, A.H.; Abolhassani, S.S.; Rahmani, M. Modeling and optimization of a novel solar chimney cogeneration power plant combined with solid oxide electrolysis/fuel cell. *Energy Convers. Manag.* **2015**, *105*, 423–432. [CrossRef]
100. Liso, V.; Zhao, Y.; Yang, W.; Nielsen, M. Modelling of a Solid Oxide Fuel Cell CHP System Coupled with a Hot Water Storage Tank for a Single Household. *Energies* **2015**, *8*, 2211–2229. [CrossRef]
101. Kupecki, J.; Jewulski, J.; Motylinski, K. Parametric evaluation of a micro-CHP unit with solid oxide fuel cells integrated with oxygen transport membranes. *Int. J. Hydrog. Energy* **2015**, *40*, 11633–11640. [CrossRef]
102. Ham, S.-W.; Jo, S.-Y.; Dong, H.-W.; Jeong, J.-W. A simplified PEM fuel cell model for building cogeneration applications. *Energy Build.* **2015**, *107*, 213–225. [CrossRef]
103. Elmer, T.; Worall, M.; Wu, S.; Riffat, S.B. Emission and economic performance assessment of a solid oxide fuel cell micro-combined heat and power system in a domestic building. *Appl. Therm. Eng.* **2015**, *90*, 1082–1089. [CrossRef]
104. Cappa, F.; Facci, A.L.; Ubertini, S. Proton exchange membrane fuel cell for cooperating households: A convenient combined heat and power solution for residential applications. *Energy* **2015**, *90*, 1229–1238. [CrossRef]
105. Canelli, M.; Entchev, E.; Sasso, M.; Yang, L.; Ghorab, M. Dynamic simulations of hybrid energy systems in load sharing application. *Appl. Therm. Eng.* **2015**, *78*, 315–325. [CrossRef]
106. Borji, M.; Atashkari, K.; Ghorbani, S.; Nariman-Zadeh, N. Parametric analysis and Pareto optimization of an integrated autothermal biomass gasification, solid oxide fuel cell and micro gas turbine CHP system. *Int. J. Hydrog. Energy* **2015**, *40*, 14202–14223. [CrossRef]
107. Arsalis, A.; Kær, S.K.; Nielsen, M.P. Modeling and optimization of a heat-pump-assisted high temperature proton exchange membrane fuel cell micro-combined-heat-and-power system for residential applications. *Appl. Energy* **2015**, *147*, 569–581. [CrossRef]
108. Antonucci, V.; Brunaccini, G.; De Pascale, A.; Ferraro, M.; Melino, F.; Orlandini, V.; Sergi, F. Integration of μ-SOFC Generator and ZEBRA Batteries for Domestic Application and Comparison with other μ-CHP Technologies. *Energy Procedia* **2015**, *75*, 999–1004. [CrossRef]
109. Worall, M.; Elmer, T.; Riffat, S.; Wu, S.; Du, S. An experimental investigation of a micro-tubular SOFC membrane-separated liquid desiccant dehumidification and cooling tri-generation system. *Appl. Therm. Eng.* **2017**, *120*, 64–73. [CrossRef]
110. Elmer, T.; Worall, M.; Wu, S.; Riffat, S. Assessment of a novel solid oxide fuel cell tri-generation system for building applications. *Energy Convers. Manag.* **2016**, *124*, 29–41. [CrossRef]
111. Zhang, S.-L.; Wang, H.; Lu, M.Y.; Zhang, A.-P.; Mogni, L.V.; Liu, Q.; Li, C.-X.; Li, C.-J.; Barnett, S.A. Cobalt-substituted SrTi 0.3 Fe 0.7 O 3−δ: A stable high-performance oxygen electrode material for intermediate-temperature solid oxide electrochemical cells. *J. Energy Environ. Sci. Technol.* **2018**, *11*, 1870–1879. [CrossRef]

112. Chen, T.; Liu, S.; Zhang, J.; Tang, M. Study on the characteristics of GDL with different PTFE content and its effect on the performance of PEMFC. *J Int. J. Heat Mass Transf.* **2019**, *128*, 1168–1174. [CrossRef]
113. Soloveichik, G.L. Flow batteries: Current status and trends. *Chem. Rev.* **2015**, *115*, 11533–11558. [CrossRef]