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Optimization strategies for Solid Oxide Fuel Cell (SOFC) application: A literature survey

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ABSTRACT

Solid Oxide Fuel Cells (SOFCs) have become the promising energy source for stationary and portable applications. The design of SOFCs including its structure and its operation are an important part to be properly optimized in order to achieve the best performance. The topic on optimization of SOFC has gained tremendous attention recently in line with the growing applications of fuel cell. This paper involves a literature survey of the application of SOFC in particular the optimization strategies. The strategies are reviewed in detail based on five features, which are the decision variable, objective analysis, constraint, method and tools. The future trends of research related to the optimization for SOFC are also discussed to provide better insight for future research work in this area.

1. Introduction

Recent research developments on renewable energy have identified fuel cell as an important potential energy source for the future. Fuel cells are a renewable energy type which converts the chemical reaction between hydrogen and oxygen into electrical voltage. It has become a competitive power source due to its advantages such as high efficiency, flexibility in the usage of the required fuels and can be developed for a wide range of operating temperatures, which makes them easy to be implemented in extensive applications [1,2].

Fuel cells have been developed in several types, namely 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 and Solid Oxide Fuel Cell (SOFC) [3]. The fuel cell study classifies PEMFC, DMFC, and PAFC as low-temperature fuel cells which have the potential to be implemented in transport applications, military, and public facilities [4–7], while PAFC, MCFC, and SOFC have higher temperature ratings and higher efficiency, which makes them suitable for power generation and hybrid-power applications [8–11].

Among the high-temperature fuel cell types, SOFC is the most widely developed due to it having a high efficiency and have the flexibility of using different hydrocarbon fuel as well as its versatility in the electrolyte material [10]. It has also become one of the most attractive fuel cell applications in combined heat-power generators [12,13] and in the building sector [14]. It also has the flexibility to be integrated with another power generation source, water heating device and cooling device used in residential homes [15]. The topics on SOFC which have been considerably reviewed over the past 10 years and more intensively developed over the last five years indicate the growing interest in this research area [16].

Improvements of SOFCs have been conducted based on modeling and simulation studies with the aim to achieve better performance [17–25]. Research in this topic has been developed in several areas involving improved model and observer studies [26–31], advanced estimation and identification [32,33], precision of control and management [34–40], and optimization of design and operation [41–54]. These previous studies frequently mentioned optimization of SOFC as a recent research topic compared to other fuel cell types such as PEMFC and MCFC [55]. The research on optimization of SOFC has been established since 1996 based on our review. Since then, optimization topics on SOFC application continued to the development of advanced computer and intelligent techniques. Fig. 1 shows the exponential trend of research in the application of SOFC based on the number of publication in a three year-wise graphic.

So far some researchers have conducted for studies with respect to

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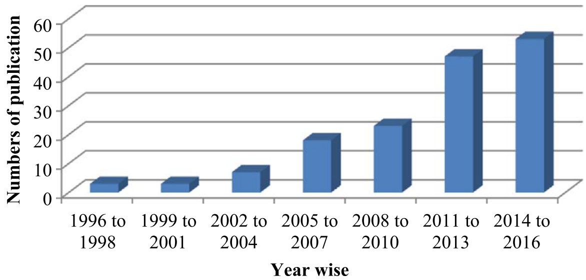

Fig. 1. Three years-wise number of publications using optimization in SOFC application.

the review of the topic on fuel cell optimization. The report from Ang [3] discussed on the optimization of fuel cell using the study case format and focus on the optimization strategy based on its decision variables and objective analysis aspects. The authors explained on how to build the optimum design and robust model for fuel cell applications. Another review by Secanell [16] studied works of literature in computational optimization for a fuel cell in a single cell design, stack design and hybrid applications. The study focused on designing and optimizing scope using complex example of model and parameters. Both of these studies did not provide the current research on SOFC optimization. In 2014, Hajimolana [56] published a review on SOFC optimization strategy including the decision variable, objective and the tools. However, the study reviewed a limited number of related researches and did not focus on the strategy in detail. Neither of the previous studies focuses on the comprehensive strategies to deal with SOFC application and do not present the recent reviews regarding the advanced development on the topic of optimization.

Since there has been no extensive review on this subject, the objective of this paper is to provide a comprehensive literatures review on the optimization of SOFC in the last 20 years. This study also focuses on the five important aspects in the optimization strategies, namely decision variables, objective function, constraints, optimization methods and optimization tools. Finally, the future development of research on SOFC application especially related to the topic of optimization is presented to analyze the opportunities for researchers interested to develop an optimization part in that area.

This paper is divided as follows. Section 2 provides the brief review of SOFC application, including its implementation of distributed generation (DG) stack system, hybrid power generation system and multi-power generation. Section 3 provides literature survey on optimization strategies for microstructure, single cell and integrated system design in SOFC application. It includes the five aspects of optimization strategy which are the decision variables, objective analysis, constraints, methods and its implemented validation. Section 4 provides the future trend of research on SOFC optimization.

2. Brief review of SOFC application

2.1. Stack system

In the late 1930s, experimentation of solid oxide electrolyte was conducted by Emil Baur, a Swiss scientist and his colleague Preis [57]. Williams [58] achieved the temperature operation of the first ceramic solid oxide at 1000 °C in 1937. Since then, the research in microstructure of solid oxide ceramics became more challenged in increasing its conductivity and mechanical strength. Research by Davtyan in the 1940s experienced an unwanted chemical reaction which shortens the life span of electrolyte due to the mixing of the sodium carbonate with monazite sand. In 1959, based on various research works by Stimming [57] on the fuel cell, several issues on microstructure were addressed with the objective to decrease internal electrical resistance, melting due to high temperature and short circuiting due to semiconductivity.

From our review, the new energy and industrial technology development organization (NEDO), Japan, started the earliest research of SOFC for the stack system in 1989 which was set up to develop technology for fabricating SOFC. During the first period of the study, it had manufactured the 100 W class of SOFC stack. From 1992, the study of planar SOFC was conducted to generate high power density and large active area of the cell. Moreover, it also was planned to fabricate several-kW class of SOFC. From 1997 to 2000, the research focused on increasing cell stability and reliability instead of manufacturing various class of planar SOFC which initiated the development of the tubular SOFC.

In the USA, the Department of Energy (DOE) National Energy Technology Laboratory (NTRL) developed the tubular SOFC power plant with several private industries, initiated by Siemens Westinghouse Power Corporation [59]. NETL also partnered Pacific Northwest National Laboratory (PNNL) in developing a commercial, high efficiency modular, low cost and fuel flexible SOFC stack of 3 and 10 kW power.

Moreover, Delphi Corporation also started to fabricate the stack SOFC for auxiliary power unit (APU) to supply power engine-independent with high efficiency and low emissions. By taking advantages from SOFC, it increased the effectiveness of APU from 10–20% upto 30–35% compared to the engineered-powered generator. SOFC can be attractive for APU application since it does not have complicated water management for the electrolyte, compatibility in terms of temperature between reformer and stack and high tolerance to fuel impurities [58]. Optimizing of the reformer is the key point for increasing the APU efficiency instead of increasing cell voltage which causes decrease of current density. The recycled anode exhausts gas which can be fed into the reformer inlet with incoming hydrogen fuel was performed to improve fuel utilization in the APU system. Delphi developed a 5 kW SOFC APU which has a compact design, fuelled by gasoline and has a low mass system [59].

2.2. Hybrid power generation system

Developing hybrid power generation comes from the idea to optimize the exhausted heat of SOFC. Following the success in developing stack systems, Siemens Westinghouse power corporation run the hybrid project concentrating on the development of tubular SOFC [59]. It augmented the fuel cell with the turbine to utilize its byproduct heat. The additional power generation increases the overall efficiency and reduces the cost of electricity without using extra fuel. The combination also reduces further combustion of fuel in the turbine and achieves efficiency of 70% with lower of energy cost. With the hybrid project, related industries such as Rolls Royce and General Electric also developed stack SOFC combined with the gas turbine (GT) for distributed generation following requirement of clean energy in The Vision 21 [60]. In 1995, Domeracki patented an improvement for hybrid power generation [61] including attached compressor that producing compressed air. In the combustion process, the unreacted portion of fuel was combusted with oxygen for further heating of the hot gas and the second steam of fuel was used to increase the temperature of the hot gas before it was expanded to the turbine.

Developing of hybrid system was expanded to utilize other thermal generators as Stirling heat engines (SHE) and steam turbines (ST). Arsalis [62] studied the hybrid SOFC-GT-ST model and the parametric study of the system using thermo-economic analysis. The model was developed based on thermodynamic, kinetic, geometric and costing with size ranging from 1.5 MWe to 10 MWe. The heat recovery system generator (HRSG) was added to produce steam which drives the steam turbine for additional power output. Four different steam turbine cycles were considered in the study to design the hybrid system adequately. Ugartemendia [63] developed an optimum management in the hybrid SOFC-ST system using proportional-integral (PI) control for fuel utilization and operating temperature of the scheme. Management of the stack resulted in the increasing of fuel efficiency at the rated power levels. For the case study, it achieved 120 kW of the SOFC rated power, optimal efficiency at 66% when the fuel utilization at 6.5 and operating temperature at 900 °C. Chen [64] performed regenerator implementation for the hybrid system between SOFC-SHE. It acts as a counter-flow heat exchanger which absorbs the heat in the high temperature to preheat the reactants to attain the reaction temperature. The study considered hybrid SOFC-SHE system as the efficient power generator and flexible fuel utilization.

2.3. Multi-power generation system

In further enhancement to the power generation system, utilization of waste heat from SOFC was not limited to trigger another heat generator, but to also develop for satisfying heat demand. Coming from the requirement of water and space heating, the integrated SOFC for combined heat and power (CHP) becomes a valuable system since it does not require fuel as much as the separated heating and cooling system. This system is expected to be the first commercialized application for residential power generation which have been successfully demonstrated by several companies such as Hexis (Switzerland), Ceres Power (UK), in partnership with British Gas and Ceramic Fuel Cells Ltd (Australia) [65].

Since the early 1990s, many authors has been publicizing the development of SOFC based CHP system. Riensche [66] developed a 200 kW SOFC based cogeneration system by considering the parameter study of the system such as air temperature increase in the stack, degree of internal reforming, cell voltage and fuel utilization. Based on the study, two main parameters affecting the cost in the CHP system are the temperature of the pre-heated air for stack cooling and the active cell area of the chimney. Adjusted fuel utilization, increasing air temperature, adapting internal reforming instead of external bring cost reduction by about 5%, 20% and 50%, respectively. Residential cogeneration system has also been optimized using the soft computing approach by Entchev [14]. This study used intelligent control strategy to adjust the water temperature according to the number of occupants. It implemented the control mechanism using two sensors employed in the water storage tank and thermostat in the room space. The proposed control claimed to increase the overall efficiency by about 8–10% and reduce pollutants by 25–30%. After 2010, the development of SOFC based CHP system focused on reducing the cost and unwanted gas emission and simultaneously decreasing the overall performance of energy and exergy [67–80]. In the recent development, micro-CHP system which has a rated power of 1–50 kW became more advantageous to be developed for house residential and small building [72].

Following the successful development of the CHP system, the research on SOFC based combined, cooling, heating and power (CCHP) has been attractively increasing. The slight difference between CHP and CCHP is the cooling device fed by the heat output from SOFC as the prime mover. In CCHP system, with similar fuel utilization, the system efficiently meet the requirement of electrical power, water and space heating and also water and space cooling. It uses some cooling device as absorption chiller, electric chiller and refrigerator. As researched by Chen [81], the developed CCHP for the case study of a Hotel in Hong Kong was more efficient than the CHP system. The overall efficiency of CCHP and CHP system for the study were found to be 93.86% and 84.02%, respectively. However, due to some extra cooling system, CCHP has higher investment costs than the CHP system. CCHP has payback period of about 4.3 years longer than the CHP system. In a different study by Chitsaz [82], it was revealed that the proposed CCHP achieved exergy efficiency of 46%. It is 5% higher than the exergy efficiency obtained by the standalone SOFC system.

Developing the stack and integrated system from laboratory research into the commercialized system has to deal with several issues. Those aspects come from the technical, economic, environmental and social political viewpoints. As presented in Table 1, those issues should be handled by rightly designing the SOFC based system before it is commercialized. From these aspects, the optimization approach is useful in proposing the applications which can be beneficial in relates to these issues i.e. technical, economic, environmental and also social politic objective. Hence, the review of optimization strategies for SOFC is highly important to tackle the issues related to SOFC application in the real world.

3. Literature survey on optimization strategies for SOFC application

Optimization involves the process of finding the best solution from all feasible solutions [83]. Optimization strategies are systematic steps to define optimum solutions towards one or multi-parameters with specified constraints to maximize or minimize the objective of those solutions [84]. In the fuel cell research area, some investigations have been carried out for SOFC optimization and its implementations over the years. For improving the SOFC performance, this optimization turns out to be a fundamental aspect which has to be performed at several aspects as depicted in Fig. 2. The key point of research trends in developing the optimization strategy is related to the optimized variables, objectives, constraints, methods and how to implement the optimization.

Appendix A lists the summary of the review papers regarding to the optimization strategies for SOFC application. It provides the previous research lists and its detailed decision variables, objectives, methods and implemented validation. The detailed explanation of the decision variable is presented in Section 3.1. It is described based three parameters for SOFC application that are micro-structure, single cell and integrated system. In Section 3.2, the objective functions from thermodynamic, economic and environmental aspects are explained based on several case studies. Section 3.3 presents the optimization constraints consist of safe operation constraints and specification ranges of the system. Section 3.4 explains the optimization methods including deterministic, stochastic and meta-heuristic method. Section 3.5 discusses optimization tools used in simulation and real experimental validation.

3.1. Decision variables

Regarding its geometrical aspect, SOFCs are categorized into two major types as depicted in Fig. 3; planar and tubular. Planar composed of several layers sandwiched between the electrodes, while the tubular SOFC is designed from many discrete electrolyte tubes in the parallel form [24]. Tubular design has been assessed to be more secure than the planar since the gap between air and fuel is sealed separately. The improvement between the planar and tubular design is the micro-tubular type which takes the advantages of the low resistance of the planar and tubular form. The design has been proven to have faster startup times compared to the planar design. It has also been improved since early 1990's due to their greater tolerance to thermal cycling, quicker start-up capability, higher output density and better portable characteristics as compared to the planar and tubular SOFCs [85].

Based on the literature, the planar, tubular and improved design of the SOFCs can be implemented into several structures namely microstructure, single and integrated system, which affects to the parameters optimized. In microstructure design, the cell thickness including the electrode, anode and cathode, grain size, distribution of porosities, all of which are important parameters to be optimized [56]. Ge [86] analyzed the parameter influences of microstructure design such as weight fraction, void fraction, particle size ratio, particle size, and density for optimizing the tubular SOFC. At the same time, the research from Shi [87] has proven that the distributions of porosities and particle sizes for electrodes can affect the current density and output cell voltage of planar SOFCs.

Table 1
Issues in implementing SOFC technology.

Technical issues	Economic issues	Environmental issues	Social political issues
Technological development for durability and affordability for SOFC commercialize type	Very costly investment	Still produce hazardous wastes as sulfur poisoning	Government regulation in grid-connected application (in some countries)
The high temperature leads to the problem in designing external reforming part as heat exchanger, piping and pumps	High cost of natural fuel		Education for public awareness in implementing SOFC based power generation
Particular problem by using brittle ceramics which is difficult to be fabricated	The market target is limited for industrial application in large scale application		Legal constraints to realize distribute power generation and grid connected
Component stress at high operating temperature which leads to the issue of life cycle reduction			
Flexibility and fast response are difficult due to preheating process needed			

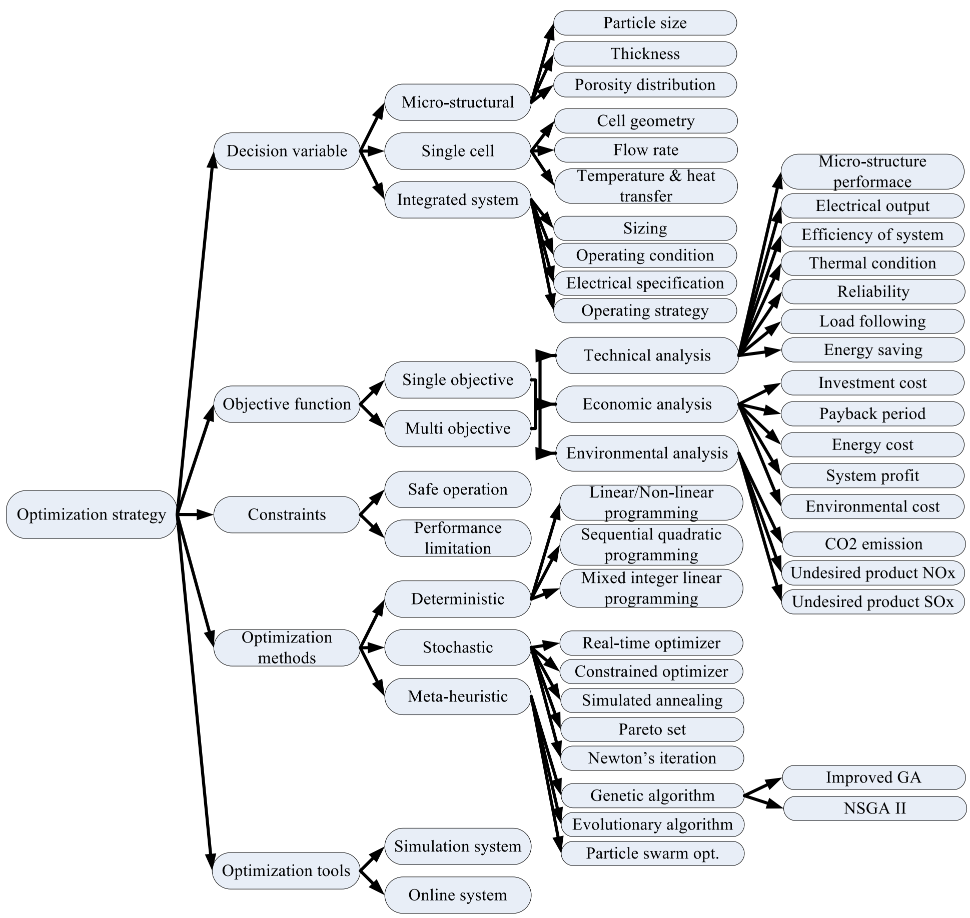

Fig. 2. A scope diagram showing the research area of this review paper.

3.1.1. *Micro-structure parameter*

Optimization of SOFC has been researched since 1996 by Kleitz [89] regarding microstructure improvements. The study found that SOFC electrode performance can be improved by mixing the conducting electrode material and increasing the reaction zone as fast as possible at medium operating temperatures. Some studies were conducted to optimize the material of micro-structure [90–93]. The study by Li [92] showed that the composition effect on the electrode can increase the exchange current density and decrease open polarization resistance. They used the SSM55 (Sm0.5Sr0.5MnO3) material in the YSZ (Yttria-stabilized Zirconia) scaffold for improving the distribution uniformity and connectivity of the nano-sized particles. Ahmed [93] studied material optimization by adding nickel oxide (NiO) and gadolinium doped ceria (GDC) as anode materials and used graphite as a pore former in the anode substrate. It obtained an increased performance in three different operating temperatures (600, 550 and 500 °C) achieving values of 0.86 V and 48.62 mW/cm^2 for open voltage and current density respectively.

For increasing the electro-chemical performance of the cell, some studies took into account the characteristic parameters of the microstructure. Costamagna [94] used an analytical model to enhance the electrode conductivity, cell polarization, ohmic effect and electrode thicknesses to maximize the current density of the cell. These studies showed that the microstructure optimization has a significant impact on the cell performance, especially the output current density and output voltage. Bhattacharya [95] optimized the porosity of electrode, effective diffusivity of the species and the rate of chemical reaction micro-structure SOFC. By using the isothermal model from his previous publication [96], the study revealed that optimizing its design and operating condition can improve the anode-supported tubular cell

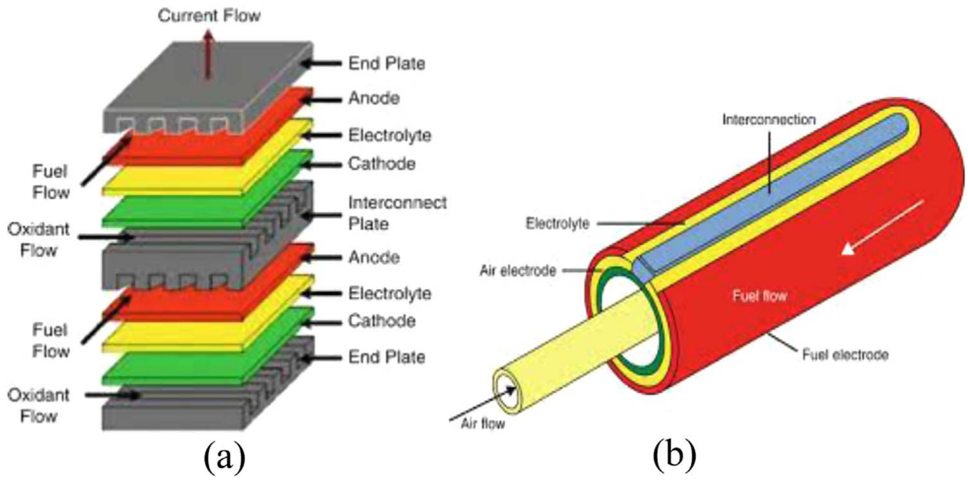

Fig. 3. SOFC structure design (a) planar cell (left) and (b) tubular cell (right) [88].

performance. Several characteristics of the cell at the optimum value can give significant impact to the output performance, particularly at the high current density.

The geometry characteristic of the microstructure has also been studied to enhance electrochemical performance of the fuel cell. Haanappel [97] studied microstructural optimization to improve electrochemical performance of LSM based anode-supported single cell. The study look at four parameters which are LSM/YSZ mass ratio of cathode functional layer, the grain size of LSM powder for cathode current collector, the thickness of cathode current collector layer and the calcination effect of YSZ powder for cathode functional layer. The results from these electrochemical measurement showed that the performance of LSM-based SOFC can be improved by varying the LSM/YSZ mass ratio of the CFL. It also showed that the thicknesses and grain size affects the current density.

3.1.2. Single cell parameter

For single cell application, optimization has been focused on increasing the output power and efficiency of the cell while reducing its cost [16]. Optimization of a single cell takes into account several factors such as composite cell and geometric parameters such as thickness of the ribs, length of TPB, cell volume, and channel height. The study from Bhattacharyya [96] analyzed the impact of cell design such as the porosity of electrodes, effective diffusivity of the species and rate of the electrochemical reaction to the cell output performance. It also took into account dimensions of the cell as the radius of the anode flow channel, the length of the canal and the annulus size while keeping the cell volume constant. Sciacovelli [48] considered geometrical aspects such as injection tube diameter in the optimization procedures to enhance entropy generation. Ji [98] studied the effects of geometrical aspects such as the channel height, rib thickness and thin-film electrode for increasing the cell efficiency. A parametric study was performed to analyze the effects of these parameters on temperature, species concentration, local current density and power density. The thicknesses and fuel cell length were also optimized by Skalar [99] and Feng [100] to minimize thermal stress and maximize the output power, respectively. It used the finite element method (FEM) in a two-dimensional model for solving these cases.

Some studies also took into account the effect of operating conditions for single cell performance such as the fuel flow rate, air flow rate, the temperature of fuel and air, pressure and fuel utilization impact. Ni [101] studied several operational parameters such as temperature, hydrogen molar fraction and pressure to maximize output power and efficiency. The study revealed that activation and ohmic overpotential resistance decreased as the temperature is increased. Furthermore, increasing the hydrogen content and pressure has been shown to enhance the SOFC output power. After that, similar parameters were also studied by Jo [102] with current density as the objective. The study showed that increasing of temperature, molar fraction and pressure give significant enhancements to output current density for the fuel cell.

3.1.3. Integrated system parameter

Due to the limited power of the output, single cell SOFC can be arranged into a stack system in series or parallel design. In these stack systems, the SOFC is attached with auxiliary devices called the balance of plant (BOP) components such as the reformer, burner, heat exchanger, air compressor and fuel processor. The stack system and its BOP components can be operated together to generate output at high temperatures (typically between 750 and 1100 °C). The stack size and efficiency become the most important aspect in developing these stack system. Moreover, the operating conditions of these BOP has also been taken into account to increase the overall efficiency of the stack systems.

Based on the literature survey, the stack system has been applied for applications such as micro-power generation [43,103–106], the standalone system [107–110], portable power generator [111], auxiliary power unit (APU) [112,113] and hybrid vehicle [47]. In larger applications, the stack system is combined with other power generators to tackle the efficiency issue of SOFC. The combination between two or more energy sources which are called 'hybridization' has been found to maximize integrated performance and hence minimize disadvantages of the coupled power sources. In its application, SOFC stack has been combined with several types of a heat-based generator such Gas Turbine (GT) [12,44,50,114–125], Steam Turbine (ST) [62–64], diesel [126,127], heat engine [128] and biomass power [129]. For power and heat power system (CHP), it also utilizes the exhaust heat of the stack SOFC to increase the efficiency of the composition [66–69,71,130–132]. In other applications, the CHP is improved by attaching cooling devices such as chiller and absorber to satisfy the cooling demand. The improved system is called the combined cooling, heating and power system (CCHP) [15,80,133,134]. In earlier implementation, the CHP system has been popular in industrial applications. However, in line with the development of micro-scale power generation, these CHP and CCHP systems have been made attractive and developed for residential and small building applications [135].

For an integrated system, optimization is conducted for several aspects of designing, controlling and management. Regarding the designing aspect, the right synthesis design and sizing are the most important part minimizing the cost of investment. Optimization of system design and its size depends on the load, weather conditions and government regulations. The plan for a residential area is different to the hotel buildings or academic buildings. Similar effects appear for the weather condition where the system design for area with four seasons is different from the tropical areas. Wipke [136] developed the size for hybrid SOFC-battery for mobile applications. It took into account several parameters such as sizing of fuel cell rated power, battery capacity and motor rated power to minimize the fuel consumption of the hybrid vehicle. The study observed that the control strategy has to be coupled with the right sizing of the device. Weber [41] synthesized a multi-generation system to size the storage tanks, SOFC capacity and absorption chiller. The case study was done in an office building in Tokyo with the objective for reducing CO2 emission and cost. The study used 12 types of differential load profile based on the behavior of occupants and the weather conditions. Optimal sizing of hybrid systems has also been investigated by Deng [137] to minimize the cost and environmental emission. It took into account the size of the wind turbine, PV array and CHP system containing the combination of the SOFC and gas turbine hybrid system. The micro-grid system was designed to meet the electricity and heat load profile for the specified case study in hand.

In addition, the design of the operating conditions also takes into account to increase the performance of the system and also decrease the cost and environmental effects. Operating condition involves several aspects such as the characteristic of components, operating point of devices and operating strategy to operate the system. Shirazi [138] conducted optimization of the SOFC-turbine hybrid system for the thermal-economic-environmental aspects. It involved several characteristics of the hybrid system and its operating points such as air compressor pressure ratio, air compressor efficiency, gas turbine isentropic efficiency, current density, fuel utilization, air utilization and steam to carbon ratio. It implemented an integrated system in simulation and validated with the real device. Najafi conducted similar work [139] which optimize the hybrid SOFC-GT based on the exergetic aspect. It improved the system by adding several parameters such as temperature point, inlet motive steam temperature, the number of desalination stages and brine temperature in the last stage. Since the exergetic aspect is related to the temperature range, the study conducted optimization considering these temperature points. Regarding the operating strategy, Napoli [72] proposed four modulation strategies to apply for CHP system in residential areas namely without modulation, day-night modulation, segmented modulation and load-following. By using constant fuel utilization and varying the current density, the study applied the strategies for reducing the cost and enhancing the system performance. Based on these results, the best scenario was found to be the day-night modulation due to the lower ramp rate of SOFC which reduces the tendency to follow the user's request exactly.

3.2. Objective function

An important part of the optimization strategy is the objective to be maximized or minimized. In calculus-based optimization, the objective is numerally represented as follows [16]

$$\begin{aligned}
&\text{minimize} \quad f(x) \quad \text{(a)}\\
&\text{w.r.t.} \quad x_k \quad \text{for } k = 1, 2, \ldots n \quad \text{(b)}\\
&\text{subject to:} \quad h_i(x) = 0 \quad \text{for } i = 1, 2, \ldots p \quad \text{(c)}\\
&g_j(x) \le 0 \quad \text{for } j = 1, 2, \ldots q \quad \text{(d)}\\
&x_L \le x \le x_U \quad \text{(e)}
\end{aligned} \tag{1}$$

where $f(x)$ is the objective function to be minimized. The equation of $h_i(x)=0$ are equality constraints, while $g_j(x) \le 0$ are inequality constraints towards the decision variables x. The equation X_L and X_U represent vector of lower and upper bound of decision variables. In some cases, $f(x)$, $h_i(x)$ and $g_j(x)$ are nonlinear, continuous and have continuous first and second order derivatives [16]. In SOFC application, there are several objectives to be considered based on thermodynamic, economic and environmental aspects. The objective function can be single or in combination between several aspects that depends on the decision variable x. The decision variables can consist of single or k variables considering micro-structure, single cell or integrated system parameters.

In simple system, the optimization is solved for one objective function. However in complex system such as the SOFC, the objective can be more than one. One of the objectives can be a constraint to be satisfied by the others and vice versa. For example, to optimize the output power, several constraints can be used such as cell cost, efficiency, and fuel utilization which refers to the energy price. This problem is called multi-objective function not only having complicated functions, but also has conflicted objective and constraints to be addressed. In optimizing SOFC applications, several goals can be taken into account such as the thermodynamic aspects, economic aspects and environmental aspects which will be elaborated below.

3.2.1. Thermodynamic aspects

Regarding the thermodynamic aspect, system performance such as energy output, efficiency and electrical characteristic are the objectives to be optimized. In the single cell design, outcome performance includes the current density [87], power density [140,141], output voltage [142], cell power [143], cell efficiency [144] and conductivity [145] which should be maximized. When the outputs such as ohmic resistance [146,147], potential losses [148] and temperature [149] should be minimized. Tikiz [13] performed an experimental investigation of SOFC performance based on its current density. It was found that the hydrogen flow rate and temperature were the fundamental operating parameters which affect the current density of the solid oxide fuel cell. Maximizing the output power was performed by Shi [150] with consideration of H_2 and H_2O concentration ratio. Song [53] conducted experimental research studies to minimize the resistance at the base of the fuel cell by optimizing the shape of the nano-composite cathode. The strategy was presented to identify the characteristics of the optimal microstructure using the topology optimization. The study by Wen [148] proposed a microstructure optimization for finding the optimum thickness of the active reaction to minimize the total potential losses and maximize the output power. It conducted three-way single SOFC optimization on the active reaction layer thicknesses, operating temperature and electrode porosity. For the various ranges of electrode thicknesses studied, the variation of net power density achieved 20% by this three-way optimization strategy.

In the stack and integrated system, some thermodynamic aspects relating to the system performance can be considered as the objectives. Electrical output parameters of SOFC system include electrical output power, electrical output efficiency and limiting current density. Moreover, thermal output power and temperature of system influence the overall efficiency of the system. Inui [42] performed an analytical investigation to minimize temperature condition of the CHP system by optimizing air utilization and inlet gas temperature. It conducted numerical optimization considering the stress temperature aspect in the material of micro-structure SOFC. The proposed method is highly efficient reducing the temperature gradient for various temperatures even in at very low levels without lowering the single cell voltage.

Regarding the electrical output parameters, energy saving and energy usage have also frequently been used to maximize the benefit of the system. Moreover, device lifetime has also been considered as the optimization objective to ensure the system is reliable and profitable. Liso [74] studied the effect of heat-to-power ratio for SOFC running time to maximize the economical profit. Based on the research, optimizing the heat-to-power ratio of system is not sufficient to cover the heat demand during the winter period for countries with four seasons. Therefore utilization of auxiliary devices such as boiler and hot water storage must be coupled. However, for tropical or warm season countries, the heat-to-power ratio is sufficient to cover the heat requirement. Wakui [132] decompose the design and operating variable of the CHP system using a simulation approach to minimize annual primary energy consumption. Variations of battery utilization and operational restrictions were performed to obtain the optimum design and synthesis of CHP system. The study revealed that use of battery significantly improves the performance and hence the primary energy savings (PES). Similar assessment also has been conducted by Dorer [151] considering non-renewable primary energy consumption as the objective. The assessment took into account aspects of building type, climate, hot water demand, electricity demand, control option, storage size and operational option as the optimized variables. The study showed that following the heat demand is much better to reduce non-renewable energy consumption than utilizing the hot water storage.

If energy is used as an indicator of system performance regarding the thermodynamic aspect, exergy analysis defines the energy quality impact to the environmental issue. Energy and exergy have several differences presented by Dincer and Roses [152]. Exergy can be evaluated from several parameters such as chemical, temperature and mechanical. The chemical process, temperature setting of SOFC and its BOP to generate both electrical and heat power influences the quality of energy to the environmental aspect. Therefore, research work to improve exergy efficiency is as important as the improvement of energy efficiency.

Moller minimized exergy losses as an indicator of energy quality to the environmental impact [153]. It considered heat exchanger temperature, burner temperature, turbo machinery temperature and the flow rate of gas leaving the plant to be optimized. Comparative assessment of the PEMFC and SOFC integrated systems was performed by Mert [154]. The study optimized operating point parameters to maximize output power, energy and exergy efficiency. It used various combinations of weight sum and five different models of the fuel cell as the application. Ford conducted Micro-structure optimization [155] to maximize exergy efficiency and minimize gross entropy generation. Interconnected aspect ratio, electrode/electrolyte ratio and gas channel width were used as the decision variables. The one dimension planar SOFC model was built with a current density of 0.4 A/m^2 to realize the higher efficiencies.

3.2.2. Economic aspects

Economic objectives are important since most applications are profit-driven and there is strong relationship between profit with both energy and environmental aspects [156]. From an economic perspective, the cost for the whole system is the most important objective to be optimized. The cost of the system consists of the real cost such as investment cost, fuel consumption cost and electricity cost. While the operational cost is calculated based on the increasing or decreasing of the system value from year to year. It includes the life cycle cost, profitability index, payback period, environmental cost and gross operative margins (GOM).

Calise [116] carried out the synthesis and design of a SOFC-GT system using economic analysis. For each component, it estimated the capital cost and fuel cost. The overall life cycle cost calculated by the sum of fuel cost and the capital cost was used as the objective function. The cost of waste heat was also considered instead of maintenance cost since the aim is independent of the standard deviation variables. In another study, Tan [157] decomposed capital cost from operating cost and investment cost for each subsystem and component. The capital cost consists of purchase cost, maintenance cost and annual amortization. The price represents the income tax, depreciation and property insurance. Both annual amortization and maintenance cost are calculated as the percentage of the purchased price. For the SOFC component, the interconnect cost and balance of plant (BOP) cost are also considered and assumed to be 60% of the acquisition price. The cost function discussed by Elliot [158] took into account a material property β, which is the first parameter in diffusion model. The proposed finite volume cost model is computationally expensive because a full flow solution is required for every design variable.

The levelized cost of energy (LCE) expresses the net present value of the unit cost of energy over the lifetime of utilization. Simply, LCE is calculated by dividing the overall life cycle cost and the lifetime energy production. For computing and financial analysis, the equation can include several factors such as financing, insurance, maintenance and different types of depreciation schedules [159]. The study from Amer [160] considered LCE which consists of the capital cost recovery factor, installed capital cost and annual operating expenses. The capital cost recovery is expressed by the interest rate of operational life, while the operating cost expenses contain annualized cost of insurance and other expenditures and operation and maintenance costs (O & M). The analysis has been proposed to optimize the most suitable technology for generated power from a number of possible sources.

3.2.3. Environmental aspect

In addition to the environmental analysis, CO_2 emission rate is also performed to measure the rate of CO_2 gas in the exhaust of the fuel cell system expressed in units of Kg/MW h. The mass of CO2 is divided by the generated electrical power hourly as follows [82].

$$Emi_{CO_2} = \frac{mCO_2}{W_{net} + Q_h + Q_c} x \quad 3600 \tag{2}$$

Where mCO_2 represents the mass of CO_2 emission during generation, W_{net} expresses the electrical output net of the power generation. In a tri-generation system, Q_h defines the heat generation and Q_c represents the cooling power from the system.

Kazempoor [161] modeled and evaluated the CO_2 emission for a building integrated with a SOFC system. By using validated simulation models, the study estimated cogeneration and poly-generation systems to obtain the minimum non-renewable primary energy and carbon dioxide equivalent. Based on the case study, the SOFC based CHP system can save 66% of renewable energy and minimize of 14% emission compared to the separated heating system. Reducing CO_2 emission coupled with exergy destruction has also been performed by Chitsaz [82]. The research studied four cases that involve the electrical power generator, electric energy and cooling cogeneration, electrical and heat cogeneration and tri-generation. It examined several operating conditions of the system towards environmental performance i.e. exergy efficiency, exergy destruction rate and greenhouse gas emission. The study shows that tri-generation achieves higher exergy efficiency than a standalone system (about 5% higher). Moreover, the heat air exchanger and the afterburner are the sources of exergy destruction in tri-generation system. However, the emission reduction is considerably higher for the standalone system than others where the value is decreased by about half to that of tri-generation system.

The summary of objective function utilized in optimization strategy of SOFC application is listed in Table 2. It includes mathematic equation from thermodynamic, economic and environmental analysis. The most of technical aspect is to maximize or increase output performance of system, while in economic and environment aspect are objected to minimize the cost and unwanted emissions from the SOFC system.

3.3. Constraints

Most thermodynamic, economic and environmental decisions are the result of an optimization problem subject to one or several constraints. In SOFC applications, optimization problem takes two types of constraints which are safe operation and limitation of performance. For safe operation, the objectives must be reached without harming the system due to overheated, overflow or overpressure. On the other hand, the specification range refers to the set of the limited capacity of components for the system. Concerning SOFC as the prime mover, the range of size refers to the current density, voltage,

Table 2
The list of objective functions used in optimization SOFC.

Objective Analysis	Objective function	Ref.
Thermodynamic aspect:		
Maximizing open-circuit voltage	$V{=}V_N - V_{ohm} - V_{act} - V_{con}$	[126,162]
Maximizing TPB length	$l_{TPB} = f_c sN_{j,i}^{b}\rho_j^{vol}$	[86]
Maximize electric conductivity	$\sigma[Scm^{-1}] = dI/\pi r^2 \Delta V$	[145]
Minimize ohmic drop and diffusion over potential	$Ohmic\ drop{:}U{=}\frac{\rho_e i}{4th}r^2$	[89]
	$Overpotential{:}\eta_{diff} = \frac{RT}{4F}log\frac{P_{el}}{P_g}$	
Minimizing cathode total resistance	$\eta_{c,tot} = \frac{R_{LSM}^{eff}R_{YSZ}^{eff}}{R_{LSM}^{eff}+R_{YSZ}^{eff}}\left(\frac{\eta_c(0)}{R_{YSZ}^{eff}} + i_{tot}\delta_c + \frac{\eta_c(\delta_c)}{R_{LSM}^{eff}}\right)$	[146]
	$R_{c,tot} = \frac{\eta_{c,tot}}{i_{tot}}$	
Maximizing cell power of SOFC	$P_{cell}{=}M\ x \sum_{V_{cell}} jV_{cel}$	[150,163]
Maximizing cell efficiency of SOFC	$\eta{=} \sum_{j=1}^{m}\left(rj\frac{P_{net,j}}{P_{system,j}}\right)$	[71,98,144,164]
Maximizing current density of SOFC	$j_{0,a} = k_a\frac{72X[D_p-(D_p+D_s)n]n}{D_s^2D_p^2\left(1-\sqrt{1-x^2}\right)}x\left(\frac{P_{H_2}}{P_{ref}}\right)\left(\frac{P_{H_2o}}{P_{ref}}\right)exp\left(-\frac{E_{act,a}}{RT}\right)$	[165]
	$j_{0,c} = k_c\frac{72X[D_p-(D_p+D_s)n]n}{D_s^2D_p^2\left(1-\sqrt{1-x^2}\right)}x\left(\frac{P_{O_2}}{P_{ref}}\right)^{0.25}exp\left(-\frac{E_{act,c}}{RT}\right)$	
Maximizing electric generation	$P = VI = V\,x(U_f nFN_{fuel})x\ A$	[78,80,91]
Minimizing temperature of stack	$T_{tube}(z) = \frac{h_{tube}(T_{tube}-T_s)d_{tube}\pi z}{f_{gas}C_{gas}}$	[166]
Minimizing entropy generation	$g_p = \int\left(g_\mu + g_h + g_m + g_c + g_{ohm}\right)dV{+}\int g_{rad}dA$	[48]
Minimizing resistance at the base of the cell	$R_p = \frac{\phi\infty}{\frac{1}{B}\int_{\Gamma 0}-\sigma 0\,\nabla\phi\,.\,n0dl} - \frac{d}{\sigma 0}$	[53]
Maximizing system efficiency	$\eta_{elect} = \frac{P}{n\,\Delta H_{fuel} + n\,\Delta H_{air}}x100\%$	[77,78]
Minimizing exergy losses	$X_{dst} = \int\left(1{-}\frac{T_0}{T}\right)\sigma Q - \Delta X$	[153]
Maximizing exergetic efficiency	$\eta_{Ex,syst} = \frac{W_{net}}{Ex_{in}}$	[154]
primary energy consumption	$J_{CGS} = \sum_{m=1}^{M}N(m)\{\sum_{k=1}^{K}[\varnothing_E(k)E_P(k,\ m) + \varnothing_G F_p(k,\ m)]\Delta t\}{+}k$ $(\sum_{i=1}^{I}\gamma CGSi + \gamma BT{+}\sum_{l=1}^{L}\gamma PDI)$	[132]
Maximize primary energy saving	$PES_{FC}{=}1{-}\frac{E_{fuel}}{\frac{E_{el}}{\eta_{el,s}}+\frac{E_{th}}{\eta_{th,s}}}$	[72]
Minimize non-renewable primary energy (NRPE)	$\eta_{NRPE} = \frac{ND_{EL}+ND_{SH}+ND_{DHW}+ND_{EL-surplus}}{pef_{el-grid}+DD_{el-grid}+pef_{NG}DD_{NG}}$	[167]
Maximize heat efficiency	$\frac{\Delta H_{react}}{n\,\Delta H_{fuel}+\frac{n}{2}\Delta H_{air}}x100\%$	[78]
Maximize electric load factor	$U_E = \frac{\sum_{m=1}^{M}\sum_{K=1}^{k}\sum_{n=1}^{N}E_{FC}(n,k,m)\,\Delta t}{MKNE_{FC}^{R}\,\Delta t}x100$	[69]
Minimize electric supply proportion	$P_E = \frac{\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}\{E_{FC}(n,k,m)-E_{EH}(n,k,m)\}\,\Delta t}{\sum_{m=1}^{M}\sum_{k=1}^{K}\sum_{n=1}^{N}E_D(n,k,m)\,\Delta t}x100$	[69]
Maximize electrical to heating ratio	$TER{=}\frac{Q_{CHP}}{P_{AC,net}}$	[161]
Minimize stack temperature gradient	$dT{=}\frac{1}{3}\sum_{i=1}^{3}\left(\frac{\Delta T_{max}}{L_x}\right)^{cell,i}dx{+}\left(\frac{\Delta T_{max}}{L_z}\right)dz$	[168]
Maximize reliability	$LPSP{=}\frac{\sum_{t=1}^{N_h}hours[P_{supply}(t) < P_{needed}(t)]}{N_h}x100$	[15]
Economic aspect:		
Minimize capital cost	$C_{unit} = C_{N_{base}}\left(\frac{N_{unit}}{N_{base}}\right)^{\alpha}$	[169]
Minimize cost of electricity	$COE{=}F_1\frac{R_C C_{cap}}{C_E} + F_2C_M + F_3\frac{C_F}{\eta_{sys}} - F_3\frac{\left(\eta_{cog}-\eta_{sys}\right)C_F}{\eta_{sys}\eta_R}$	[170]
Minimize fuel cost	$CFE{=}\frac{1}{\left[\left(\frac{0.55}{city\_FE}\right)+\left(\frac{0.45}{hwy\_FE}\right)\right]}$	[136]
Minimize life-cycle cost	$C_{LCC(SOFC-PEMFC)} = C_{SO} + C_{PEM} + C_{FPS} + c_{fuel}\eta_{fuel}T_{life}t_{oper}$	[157]
Maximizing profitability index (PI)	$PI{=}\frac{PV_{in}-PV_{out}}{INV_F+I_sP_e+C_LL_P}{-}1$	[45]
Maximizing the net present value (NPV)	$NPV{=}\sum_{i=0}^{y}CF_0(i)$	[134]
Maximizing GOM (Gross Operative Margin)	$GOM = \sum_{i,j,k}\{R_{i,j}(k) - C_{i,j}(k)\}.\ \Delta t.\ g_{i,j}(k)$	[171]
Minimize payback period		[81]

(continued on next page)

Table 2 *(continued)*

Objective Analysis	Objective function	Ref.
	$PBP=(y_{cash}-1)+\frac{Cost-CCF^{(y_{cash}-1)}}{CF^{y_{cash}}}$	
Minimize Cost of exergy	$\sum(C_{out}E_{out})k+C_{w,k}W_k=C_{Q,k}E_{Q,k}+\sum(C_{in}E_{in})+Z_k$	[172]
Minimize levelized electricity cost	$LEC_i(RC)=\left\lvert\frac{LEC_i(ES1)-LEC_i(FIX)}{LEC_i(FIX)}\right\rvert$	[173]
Environmental aspect:		
Minimize CO_2 Emission	$z=g_g\sum_1^t(G_{t,FC}+G_{t,aux})+g_e\sum_1^t(Qreq_{t,ele}+Q_{t,f,c,ele})$	[67]
Maximizing C_2 production	$S_{C_2}=\frac{2\left(F_{C_2H_6}+F_{C_2H_4}\right)}{F^0_{CH_4}-F_{CH_4}}$	[49]
Minimizing carbondioxide equivalent (CO_2-eq)	$GHG=0.001.\ FU.\ HLV.E_{fct}$	[161]

rated output/net power and heat power.

3.3.1. Safe operation

The working temperature is one of the most significant parameter affecting the SOFC based system performance. Since it operates at a high temperature, SOFC faces several problems in the endurance of material used as well as the efficiency of the electrode. Therefore, many researchers take into account the range of safe operation for fuel and air temperatures. Milewski [120] defined that for running the SOFC hybrid system, cell temperature should be kept constant on 800 °C and gas turbine inlet at the maximum temperature of 1100 °C. It reached the maximum system efficiency with changes of turbine pressure ratio, SOFC fuel utilization, heat exchanger effectiveness and current density with a constant control of temperature. An experimental investigation was made by Bunin [174] using real-time optimization (RTO). The study was conducted to maximize system efficiency with considering fuel utilization, voltage and air ratio as the inputs. It used constraints-adaptation RTO schemes to meet the load-following at the optimum cell efficiency. At its operating condition, the set of limit for fuel utilization, air excess ratio and rate of input changes were applied to avoid the fuel starvation, step gradient in thermal changes and the damage in the stack, respectively.

3.3.2. Specification ranges

The range of characteristic relates to the cell geometry, material and electrical parameters. Geometrical parameters consist of electrode and rib thicknesses, the length of cell and channel. Material parameters consider the composite of the electrode, anode and cathode, while electrical parameters take into account the current density, voltage output power and heat. The study from Wen [175] optimized single planar cell while considering the cell volume as a constraint and interconnect thicknesses as a constant. The thicknesses of anode, cathode and electrolyte layer were changed into the optimum values to maximize the output power.

In another case study, social and government rules are taken as the legal constraint to optimize SOFC based power generation in a CHP/CCHP system. Based on the study by Chen [81], the legal restriction based on the government policy to sell back the power from the private power generation to the grid affects the economical aspect of implementing co/trigeneration system. Since the case study involves a hotel building in Hong Kong, it did not implement the operating strategy of selling back the electric to the grid due to the government rule. At the same time, load requirement is one of the most important constraints when designing the capacity of co/trigeneration. The payback period becomes longer if failing to amend the total size of the prime mover and heat devices since buildings such as hotel, office and residential houses have a fluctuating demand for electricity, heat and cooling.

3.4. Optimization methods

From this literature review, SOFC optimization has been conducted using several types of methods. These methods can be divided into three categories i.e. deterministic, stochastic and meta-heuristic methods.

3.4.1. Deterministic methods

Deterministic method refers to the methods that utilize calculus-based iteration to optimize the parameters with mathematical calculations. Deterministic optimization has been conducted using simplex algorithm, numerical computation and linear programming to obtain the optimum variables for simple single SOFC parameters. Oh [176] employed numerical simulation to optimize and control a 5 kW class of tubular SOFC stack. It applied the proposed method for optimizing the fuel flow as well as controlling the current density, optimum fuel flow and generator power to meet the load change. At the microstructure level, numerical simulation has also been done by Wen [175] by using geometry parameters of the cell as the benchmark study to obtain maximum nominal current and electrical power. Weber [41] integrated sizing optimization and operating strategy optimization using an evolutionary algorithm and linear programming. The AMPL programming language was used to implement linear programming in the daily operation of the system which uses independent decision variables such as the amount of electricity, HEX size, storage size and absorption chiller size.

Several deterministic approaches using computer programs and dynamic methods are employed to optimize the design and operating condition of SOFC. It includes Non-Linear Programming (NLP), Sequential Quadratic Programming (SQP), and Mixed Integer Linear Programming (MILP). Spivey [52] implemented constrained non-linear programming to optimize the number of cells in a stack SOFC and its operating parameters for control application. Goyal [177] proposed non-linear programming for designing SOFC-PEM power generation by taking into account the fuel utilization of SOFC, PEM pressure and equivalence ratio for SOFC. The combination between SOFC and PEMFC raises the current density by about 12% compared to the separate application. In other studies, Wakui [69,131,132,178] proposed mixed integer linear programming for optimizing the size and operating strategy of an integrated SOFC stack system. By taking advantages of MILP, large variables can be optimized consisting of integer values for operating strategy and non-integer values for SOFC size, energy flow and storage size.

3.4.2. Stochastic methods

On the other hand, stochastic approaches are utilized for complex problems which have uncertain objectives, decision variables, and constraints. These approaches generate exact and approximate best solutions for each of the individual goals. However, it can get stuck in local optima when applied to complex systems depending on the constraints. It also faces a computational time issue due to solving complex problems for the exact solution. Several stochastic methods have been proposed in the literature to optimize SOFC which are the Lagrange method, Pareto set, Real Time Optimization (RTO) and Newton's iteration.

Cheddie [119] conducted Thermo-economic optimization using a Lagrange multiplier method. Sizing and operating condition were used as the optimized variables to find the minimum lifecycle cost per generated energy of the plant. Moreover, multi-objective optimizer (MOO) based on Pareto frontier was proposed by Curletti [134]. The study maximized the net electrical efficiency as well as the net present value at the end of life for the integrated CCHP system. It performed the sensitivity analysis for area specific resistant (ASR), global electrical efficiency and net present value of the system. Baghernejad [133] also conducted a Pareto frontier for exergonomic optimization in CCHP systems. The research took into account characteristic and design of CCHP components consisting of SOFC output power, percentage of SOFC share, electrical to heat ratio and electrical to cooling ratio. It made an optimization with conflicting objectives which involves maximizing efficiency with minimizing unit cost and CO2 emission. Francois [179] proposed real-time optimization via modifier adaptation to optimize the electrical efficiency of SOFC power generation. The method has the advantage to deal with uncertainties and disturbances during the operation. Bunin conducted similar study [103,174] via an iterative algorithm for optimizing the steady-state voltage of SOFC cell and plant to maximize the system efficiency.

3.4.3. Meta-heuristic methods

If stochastic approach runs with randomize approximate solutions, the meta-heuristic improves the search method to get more accurate solutions with faster computational time. It is called as intelligent optimization methods running with controllable and evaluated random solutions. Its evaluation uses a nature-inspired algorithm such as selection, mutation and crossover in Genetic Algorithm (GA), spread and movement in swarm-based optimization and regeneration in Evolutionary Algorithm (EA). The best solution or group of solutions is reached to avoid being stuck in local optima. It also faces the computational time issue due to having a simple computing process rather than the stochastic method. In the last five years, these methods have been an attractive prospect to be implemented in the SOFC power system. It includes several methods in development, namely Simulate Annealing (SA), Particle Swarm Optimization (PSO), Evolutionary Algorithm (EA) and Genetic Algorithm (GA). For SOFC applications, they have been intensively studied expanding the last method and has been improved into several modified methods such as the Non-dominated Sorting GA (NSGA-II) and Improved GA (IGA). Table 3 provides the summary of methods used for optimizing SOFC and the technical comparison between these methods.

Moller [115] implemented genetic algorithm with tournament selection to optimize several operating parameters in the integrated SOFC-GT system. The study showed that stack temperature is the most significant parameter to increase power efficiency compared with other parameters. Shi [150] conducted microstructure optimization by using GA to obtain an optimum distribution of porosity and electrode pore size. It performed an optimization in several cases to maximize output power of cell based on the ratio between H_2O and H_2 concentration. The improved GA (IGA) was proposed by Yang [184] by modifying several steps on GA optimization including modification of decision value, objective function, crossover and adaptive mutation. The proposed method gave an improvement in reduction of error between sample voltage and optimum voltage. The research from Entchev [14] proposed simulated annealing combined with fuzzy logic control. It had an objective to find the optimum temperature of water and adjust the current water temperature according to the outdoor temperature and occupant's behavior. Lopez [45] optimized the location of supply area and its net present value by using particle swarm optimization (PSO). It compared PSO with GA method for finding the best method for optimizing an integrated SOFC-GT system and for maximizing the profitability index. The easy implemented of PSO with a few parameters to be adjusted make PSO superior to GA in this case study.

3.5. Optimization tools

Optimizing the parameter to maximize or minimize the objective function cannot be handled only by modeling. Some validations should be carried out to verify that the system is successfully optimized. This validation can be conducted by simulation, online implementation or both. In the literature, most of the validation has been done using simulated software, but several sources of literature show that real implementation has also been performed to validate these solutions.

3.5.1. Simulation system

In simulation, the MATLAB software seems to be the most common tool used to optimize SOFC in a single cell, stack, even for hybrid power application. It has been known to be a friendly user software which can be utilized independently or easily be integrated with other modeling simulated software such as COMSOLE [87,150,187], DAEPACK [105], FLUENT [141,142], EES [76], UESR2 using Fortran [54], BELSIMVAL [124,173], and EASY [44], ANSYS [111] and LENI [43]. Several types of optimization software are also available such as the optimizers that are GA optimizer [115], EA optimizer [12], NLP optimizer [2,169], SQP solver [122], GPROMS [181], GAMS [67,132], CVODE [70] and CPLEX [171,178].

Micro-structure designing was conducted by Shi [87,150] using COMSOLE Multiphysics 3.5a to maximize cell average current density under certain cell voltage. The study from Chachuat [105] employed DAEPACK software to conduct numerical simulation for design and operation of SOFC based power generation system. SQP solver was used as optimizer for maximizing power density of the system by changing the design and operation point of its power generation. Odukoya [122] applied SQP solver in MATLAB to minimize the error plant when performing energy balance of modeled system and maximize the net output, thermal efficiency and cogeneration efficiency. By using GAMS 23.4, Arcuri [171] modeled the small size of trigeneration system and performed optimization for its design, equipment characteristic and its operating condition using CPLEX 10.2. Simulation based optimization has also been conducted by Pla [111] using ANSYS for computational fluid dynamic (CFD) analysis and using FLUENT as the optimization solver. The objective of the study is to design a micro-power generator using micro-tubular fuel cells.

3.5.2. Online system

At the same time, real experiments using the SOFC fuel cell seems to be quite valuable to be implemented to enhance the actual power output. Zhang [50] studied an actual experiment for SOFC-GT electricity generation to evaluate its optimum performance. The real test was also carried out by Song [53] and Bunin [103] to optimize the dimension of a single cell and operating conditions using Real Time Optimization (RTO). Faes [145] studied microstructure optimization using Design of Experiment (DOE) and Response Surface Methodology (RSM) methods on the real experimental system.

4. The future trends for research on SOFC optimization

Since more than a decade, optimization has become an attractive approach to enhance the performance of the SOFC-based power generators. In the early years of development, deterministic and straightforward search algorithms have dominated the optimization approaches. In previous studies, the parametric study using gradient-based algorithms such NLP, MILP, and newton's approaches were mostly applied in a single-objective optimization problem. However, in line with the increased complexity in SOFC modeling and application,

Table 3
Comparison of several methods in SOFC optimization.

Used method in SOFC optimization	Remarks	Advantages	Limitations	Ref.
Deterministic:				
Linear Programming (LP)	Using a set of linear equations which represent the condition of problem	Simplicity and easy way to understand	Non-linear function cannot be solved	[41,48,109,124]
Graphical Algorithm	Using graphic to define variables to the objective	Very good learning tool	Cannot solve many variables problem due to difficulty on graphing and evaluating the variables	[100,146,180]
Simplex Algorithm	Using iterative method to solve the problem	Containing hundreds of decision variables and constraints	Cannot be performed for complex problem	[47,109,124]
Numerical analysis	Usually employ mathematical programming, use past information to generate better solutions	Has a good performance for local optimization	Initial information decides whether the optimization is good or not	[98,143]
Non-linear Programming (NLP)	Some of constraints and objectives are non-linear, subjects has equality or inequality constraints	Can solve non-linear problem	Often the solution found is only a local optimum	[51,177,181]
Sequential Quadratic Programming (SQP)	Used for solving non-linear constrained optimization problem	Has ability to solve a large number of variables and constraints	Can be slow when solving large or badly scaled problems	[105,122]
Mixed Integer Linear Program (MILP)	Contains some of variables are constrained integers and others are non-integers	Ability to solve more complex problems	The branch and bound method is time consuming	[67,69,130–132,178]
Stochastic:				
Lagrange Method (LM)	Finding the local maxima or minima of a function subject to equality constraint	Equations are easy to remember	The reached objective is not guaranteed to be a maximum or minimum point, it could be a saddle point	[119]
Pareto optimal (Global optimization)	Searching solution with taking trade-off within the constraints set of parameters	Good performance on conflicting objectives	Generates set of solutions rather than max/min objective point	[2,12,44]
Newton's Iteration	Generates a sequence variable to find the root of objective function with initial guess	Has an excellent performance on local convergence	The finding of global optima is based on its starting point	[158]
Real-Time Optimization (RTO)	Calculates optimum variables on the real-time problem	Can be integrated with control or prediction	Heavy computational cost	[106,174,179]
Meta-heuristic:				
Simulate Annealing (SA)	Random search which work from the bound of searching area into the optimum point	Can avoid to be trapped in local optima	There is a clear tradeoff between the quality of the solutions and the time required to compute them	[14]
Genetic Algorithm (GA)	Searching process of optimum solution using evolution technique	The robust algorithm for multi-objectives problem	The solution is approximately optimum	[15,43,54,87,104,115–117,138,139,157,182,183]
Improved GA (IGA)	Improvement in fitness value, crossover, adaptive mutation and best individual approach	Generate better performance than simple GA	Improved part may varied based on the case	[184]
Non-dominated sorting GA (NSGA II)	Uses an elitist principle and non-dominated solution	Elitism does not allow an already found Pareto optimal solution to be deleted	Crowded comparison can restrict the convergence	[49]
Evolutionary Algorithm (EA)	Use vectors of real-valued numbers as representation	Robust with respect to complicated objective function	Premature convergence to a local extreme may result from adverse configuration	[185,41]
Particle Swarm Optimization (PSO)	Population based optimization which incorporates swarming behavior	Easy to be used, derivative free, efficient global search algorithm	Tendency to a fast and premature convergence in mid optimum points	[45,125,160,186]

the gradient-based algorithms have been replaced with more advanced methods to save computational time and efficiency. The development of population-based algorithms such evolutionary algorithm, genetic algorithm, and swarm-based algorithm are dramatically increasing to deal with the complexity of the system. These methods, however, started to face challenges in handling the multi-objective and multi-constraint problems [87,115,117,125,137,138,157,184,188,189].

In line with that, several works in the literature have shown the attractive approach to deal with multi-level issues in SOFC such as for the microstructure, stack, and hybrid systems [41,190,191]. In line with this, multi-level optimization has been conducted using stochastic and meta-heuristic methods. Optimization has been performed for sizing the SOFC power and also optimizing the operational condition using these hybrid evolutionary algorithm-linear programming [123,124,166]. In other cases [101,143,192], micro-structural and stack-level optimization were investigated in tubular stack SOFC for parametric study. Using similar methods, geometry and operating conditions were employed as parameters to be optimized in the microstructure and stack-level of the SOFC model [102,142]. The study from [41,116] also performed the optimization for stack and hybrid-level using a multi-objective genetic algorithm. Hence it is expected for future research that the multi-level optimization will be simultaneously developed for microstructure, stack, and hybrid systems.

For the hybrid methods, several studies [14,42,63,106,113,125,136,170,176,193] have presented combined optimization along with several approaches for the prediction, control and management. In fact, the combined approach has been an interesting topic since 2001 and has grown in the past five years. Most of the studies in combined approach are related to the hybrid between optimization and control as well as optimization with management applied for operating the SOFC. Also, several works in the literature have shown these hybrid approaches between optimization and prediction in SOFC microstructure and stack models [51,103,107]. An interesting topic regarding the hybrid approaches has been performed by optimizing the control and prediction parameters [55,182,194]. It did not limit to the combination, but involve tuning and optimizing the parameter to enhance the accuracy of prediction and control. Hence, for the future research direction, optimization is expected to be applied in wider applications of SOFC in microstructure, single cell and also integrated systems. It is not limited to be performed to generate optimum parameters of SOFC model, yet should be employed as a tuning and optimizing tools for increasing in its prediction, control and management performance.

5. Summary

Optimization of SOFC is an interesting topic that has been increasingly studied recently. Based on this literature work, this study has shown that research surveys on SOFC optimization is increasing from year to year. The escalation of research interest is pointed out concerning the implemented system, optimization strategy and research trend of SOFC application.

In its development, there are several aspects of strategy in optimizing SOFC model in single, stack and hybrid application. This study has investigated the strategy into five aspects, which are the decision variables, objective analysis, methods, constraints, and tools. These procedures are explained in detail based on the related works of literature.

At the end of this paper, it also presented the trend of future research direction in SOFC optimization. Based on the literature, interesting research topic has been growing in the area of the population-based algorithm in optimizing the complex model of SOFC. Multi-level optimization has been dramatically increasing to develop hybrid algorithm to face the multi-issues of SOFC. Moreover, some attractive research topics in hybrid-algorithm have also pointed the future for combining approach between optimization, control, management, and prediction. The optimizer is expected to be employed in improving the accuracy of prediction and control area and increasing management performance, especially for SOFC application.

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Appendix A

Decision variables	Parameters	Objective	Method and its implementation	SOFC application	Author (s)
Processing condition	Duration of reaction zone	Ohmic drop and diffusion over potential	Real experiment using online system	Micro-structure	Kleitz and Petitbon [89]
Characteristic; geometry	Length, thickness, polarization and ohmic effect	Electrode conductivity	Monte-Carlo analytical model	Single cell	Costamagna et al. [94]
Characteristic; operating condition	Cell voltage, fuel utilization, reforming, air temperature increase in stack	Annual total cost of system, efficiency of system	Deterministic using MATLAB	Integrated system (CHP)	Riensche et al. [66]
Characteristic	Net electric power, exergy cont., elect. energy eff., elect. exergy eff., total energy eff., total exergy eff.	Maximize total exergetic efficiency	SIMPLEX Algorithm	Integrated system (Stack)	Monanteras and Frangopaulos [109]
Sizing; management	FC Peak power, Motor peak power, battery num., battery cap., min power set, max power set, charge power set, min off time set	Fuel cost consumption	Genetic Algorithm (GA) using Advisor 3.1 combined with MATLAB	Integrated system (Hybrid)	Wipke et al. [136]
Operating condition	SOFC fuel utilization, PEM pressure, equivalence ratio SOFC	Capital cost, cost of electricity, CO_2 emissions, current density SOFC, current density PEM,	Non-linear programming (NLP) using MATLAB	Integrated system (Hybrid)	Goyal and Diwekar [177]

		overall efficiency, power rating			
Operating condition; control	SOFC Fuel flow, pinch heat recovery, working temperature, working pressure, heat pump, desorption WT, desorption load	Total annual cost of power, heating, and cooling generation, annual CO2 emission	Pareto optimal (Global optimization) using EA optimizer	Integrated system (SOFC-GT)	Burer et al. [12]
Operating condition; control	Water temperature	Overall efficiency	Stochastic opt & fuzzy control using modular structure	Integrated system (CHP)	Entchev [14]
Operating condition	Moisture content, pressure ratio, excess air, LPC pressure ratio	Total power and electric efficiency	Deterministic using Advance Power System Analysis Tools (APSAT) and Design of Experiment (DOEx)	Integrated system (SOFC-ICGT)	Yi et al. [114]
Operating condition	Fuel utilization, equivalence ratio, pressure of the PEM, fuel flow, air flow	Capital cost, cost of electricity, CO2 emissions, current density, SOFC, current density PEM, overall efficiency	Non-dominated (Pareto set), MINSOOP algorithm using NLP optimizer	Integrated system (Hybrid)	Subramanyan et al. [2]
Operating condition	Air flow, fuel flows, cell voltage in the stacks, air temperature at the stack inlet, reformer duty and pressure ratio	Power efficiency	Genetic Algorithm (GA) using GA optimizer	Integrated system (SOFC-GT)	Möller et al. [115]
Geometry; operating condition	The cell total area and geometry (length, aspect ratio), inlet position, gas diffusion layer and interconnect thickness, operating variables such as the fuel and air flow rates	power output per unit volume in W/cm3 and temperature of the solid	Parameter study using gPROMS and solver	Integrated system (Stack)	Larrain et al. [181]
Synthesis/ Design; sizing	Steam methane reformer size, heat exchanger size	Life cycle cost	Dynamic Iterative Local Global (DILGO) using gPROMS	Integrated system (APU)	Rancruel [112]
Operating condition; sizing	Temperature, cell voltage, ammonia inlet flow rate, air inlet flow rate, butane inlet flow rate, volumes of the reactor, fuel cell and burner	Fuel energy density	Sequential Quadrating Programming (SQP) using DAEPACK and SQP solver	Integrated system (Micro-PG)	Chachuat, Mitsos and Burton [105]
Material; geometry	The LSM/YSZ mass ratio, grain size of LSM powder, thickness of the cathode, influence of calcination of YSZ powder	Output power	Parameter study using online experiment	Micro-structure	Haanappel et al. [97]
Characteristic; operating condition	Aspect ratio, interconnect thickness, cell area, air ratio, environment temp., air inlet temperature difference, fuel flow	Temperature difference in the cell, power density	Evolutionary Algorithm & NLP using simulated software	Integrated system (Stack)	Larrain [166]
Load type; sizing	Climate, building types, energy eff. level of building, domestic hot water demand, elect. demand, micro-cog. unit, add. heat gen., hot water storage size, control option, opt. option, fuel, elect. mix	Non-renewable primary energy (NRPE) and CO2 emissions	Numeric simulation using Transys	Integrated system (Stack)	Dorrer et al. [167]
Operating strategy; sizing	The sizes and configuration of the storage tanks, SOFC and absorption-chillers	CO2 emissions and cost	Evolutionary Algorithm (EA) and linear programming (LP) using Multi-objective optimizer	Integrated system (Multi-generation)	Weber et al. [41]
Geometry; operating condition	19 parameters	Overall plant cost	Genetic Algorithm (GA) using MATLAB	Integrated system (SOFC-GT)	Calise et al. [116]
Geometry	Channel height, thin-film electrolyte, rib thickness, height of channels, rib width or cell volume	Output efficiency	Numerical simulation using online experiment	Micro-structure; single cell SOFC	Ji et al. [98]
Characteristic; geometry	Ribs height, Ribs resistance, Ribs amount, Interconnect resistance, chatode thickness	Output power	Micro-structure analysis using online experiment	Micro-structure	Lu and Schaefer [143]

Operating condition	air utilization and the inlet gas temperature	temperature condition	Numeric simulation	Integrated system (Stack)	Inui et al. [42]
Design; sizing	Synthesis and design variable decision and single cell operation parameter	Cost	Genetic Algorithm (GA) using MATLAB	Integrated system (SOFC-GT)	Calise et al. [117]
Geometry; operating condition	Pores size, temperature, hydrogen molar fraction, and pressure	Output power and current density	Thermodynamic analysis using simulated software	Micro-structure; Single cell SOFC	Leung and Leung [101]
Operating condition	Reformer temperature, air utilization, oxygen to carbon ratio, steam to carbon, air excess, compressor pressure, current density, input turbine temperature	System cost and efficiency	Pareto frontier using BELSIM-VALI, EASY and MATLAB	Integrated system (SOFC-GT)	Autissier et al. [44]
Operating condition	Fuel utilization, operating temperature, steam-to-carbon ratio, operating pressure, cost of fuel	System efficiency, system cost	Thermo-economic analysis	SOFC hybrid power generation	Arsalis [62]
Operating condition	Reformer temperature, air utilization, oxygen to carbon ratio, steam to carbon, air excess	Cost, efficiency	Genetic Algorithm (GA) using LENI	Integrated system (Stack)	Palazzi et al. [43]
Geometry	Electrode thickness (anode or cathode), shoulder channel to aspect ratio, total number of reactant channel	Power density	Technical analysis using simulated software	Micro-structure	Ordonez et al. [195]
Sizing	SOFC capacity and thermal energy storage (TES)	Cost, efficiency, and emission reduction	Technical, economic and environmental analysis using CODEGen	Integrated system (CHP)	Hawkes [196]
Characteristic; design	Location and supply area of the biomass plant, net present value and generated electric power	Profitability Index	Particle swarm optimization (PSO) (Compared with GA) using MATLAB	Integrated system (SOFC-GT)	Lopez et al. [45]
Operating condition	Inlet fuel flow rate, the extent of methane pre-reforming, fuel utilization factor, cell voltage and cathode gas recycling rate	Efficiency, cost of electricity	Thermodynamic analysis using Fortran	Integrated system (CHP)	Lee [170]
Operating condition	Temperature and partial pressure of hydrogen (PH2), exchange current densities and the limiting current densities	Net power of the system, working efficiency, material cost of cell and the fuel utilization	Simulated Annealing (SA) and Genetic Algorithm (GA) using C++	Single cell	Zhao et al. [164]
Characteristic	Heat transfer irreversibility	Fuel cell volume, efficiency	SIMPLE Algorithm using Computational Fluid Dynamic (CFD) using Fluent	Integrated system (Hybrid)	Sciacovelli and Verda [47]
Operating condition; characteristic; geometry	Flow rate H2, Inlet temperature and Inlet pressure, porosity of the electrodes, effective diffusivity of the species, and the rate of the electrochemical reactions, thickness of the electrodes and the electrolyte on the steady-state polarization curve	Fuel cell power	Thermodynamic analysis using MATLAB	Single cell	Bhattacharyya and Rengaswamy [95]
Characteristic; operating condition	Mass Flow, Hydraulic diameter, Interconnected material conductivity	Output power	Thermodynamic analysis using COMSOL	Single cell	Pulagam [46]
Cost design	Cost parameters	Cost	GMRES to solve Newton's iteration optimizer using MATLAB	Integrated system (Stack)	Elliot et al. [158]
Characteristic; operating condition	Temperature, GT Cycle Temperature Ratio, Heat Loss, Finite-rate Heat Transfer	Output power and efficiency	Thermodynamic analysis	Integrated system (SOFC-GT)	Zhao, Shah and Brandon [197]
Operating condition;	Fuel steam and Air flow rates at given load current	Efficiency and control battery current during load change	Numerical calculation using MATLAB	Integrated system	Chen and Sun [113]

control				(APU)	
Synthesis and design parameter	Heat transfer parameter between fuel cell and heat engine, heat transfer engine to surrounding	Power output and power efficiency	Graphical method using MATLAB	Integrated system (SOFC-HE)	Zhao and Chen [128]
Characteristic; geometry	Distributions of porosity and particle size for electrode	Output power	Genetic Algorithm using COMSOL MULTIPHYSICS	Micro-structure	Shi and Xue [150]
Characteristic	Heat transfer, viscous flow, coupling between heat and mass transfer, diffusive term, and current transfer	Entropy generation	Thermodynamic analysis using Simplex optimizer	Single cell	Sciacovelli [48]
Electrical parameter	Steady state voltage cell and plant	Efficiency	Iterative algorithm using Real-Time Optimizer (RTO)	Integrated system (Stack)	Bunin, Francois and Bovin [103]
Geometry	Thickness(Anode, Cathode, Electrolyte), wire radius	Power density	Micro-structure analysis using simulated software	Micro-structure	Vogler et al. [140]
Operating condition; characteristic	Temperature, load resistance, methane concentration, catalyst weight	C2 production, Cox production, Power, Cox emission	Elitist non-dominated sorting genetic algorithm (NSGA-II) using Visual Fortran 6.6	Single cell	Quddus, Zhang and Ray [49]
Characteristic	Porosity, electrical conductivity, and gas permeability coefficient at room temperature	Power density	Thermodynamic analysis using FLUENT v.6.3	Single cell	Funahashi et al. (2010) [141]
Characteristic	Heat and Pressure coefficient, turbo machinery Efficiency	System efficiency	Thermodynamic analysis via online experiment	Integrated system (SOFC-GT)	Brear and Dunkley [121]
Design/ synthesis	Combined SOFC in several study cases	Energy and exergy efficiency	Thermodynamic analysis using simulated software	Integrated system (Micro-CHP)	Moller [68]
Operating condition; control	Fuel flow	Pnet and achieving load change	Numerical calculation	Integrated system (SOFC-GT)	Oh and Sun [176]
Characteristic	Capacitance, Activation resistance, Electrolyte resistance	Differences between identification models and experimental data	Genetic Algorithm (GA) using MATLAB	Micro-structure	Cao et al. [198]
Design; management	Data communication layer, Data processing layer, and data management	Saving memory resources, ensures continuity and integrity of database	Design of experiment (DOE) via online experiment	Integrated system (Stack)	Yang et al. [199]
Design/ synthesis; Operating strategy	On–off and load statuses of the operation of the system components, energy flow rates, and stored heat	primary energy consumption subject to the satisfaction of energy demand requirements	Mixed-integer linear programming (MILP) using simulated software	Integrated system (CHP)	Wakui et al. [130]
Operating condition	Anode/cathode flow input and temperature	Exergy efficiency	Thermodynamic analysis using AspenPlus	Integrated system (CHP)	Perdikaris et al. [73]
Operating condition	Irreversible losses in current density, power output density, temperature ratio, coefficient of temperature	Power efficiency and power output	Numerical calculation	Integrated system (SOFC-GT)	Zhang et al. [50]
Design	Synthesis and design parameter	Output power and efficiency	Thermodynamic analysis using MATLAB	Integrated system (SOFC-GT)	Zhao et al. [118]
Operating condition	Inlet temperature, steam reforming temperature, steam to carbon ratio, fuel cell air excess, pressure ratio, fuel cell fuel utilization	Choose design and maximize efficiency	Pareto frontier using BELSIM-VAL	Integrated system (SOFC-Diesel)	Facchinetti et al. [127]
Operating condition	S/C ratio, AOG recirculation ratio, CO2 adsorption percentage, and SOFC temperature	Open-circuit voltage, the terminal voltage, the peak power density, and the limiting current density	Linear programming	Integrated system (SOFC-Diesel)	Lee et al. [126]
Operating condition; sizing	Active surface area, molar flow rate of methane, molar flow rate of oxygen, fraction of the	Size the SOFC, the lifecycle per-unit energy cost of the power plant.	Lagrange multiple method using ADVISOR MATLAB	SOFC-GT power generation	Cheddie [119]

	SOFC anode outlet recycled back to the inlet				
Characteristic; modeling	Open-circuit voltage, cell active are, fuel crossover equivalent current density, exchange current, area specific resistance, constant coefficient in mass-transfer overvoltage, constant coefficient in mass transfer voltage	Mean Square Error (MSE) of sample voltage and optimum voltage	Genetic Algorithm and improved GA (IGA) using MATLAB	Integrated system (Stack)	Yang et al. [184]
Characteristic; operating condition	Gas turbine pressure ratio, SOFC fuel utilization factor, SOFC anode recycle ratio, SOFC cathode recycle ratio, Heat exchange effectiveness, maximum current density	System efficiency	Non-linear optimization using Box method	Integrated system (SOFC-GT)	Milewski [120]
Characteristic	Distributions of porosities and particle sizes for electrodes	Cell average current density	Genetic Algorithm (GA) using COMSOL MULTIPHYSICS version 3.5a	Single cell	Shi and Xue [87]
Geometry; operating condition	The airflow, fuel flows, cell voltage in the stacks, air temperature at the stack inlet, reformer duty and pressure ratio	Power density	Neural Network, Genetic Algorithm (GA) using MATLAB	Micro-structure	Bozorgmehri and Hamedi [55]
Geometry; operating condition	Cell temperature, fuel and air concentration, air and fuel pressure, ribs width, channel height	Output voltage	Thermodynamic analysis using FLUENT	Single SOFC	Sembler and Kumar [142]
Geometry; material; operating condition	Pore Size, porosity, graded electrode, temperature, gas composition, pressure	Cell power density	Thermodynamic analysis	Micro-structure; Single cell	Jo et al. [102]
Characteristic; geometry	Porosity, thickness, LSM particle size, particle size ratio, volume fraction of LSM particles, temperature, bulk oxygen partial pressure	Cathode total resistance,	Gradient optimization (graphic)	Micro-structure	Farhad and Hamdullahpur [146]
Operating condition	Pressure ratio, temperature SOFC, and gas turbine inlet temperature	Error of plant, network output, combined cycle thermal efficiency, and combined cycle cogeneration efficiency	Quasi-Newton Algorithm using SQP solver MATLAB	Integrated system (SOFC-GT)	Odukoya, Carretero and Reddy [122]
Sizing	Wind turbine, PV array, and CHP (SOFC and micro turbine) size	Economic costs and environmental costs, meet electricity load and heat load of customers	Genetic Algorithm (GA) using MATLAB	Integrated system (Hybrid RE)	Deng et al. [137]
Geometry	Thickness of anode layer, electrolyte, and cathode layer	Output power	Thermodynamic analysis	Micro-structure; single cell	Wen [163]
Geometry of cell	Thickness of the anode support and the distance between the electrical contacts at the surface of the anode	Electric conductivity	Design of experiment (DoE) and response surface methodology (RSM) via online experiment	Single cell	Faes et al. [145]
Operating condition	Heat exchanging, the burner, the turbo machinery and the flue gas leaving the plant	Exergy losses or destructions	Thermodynamic analysis via online experiment	Integrated system (SOFC-GT)	Møller [153]
Geometry	Active reaction layer thicknesses at both electrodes, operating temperature and electrode porosity	total potential losses, fuel cell net power output	Numerical calculation using Fortran	Micro-structure	Wen et al. [175]
Operating condition; sizing	Number of cells, size of cell, system pressure, cell voltage, temperature input, fuel concentration	Fuel cell efficiency and cost	Non-linear programming (NLP) using MATLAB	Integrated system (Stack)	Spivey [200]
Characteristic; operating condition	Two operating point cases including FU, Air excess ratio, and voltage	Non-renewable primary energy (NRPE) and carbon dioxide equivalent (CO2-eq)	Thermodynamic analysis	Integrated system (CCHP)	Kazempoor et al. [161]

Characteristic	Heat-to-power ratio	Running time of SOFC, economic and environmental perspective	Thermo-economic and environmental analysis using HOT2000	Integrated system (CHP)	Liso et al. [74]
Characteristic; operating condition	Hydrogen flux, current, air ratio, fuel utilization, cell voltage	System efficiency	Non-linear programming (NLP)	Integrated system (Stack)	Bunin et al. [174]
Geometry	Weight fraction, Void fraction, Particle size ratio, particle size, density	TPB length	Micro-structure analysis using Home-built Mathematica 7	Single SOFC	Ge et al. [86]
Design; operating condition	Flash temp., reheat temp., HP power recycle, power recycle, steam reforming temp., steam ref. press., methane purity, S/C ratio, max temp., FU, cathode GT press. ratio, anode GT press. ratio, GT temp., compressor temp.	Energy and exergy efficiency	mixed integer linear programming (MILP) and EA	Integrated system (SOFC-GT)	Facchinetti et al. [123]
Characteristic; sizing	Optimum cell number and steady state MV parameter	Life time and annual operating cost	MPC control and constrained optimization using APOPT Solver and MATLAB Simulink	Integrated system (Stack)	Spivey et al. [52]
Characteristic; operating condition	Air compressor pressure ratio, air compressor isentropic eff., gas turbine isentropic eff., the power turbine isentropic eff., current density, FU, AU, S/C ratio	Exergy efficiency and total cost	Genetic Algorithm (GA) using simulated software and online experiment	Integrated system (SOFC-GT)	Shirazi et al. [138]
Characteristic; geometry	Interconnect aspect ratio, electrode /electrolyte ratio, slenderness ratio, dimensionless gas channel width	Exergetic efficiency and gross entropy generation	Numeric simulation (Max-Min) using MATLAB	Micro-structure	Ford [155]
Sizing	Energy flow rate of the input, and outputs; heat stored	PES, electric load factor, electric supply proportion, Hot water utilization efficiency, and hot water supply proportion	Mixed integer Non-linear programming (MINLP)	Integrated system (CHP)	Wakui and Yokohama [69]
Operating condition; control	Temperature and fuel	Stack temperature & fuel utilization	Stochastic method using MATLAB Simulink and C-MEXS	Integrated system (SOFC-ST)	Ugartemendia et al. [63]
Characteristic; operating condition	Current density and temperature	Output power and efficiency of power	Curve / graphical method	Integrated system (SOFC-ST)	Chen et al. [64]
Geometry	Shapes of cathode	Resistance at the base of the cell (boundary 0)	Topology optimization using online experiment	Single cell	Song et al. [53]
Design; operating condition	Weather conditions and associated energy demands	CO2 emissions	Mixed integer nonlinear programming (MINLP) using GAMS	Integrated system (CHP)	Adam et al. [67]
Operating condition	Temperature, the cathode and anode pressures and the mass fraction of the hydrogen and oxygen	Output power, Pressure exerted in cathode and anode	Genetic Algorithm (GA) using MATLAB and Java-based multi-objective GA package	Single cell	Hobold and Agarwal [182]
Characteristic; operating condition	Current density, pressure, and temperature	Output power, cost, efficiency of power	Genetic Algorithm using MATLAB	Integrated system (Stack)	Roshandel and Forough [104]
Geometry of cell	Active reaction layer thicknesses at both electrodes, operating temperature and electrode porosity	Nominal current and electrical power	Numerical calculation using Fortran	Micro-structure	Wen et al. [148]
Operating condition; prediction	Air flow deviation, Mole flow rate, H2 mole, CO2 mole, H2O mole, H2 mole, flow rate in cathode inlet	Improve an accuration on predicted model	Prediction: BPNN Optimization: Mathematical algorithm using Fortran	Integrated system (Stack)	Wang et al. [201]
Operating condition; control	Temperature inlet, outlet, burner	System efficiency	Traverse method using MATLAB	Integrated system (Stack)	Cao et al. [108]
Operating	Inlet and outlet manifold fuel	Output power	Thermodynamic analysis via	Integrated	Chen et al.

condition	flow		online experiment	system (Stack)	[202]
Design; operating condition	Operating pressure, stack temp, fuel inlet temp, air inlet temp, fuel pre heated temp, air pre heated temp, s/c, fu, au	Energy efficiency and emission	Non-linear programming (NLP) using STAR	Integrated system (Stack)	Wang [194]
Operating condition	Fuel flow, air flow, temperature, fuel utilization	Efficiency of stack system	Thermodynamic analysis via online experiment	Integrated system (CHP)	Xu et al. [75]
Characteristic; geometry	Distributions of porosities and particle sizes for electrodes	Electrical efficiency	Thermodynamic analysis	Micro-structure	Bertei et al. [144]
Geometric, operating condition	19 geometric variables and 10 operational variables	Life cycle cost and the net electrical efficiency	Genetic Algorithm (GA) using MATLAB	Integrated system (SOFC-PEMFC)	Tan et al. [157]
Operating condition	Hydrogen flow rate, oxygen flow rate, nitrogen flow rate and cell temperature	Power density	Thermodynamic analysis using Design Expert 7.0 software	Single cell	Tikiz and Taymaz [13]
Operating condition	Fuel flow, air flow, circulating water flow in Rankine cycle, coolant flow in Rankine cycle	Efficiency, environmental impact	GA using UESR2 using FORTRAN language, MATLAB, and VB	Integrated system (Stack)	Kosaksri et al. [54]
Geometry	Ribs cathode and anode width	Current density	Thermodynamic analysis using COMSOL MULTIPHSICS	Integrated system (Stack)	Kong et al. [187]
Sizing	Fuel processing, fuel cell, and gas turbine.	Thermodynamic performance and exergy losses	Simplex optimization using BELSIM-VAL	Integrated system (SOFC-GT)	Facchinetti et al. [124]
Characteristic; operating condition	Air compr. press. ratio, Eff. air compr., Eff. gen. Eff. of power tb, Current density, AU, FU, S/C ratio, temp. pinch point, numb. des. stages, inlet motive steam temp., brine temp., top brine temp.	Exergetic efficiency, total cost rate of the system	Genetic Algorithm (GA) using MATLAB	Integrated system (SOFC-GT)	Najafi et al. [139]
Geometry	Geometry of cell and thicknesses	Thermal stress	Thermal analysis via online experiment	Single cell	Skalar et al. [99]
Design; operating condition	Solar radiation, operating temperature of RSOFC, H2 utilization of SOFC	H2 generation efficiency, energy efficiency, net electrical power, electrical to heating ratio, unit cost energy	Numerical simulation using MATLAB	Integrated system (CHP)	Akikur et al. [77]
Design; characteristic	Cost of SOFC, absorption chiller, auxiliary components, government subsidy, price of fuel, and electric and maintenance cost	Payback period	Simulation	Integrated system (Multi-generation)	Chen and Ni [81]
Characteristic; operating condition	Equivalence ratio of fuel and fuel utilization	Air excess ratio, output power of the stack, SOFC stack electric efficiency, system electric efficiency, CHP efficiency, CCHP efficiency, and thermal to electric ratio	Simulation	Integrated system (CCHP)	Wang et al. [135]
Material	Nickel Oxide (NiO) and Gadolinium doped Ceria (GDC) used as anode materials. And graphite used as a pore former in the anode substrate	Power density at intermediate temperature	Material analysis via online experiment	Micro-structure	Ahmed and Sathish [93]
Characteristic; operating condition	SOFC inlet temp., FU, current density and S/C ratio	Exergy efficiency and the total product unit cost	Pareto optimal using GA via MATLAB	Integrated system (CCHP)	Sadeghi et al. [15]
Operating condition	Air flow distribution	Temperature gradient	sequential quadratic programming (SQP) using AspenPlus	Single cell	Amiri et al. [149]
Characteristic; operating condition	Operating temperature, Operating pressure, membrane thicknesses(PEMFC), current density, stack thicknesses	Output power, energy efficiency, exergy efficiency, cost of production	MOO Genetic Algorithm using MULOP (Multi-objective optimizer)	Integrated system (Stack)	Mert et al. [154]

	(SOFC)				
Graphic optimization	Preheated air temperature, Thicknesses of anode and fuel cell length	Output power	Graphic optimization	Single cell	Feng et al. [100]
Operating condition; control	System current, FU, AU and bypass opening ratio	Efficiency	Traverse optimization process including cubic convolution interpolation algorithm	Integrated system (Stack)	Zhang et al. [203]
Operating condition	Fuel utilization, stack temperature, stack pressure	Net electrical efficiency; net present value at the end of life	MOO Pareto front using ASPEN plus and MATLAB	Integrated system (CCHP)	Curletti et al. [134]
Operating condition; sizing	SOFC cell number, SOFC cell diameter and length, HRSG pressure, approach point, pinch point, steam temperature, solar chimney height and diameter, collector diameter, SOEC cell number, SOEC cell diameter and length	Cost	Genetic Algorithm (GA) using MATLAB	Integrated system (SOFC-SOEC)	Shariatzadeh et al. [204]
Operating condition	Air ratio, fuel utilization, average current density, steam to carbon ratio, and pre-reforming rate of methane	Cell efficiency and output power	Genetic Algorithm (GA) using MATLAB	Single cell	Borji et al. [205]
Characteristic; design	Output power of SOFC, SOFC share, electrical to heating energy ratio, electrical to cooling energy ratio	Unit cost, CO2 emission, exergy efficiency	Pareto optimal using MATLAB	Integrated system (CCHP)	Baghernejad et al. [133]
Characteristic; operating condition	Air to steam ratio, modified equivalence ratio, average current density, the fuel utilization factor, air ratio and SOFC inlet temperature	Cooled gas and CHP efficiencies of the plant, total electric power, electric and CHP efficiencies of the hybrid system	Non-dominated sorting GA using FORTRAN 90	Integrated system (CHP)	Borji et al. [71]
Operating strategy; sizing	Using or not using battery, No modulation, day-night modulation, intervals modulation, load following strategies, Prime mover capacity, inlet power, net power, net heat from cogeneration	Primary energy saving, cost	Thermo-economic analysis using MATLAB	Integrated system (Micro-CHP)	Napoli et al. [72]
Design; operating strategy	Design and operation variables expressed with binary variables	Annual primary energy consumption	MINLP with decomposition approach using GAMS and CPLEX	Integrated system (CHP)	Wakui and yokohama [132]
Design; characteristic; operating condition	Cog. elect. nom. power, Cog. th. nom. power, nom. power supp. by fuel-co, Cog. elect. power, cog. th. power, fuel power, boiler power, diss. th. power, elect. power sold, elect. power bought, elect. to heat ratio, elect. to cool ratio, therm. out cmp., cool out cmp, cool out. abs., Cool bought, cog on/off	GOM (Gross Operative Margin)	MINLP using GAMS and CPLEX	Integrated system (CCHP)	Arcuri et al. [171]
Geometry; operating condition; sizing	20 geometric variables and 6 operating condition	Electricity efficiency, SOFC current density and capital cost of system	Pareto optimal using NLP optimizer	Integrated system (SOFC-PEMFC)	Tan et al. [169]
Geometry	The interconnect structure, rib size, pitch width and contact resistance	Output current density	Structure analysis via online experiment	Micro-structure	Gao et al. [165]
Processing condition	NiO–YSZ anodes (~20 m thickness) separated by a relatively thin YSZ electrolyte (~500 m) surface	Polarization resistance	Laser melting treatments via online experiment	Micro-structure	Cubero et al. [206]
Sizing	Numb. PV panels, Max. numb. PV panels, power of SOFC-GT,	Cost, pollutant emissions, and reliability	Evolutionary Algorithm using simulated software	Integrated system	Sadeghi and Ameri [15]

	and power of electrolyzer			(SOFC-GT-PV)	
Operating condition	Thermal conductivity, thickness, mass flow rates of fuels, power supplied to the heaters, the heat released and the target temperatures	Startup time and power output	Thermal analysis using ANSYS and FLUENT Solver	Integrated system (Micro-stack)	Pla et al. [111]
Geometry; operating condition	Controlling the thickness of the cathode layer and sintering temperatures	Ohmic and electrode-reaction resistances, output open voltage	Thermodynamic analysis using simulated software	Micro-structure	Li et al. [162]
Operating condition	Reformer temperature, ethanol price	Cost of exergy	Deterministic	Integrated system (Stack)	Ledon et al. [172]
Characteristic; operating condition	Cell potential and Fuel utilization	Electrical efficiency	RTO via modifier adaptation (RTO-MA)	Integrated system (Stack)	Francois et al. [179]
Operating condition	Hot storage temperature (35, 45, and without SOFC)	Heat efficiency	Thermal analysis using SimulationX and CVODE-solver	Integrated system (CHP)	windeknecht and tzscheutschler [70]
Operating condition	Fuel flow rate, hydrogen content of cog., fuel utilization factor, operating pressure	SOFC efficiency, total power efficiency, overall system efficiency, power, heating and cooling	Thermodynamic analysis using AspenPlus	Integrated system (CCHP)	Zhao [207]
Design; operating strategy	Electrical power generator, electrical power and cooling cogeneration, electrical power and heating cogeneration and tri-generation	Exergy efficiency, exergy destruction rate, and greenhouse gas emissions	Environmental analysis	Integrated system (CCHP)	Chitsaz et al. [82]
Characteristic; operating condition	Current density of the SOFC, the voltage output of the TIG, and the ratio of the areas of the SOFC and TIG	Power output density and efficiency	Thermodynamic analysis	Integrated system (SOFC-TIG)	Wang et al. [208]
Geometry; characteristic; operating condition	Operating properties, geometry and material properties	Output power and efficiency of power	Thermodynamic analysis via Design of experiment (DOE)	Integrated system (SOFC-MT)	Hering et al. [209]
Design; operating strategy	SOFC, boiler, mechanical chiller and absorption chiller design and operation strategy	Cost and PEC control strategy	Assessment	Integrated system (CCHP)	Facci et al. [210]
Characteristic; operating condition	Inlet temp., pressure, air compr. pressure ratio, isentropic eff., RE share, cool and heat to elect ratio	Exergy efficiency and unit cost	Pareto optimal using GA using MATLAB	Integrated system (CCHP)	Baghernejad et al. [211]
Characteristic; operating condition	Current density, fuel utilization factor, pressure ratio, air utilization factor	Exergy efficiency and SUCP	Genetic Algorithm (GA) using MATLAB	Integrated system (CHP)	Khani et al. [76]
Material	Sm0.5Sr0.5MnO3 (SSM55)-Y2O3 stabilized ZrO2 (YSZ) composite cathodes	Open circuit polarization resistance and exchange current density	Material analysis via online experiment	Micro-structure	Li et al. [212]
Characteristic; operating condition	Current, inlet air temperature in air, inlet fuel temperature fuel, inlet air flow rate and inlet fuel flow rate	Efficiency and temperature safety	Analyzed - optimization combined with travers optimization	Integrated system (Stack)	Cheng et al. [213]
Characteristic; operating condition	Fuel cell temperature and current density	System profit through its lifetime	DBO (degradation based optimization) based on GA	Integrated system (Stack)	Roshandel and Parhizkar [214]
Characteristic; operating condition	Air compr. press. ratio, current density, AU, FU, S/C ratio and the HRSG evaporation press.	Exergetic efficiency and total cost rate of the plant	Pareto optimal and TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) decision-making method using MATLAB	Integrated system (SOFC-ORC-GT)	Aminyavaria et al. [129]
Operating condition;	Mass flow rate, compr. ratio, exit temp., numb. of cells, FU,	Period of return and exergy efficiency	GA using MATLAB	Integrated system	Reyhani et al. [215]

sizing	recycle ratio, turbine isentropic eff., compr. isentropic eff., out pump press, pump, out steam quality, compr. ratio in MED ejector			(CHP)	
Operating condition	Molar ratio of carbon monoxide to hydrogen, the working temperature of the SOFC	Output power and efficiency	Numerical simulation using MATLAB	Integrated system (CCHP)	Zhang et al. [80]
Material; operating condition	Three types of powders and sintered at different temperatures, and thin EB-PVD electrolyte film	Ionic conductivity	Material analysis via online experiment	Micro-structure	Vasylyev et al. [90]
Geometry; material	Nonlinear particle-size- and porosity-graded electrodes, ionic electronic particle size ratio	Temperature and output power	Numerical Algorithm using simulated software	Micro-structure; Single cell SOFC	Abdullah and Liu [91]
Operating condition	Oxygen concentration in cathode gas, gases' temperature difference at cell's, excess air flow	Undesirable temperature gradients and stack efficiency	Pareto set using MATLAB	Integrated system (Stack)	Amiri et al. [168]
Characteristic; operating condition	FC stack avr. cur. dens., Pre-reformer out temp., air heater tube temp., FU, AU, fuel pre-reforming extent, S/C ratio, press gas compr., press. air compr., press. pump, boiler tube temp., eject. exp. ratio	Power production, heat production and exergy destruction	Thermo-environment analysis using gPROMS Model Builder 3.4.0	Integrated system (CHP)	Hassanzadeh et al. [79]
Geometry	Representative volume element (RVE) size and the number of its voxels	Cell potential resistance	Phase recovery algorithm using simulated software	Micro-structure	Hasanabadi et al. [147]
Operating condition	Uniformity of fuel flow rate	Output power	Thermodynamic analysis using CFD simulation software	Integrated system (Stack)	Rashid et al. [216]
Operating condition	FC current density, GT air flow rate, GT inlet temp., comp. press. ratio, FU, S/C ratio	Exergy efficiency and sum of the unit costs of products	GA using EES and MATLAB	Integrated system (SOFC-GT in CHP)	Khani et al. [76]
Operating condition	S/C ratio, tmp. out, in tmp. FC, FU, in tmp. GTC, P GTC turbine, P GTC comp., P GTA turbine, P GTA comp., P CO2 turbine	Levelized electricity cost and annualized capital cost	Pareto optimal front using BELSIM-VAL	Integrated system (SOFC-GT)	Sharma et al. [173]
Design; operating strategy	Flow rates of the input and output energies, i.e. E, Q, and G, and the amounts of stored heat. The binary variables, d, express the operating status for each component at each sampling time.	Primary energy saving	MINLP	Integrated system (CHP)	Wakui et al. [178]

References

[1] Hossain FM, Hasanuzzaman M, Rahim NA, Ping HW. Impact of renewable energy on rural electrification in Malaysia: a review. Clean Technol Environ Policy 2015;17:859–71.

[2] Subramanyan K, Diwekar UM, Goyal A. Multi-objective optimization for hybrid fuel cells power system under uncertainty. J Power Sources 2004;132:99–112.

[3] Ang SMC, Fraga ES, Brandon NP, Samsatli NJ, Brett DJL. Fuel cell systems optimisation – Methods and strategies. Int J Hydrog Energy 2011;36:14678–703.

[4] Isa ZM, Rahim NA. PEM fuel cell model parameters optimization using modified particle swarm optimization algorithm. IEEE Conference on Clean Energy and Technology (CEAT). 4 ed: IEEE; 2013. p. 442–445.

[5] Borhanazad H, Mekhilef S, Gounder Ganapathy V, Modiri-Delshad M, Mirtaheri A. Optimization of micro-grid system using MOPSO. Renew Energy 2014;71:295–306.

[6] Ramadhani F, Bakar KA, Shafer MG. Optimization of standalone street light system with consideration of lighting control. Technological advances in electrical, electronics and computer engineering (TAEECE), international conference on: IEEE; 2013. p. 583–588.

[7] Ramadhani F, Bakar KA, Hussain MA, Erixno O, Nazir R. Optimization with traffic-based control for designing standalone streetlight system: a case study. Renew Energy 2017;105:149–59.

[8] Stambouli AB, Traversa E. Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. Renew Sustain Energy Rev 2002;6:433–55.

[9] Mohamad H, Abu Bakar AH, Ping HW, Mokhlis H. An adaptive controller of hydro generators for smart grid application in Malaysia. In: 2010 International Conference on Power System Technology (POWERCON). IEEE; 2010, p. 1–6.

[10] Moosavian SM, Modiri-Delshad M, Rahim NA, Selvaraj J. Imperialistic competition algorithm: novel advanced approach to optimal sizing of hybrid power system. J Renew Sustain Energy 2013;5:31–41.

[11] Choudhury A, Chandra H, Arora A. Application of solid oxide fuel cell technology for power generation—a review. Renew Sustain Energy Rev 2013;20:430–42.

[12] Burer M, Tanaka K, Favrat D, Yamada K. Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell–gas turbine combined cycle, heat pumps and chillers. Energy 2003;28:497–518.
[13] Tikiz I, Taymaz I. An experimental investigation of solid oxide fuel cell performance at variable operating conditions. Therm Sci 2014;00:1–16.
[14] Entchev E. Residential fuel cell energy systems performance optimization using "soft computing" techniques. J Power Sources 2003;118:212–7.
[15] Sadeghi M, Chitsaz A, Mahmoudi SMS, Rosen MA. Thermoeconomic optimization using an evolutionary algorithm of a trigeneration system driven by a solid oxide fuel cell. Energy 2015;89:191–204.
[16] Secanell M, Wishart J, Dobson P. Computational design and optimization of fuel cells and fuel cell systems: a review. J Power Sources 2011;196:3690–704.
[17] Achenbach E. Three-dimensional and time dependent simulation of a planar solid oxide fuel cell stack. J Power Sources 1994;49:333–48.
[18] Achenbach E. Response of a solid oxide fuel cell to load change. J Power Sources 1995;57:105–9.
[19] GWA J Padulles, McDonald JR. An integrated SOFC plant dynamic model for power systems simulation. J Power Sources 2000;86:495–500.
[20] Nagata S, Momma A, Kato T, Kasuga Y. Numerical analysis of output characteristics of tubular SOFC with internal reformer. J Power Sources 2001;101:60–71.
[21] Burt AC, Celik IB, Gemmen RS, Smirnov AV. A numerical study of cell-to-cell variations in a SOFC stack. J Power Sources 2004;126:76–87.
[22] Chaisantikulwat A, Diaz-Goano C, Meadows ES. Dynamic modelling and control of planar anode-supported solid oxide fuel cell. Comput Chem Eng 2008;32:2365–81.
[23] Bessler W. Multi-scale modeling of solid oxide fuel cells: from patterned anodes to a power plant system. ECS Trans 2011;35:859–69.
[24] Hajimolana SA, Hussain MA, Daud WMAW, Soroush M, Shamiri A. Mathematical modeling of solid oxide fuel cells: a review. Renew Sustain Energy Rev 2011;15:1893–917.
[25] Hajimolana SA, Hussain MA, M, Soroush WMA, Daud W, Chakrabarti MH. Modeling of a Tubular-SOFC: the effect of the thermal radiation of fuel components and CO participating in the electrochemical process. Fuel Cells 2012;12:761–72.
[26] Xue X, Tang J, Sammes N, Du Y. Dynamic modeling of single tubular SOFC combining heat/mass transfer and electrochemical reaction effects. J Power Sources 2005;142:211–22.
[27] Laurencin J, Delette G, Lefebvre-Joud F, Dupeux M. A numerical tool to estimate SOFC mechanical degradation: case of the planar cell configuration. J Eur Ceram Soc 2008;28:1857–69.
[28] Hashimoto S, Nishino H, Liu Y, Asano K, Mori M, Funahashi Y, et al. The electrochemical cell temperature estimation of micro-tubular SOFCs during the power generation. J Power Sources 2008;181:244–50.
[29] Ali JM, Hussain MA, Tade MO, Zhang J. Artificial intelligence techniques applied as estimator in chemical process systems – a literature survey. Expert Syst Appl 2015;42:5915–31.
[30] Ali JM, Ha Hoang N, Hussain MA, Dochain D. Review and classification of recent observers applied in chemical process systems. Comput Chem Eng 2015;76:27–41.
[31] Ali JM, Hoang NH, Hussain M, Dochain D. Hybrid observer for parameters estimation in ethylene polymerization reactor: a simulation study. Appl Soft Comput 2016;49:687–98.
[32] Lockett M, Simmons MJH, Kendall K. CFD to predict temperature profile for scale up of micro-tubular SOFC stacks. J Power Sources 2004;131:243–6.
[33] Jayasankar BR, Ben-Zvi A, Huang B. Identifiability and estimability study for a dynamic solid oxide fuel cell model. Comput Chem Eng 2009;33:484–92.
[34] Hajimolana S, Hussain MA, Soroush M, Wan Daud WA, Chakrabarti MH. Multilinear-model predictive control of a tubular solid oxide fuel cell System. Ind Eng Chem Res 2012, [121218163527007].
[35] Hajimolana SA, Tonekabonimoghadam SM, Hussain MA, Chakrabarti MH, Jayakumar NS, Hashim MA. Thermal stress management of a solid oxide fuel cell using neural network predictive control. Energy 2013;62:320–9.
[36] Georgis D, Jogwar SS, Almansoori AS, Daoutidis P. Impact of steam reformer on the design and control of an energy integrated solid oxide fuel cell system. In: Proceedings of the 19th Mediterranean Conference on Control and Automation, MED; 2011, p. 576–581.
[37] Moghaddam AA, Seifi A, Niknam T, Alizadeh Pahlavani MR. Multi-objective operation management of a renewable MG (micro-grid) with back-up micro-turbine/fuel cell/battery hybrid power source. Energy 2011;36:6490–507.
[38] Sanandaji BM, Vincent TL, Colclasure AM, Kee RJ. Modeling and control of tubular solid-oxide fuel cell systems: II. Nonlinear model reduction and model predictive control. J Power Sources 2011;196:208–17.
[39] Hajimolana S, Hussain MA, Soroush M, Daud WAW, Chakrabarti MH. Multilinear-model predictive control of a tubular solid oxide fuel cell system. Ind Eng Chem Res 2012;52(1):430–41.
[40] Georgis D, Jogwar SS, Almansoori AS, Daoutidis P. Design and control of energy integrated SOFC systems for in situ hydrogen production and power generation. Comput Chem Eng 2011;35:1691–704.
[41] Weber C, Maréchal F, Favrat D, Kraines S. Optimization of an SOFC-based decentralized polygeneration system for providing energy services in an office-building in Tōkyō. Appl Therm Eng 2006;26:1409–19.
[42] Inui Y, Ito N, Nakajima T, Urata A. Analytical investigation on cell temperature control method of planar solid oxide fuel cell. Energy Convers Manag 2006;47:2319–28.
[43] Palazzi F, Autissier N, Marechal FMA, Favrat D. A methodology for thermo-economic modeling and optimization of solid oxide fuel cell systems. Appl Therm Eng 2007;27:2703–12.
[44] Autissier N, Palazzi F, Marechal F, van Herle J, Favrat D. Thermo-economic optimization of a solid oxide fuel cell, gas turbine hybrid system. J Fuel Cell Sci Technol 2007;4:123.
[45] López PR, González MG, Reyes NR, Jurado F. optimization of biomass fuelled systems for distributed power generation using particle swarm optimization. Electr Power Syst Res 2008;78:1448–55.
[46] Pulagam K. Optimization of solid oxide fuel cell interconnect design [Dissertation]. Las Vegas: University of Nevada; 2009.
[47] Sciacovelli A, Verda V. Optimal design of a solid oxide fuel cell for hybrid vehicle application. In: Proceedings of the 4th European automotive simulation conference. Munich, Germany; 2009.
[48] Sciacovelli A. Thermodynamic optimization of a monolithic-type solid oxide fuel cell. Int J Thermodyn 2010;13:95–103.
[49] Quddus MR, Zhang Y, Ray AK. Multi-objective optimization in solid oxide fuel cell for oxidative coupling of methane. Chem Eng J 2010;165:639–48.
[50] Zhang X, Su S, Chen J, Zhao Y, Brandon N. A new analytical approach to evaluate and optimize the performance of an irreversible solid oxide fuel cell-gas turbine hybrid system. Int J Hydrog Energy 2011;36:15304–12.
[51] Marchetti A, Gopalakrishnan A, Chachuat B, Bonvin D, Tsikonis L, Nakajo A, et al. Robust real-time optimization of a solid oxide fuel cell stack. J Fuel Cell Sci Technol 2011;8:051001.
[52] Spivey BJ, Hedengren JD, Edgar TF. Constrained control and optimization of tubular solid oxide. American control conference. Fairmont Queen Elizabeth, Montréal, Canada; 2012.
[53] Song X, Diaz AR, Benard A, Nicholas JD. A 2D model for shape optimization of solid oxide fuel cell cathodes. Struct Multidiscip Optim 2013;47:453–64.
[54] Kosaksri K, Jongjitjaroen M, Srinophakun T, Fowler MW, Croiset E. Optimal operation of tubular solid oxide fuel cell based on efficiency and environmental impact. Nat Sci 2014;48:474–86.
[55] Bozorgmehri S, Hamedi M. Modeling and optimization of anode-supported solid oxide fuel cells on cell parameters via artificial neural network and genetic algorithm. Fuel Cells 2012;12:11–23.
[56] Hajimolana SA, Hussain MA, Subramanian Nayagar JN, Chakrabarti MH. Optimization of solid oxide fuel cell operation parameters: a review. In: Proceedings of the international conference on renewable energies and power quality (ICREPQ'14). Cordoba, Spain; 2014.
[57] Stimming U, Singhal SC, Tagawa H. In: Proceedings of the Fifth International Symposium on Solid Oxide Fuel Cells (SOFC-V). Electrochemical Society; 1997.
[58] Williams MC, Strakey JPUS. Singhal SC, Dokiya M, editors. DOE Office of fossil energy's solid oxide fuel cell programs. The Electrochemical Society Inc.; 2003. p. 3–8.
[59] Singhal SC, Dokiya M, Division ESHTM, Division ESB, Japan SSo. Solid Oxide Fuel Cells (SOFC VI): In: Proceedings of the sixth international symposium. Electrochemical Society; 1999.
[60] Singhal SC, Dokiya M, Division ESHTM, Division ESB, Division ESET, Japan SSo. Solid Oxide Fuel Cells VIII: (SOFC VIII). In: Proceedings of the international symposium. Electrochemical Society; 2003.
Domeracki et al., 1995 [61] Domeracki WF, Lundberg WL, Dowdy TE, Linder JAM. Integrated gas turbine solid oxide fuel cell system. Google Patents; 1995.
[62] Arsalis A. Thermoeconomic modeling and parametric study hybrid solid oxide fuel cell – gas turbine – steam turbine power plants ranging from 1.5 MWe to 10 MWe. Blacksburg, Virginia: Virginia Polytechnic Institute and State University; 2007.
[63] Ugartemendia J, Ostolaza J, Zubia I. Operating point optimization of a hydrogen fueled hybrid Solid Oxide Fuel Cell-Steam Turbine (SOFC-ST) plant. Energies 2013;6:5046–68.
[64] Chen L, Gao S, Zhang H. Performance analysis and multi-objective optimization of an irreversible solid oxide fuel cell-stirling heat engine hybrid system. Int J Electrochem Sci 2013;8:10772–87.
[65] Irvine JTS, Connor P. Solid Oxide Fuels Cells: facts and figures. Past present and future perspectives for SOFC technologies. London: Springer; 2012.
[66] Riensche E, Stimming U, Unverzagt G. Optimization of a 200 kW SOFC cogeneration power plant Part I: variation of process parameters. J Power Sources 1998;73:251–6.
[67] Adam A, Fraga ES. Modelling and optimisation in terms of CO_2 emissions of a solid oxide fuel cell based micro-CHP system in a four bedroom house in London. Energy Procedia 2013;42:201–9.
[68] Bang-Møller C. Design and optimization of an integrated biomass Gasifi cation and solid oxide fuel cell system. Denmark: Technical University of Denmark; 2010.
[69] Wakui T, Yokoyama R. Optimal sizing of residential SOFC cogeneration system for power interchange operation in housing complex from energy-saving viewpoint. Energy 2012;41:65–74.
[70] Windeknecht M, Tzscheutschler P. Optimization of the heat output of high temperature fuel cell Micro-CHP in single family homes. Energy Procedia 2015;78:2160–5.
[71] 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;40:14202–23.
[72] 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;103:131–46.
[73] Perdikaris N, Panopoulos KD, Hofmann P, Spyrakis S, Kakaras E. Design and exergetic analysis of a novel carbon free tri-generation system for hydrogen, power

and heat production from natural gas, based on combined solid oxide fuel and electrolyser cells. Int J Hydrog Energy 2010;35:2446–56.
[74] Liso V, Zhao Y, Brandon N, Nielsen MP, Kær SK. Analysis of the impact of heat-to-power ratio for a SOFC-based mCHP system for residential application under different climate regions in Europe. Int J Hydrog Energy 2011;36:13715–26.
[75] Xu H, Dang Z, Bai B-F. Analysis of a 1 kW residential combined heating and power system based on solid oxide fuel cell. Appl Therm Eng 2013;50:1101–10.
[76] Khani L, Mehr AS, Yari M, Mahmoudi SMS. Multi-objective optimization of an indirectly integrated solid oxide fuel cell-gas turbine cogeneration system. Int J Hydrog Energy 2016;41:21470–88.
[77] Akikur RK, Saidur R, Ping HW, Ullah KR. Performance analysis of a co-generation system using solar energy and SOFC technology. Energy Convers Manag 2014;79:415–30.
[78] Ullah KR, Akikur RK, Ping HW, Saidur R, Hajimolana SA, Hussain MA. An experimental investigation on a single tubular SOFC for renewable energy based cogeneration system. Energy Convers Manag 2015;94:139–49.
[79] Hassanzadeh H, Farzad MA, Safavinejad A, Agaebrahimi MR. Performance assessment of a SOFC cogeneration system for residential buildings located in eastern Iran. Iran J Hydrog Fuel Cell 2016;2:81–97.
[80] 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 H2 and CO. Appl Therm Eng 2016;108:347–52.
[81] Chen JMP, Ni M. Economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong. Energy Build 2014;75:160–9.
[82] Chitsaz A, Mahmoudi SM S, Rosen MA. Greenhouse gas emission and exergy analyses of an integrated trigeneration system driven by a solid oxide fuel cell. Appl Therm Eng 2015;86:81–90.
[83] Grefenstette JJJJ. Optimization of control parameters for genetic algorithms. IEEE Trans Syst Man Cybern 1986;16:122–8.
[84] Zavattieri PD, Dari EA, Buscaglia GC. Optimization strategies in unstructured mesh generation. Int J Numer Methods Eng 1996;39:2055–71.
[85] Buonomano A, Calise F, d'Accadia MD, Palombo A, Vicidomini M. Hybrid solid oxide fuel cells–gas turbine systems for combined heat and power: a review. Appl Energy 2015;156:32–85.
[86] Ge XM, Fang YN, Chan SH. Design and optimization of composite electrodes in solid oxide cells. Fuel Cells 2012;12:61–76.
[87] Shi J, Xue X. Microstructure optimization designs for anode-supported planar solid oxide fuel cells. J Fuel Cell Sci Technol 2011;8:061006.
[88] Singhal SC. Solid oxide fuel cells. History 2014:2008–18.
[89] Kleitz M, Petitbon F. Optimized SOFC electrode micro-structure. Solid State Ion 1996;92:65–74.
[90] Vasylyev O, Brychevskyi M, Brodnikovskyi Y. The Structural optimization of ceramic fuel cells. Univers J Chem 2016;4:31–54.
[91] Abdullah T, Liu L. Simulation-based microstructural optimization of solid oxide fuel cell for low temperature operation. Int J Hydrog Energy 2016;41:13632–43.
[92] Li W, Xiong C, Zhang Q, Jia L, Chi B, Pu J, et al. Composition optimization of samarium strontium manganite-yttria stabilized zirconia cathode for high performance intermediate temperature solid oxide fuel cells. Electrochim Acta 2016;190:531–7.
[93] Ahmed AJ, P S. Optimizing anode microstructure of intermediate temperature solid oxide fuel cell based on gadolinium doped ceria. In: Proceedings of the 3rd international conference on the developments in renewable energy technology (ICDRET), IEEE; 2014.
[94] Costamagna P, Costa P, Arato E. Some More considerations on the optimization of cermet solid oxide fuel cell electrodes. Electrochim Acta 1997;43:967–72.
[95] Bhattacharyya D, Rengaswamy R. Transport, sensitivity, and dimensional optimization studies of a tubular Solid Oxide Fuel Cell. J Power Sources 2009;190:499–510.
[96] Bhattacharyya D, Rengaswamy R, Finnerty CY. Isothermal models for anode-supported tubular solid oxide fuel cells. Chem Eng Sci 2007;62:4250–67.
[97] Haanappel VAC, Mertens J, Rutenbeck D, Tropartz C, Herzhof W, Sebold D, et al. Optimisation of processing and microstructural parameters of LSM cathodes to improve the electrochemical performance of anode-supported SOFCs. J Power Sources 2005;141:216–26.
[98] Ji Y, Yuan K, Chung JN, Chen Y-C. Effects of transport scale on heat/mass transfer and performance optimization for solid oxide fuel cells. J Power Sources 2006;161:380–91.
[99] Skalar T, Lubej M, Marinšek M. Optimization of operating conditions in a laboratory SOFC testing device. Mater Tehnol 2015;49:731–8.
[100] Feng H, Chen L, Xie Z, Sun F. Constructal optimization for a single tubular solid oxide fuel cell. J Power Sources 2015;286:406–13.
[101] Ni M, Leung MKH, Leung DYC. Parametric study of solid oxide fuel cell performance. Energy Convers Manag 2007;48:1525–35.
[102] Jo DH, Chun JH, Park KT, Hwang JW, Lee JY, Jung HW, et al. Optimization of physical parameters of solid oxide fuel cell electrode using electrochemical model. Korean J Chem Eng 2011;28:1844–50.
[103] Bunin GA, Francois G, Bonvin D. Two-layered real-time optimization of a solid oxide fuel cell stack. In: Proceedings of the 9th international symposium on dynamics and control of process systems (DYCOPS 2010). Leuven, Belgium; 2010.
[104] Roshandel R, Behzadi Forough A. Two strategies for multi-objective optimisation of solid oxide fuel cell stacks. Int J Sustain Energy 2013;33:854–68.
[105] Chachuat B, Mitsos A, Barton PI. Optimal design and steady-state operation of micro power generation employing fuel cells. Chem Eng Sci 2005;60:4535–56.
[106] Ki J. Integrated modeling approach for solid oxide fuel cell-based power generating system. Arlington: The University of Texas; 2013.
[107] Cao H, Li X, Deng Z, Jiang J, Yang J, Li J, et al. Dynamic modeling and experimental validation for the electrical coupling in a 5-cell solid oxide fuel cell stack in the perspective of thermal coupling. Int J Hydrog Energy 2011;36:4409–18.
[108] Cao H, Li X, Deng Z, Li J, Qin Y. Thermal management oriented steady state analysis and optimization of a kW scale solid oxide fuel cell stand-alone system for maximum system efficiency. Int J Hydrog Energy 2013;38:12404–17.
[109] Monanteras NC, Frangopoulos CA. Towards synthesis optimization of a fuel-cell based plant. Energy Convers Manag 1999;40:1733–42.
[110] Zhang L, Li X, Jiang J, Li S, Yang J, Li J. Dynamic modeling and analysis of a 5-kW solid oxide fuel cell system from the perspectives of cooperative control of thermal safety and high efficiency. Int J Hydrog Energy 2015;40:456–76.
[111] Pla D, Sánchez-González A, Garbayo I, Salleras M, Morata A, Tarancón A. Is it possible to design a portable power generator based on micro-solid oxide fuel cells? A finite volume analysis. J Power Sources 2015;293:264–73.
[112] Rancruel DF. Dynamic SynthesisDesign and OperationControl optimization approach applied to a Solid Oxide Fuel Cell based auxiliary power unit under transient conditions. Blacksburg, Virginia: Virginia Polytechnic Institute and State University; 2005.
[113] Chen J, Sun J. Fuel Cell Based Auxiliary Power Unit Modeling, Optimization, and Control. In: Proceedings of the joint 48th IEEE conference on decision and control and 28th Chinese control conference. Shanghai, P.R. China; 2009. p. 5188–5193.
[114] Yi Y, Rao AD, Brouwer J, Samuelsen GS. Analysis and optimization of a solid oxide fuel cell and intercooled gas turbine (SOFC–ICGT) hybrid cycle. J Power Sources 2004;132:77–85.
[115] Fredriksson Möller B, Arriagada J, Assadi M, Potts I. Optimisation of an SOFC/GT system with CO_2-capture. J Power Sources 2004;131:320–6.
[116] Calise F, Dentice d' Accadia M, Vanoli L, von Spakovsky MR. Single-level optimization of a hybrid SOFC–GT power plant. J Power Sources 2006;159:1169–85.
[117] Calise F, Dentice d' Accadia M, Vanoli L, von Spakovsky MR. Full load synthesis/design optimization of a hybrid SOFC–GT power plant. Energy 2007;32:446–58.
[118] Zhao Y, Shah N, Brandon N. Comparison between two optimization strategies for solid oxide fuel cell–gas turbine hybrid cycles. Int J Hydrog Energy 2011;36:10235–46.
[119] Cheddie DF. Thermo-economic optimization of an indirectly coupled solid oxide fuel cell/gas turbine hybrid power plant. Int J Hydrog Energy 2011;36:1702–9.
[120] Milewski J. SOFC hybrid system optimization using an advanced model of fuel cell. Sustain Res Innov Proc 2011;3:1–9.
[121] Brear MJ, Dunkley MJ. The effect of size on optimization of solid oxide fuel cell/gas turbine hybrid cycles. J Eng Gas Turbines Power 2010;132:094502.
[122] Odukoya A, Carretero JA, Reddy BV. Thermodynamic optimization of solid oxide fuel cell-based combined cycle cogeneration plant. Int J Energy Res 2011;35:1399–411.
[123] Facchinetti E, Gassner M, D'Amelio M, Marechal F, Favrat D. Process integration and optimization of a solid oxide fuel cell – Gas turbine hybrid cycle fueled with hydrothermally gasified waste biomass. Energy 2012;41:408–19.
[124] Facchinetti E, Favrat D, Marechal F. Design and optimization of an innovative Solid Oxide Fuel Cell-Gas Turbine Hybrid Cycle for small scale distributed generation. Fuel Cells 2014;14:595–606.
[125] Wu X-J, Zhu X-J. Optimization of a solid oxide fuel cell and micro gas turbine hybrid system. Int J Energy Res 2013;37:242–9.
[126] Lee TS, Chung JN, Chen Y-C. Design and optimization of a combined fuel reforming and solid oxide fuel cell system with anode off-gas recycling. Energy Convers Manag 2011;52:3214–26.
[127] Facchinetti E, Favrat D, Marechal F. Innovative hybrid cycle solid oxide fuel cell-inverted gas turbine with CO_2 separation. Fuel Cells 2011;11:565–72.
[128] Zhao Y, Chen J. Modeling and optimization of a typical fuel cell–heat engine hybrid system and its parametric design criteria. J Power Sources 2009;186:96–103.
[129] Aminyavari M, Mamaghani AH, Shirazi A, Najafi B, Rinaldi F. Exergetic, economic, and environmental evaluations and multi-objective optimization of an internal-reforming SOFC-gas turbine cycle coupled with a Rankine cycle. Appl Therm Eng 2016;108:833–46.
[130] Wakui T, Yokoyama R, Shimizu K-i. Suitable operational strategy for power interchange operation using multiple residential SOFC (solid oxide fuel cell) cogeneration systems. Energy 2010;35:740–50.
[131] Wakui T, Yokoyama R. Optimal structural design of residential cogeneration systems in consideration of their operating restrictions. Energy 2014;64:719–33.
[132] 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;84:106–20.
[133] Baghernejad A, Yaghoubi M, Jafarpur K. Optimum power performance of a new integrated SOFC-trigeneration system by multi-objective exergoeconomic optimization. Int J Electr Power Energy Syst 2015;73:899–912.
[134] Curletti F, Gandiglio M, Lanzini A, Santarelli M, Maréchal F. Large size biogas-fed Solid Oxide Fuel Cell power plants with carbon dioxide management: technical and economic optimization. J Power Sources 2015;294:669–90.
[135] Wang Y, Shi Y, Ni M, Cai N. A micro tri-generation system based on direct flame fuel cells for residential applications. Int J Hydrog Energy 2014;39:5996–6005.
[136] Wipke K, Markel T, Nelson D. Optimizing Energy Management Strategy and Degree of Hybridization for a Hydrogen Fuel Cell SUV. In: Proceedings of the 18th electric vehicle symposium; 2001.
[137] Deng Q, Gao X, Zhou H, Hu W. System modeling and optimization of microgrid using genetic algorithm. In: 2011 2nd International Conference on In Intelligent Control and Information Processing (ICICIP), vol. 1. IEEE; 2011, p. 540–544.
[138] Shirazi A, Aminyavari M, Najafi B, Rinaldi F, Razaghi M. Thermal–economic–

environmental analysis and multi-objective optimization of an internal-reforming solid oxide fuel cell–gas turbine hybrid system. Int J Hydrog Energy 2012;37:19111–24.
[139] Najafi B, Shirazi A, Aminyavari M, Rinaldi F, Taylor RA. Exergetic, economic and environmental analyses and multi-objective optimization of an SOFC-gas turbine hybrid cycle coupled with an MSF desalination system. Desalination 2014;334:46–59.
[140] Vogler M, Horiuchi M, Bessler WG. Modeling, simulation and optimization of a no-chamber solid oxide fuel cell operated with a flat-flame burner. J Power Sources 2010;195:7067–77.
[141] Funahashi Y, Shimamori T, Suzuki T, Fujishiro Y, Awano M. Simulation study for the optimization of microtubular Solid Oxide Fuel Cell bundles. J Fuel Cell Sci Technol 2010;7:021015.
[142] Sembler WJ, Kumar S. Optimization of a Single-Cell Solid-Oxide Fuel cell using computational fluid dynamics. J Fuel Cell Sci Technol 2011;8:021007.
[143] Lu Y, Schaefer L. Numerical study of a flat-tube high power density solid oxide fuel cell Part II: Cell performance and stack optimization. J Power Sources 2006;153:68–75.
[144] Bertei A, Nucci B, Nicolella C. Engineered electrode microstructure for optimization of solid oxide fuel cells. Chem Eng Trans 2013;32:2293–8.
[145] Faes A, Fuerbringer J-M, Mohamedi D, Hessler-Wyser A, Caboche G, Van Herle J. Design of experiment approach applied to reducing and oxidizing tolerance of anode supported solid oxide fuel cell. Part I: microstructure optimization. J Power Sources 2011;196:7058–69.
[146] Farhad S, Hamdullahpur F. Optimization of the microstructure of porous composite cathodes in solid oxide fuel cells. AIChE J 2012;58:1248–61.
[147] Hasanabadi A, Baniassadi M, Abrinia K, Safdari M, Garmestani H. Optimization of solid oxide fuel cell cathodes using two-point correlation functions. Comput Mater Sci 2016;123:268–76.
[148] Wen H, Ordonez JC, Vargas JVC. Composite electrode modelling and optimization for solid oxide fuel cells. Int J Energy Res 2013;37:95–104.
[149] Amiri A, Vijay P, Tadé MO, Ahmed K, Ingram GD, Pareek V, et al. Solid oxide fuel cell reactor analysis and optimisation through a novel multi-scale modelling strategy. Comput Chem Eng 2015;78:10–23.
[150] Shi J, Xue X. Optimization design of electrodes for anode-supported solid Oxide Fuel Cells via genetic algorithm. J Electrochem Soc 2010;158:B143.
[151] Dorer V, Weber A. Energy and CO_2 emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs. Energy Convers Manag 2009;50:648–57.
[152] Dincer I, Rosen MA. EXERGY: energy, environment and sustainable development. Elsevier Science; 2012.
[153] Bang-Møller C, Rokni M, Elmegaard B. Exergy analysis and optimization of a biomass gasification, solid oxide fuel cell and micro gas turbine hybrid system. Energy 2011;36:4740–52.
[154] Mert SO, Ozcelik Z, Dincer I. Comparative assessment and optimization of fuel cells. Int J Hydrog Energy 2015;40:7835–45.
[155] Ford JC. Thermodynamic optimization of a planar solid oxide fuel cell. Doctoral dissertation. Georgia Institute of Technology; 2012.
[156] Rangaiah GP. Multi-objective optimization: techniques and applications in chemical engineering, 1. World Scientific; 2009.
[157] Tan L, Yang C, Zhou N. Thermoeconomic optimization of a solid oxide fuel cell and proton exchange membrane fuel cell hybrid power system. J Fuel Cell Sci Technol 2014;11:011005.
[158] Elliott L, Anderson WK, Kapadia S. Solid oxide fuel cell design optimization with numerical adjoint techniques. J Fuel Cell Sci Technol 2009;6:041018.
[159] Darling SB, You F, Veselka T, Velosa A. Assumptions and the levelized cost of energy for photovoltaics. Energy Environ Sci 2011;4:3133–9.
[160] Amer M, Namaane A, M'Sirdi NK. Optimization of Hybrid Renewable Energy Systems (HRES) Using PSO for cost reduction. Energy Procedia 2013;42:318–27.
[161] Kazempoor P, Dorer V, Weber A. Modelling and evaluation of building integrated SOFC systems. Int J Hydrog Energy 2011;36:13241–9.
[162] Li L, Zhong Q, Bu Y, Song Y. Improvement of BaCe0.8Sm0.1Y0.1O3-δ-based IT-SOFC by optimizing spin-coated process of cathode and sintering temperature. Ionics 2014;21:817–22.
[163] Wen H. Single Solid Oxide Fuel Cell modeling and optimization. The Florida State University; 2011.
[164] Zhao D, Dong W, Xue D. A hybrid model for Optimal Concurrent design of solid oxide fuel cell System considering functional performance and production cost. Concurr Eng 2008;16:161–72.
[165] Gao X, Zhang Q, Zhang W, Chen D. Optimization of distributed cylindrical interconnect ribs for anode- and cathode-supported solid oxide fuel cell. Int J Electrochem Sci Sci Bull 2015;10:7521–34.
[166] Larrain D. Solid Oxide Fuel Cell stack simulation and optimization including experimental validation and transient behaviour. Lausanne, French: Federal Institute of Technology; 2005.
[167] Dorer V, Weber R, Weber A. Performance assessment of fuel cell micro-cogeneration systems for residential buildings. Energy Build 2005;37:1132–46.
[168] Amiri A, Tang S, Vijay P, Tadé MO. Planar solid oxide fuel cell modeling and optimization Targeting the stack's temperature gradient minimization. Ind Eng Chem Res 2016;55:7446–55.
[169] Tan L, Yang C, Zhou N. Synthesis/design optimization of SOFC–PEM hybrid system under uncertainty. Chin J Chem Eng 2015;23:128–37.
[170] Lee KH. Configuration and operating condition design analysis of SOFC systems for building applicationsUrbana, Illionis. University of Illinois; 2008.
[171] Arcuri P, Beraldi P, Florio G, Fragiacomo P. Optimal design of a small size trigeneration plant in civil users: a MINLP (Mixed Integer Non Linear Programming Model). Energy 2015;80:628–41.
[172] Casas Ledón Y, Arteaga-Perez LE, Toledo J, Dewulf J. Exergoeconomic evaluation of an ethanol-fueled solid oxide fuel cell power plant. Energy 2015;93:1287–95.
[173] Sharma S, Dilan CA, Peduzzi E, Maréchal F, Ensinas AV. Multi-objective optimization of solid oxide fuel cell–gas turbine hybrid cycle and uncertainty Analysis. In: Proceedings of ECOS 2016 (No. EPFL-CONF-220525). University of Ljubljana; 2016.
[174] Bunin GA, Wuillemin Z, Francois G, Nakajo A, Tsikonis L, Bonvin D. Experimental real-time optimization of a solid oxide fuel cell. Energy 2012;39:54–62.
[175] Wen H, Ordonez JC, Vargas JVC. Single solid oxide fuel cell modeling and optimization. J Power Sources 2011;196:7519–32.
[176] Oh S-R, Sun J. Optimization and Load-Following Characteristics of 5kW-Class Tubular Solid Oxide Fuel Cell/Gas Turbine Hybrid Systems. In: American Control Conference (ACC); 2010, p. 417–422.
[177] Goyal A, Diwekar U. Multi-objective optimization for hybrid fuel cells power System design. J Chem Inf Model 2001;53:1689–709.
[178] Wakui T, Kawayoshi H, Yokoyama R, Aki H. Operation management of residential energy-supplying networks based on optimization approaches. Appl Energy 2016;183:340–57.
[179] François G, Costello S, Bonvin D. Application of real-time optimization methods to energy systems in the presence of uncertainties and disturbances. TMC Acad J 2015;9:19–40.
[180] 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;8:2211–29.
[181] Larrain D, Van herle J, Maréchal F, Favrat D. Generalized model of planar SOFC repeat element for design optimization. J Power Sources 2004;131:304–12.
[182] Hobold GM, Agarwal RK. Prediction and optimization of fuel cell performance using a multi-objective genetic algorithm. Int J Energy Environ 2013;4:721–42.
[183] Ahmadi S, Bathaee SMT. Multi-objective genetic optimization of the fuel cell hybrid vehicle supervisory system: fuzzy logic and operating mode control strategies. Int J Hydrog Energy 2015;40:12512–21.
[184] Yang J, Li X, Jiang JH, Jian L, Zhao L, Jiang JG, et al. Parameter optimization for tubular solid oxide fuel cell stack based on the dynamic model and an improved genetic algorithm. Int J Hydrog Energy 2011;36:6160–74.
[185] Marler RT, Arora JS. Survey of multi-objective optimization methods for engineering. Struct Multidiscip Optim 2004;26:369–95.
[186] Hakimi SM, Moghaddas-Tafreshi SM. Optimal sizing of a stand-alone hybrid power system via particle swarm optimization for Kahnouj area in south-east of Iran. Renew Energy 2009;34:1855–62.
[187] Kong W, Gao X, Liu S, Su S, Chen D. Optimization of the interconnect ribs for a cathode-supported Solid Oxide Fuel Cell. Energies 2014;7:295–313.
[188] Iverson Z, Achuthan A, Marzocca P, Aidun D. Optimal design of hybrid renewable energy systems (HRES) using hydrogen storage technology for data center applications. Renew Energy 2013;52:79–87.
[189] Ahmadi P. Modeling, analysis and optimization of integrated energy systems for multigeneration Purposes. Oshawa, Ontario, Canada: University of Ontario Institute of Technology; 2013.
[190] Chachuat B, Marchetti A, Bonvin D. Process optimization via constraints adaptation. J Process Control 2008;18:244–57.
[191] Mazumder SK, Pradhan SK, Hartvigsen J, Rancruel D, von Spakovsky MR, Khaleel M. A multidiscipline and multi-rate modeling framework for planar solid-oxide-fuel-cell based power-conditioning system for vehicular APU. Simulation 2008;84:413–26.
[192] Lu Y, Schaefer L, Li P. Numerical study of a flat-tube high power density solid oxide fuel cellPart I. Heat/mass transfer and fluid flow. J Power Sources 2005;140:331–9.
[193] Entchev E, Yang L. Application of adaptive neuro-fuzzy inference system techniques and artificial neural networks to predict solid oxide fuel cell performance in residential microgeneration installation. J Power Sources 2007;170:122–9.
[194] Wang B, Zhang N, Hwang S, Kim J-K. Process integration of solid oxide fuel cells with process utility systems. Clean Technol Environ Policy 2013;15:801–15.
[195] Ordonez JC, Chen S, Vargas JVC, Dias FG, Gardolinski JEFC, Vlassov D. Constructal flow structure for a single SOFC. Int J Energy Res 2007;31:1337–57.
[196] Hawkes A, Leach M. Cost-effective operating strategy for residential micro-combined heat and power. Energy 2007;32:711–23.
[197] Zhao Y, Shah N, Brandon N. The development and application of a novel optimisation strategy for solid oxide fuel cell-gas turbine hybrid cycles. Fuel Cells 2009;10(1):181–93.
[198] Cao H, Deng Z, Li X, Yang J, Qin Y. Dynamic modeling of electrical characteristics of solid oxide fuel cells using fractional derivatives. Int J Hydrog Energy 2010;35:1749–58.
[199] Suying Y, Meng W, Jianying L, Kuijun M. Optim Des Superv Control SOFC Integr Syst 2010:576–9.
[200] Spivey BJ, Edgar TF. Dynamic modeling, simulation, and MIMO predictive control of a tubular solid oxide fuel cell. J Process Control 2012;22:1502–20.
[201] Wang S-B, Wu C-F, Liu S-F, Yuan P. Performance optimization and selection of operating parameters for a solid oxide fuel cell stack. J Fuel Cell Sci Technol 2013;10:051005.
[202] Chen D, Zeng Q, Su S, Bi W, Ren Z. Geometric optimization of a 10-cell modular planar solid oxide fuel cell stack manifold. Appl Energy 2013;112:1100–7.
[203] Zhang L, Jiang J, Cheng H, Deng Z, Li X. Control strategy for power management, efficiency-optimization and operating-safety of a 5-kW solid oxide fuel cell system. Electrochim Acta 2015;177:237–49.

[204] Shariatzadeh JO, Refahi AH, Abolhassani SS, Rahmani M. Modeling and optimization of a novel solar chimney cogeneration power plant combined with solid oxide electrolysis/fuel cell. Energy Convers Manag 2015;105:423–32.

[205] Borji M, Atashkari K, Nariman-zadeh N, Masoumpour M. Modeling, parametric analysis and optimization of an anode-supported planar solid oxide fuel cell. In: Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 229 (17), 2015, 3125–3140.

[206] Cubero A, Peña JI, Laguna-Bercero MA. Optimization of Ni–YSZ solid oxide fuel cell anodes by surface laser melting. Appl Surf Sci 2015;335:39–43.

[207] Zhao H, Jiang T, Hou H. Performance analysis of the SOFC–CCHP system based on H2O/Li–Br absorption refrigeration cycle fueled by coke oven gas. Energy 2015;91:983–93.

[208] Wang Y, Cai L, Liu T, Wang J, Chen J. An efficient strategy exploiting the waste heat in a solid oxide fuel cell system. Energy 2015;93:900–7.

[209] Hering M, Brouwer J, Winkler W. Evaluation and optimization of a micro-tubular solid oxide fuel cell stack model including an integrated cooling system. J Power Sources 2016;303:10–6.

[210] Facci AL, Cigolotti V, Jannelli E, Ubertini S. Technical and economic assessment of a SOFC-based energy system for combined cooling, heating and power. Appl Energy 2016.

[211] Baghernejad A, Yaghoubi M, Jafarpur K. Exergoeconomic comparison of three novel trigeneration systems using SOFC, biomass and solar energies. Appl Therm Eng 2016;104:534–55.

[212] Li TX, Wu S, Yan T, Xu JX, Wang RZ. A novel solid–gas thermochemical multilevel sorption thermal battery for cascaded solar thermal energy storage. Appl Energy 2016;161:1–10.

[213] Cheng H, Jing S, Xu Y, Deng Z, Li J, Li X. Control-oriented modeling analysis and optimization of planar solid oxide fuel cell system. Int J Hydrog Energy 2016;41:22285–304.

[214] Roshandel R, Parhizkar T. Degradation based optimization framework for long term applications of energy systems, case study: solid oxide fuel cell stacks. Energy 2016;107:172–81.

[215] Reyhani HA, 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;107:141–64.

[216] Rashid K, Dong SK, Khan RA, Park SH. Optimization of manifold design for 1 kW-class flat-tubular solid oxide fuel cell stack operating on reformed natural gas. J Power Sources 2016;327:638–52.