A Review on Modeling of Hybrid Solid Oxide Fuel Cell Systems

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ABSTRACT

Over the past 2 decades, there has been tremendous progress on numerical and computational tools for fuel cells and energy systems based on them. The purpose of this work is to summarize the current status of hybrid solid oxide fuel cell (SOFC) cycles and identify areas that require further studies.

In this review paper, a comprehensive literature survey on different types of SOFC hybrid systems modeling is presented. The paper has three parts. First, it describes the importance of the fuel cells modeling especially in SOFC hybrid cycles. Key features of the fuel cell models are highlighted and model selection criteria are explained. In the second part, the models in the open literature are categorized and discussed. It includes discussion on a detail example of SOFC-gas turbine cycle model, description of early models, models with different objectives such as parametric analysis, comparison of configurations, exergy analysis, optimization, non-stationary power generation applications, transient and off-design analysis, thermoeconomic analysis and so on. Finally, in the last section, key features of selected models are summarized and suggestions for areas that require further studies are presented. In this paper, a hybrid cycle can be any combination of SOFC and gas turbine, steam turbine, coal integrated gasification, and application in combined heat and power cycle.

Keywords: Solid Oxide Fuel Cells, SOFC, Hybrid Energy Systems, Steady State and Dynamic Modeling.

1. INTRODUCTION

We owe our sophisticated society and current standard of living to energy infrastructure development and its consequences in the last century. But, global climate change and natural resources pollution cause significant worldwide concerns about current trend in energy systems development. According to the World Energy Outlook published by the International Energy Agency (IEA) [1], the world's total electricity consumption would be doubled between 2003 and 2030. This report predicted that the share of fossil fuels as energy supplies for electricity generation will remain constant at nearly 65%. Power generation is responsible for half of the increase in global greenhouse gas emissions over the projection period. As a result of all these problems, sustainability considerations should be involved in all major energy development plans all over the world. There are various definitions for sustainability. Probably the simplest one is that sustainable activities are the activities that help existing generation to meet their needs without destroying the ability of future generations to meet theirs [2].

Fuel cells are very interesting alternative for conventional power generation technologies because of their high efficiency and very low environmental effects. In conventional power generation systems, fuel should be combusted to generate heat and then heat should be converted to mechanical energy, before it can be used to produce electrical energy. The maximum efficiency that a thermal engine can achieve is when it operates at Carnot cycle. The efficiency of this cycle is related to the ratio of the heat source and sink absolute temperature. However, fuel cells operation is based on electrochemical reactions and not fuel combustion; therefore, their efficiency is not limited by the thermodynamics laws and Carnot cycle. Instead, their efficiency is limited by the ratio of released Gibbs free energy to the inlet fuel heating value. It is interesting to note that this maximum efficiency is equal to the Carnot efficiency calculated at the temperature at which the combustion is reversible [3]. Furthermore, since there is no combustion, none of the pollutants, commonly produced by fuel combustors, is emitted.

In this review paper, a comprehensive literature survey on different types of SOFC hybrid systems modeling is presented. It begins with a general discussion on roles of fuel cell and SOFC hybrid systems modeling and importance of review papers in this field. Then, key features of the fuel cell models are highlighted and model selection criteria are explained. In the second part, the models in the open literature are categorized and discussed based on selected criteria. Finally, in the last section, key features of selected models are summarized and suggestions for areas that require further studies are presented.

2. FUEL CELL MODELING

Simulation and mathematical models are certainly helpful for development of various power generation technologies; however, they are probably more important for fuel cell development. This is due to complexity of fuel cells and systems based on them, and the difficulty in experimentally characterizing their internal operation. This complexity can be explained based on the fact that within the fuel cell, tightly coupled electrochemical reactions, electrical conduction, ionic conduction, and heat transfer take place simultaneously. That is why a comprehensive study of fuel cells needs a multidisciplinary approach. Modeling can help to understand what is really happening within the fuel cells [4].

Understanding the internal physics and chemistry of fuel cells are often difficult. This is because of great number of physical and chemical processes in the fuel cells, difficulty in independent controlling of the fuel cells parameters, and access limitations to inside of the fuel cells [5].

In addition, fuel cells simulation can help to focus experimental researches and to improve accuracy of interpolations and extrapolations of the results. Furthermore, mathematical models can serve as valuable tools to design and optimize fuel cell systems. On the other hand, dynamic models can be used to design and test fuel cell systems' control algorithms. Finally, models can be developed to evaluate whether characteristics of specific type of fuel cell can meet the requirements of an application and its cost-effectiveness [4].

Due to its importance, in the past 2 decades there has been tremendous progress on numerical and computational tools for fuel cells and energy systems based on them, and virtually unlimited number of papers has been published on fuel cells modeling and simulation. With this large amount of literature, it is very difficult to keep track of the developments in the field. This problem can be intensified for new researchers as they can be easily overwhelmed by this sheer volume of resources. As such, review papers can be very useful. That is why there have been many review papers on modeling of different types of fuel cells especially for modeling and simulation of Proton Exchange Membrane Fuel Cells (PEMFC) [6, 7, 8, 9, 10, 11], Solid Oxide Fuel Cells

(SOFC) [10, 11, 12, 13, 14] and to a lesser extent, Molten Carbonate Fuel Cells (MCFC) [15]. In addition, review papers can be helpful to summarize the current status of global research efforts so that unresolved problems can be identified and addressed in future works.

3. SOFC HYBRID CYCLES

Among different types of fuel cells, high temperature fuel cells, namely, SOFC and MCFC, are very interesting. Because of high operating temperature, their application can lead to some advantages, such as:

- ability to incorporate bottoming cycles to generate further power from high temperature exhaust stream,
- ability to reform hydrocarbons which results in fuel flexibility,
- capability to consume CO as fuel,
- no need for noble metal, such as platinum, as electro-catalysts,

And in case of SOFC:

- high oxide-ion conductivity,
- high energy conversion efficiency due to high rate of reaction kinetics
- solid electrolyte and existence of only solid and gas phases result in:
  - simplicity in concept,
  - ability to be casted into various shapes (that is why wide range of cell and stack geometries have been proposed for SOFC),
  - accurate and appropriate design of the three-phase boundary,
  - no electrolyte management constraints.

In a fuel cell hybrid cycle both SOFC and MCFC can be utilized in fuel cell part, but the focus of this paper is only on SOFC hybrid cycles. An excellent historical and technical review of SOFCs can be found in [16], and also in [17, 18, 19, 20]. Moreover, Dokiya [21] studied materials and fabrication technologies deployed for manufacturing of different cell components, investigated the performance of the fuel cells manufactured using these materials, and reviewed efforts to reduce fuel cell costs.

As mentioned, high temperature of fuel cell product provides very good opportunity for hybrid high temperature fuel cell systems especially for distributed generation (DG). Rajashekara [22] classified the hybrid fuel-cell systems as Type-1 and Type-2 systems. They are mainly suited for combined cycles power generation and backup or peak shaving power systems, respectively. An example of Type–1 hybrid systems is hybrid fuel cell and GT cycle, where high temperature of fuel cell off-gas is used in GT to increase the efficiency of combined system. Another example of this type of combined cycle is designs that combine different fuel cell technologies. Examples of Type–2 hybrid systems are designs that combine a fuel cell with wind or solar power generation systems which integrate the operating characteristics of the individual units, such as their availability of power.

By definition, proposed by Winkler et al. [23], any combination of a fuel cell and a heat engine can be considered as fuel cell hybrid system. In these combinations, the heat energy of the fuel cell off-gas is used to generate further electricity in the heat engine. Here, we extend this definition to include combined heat and power systems to make this review paper extensive and exhaustive. Therefore, in this paper, a hybrid cycle can be any combination of SOFC and gas turbine (GT), steam and gas turbine combined cycle (CC), steam turbine, coal integrated gasification (IG), and integrated gasification combined cycle (IGCC) and application in combined heat and power (CHP) cycle.

In Type–1 hybrid systems, if the fuel cell is operated at atmospheric pressure, the exhaust gases can be passed through series of heat exchangers to generate either hot water and low-pressure steam for industrial applications [24] or high-pressure steam for a Rankine power plant. The latter scheme was proposed as early as 1990 [25].

The fuel cell may also operate at high pressure. In this case, the pressurized hot combustion gases exiting combustor at the bottom of SOFC can be used to drive a gas turbine with or without a bottoming steam cycle. This scheme was proposed in 1991 [26].

Among the various hybrid schemes proposed for pressurized fuel cells, probably SOFC-GT hybrid cycles are the most popular systems being studied theoretically and the only one being studied experimentally. There are two main designs to combine SOFC and GT. The difference between these designs is how they extract heat from fuel cell exhaust. In the first design, fuel cell off-gas directly passes through GT. That means the gas turbine combustor is replaced by the fuel cell stack. But in the second scheme, the fuel cell off-gas passes through high temperature recuperator which, in fact, replaces the combustor of the gas turbine cycle [27].

From operational point of view, these designs are distinguished by the operating pressure of the fuel cell. Their operating pressure is equal to operating pressure of the gas turbine and slightly above atmospheric pressure, respectively. It should be mentioned that in all cases a steam cycle [28] and CHP plants can be integrated to the hybrid system to recover more energy from exhaust.

So far, to the authors' best knowledge, there have been three proof-of-concept and demonstration SOFC-GT power plants installed in the world. Siemens claimed that it successfully demonstrated its pressurised SOFC-GT hybrid system and has two units; a 220 kW at the University of California, Irvine and a 300 kW unit in Pittsburgh [29, 30]. Also, in 2006 Mitsubishi Heavy Industries, Ltd. (MHI, Japan) claimed that it succeeded in verification testing of a 75 kW SOFC-MGT hybrid cycle [31].

As mentioned, although both SOFC and MCFC can be used in hybrid cycle, due to the cell reactions and the molten nature of the electrolyte and lower efficiency of MCFC [32] vast majority of research in this field are in SOFC hybrid cycles. There are some steady state [33, 34, 35, 36] and dynamic [37] modeling on the hybrid MCFC-GT cycles. However, the number of papers and diversity of such are not comparable with papers on SOFC hybrid cycle modeling.

The complex nature of interaction between the already complicated fuel cell and bottoming cycle make simulation and modeling an essential tool for researchers in this field. In the next section the ways to categorize SOFC hybrid cycles will be discussed.

4. SOFC HYBRID SYSTEMS MODELING CATEGORIZATION

Haraldsson and Wipke [7] summarized the key features of the fuel cells models as follows:

- modeling approach (theoretical, semi-empirical)
- model state (steady state, transient)
- system boundary (atomic/molecular, cell, stack, and system)
- spatial dimension (zero to three dimensions)
- complexity/details (electrochemical, thermodynamic, fluid dynamic relationships)
- speed, accuracy, and flexibility
- source code (open, proprietary)
- graphical representation of model
- library of models, components, and thermodynamic properties
- validation

Although they provided this for PEMFC, it could be equally applied for SOFC modeling. They described the approach of a model as being either theoretical (mechanistic) or semi-empirical. The mechanistic models are based upon electrochemical, thermodynamic, and fluid dynamic relationships, whereas, the semi-empirical models use experimental data to predict system behaviors.

The state of the model, either steady state or transient, shows whether the model can simulate system only at single operating condition or it can be used in dynamic conditions, including start-up, shut-down and load changes, too.

Spatial dimension of a model can be zero to three dimensions. Zero-dimension models only consider current-voltage (I-V) curves whereas mechanistic approaches that address governing laws including mass, momentum, and energy balances, and the electrochemical reactions need the explicit treatment of geometry [38]. This will be explained in detail later on.

It is noteworthy that the novel central part of the hybrid system is SOFC, so the categorization is mainly based on this component, although well established bottoming cycle can be considered as well.

Singhal and Kendall [16] categorized the resolution of SOFC models in four levels: atomic/molecular, cell, stack, and system. As Singhal and Kendall pointed out, “the appropriate level of modeling resolution and approach depended upon the objectives of the modeling exercise”. For instance, recommended approach for IEA Annex 42, model specifications for a fuel cell cogeneration device, was system level approach. Because the Annex 42 cogeneration models included the models of associated plant components, such as hot-water storage, peak-load boilers and heaters, pumps, fans, and heat exchangers. In addition, the systems models should be able to couple to the building models. These models simulate the building to predict its thermal and electrical demands [38].

On the other hand, the models can be categorized based on their SOFC type rather than modeling approach. For instance,

- Fuel cell type :
  - Planar
  - Tubular
  - Monolithic (MSOFC)
  - Integrated Planar (IP-SOFC)
- Cell and stack design (anode-, cathode-, electrolyte-supported and co-, cross-, and counter- flow types)
- Temperature level:
  - Low temperature (LT-SOFC, 500–650 ˚C)
  - Intermediate temperature (IT-SOFC, 650–800 ˚C)
  - High temperature (HT-SOFC, 800–1000 ˚C)
- Fuel reforming type
  - External steam reforming
  - Internal steam reforming
  - Partial oxidation (POX)
- Anode recirculation
- Fuel type

They can even be categorized by the cycles that used to form hybrid system with SOFC, such as GT, CC, IGCC, and CHP. Alternatively, purpose of the modeling like parametric sensitivity analysis, optimization, exergy analysis, economical analysis, configuration analysis, feasibility studies, partial load and transient conditions analysis can be considered for categorizing SOFC hybrid models. In this review, we will categorize and explain papers based on one of the aforementioned categories whenever appropriate.

Table 1 categorizes some of the papers in the open literature based on the criteria discussed in this section. In this table, the purposes of the papers are divided into parametric, configuration, partial load, optimization, and economical analysis. They can be identified based on the intersection of rows and columns. Also, the system or cycle which combined with SOFC to form hybrid cycle can be identified by shape of each icon. For example, square represents SOFC-GT hybrid cycle. Line type and color of each icon are used to recognize the number of geometrical axes through which the flow parameters vary and time dependency of the model, respectively. For instance, a black circle with solid line represents SOFC-CHP steady state 0-D model. Finally, the direction of the shading shows fuel cell type, i.e., tubular or planar.

There are a few points about this table that should be mentioned. First, when spatial dimension of model is not mentioned in the paper, it is shown in solid line (similar to 0-D model). Also, papers concerning feasibility study and conceptual design are considered as configuration analysis. Monolithic SOFC (MSOFC) and integrated planar solid oxide fuel cell (IP-SOFC) are considered as planar and tubular fuel cells, respectively.

	Parametric analysis	Configuration analysis	Partial load	Optimization	Economical analysis
Parametric analysis	4, 5, 6, 27		GT; Steam Turbine; CO_2 Capture; IG; CHP; — 0-D; - - >0-D; Black: Steady State; Gray: Transient or Both; Shades: Tubular, Planar, Both, Unknown		
Configuration analysis	2, 3, 8, 11, 12, 13, 21, 24, 29	9, 19, 22, 23, 25, 26, 28			
Partial load	10, 17, 30, 32		1, 31, 33, 34, 35, 36, 37		
Optimization				18	
Economical analysis	14	15, 16, 20		7, 38	39

TABLE 1: Categorization of sample papers in the open literature

1. Roberts et al. [27] and Mueller et al. [102]
2. Song et al. [32]
3. Harvey and Richter [52],[54]
4. Suther et al. [46] and Zabihian et al. [119]
5. Palsson et al. [56]
6. Chan et al. [57],[58]
7. Calise et al. [59],[79].[116]
8. Stiller et al. [60]
9. Selimovic and Palsson [61]
10. Magistri et al. [62]

11. Granovskii et al. [63],[77],[80]
12. Pangalis et al. [65] and Cunnel et al. [66]
13. Kuchonthara et al. [67],[69]
14. Tanaka et al [68]
15. Lundbergm et al. [70]
16. Rao and Samuelsen [72]
17. Song et al. [73]
18. Möller et al. [75]
19. Riensche et al. [81]
20. Franzoni et al. [83]
21. Massardo et al. [84]
22. Inui et al. [85]
23. Campanari and Chiesa [86]
24. Lobachyov and Richter [88]
25. Kivisaari et al. [89]
26. Kuchonthara et al. [90]
27. Van Herle et al. [93]
28. Braun et al. [97]
29. Winkler and Lorenz [98]
30. Steffen et al. [99] and Freeh et al. [100]
31. Costamagna et al. [101]
32. Stiller et al. [104],[105],[110]
33. Chan et al. [107]
34. Zhang et al. [108]
35. Zhu and Tomsovic [109]
36. Kemm et al. [111]
37. Lin and Hong [112]
38. Riensche et al. [113],[114]
39. Fontell et al. [115]

5. MODELING STEPS

Before starting modeling of a hybrid system, it is very important to define what the purpose of desired model is and then to determine the key features of the model. The best modeling approach and the characteristics of the model depend on the application. Although this is a vital step, there is high tendency to be oversight. After finalizing these criteria, details of the model can be identified [7].

Similar to modeling of other thermal systems, the first step in the modeling of a SOFC hybrid system is to understand the system and translate it into mathematical equations and statements. The common steps for model development are as follows:

- specifying a control volume around desired system,
- writing general laws (including conservation of mass, energy, and momentum; second law of thermodynamics; charge balance; and so on),
- specifying boundary and initial conditions,
- solving governing equations by considering boundary and initial conditions (analytical or numerical solution),
- validating the model.

Although fuel cell simulation is a three dimensional and time dependent problem, by proper assumptions it can be simplified to a steady state, 2-D, 1-D, or 0-D problem for different applications and objectives [12].

As it will be shown later on, most of the SOFC hybrid system simulations in the open literature are 0-D models. In this type of modeling, series of mathematical formulations are utilized to define output variables based on input ones. In this approach, fuel cell is treated as a dimensionless box and that is why some authors referred it as box modeling. Despite the large numbers of assumptions and simplifications in this method, it is useful to analyze the effects of various operational parameters on the cycles overall performance, perform sensitivity analysis, and compare different configurations.

When the objective of modeling is to investigate the inner working of SOFC, 0-D approach is not appropriate. However, for hybrid SOFC system simulation, where emphasize is placed on interaction of fuel cell and rest of the system and how fuel cell can affect the overall performance of the system, this approach can be suitable.

In this level of system modeling, there are variety of assumptions and simplifications. For instance, Winkler et al. [23] developed a hybrid fuel cell cycle and assumed that the fuel cell was operated reversibly, representing any fuel cell type, and the heat engine was a Carnot cycle, representing any heat engine.

Different software and programming languages have been used in hybrid SOFC systems simulation. Since there is no commercially available model for SOFC stack, all modelers should prepare their own model with appropriate details and assumptions. Therefore, from this point of view, what differentiates models is how they simulate the other components of the system. Generally, they can be divided into two categories. In the first approach, whole models can be developed in programming languages such as Fortran or high level software such as MATLAB/Simulink® platform to solve governing equations of the system. In the second approach, the modelers can take advantage of commercial software such as Aspen Plus® to model conventional components of the cycle. These approaches will be discussed in detail later on.

Due to the nature of numerical modeling, its results should be used carefully. In every modeling, the physical realities of the system should be translated into mathematical equations and solution of these equations is used to express behavior of the system. In case of fuel cells, the physical realities are extremely complex and some of which are completely unknown. Therefore, in order to extract these governing equations, high level of assumptions and simplifications should be considered which in turn introduce inaccuracy to the final results. This means fuel cell models are a “simplified representation of real physics” and even with appropriate validation accuracy of their results cannot be guaranteed [14].

For instance, one should be aware of the possible problems that can arise when local equations are considered as global. Bove et al. [39] highlighted such problem in their paper. They described the main problem of using 0-D approach for modeling was the negligence of variation in the fuel, air, and exhaust gas compositions through the fuel cell. As a consequence of this problem, when the inlet, outlet or an average value of the gas composition was used in the modeling, different results could be obtained. In particular, it was shown that it was impossible to evaluate effects of fuel utilization variation through the fuel cell when inlet gas composition was considered. On the other hand, considering output streams composition could result in underestimating cell voltage and power output.

However, Magistri et al. [40] studied simplified versus detailed SOFC models and how this affected the predictions of the design-point performance of the hybrid systems. They emphasized the usefulness of the simplified model for hybrid system design and off-design analysis and detailed model for complete description of the SOFC internal behavior. More discussion and examples on this issue can be found in section “2-Dimentional models”.

Judkoff and Neymark [41] classified the sources of simulation errors into three groups (these were provided for building simulation programs, but they were equally applicable to SOFC hybrid systems simulation):

- Errors introduced due to assumptions and simplifications,
- Errors or inaccuracies in solving mathematical equations,
- Coding errors.

They also proposed a pragmatic, three-step approach to identify these errors. In the first approach, comparative testing, the results of the model should be compared with the results of other models for the same problem with the similar initial and boundary conditions. If the results of the models match with acceptable error, it means the implementations are acceptable. However, this does not guarantee the correctness of the results because they all can be incorrect. In the second approach, analytical validation, the results of the model for a simple case are compared with the results of available analytical solution. Finally, in empirical validation the results of the simulation are compared with real data from the actual system under laboratory or field conditions.

Finally, the validation of a model is important because a model must be validated to be a credible tool. Appropriate data are needed for validation. With limited resources, this can be difficult because most data cannot be found in the open literature. Although performance data from an entire hybrid power generation systems are usually proprietary and are not available in the literature, this information from single system is easier to find. Therefore, a way to resolve the problem of limited performance data is to develop and validate well defined sub-system models, and then integrate them to have a complete model of a large hybrid power generation system.

Although SOFC is considered as the heart of these hybrid cycles, its detailed mathematical modeling and simulation methodology is not included in this review. The focus here is on the evaluation of overall system performance and not its components performance. One can refer to references [10, 11, 12, 13, 14] for review papers on SOFC modeling. In addition, some good examples of such simulations can be found in [42, 43] for steady state and [44, 45] for transient and dynamic modeling.

6. A DETAILED EXAMPLE OF SOFC-GT HYBRID CYCLE

The purpose of this section is to explain the general steps discussed earlier in the context of a real example from the open literature. Suther et al. [46] developed a steady state thermodynamic model of a hybrid SOFC-GT cycle using a commercial process simulation software Aspen Plus®. Their hybrid cycle model incorporated a 0-D macro level SOFC model. As noted, there is no built-in SOFC model available in this software. Therefore, they first developed 0-D model of a SOFC stack using Fortran programming language as user defined model in Aspen Plus®.

Aspen Plus® is a computerized process simulation tool that can be used for realistic steady state simulation of thermodynamic cycles. In this software, built-in and user defined models can be connected with material, work, and heat streams to form a model of an actual system [47].The user defined models can be created using Fortran, Aspen Custom Modeler®, or Microsoft Excel®. There are various physical property models that can be selected for the flow sheet calculations [47]. One of the inherent characteristic of Aspen Plus® is its sequential modular approach to modeling. That means each component, either built-in or user defined models, is treated independently and calculation results for each block are considered the input for the next block [39].

Therefore, the model was consisted of two main parts; the cycle model with various equipments and the SOFC model. The cycle model included all required system equipments such as fuel reformer, compressors, combustor, heat exchangers, mixing chambers, pump and the fuel cell stack which were linked together with material and energy streams. The SOFC stack model was developed using fundamental equations of thermodynamics, chemical reactions, and electrochemistry. For chemical reactions, they assumed three reactions taking place within the SOFC: reaction of H_2 with O_2 forming H_2O, methane steam-reforming reaction, CO shift reaction. They used electrochemical calculations to estimate the power output of SOFC. In order to estimate actual operating voltage of the SOFC, the open-circuit voltage was first calculated, and then the three overpotentials (losses) namely, the activation, ohmic, and concentration losses were deducted. The thermodynamics equations were also applied to estimate the heat output from the stack and the outlet temperature.

The model constants were determined by using the data from Siemens-Westinghouse SOFC systems [29, 30] as well as considering the ranges available in the literature. As a last step for stack modeling, the model was validated using experimental data from Siemens Westinghouse SOFC [29, 30]. They found that the model fitted the data well especially at medium and high current densities. After integrating all equipments, they were able to investigate two configurations with the same model: with the anode exhaust recirculation and with the heat recovery steam generator, both for maintaining the steam-to-carbon ratio of the reformer. They carried out parametric study using this hybrid model. The results will be explained later on.

Next section will highlight very early modeling experience on SOFC hybrid cycles in the open literature.

7. EARLY MODELS

The SOFC development has started in the late 1950s, the longest continuous development period among various types of fuel cells [4]. However, it was not until the mid 1980s that results of first simple SOFC models were published in the open literature. For SOFC hybrid cycle, the first papers were being published in early 1990s.

Dunbar and Gaggioli have been considered as pioneers in the field of SOFC modeling and their integration with Rankine cycle. They published their first paper on the results of mathematical modeling of the performance of solid electrolyte fuel cells as early as 1988 [48]. In 1990 [25], they proposed integrating SOFC units into a conventional Rankine steam cycle power plant. That study revealed significant efficiency increase, up to 62%, compared to the maximum conventional plant efficiency of about 42% in those days [25]. They found that the main reason for this efficiency improvement was higher exergetic efficiency of SOFC as contrasted with the combustion process in conventional fossil fuel fired power plants [49]. They also investigated [50] the exergetic effects of the major plant components as a function of fuel cell unit size. The results showed that specific fuel consumption might be reduced by as much as 32% in hybrid cycle.

Harvey and Richter, who proposed a hybrid thermodynamic cycle combining a gas turbine and a fuel cell, are the pioneers in this area. Harvey et al. [51] first proposed the idea in 1993 by conducting one of the earliest modeling works in SOFC-GT hybrid cycle. They developed a model [52] to simulate monolithic SOFC (MSOFC) combined with intercooled GT in Aspen Plus® and a fuel cell simulator developed by Argonne National Laboratory [53]. They found that for a power plant with net electricity generation of 100 MW, about 61 MW were produced by the SOFC with the thermal efficiency of 77.7% (lower heating value, LHV). In addition their second law analysis noted the large exergy destruction in SOFC, combustor, and air mixer. They concluded that internal reforming could improve both system efficiency and its simplicity.

In their following paper [54], they improved the model by incorporating internal reformer to the cycle and taking into account all major cycle overpotentials. This time the cycle efficiency was 68%. Moreover, they noted that the system efficiency increased with cycle pressure. They determined that maximum efficiency could be achieved at system operating pressure equal to 15 bar while satisfying the system constraints. They also compared efficiency of cycle with internal and external reforming and surprisingly found that their efficiencies were almost identical. The thermodynamics second law analysis showed that exergy destructions in internal reforming cycle were marginally higher than those of external reforming cycle (275 versus 273 MJ/s).

For the successful integration of the SOFCs with other power generating technologies such as gas turbines, models that can accurately address steady state and dynamic behavior of systems with different configurations, optimization, fluctuating power demands and techno-economic evaluation are required. In the next sections, models that addressed these objectives will be discussed.

8. PARAMETRIC STUDIES

One of the primary aims of any system simulation is to evaluate the effects of various parameters on system performance. By doing so, the most influential parameters can be identified. In turn, these parameters should be considered for system optimization within system constraints.

The curves in Figure 1 are presented to quickly summarize the results of these parametric studies in the literature. For instance, if a performance parameter is linearly increasing, Curve 2 will be referred to describe the trend [55].

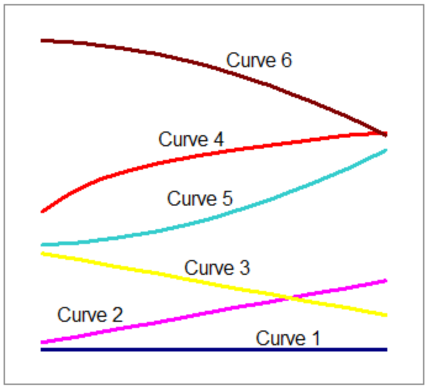

FIGURE 1: Performance parameter symbolic curves [55].

The first study to be reviewed in this section is presented by Suther et al. [46]. The model has already been explained in “A detailed example of SOFC-GT hybrid cycle” section. They studied the effects of system pressure, SOFC operating temperature, turbine inlet temperature (TIT), steam-to-carbon ratio (SCR), SOFC fuel utilization factor, and GT isentropic efficiency on the specific work output and efficiency of two generic hybrid cycles with and without anode off-gas recirculation.

They chose specific work output (actual work divided by air mass flow rate) and cycle efficiency as two main performance parameters. The high specific work output was preferred because it meant lower air flow rate was required for the same system power output, which translated into smaller equipments.

They found cycle specific work and thermal efficiency with respect to system parameters to follow curves in Figure 1 as follows:

- Specific work and efficiency with respect to system pressure followed Curve 4 and Curve 5 for system with anode off-gas recirculation and Curve 4 and Curve 2 for system without anode off-gas recirculation, respectively.
- Specific work and efficiency with respect to SOFC operating temperature followed Curve 3 and Curve 2, respectively, for both systems with and without anode off-gas recirculation.
- Specific work and efficiency with respect to TIT followed Curve 2 and Curve 3, respectively, for both configurations.
- Specific work and efficiency with respect to SOFC current density followed Curve 3 for both configurations.
- Specific work and efficiency with respect to SCR followed Curve 2 and Curve 3, respectively, for both configurations.
- Specific work and efficiency with respect to SOFC fuel utilization factor followed Curve 5 and Curve 2 or 3 (depending on GT isentropic efficiency), respectively, for both configurations.

The results showed that the cycle efficiencies with and without anode off-gas recirculation were very close with variation in many of the system parameters.

Palsson et al. [56] developed a steady state model for a combined SOFC-GT system featuring external pre-reforming and recirculation of anode gases in Apsen Plus® by using their SOFC model as a user defined unit and other components modeled as standard unit operation models. In order to model SOFC, they used 2-D model of planar electrolyte-supported SOFC.

The finite volume method was used to discretize cell geometry by considering resistance and activation polarisation. Their system size was 500 kW because they believed this was proper size for demonstration and market entry purposes. It should be noted that they added primary fuel to increase TIT but they maintained fuel flow to the system constant. Furthermore, in order to provide heat for district heating system, they added a cooler to cycle exhaust stream. This simple cooler limited the exhaust temperature to a specific value (80 ºC). They studied various system parameters, including the electrical efficiency, specific work, TIT, and SOFC temperature with respect to the pressure ratio. Their sensitivity studies revealed that these parameters varied according to Curve 6, Curve 4, Curve 2, and Curve 1, respectively. Moreover, the electrical efficiency and SOFC temperature varied with respect to the cycle inlet air flow rate according to Curve 3 and Curve 2, respectively. They found that increasing TIT did not improve system efficiency and specific work. Because in order to increase TIT, more fuel should be combusted at GT combustion chamber, thus less fuel remained to be consumed in SOFC unit. Their analysis showed that system operating pressure had great impact on hybrid system performance. At lower pressure ratios (PRs), the efficiency increased slightly to an optimum point and then sharply decreased for higher PRs. A maximum efficiency of 65% could be achieved at a pressure ratio of 2. At this point the GT output was almost zero; therefore, this efficiency was equal to SOFC efficiency. The slight improvement in system efficiency stemmed in increased efficiency of SOFC. At higher PRs, more power output from the gas turbine and less from the SOFC decreased system overall efficiency. In addition, they pointed out that cell voltage had no impact on system performance. Similarly, they investigated the performance improvement of the system when the intercooling of air compressor and gas turbine reheat were added and found that their application would not be worthwhile because of their relatively small impact, particularly for the reheat case.

The discrepancy between the results of Suther et al. [46] and Palsson et al. [56] is due to the different control strategies of the two systems. In the former, the fuel flow was kept constant when varying the system operating pressure. But in latter, as mentioned earlier in this section, although the total fuel flow rate was held constant, part of this fuel fed to the gas turbine combustor to sustain the turbine exhaust temperature in specified range. Therefore, in the case of Palsson et al. [56], at high system operating pressures more fuel combusted in the GT combustor resulting in more work to be generated in GT at lower efficiency, which in turn lowered cycle overall efficiency.

Chan et al. [57, 58] developed a model of simple SOFC-GT-CHP power system and performed the first law of thermodynamics energy analysis on the model. Their model achieved electrical and total efficiencies of over 62% and 83%, respectively. Then, they investigated the effects of system operating pressure and fuel flow rate on the system overall performance. They showed that system efficiency with respect to pressure and fuel flow rate followed Curve 2 and 3, respectively. Their results and Palsson et al. [56] results do not show the same trend. The reason is similar to what was explained in previous paragraph.

Calise et al. [59] investigated the impacts of current density, system operating pressure, fuel-to-oxygen ratio, water-to-methane ratio, and fuel utilization factor on the electrical efficiency of a hybrid SOFC-GT system and found the electrical efficiency to follow Curve 3, Curve 4, Curve 4, Curve 1, and Curve 2, respectively, when varying these parameters. They also showed that increasing the fuel utilization factor of SOFC could slightly improve cycle performance. In contrast with the fuel utilization factor, the effect of SCR was not favorable. It was stated that this was as a results of more energy being used to generate steam in heat recovery steam generator and less energy for power generation. These results are in agreement with Suther et al. [46] results.

9. 2-DIMENSIONAL MODELS

As noted earlier, one method to categorize SOFC models is based on the number of geometrical axes through which the flow parameters vary, namely, 0-D, 1-D, 2-D, or 3-D models. It should be noted that, in this review, dimension of the model is defined by SOFC model dimension not the other components. Due to the objective and complexity of hybrid SOFC cycle modeling, most of the simulations in the open literature were 0-D. However, there are some papers that used multi-dimensional approach to model SOFC stack such as Palsson et al. [56] which was discussed previously and Stiller et al. [60] which will be explained later on. In this section, one example of such models will be reviewed.

Song et al. [32] developed a model to evaluate the impacts of system parameters on the performance of the hybrid tubular SOFC-micro gas turbine (MGT) system. They used quasi-two dimensional approach in their model. In this approach, in order to achieve a two-dimensional model, fuel cell was discretized into number of one-dimensional sections and they were dynamically coupled (input of i^{th} section = output of $(i-1)^{th}$ section) [14], as shown in Figure 2. To implement this approach, they divided the fuel cell tubes into segments, considering control volumes around air and fuel streams for each segment. For each control volume, heat and mass transfer, electrochemical reactions, reforming, and steam shifting were considered. The heat transfer was assumed to be in the longitudinal direction through the walls that separate the streams. In addition, the mass transfer and electrochemical reactions were considered in the longitudinal and perpendicular direction, respectively.

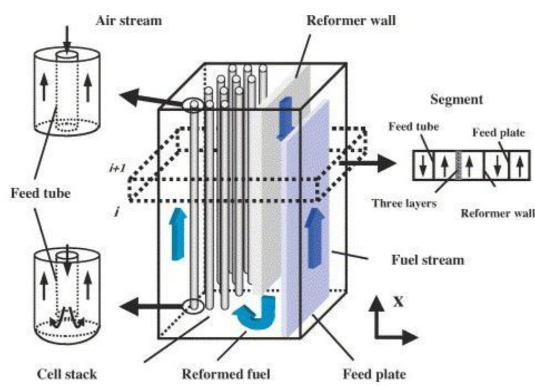

FIGURE 2: Tubular SOFC discretization along longitudinal direction for quasi-two dimensional model [32].

The most important parameter influencing the accuracy of this approach was proper selection of the number of segments along the longitudinal direction of the SOFC tubes. It was shown that the distributions of cell temperature along the longitudinal direction tended to converge to a specific pattern when the number of segments increased. This, again, shows the importance of reasonable and accurate assumptions, in this case the number of geometrical axes through which the flow parameters vary. For instance, in the lumped model (when the number of segments is equal to one) the mean value of cell temperature was underestimated in comparison to the converged quasi -2-D model (about 900℃ vs. 930 ℃). Also, in the lumped model the temperature difference along the length of the SOFC (74.1℃) was neglected.

Furthermore, they evaluated and compared system performance for different configurations, including co- and counter-flow SOFC, systems with and without pre-reformer, and various catalyst densities of reformer. They found that, for instance, although flow direction did not have significant impact on SOFC efficiency, the hybrid system efficiency for co-flow SOFC was higher than that of counter-flow SOFC (about 60% vs. 58%). As a result, they concluded that the system configuration and its component characteristics could significantly influence hybrid system performance.

10. MODELS FOR COMPARISON OF CONFIGURATIONS

As stated, an important objective of hybrid SOFC systems modeling is to predict system performance for different configurations. There have been huge number of proposed hybrid SOFC systems in the open literature that combined SOFC stacks with heat exchangers, compressors, GTs, pre-reformers, mixers, heat recovery steam generators (HRSGs), CO_2 capture, combustors and so on (such as Campanari et al. [28]). However, there have been no universally accepted configuration(s) yet and scientists are still trying to propose innovative cycles for the SOFC hybrid systems. In this section, various configurations proposed in the open literature for stack and equipments will be reviewed.

Stiller et al. [60] developed 2-D planar and 1-D tubular SOFC models to simulate SOFC-GT hybrid cycle. They investigated effects of different parameters such as pressure ratio, air inlet temperature and so on to compare performance of two cycles. It was shown that hybrid systems could achieve efficiencies above 65% with both planar and tubular SOFC. The main difference between the planar and the tubular SOFC cycles was the internal pre-heating of the air in the tubular system which allowed a lower air inlet temperature to the stack. This reduced the amount of required high temperature heating in the pre-heating. This effect was compensated by lower efficiency of the tubular fuel cell stack, due to its higher ohmic loss.

Selimovic and Palsson [61] investigated the effect of networked SOFC stacks, i.e., using two smaller stacks in series (in terms of fuel and air flow) instead of conventional one stage stack. They used same model as [56], with minor modifications. They showed that for a stand-alone SOFC, fuelled by hydrogen or 30% pre-reformed methane, dividing the single stage stack into two smaller stacks in series (staged stacks) increased the power output by 2.7% and 0.6%, respectively. The reason stemmed in increased uniformity of current density in staged system. Then, they examined SOFC-GT hybrid cycle fuelled by natural gas (NG) for two options, both the air and fuel stream in series (network A) or only the fuel stream in series and air stream divided (network B). The results signified that there was 4.7% points performance improvement in network A, whereas efficiency was reduced by 1.5% points for network B. They concluded that for relatively small stacks, networked stacks could reduce cooling demand of the cells, so they were preferred.

Magistri et al. [62] developed a model to investigate the performance of a hybrid system consisting of integrated planar SOFC (IP-SOFC), GT, and district heating. They found that overall efficiency of atmospheric hybrid system was 10% lower than that of pressurized system.

In 2007, Granovskii et al. [63] presented results of their simulation of combined SOFC–GT system for two possible configurations to provide required steam-to-methane ratio (in all cases higher than 2 [64]), cycle with anode exhaust recirculation and cycle with HRSG for steam generation. They also added a Rankine steam cycle at the bottom of GT for the configuration with anode exhaust recirculation. They preformed energy and exergy analysis on the models and determined that the suitability of these schemes depended on the application of the power generation system. For example, although configuration with anode off-gas recycle had higher exergy and energy efficiencies, the other scheme was associated with a higher power generation capacity.

Pangalis et al. [65] and Cunnel et al. [66] modeled and compared six different configurations of hybrid SOFC-GT systems by considering variety of features in each system, including combustion chamber, recuperator, intercooler, and reheat SOFC stack. They showed that both thermal efficiency and net specific power versus compression ratio for most of the configurations followed Curve 4. They found that the optimal configuration in terms of efficiency could be achieved when GT with intercooler and recuperator were integrated to primary SOFC (ahead of the combustor) and reheat SOFC (between high- and low- pressure GT) with efficiency of 76%. Also, they showed that in configuration with intercooler and recuperator integrated to primary SOFC, the net specific power was maximized. Again, they concluded that the most important factor for selecting hybrid SOFC system configuration was the application of power plant. For example, recuperated GT with SOFC ahead of combustor with thermal efficiency of 64% at relatively low pressure ratio of 14 and the specific power of 520 kW/kg was probably the most suitable configuration for small and medium scale power generation.

Kuchonthara et al. [67] developed their hybrid SOFC model by writing a Fortran code for SOFC and running it in Aspen Plus®. They conducted a parametric analysis on two hybrid SOFC system configurations: hybrid SOFC-GT with heat recuperation (HR) system and hybrid SOFC-GT with heat and steam recuperation (HSR) system. In the former, heat from the GT exhaust was recovered by an air preheating system whereas, in latter, an air preheating system and a HRSG were used for this purpose. In HSR system, in order to increase net mass flow and power output of GT, the generated steam was directly injected into the combustor. They found that GT power output and system overall thermal efficiency were higher in HSR configuration, due to higher energy recuperation rate in this configuration. Also, they illustrated that higher pressure ratios increased the synergetic effect of steam recuperation. Furthermore, their parametric analysis showed that the SOFC work, GT work, TIT, and thermal efficiency with respect to the SOFC fuel utilization factor varied according to Curve 2, Curve 3, Curve 3, and Curve 4, respectively. Also, the cycle specific work and thermal efficiency with respect to the TIT followed Curve 5 and Curve 6, respectively.

They evaluated the overall efficiency of the cycle against TIT for different pressure ratios (PRs). They found that, at low TITs, the thermal efficiency decreased when pressure ratio increased. This was due to lower fuel utilization factor in SOFC for higher PRs. In contrast, higher PRs led to thermal efficiency improvement at high TITs due to larger GT power output. It seemed that their results completed previous studies [46, 56, 68] on the effect of TIT on cycle's overall performance. As a result, they suggested that optimal system (both high power output and high efficiency simultaneously) could be achieved when system operated at high TIT with an optimal pressure ratio.

Similarly, they published another paper [69] to evaluate performance of hybrid systems when SOFC cycle integrated with various enhanced gas turbine cycles namely, steam injected gas turbine (STIG) cycle (including additional air preheating), GT-steam turbine (ST) combined cycle, and humid air turbine (HAT). They assessed effects of operating conditions, such as TIT and PR, on the overall efficiency and specific work output of the system. They concluded that SOFC–HAT system, operating at high TIT and PR, not only could significantly improve system performance, but also could lessen the problem of water supply by reducing water consumption.

One of the challenges in SOFC hybrid systems development is to find a gas turbine that matches the requirements of hybrid cycle. Lundbergm et al. [70] studied the possibility of 20 MW-class hybrid system that integrated a pressurized SOFC with a Mercury 50 gas turbine. The Mercury 50 was chosen due to its unique characteristics, including high thermal efficiency, power rating, modular design, reliability, and low cost of maintenance. They determined the optimal size of pressurized SOFC (PSOFC) in a hybrid system with a single Mercury 50 gas turbine using the cost of electricity (COE) as the optimizing parameter. Minimum COE was achieved when four PSOFC modules and one Mercury 50 gas turbine were integrated to generate approximately 12.5 MW at an efficiency of nearly 60% (Net AC/LHV). They also explained the required modification on commercially available GTs. Furthermore, they studied different bottoming cycle options (combined cycle power plant and ammonia-water cycle) to utilize thermal energy at GT exhaust.

On the other hand, most of the works performed on the modeling of hybrid SOFC and GT concentrated on the fuel cell operation using the performance characteristics of existing GTs. However, different operating conditions of GT (i.e., the increased pressure losses) in hybrid cycle shifts the operating point of compressor and GT to an off-design areas. Sieros and Papailiou [71] examined the optimal fitting of a small GT in a hybrid SOFC-GT for both design-point and part-load operation conditions. They proposed variable geometry components, namely variable nozzle turbine and variable diffuser compressor to avoid compressor surge and increase part-load efficiency. They concluded that further work should be performed for the detailed design of these devices.

Rao and Samuelsen [72] introduced SOFC cycle coupled with intercooled-reheat GT as reference power generation system for their thermodynamic modeling. Then, they formed their alternative cases by incorporating HAT system to their reference case and also replacing reheater with second SOFC (dual SOFC-HAT). They found that efficiency of the reference case and its alternatives were 66%, 69%, and 76%, respectively. In addition, they showed that the second scenario could achieve lowest cost of electricity (COE).

Song et al. continued their previously explained work [32] in another research [73]. They extended their model to find optimal matching between a commercially available GT (Mercury 50) and a SOFC unit. The parameters to be matched were included: operating temperature, pressure and operating strategies and maximum allowable cell temperature as a limiting parameter. Based on the selected condition, the total system power at design-point condition was 11.5 MW at a system efficiency of about 59%. In comparison to the power ratio of SOFC and GT in kW-class cases described in Veyo et al. [30], the power ratio of this system was very low. Their results agreed with results found by Lundbergm et al. [70].

11. OPTIMIZATION

A quick survey of the literature in the modeling of hybrid SOFC systems shows that little has been done for optimization of these systems. In most of those few works, such as [74], sensitivity analysis of various parameters was preformed to develop an optimal SOFC hybrid power generation system. However, due to the large number of parameters involved and complex nature of their interrelation and correlation, suitability of this optimization method is controversial.
In optimization of a typical SOFC hybrid cycle 5 to 10 (or even more) [75] independent variable should be considered, depending on how complex the system and model are. Therefore, it is vital to seek for methods that can optimize these non-linear multi-dimensional systems [75].

In a considerable development in the optimization of SOFC-GT systems, Möller et al. [75] deployed genetic algorithm (GA) to optimize SOFC-GT configuration with and without a CO_2 separation plant. In order to model the SOFC stack, they used the same model as in [56]. In their optimization, the electrical efficiency was selected as the objective function. Also, the air flow, fuel flow, cell voltage in the stack, air temperature at the stack inlet, reformer duty, and pressure ratio were selected as decision parameters. The optimization procedure resulted in a SOFC-GT system with above 60% efficiency when equipped with CO_2 capture. The results showed that the system efficiency was greatly influenced by SOFC temperature. Furthermore, a low air flow and no or little supplementary fuel could improve the system efficiency.

12. EXERGY ANALYSIS

According to Dincer and Rosen [76] exergy analysis is a method that can be applied to design, improve, and analyze the energy systems. This technique considers the second law of thermodynamic as well as the conservation of mass and energy, simultaneously.

Granovskii et al. [77] evaluated the importance of exergy analysis in applying the “principles of industrial ecology” for integrating different technologies. For instance, they preformed exergy analysis on a SOFC-GT hybrid system and found that the depletion number of standalone SOFC and GT were much higher than that of hybrid system. This confirmed that the SOFC-GT hybrid system was more environmentally friendly.

The depletion number, proposed by Connelly and Koshland [78], is a concept to describe the efficiency of fossil fuel consumption according to exergy analysis and is defined based on how exergy destruction within a system is related to total exergy input.

Calise et al. in previously mentioned paper (in parametric studies section) [59] and their other paper [79] (with a few changes in system configuration) preformed the second law of thermodynamics analysis on a gas turbine cycle integrated with SOFC. Their exergy analysis illustrated that the SOFC stack and the catalytic burner were responsible for most of exergy destruction, respectively, when the hybrid system operated at design-point. This high rate of exergy destruction stemmed in inefficiencies of chemical reactions occurring in those equipments. Despite the high efficiency of SOFC, fuel cell stacks are the greatest source of exergy losses due to the number of chemical and electrochemical reactions, such as steam reforming and electrochemical oxidation, taking place simultaneously. Similarly the catalytic burner, where anode off-gas stream was combusted, demonstrated a significant exergy destruction rate. On the other hand, exergy destruction rate of turbomachineries were not remarkable because of their high isentropic efficiencies and low energy flows. They also preformed exergy analysis on partial load operation and found that although exergy destruction generally increased, its rate depended on the selected control scheme. Finally, they concluded that in hybrid energy systems design, particular emphasizes should be placed on component with highest exergy losses, i.e. SOFC stacks.

In their other paper, Granovskii et al. [80] presented exergetic performance analysis of a SOFC-GT hybrid cycle. They found that the SOFC stack and the combustion chamber were the components with highest rate of exergy destruction, respectively, similar to results of Calise et al. But in their model the difference in exergy losses of SOFC stack and combustion chamber was less than 5%.

13. CO_2 CAPTURE

Although SOFC hybrid power plants are considered to be the cleanest technology to generate electricity from fossil fuels (due to their high efficiency and minimal fuel combustion), still there is considerable amount of CO_2 in their exhaust. Therefore, integrating CO_2 separation technologies to SOFC hybrid plants is an active field of research. In this section, some of the models for such plants will be discussed.

In 1999 Riensche et al. [81] developed a model to simulate a near zero CO_2 emission hybrid SOFC-GT power plant. Their adiabatic tubular air electrode supported fuel cell model was based on one of the earliest planar SOFC model [82]. There are two approaches to separate CO_2 in the exhaust stream of power plants. In one of these approaches, the spent fuel is combusted with pure oxygen, instead of air, to avoid introducing nitrogen to the plant's off-gas stream. In their proposed model, they made use of one of the unique characteristics of SOFC cycle that other technologies cannot easily compete. They modeled a bank of oxygen ion conducting tubes (very similar to SOFC tubes) and passed the unused fuel over them. They found that system operation was optimal when the system was pressurized. It was concluded that a gross electric efficiency of about 50% to 60% for the tubular SOFC and 60% to 70% for the SOFC-GT combination were achievable in this configuration.

Franzoni et al. [83] developed a model to simulate 1.5 MW SOFC-GT hybrid system based on the model explained in [84]. They compared performance of the hybrid plant when it was integrated with two CO_2 capture technologies, namely fuel treatment and then separation of CO_2 in exhaust by chemical absorption and combustion of spent fuel with pure oxygen. In the former approach, they observed 17% efficiency penalty, from 62% to 45% with 0.15 $kgCO_2/kWh$ of CO_2 in exhaust. In second approach, the system was equipped with an air separation unit to provide oxygen for GT combustor. The efficiency loss in this case was much lower at 3.6% with near-zero CO_2. The thermoeconomic analysis showed that the cost of second plant was significantly lower.

With the same method, Inui et al. [85] used second approach (pure oxygen as the oxidant gas in GT combustion chamber) for CO_2 capture. They found that the efficiency of cycle could reach as high as 71% (LHV) indicating that the proposed system could satisfy both expectations of high efficiency and ultra clean power generation.

Campanari and Chiesa [86] compared performance of SOFC-GT cycle with two configurations for CO_2 capture process. In the first scheme, steam and CO_2 in the anode exhaust was separated by condensation and chemical absorption, respectively. Then, 30% of remaining fuel combusted in GT combustor and the rest was recycled to anode to be consumed in SOFC. In second scheme, CO in anode exhaust was converted to H_2 in shift reactor. Then, existing CO_2 was chemically absorbed, and hydrogen rich gas combusted in GT combustion chamber. The SOFC model for this plant was explained in [87]. The results showed that both plants exceed 71% (LHV) efficiency and removed 90% of CO_2 in exhaust stream. Although utilization of the shift reactor increased complexity of second scheme, it took advantage of more desirable GT to SOFC power output ratio (0.29 vs. 0.20), a lower consumption of the auxiliaries (5.5% vs. 8.2% of the net output), and better potential to increase CO_2 sequestration.

14. FUEL FLEXIBILITY

So far, in all models either natural gas or hydrogen has been considered as fuel. However, SOFC hybrid systems enjoy the advantage of being able to utilize other fuel sources. In this section, some models that use coal and biogas as fuel will be discussed.

In one of the earliest works in this field, Lobachyov and Richter [88] presented results of their theoretical study on the system that incorporated a coal gasification process into hybrid SOFC-GT cycle, which the latter was proposed by Harvey and Richter [52]. They suggested recycling of part of the hot cathode off-gas to provide the heat required for gasification. They preformed energetic and exergetic analysis on the model. They found that the cycle could achieve up to 60% efficiency (energetic). Exergy analysis revealed that the gasifier, SOFC, and steam generator were responsible for most of exergy destruction. In addition, the integration of a two-stage GT with reheater and steam turbine at the bottom of GT resulted in 0.5% and 3.2% improvement in the system overall efficiency, respectively.

Kivisaari et al. [89] preformed a feasibility study for integration of a high temperature fuel cell (either MCFC or SOFC), a gas production unit based on coal gasification and an existing networks of heat distribution among residential users (CHP plant). They considered a thermal input of 50 MW with and without anode off-gas recirculation for SOFC. They employed a one-point model to reduce calculation times and model complexity. They found that the introduction of the anode off-gas recirculation resulted in 12% increase of the power output from the SOFC because of the almost 10% increase in overall fuel utilization. These values, however, could not be trusted because their one-point model did not consider reduction in the concentration of the reacting streams. They observed that the final system, which was a combination of a gasifier, a standard low temperature gas cleanup and SOFC, could achieve an electrical and overall efficiency of about 47% and 85%, respectively.

Another study on combination of coal gasification and fuel cell for power generation was presented by Kuchonthara et al. [90]. They considered the integrated power generation cycle combining with thermochemical recuperation, brown coal gasification and a SOFC. In order to model SOFC they used the same model as in [67, 69]. Their simulation indicated that the cycle efficiency could be increased from 39.5% (higher heating value, HHV) without the SOFC to about 45% with the SOFC.

Rao et al. [91] performed thermoeconomic analysis of integrated gasification fuel cell (IGFC) plant and compared it with an integrated gasification combined cycle (IGCC). They showed that the cost of electricity of IGFC plant was compatible with that of the IGCC plant (based on $400/kW installation cost for SOFC stack).

Sucipta et al. [92] used similar model as Song et al.'s [32] and added different biomass gasification processes, namely, air-, oxygen- and steam-blown, to analyze the effect of biomass fuel composition on SOFC-GT performance. They found that efficiencies level for all three cases were reasonably high (although lower than the reference case fueled with pure methane) and concluded that the biomass fueled SOFC–MGT hybrid system was suitable alternative for conventional power plants. They pointed out that air- and steam-blown biomass fuel had the lowest and highest efficiency, respectively, for both SOFC module and for the entire hybrid system.

Van Herle et al. [93] performed the energy balance analysis on an existing biogas production unit, equipped with a 1 kW SOFC demonstrational stack as a small CHP system. The fact that they used some real data for their model and, to some extent, compared the results with measurement from the site made this paper among a few exceptions in this respect. They achieved almost 34% and 58% electrical and cogeneration thermal efficiency, respectively. The results were validated by the natural gas fueled Sulzer Hexis 1 kW systems with an electrical efficiency of 35% (direct current (DC), LHV) [94].They also compared two reformer technologies, i.e., steam reforming and partial oxidation reforming with air (POX). They also investigated the impacts of water addition for steam reforming process and observed that cogeneration thermal efficiency significantly decreased with water addition. This was due to the fact that there was no condensation in the exhaust to recover the evaporation heat consumed at the inlet.

They assessed electrical and total efficiency of the system as a function of operating parameters such as CO_2 fraction in the biogas feed, reforming conditions, air excess rate, SOFC stack temperature (followed Curve 4 and 5, respectively), and pressure (followed Curve 3 and 2, respectively). They showed the variation in electrical efficiency, when varying the CO_2 fraction in the biogas feed between extreme composition limits. Probably unexpectedly, they stated that efficiency increased when more methane was replaced by carbon-dioxide. In other words, the system performance improved when fueled with poorer biogas (richer in CO_2). They explained that higher methane content in inlet biogas fuel resulted in higher input LHV, which led to higher current, thus to higher ohmic overpotential and lower SOFC operating voltage.

They also indicated that electrical efficiency reduced when system was pressurized. Clearly, this was in contrast with other studies such as Suther et al. [46] and Chan et al. [57]. The reason could be explained based on the fact that their model did not consider two positive impacts of higher system operating pressure: more work output when high pressure hot exhaust passed through GT and improved mass transfer which led to lower electrode overpotentials. Whereas, more compression work to pressurize inlets streams reduced net work output.

15. DIFFERENT APPLICATIONS (NON-STATIONARY ELECTRICTY GENERATION)

Stationary power generation plants are not the only application of SOFC hybrid cycles. The residential CHP, mobile application, and auxiliary power unit for vehicles and aircrafts are considered as potential applications of SOFC hybrid cycles. In this section a few simulations that addressed these applications will be presented.

Nowadays, distributed generation (DG) of combined heat and power (CHP) cycles are gaining increasing attentions. This is due to the deregulation of the electricity market and widespread residential utilization of natural gas as a primary energy source. Although some authors proposed application of PEMFC for CHP application [95, 96], SOFC hybrid cycles are the most promising candidates in this field.

Braun et al. [97] developed a model to evaluate the energetic and exergetic performance of various configurations of residential-scale SOFC-CHP hybrid system, including hydrogen- and methane-fueled systems with external and internal catalytic steam reforming, and cathode and anode off-gas recirculation. They investigated the parameters influencing suitability of this system to match residential demands and found that one of the most important parameters was the thermal-to-electrical load ratio (TER) of residential unit. TER defined as the ratio of the thermal energy demand of the home to its base electrical load. Their results indicated that the optimal system included cathode and anode off-gas recirculation and internal reforming of methane. The electrical and combined heat and power efficiencies of this system were 40% and 79% (HHV), respectively.

In 2002, Winkler and Lorenz [98] investigated the potential utilization of SOFC-GT in mobile application. They first proposed a reheat SOFC-GT with the efficiency of more than 70%. They also showed that by incorporating a bottoming steam cycle to a reheat SOFC-GT hybrid system, the electrical efficiency of more than 80% could be possible. They illustrated that the electrical efficiency with respect to the SOFC pressure followed Curve 4. Their results well agreed with results of Yi et al. [74] and Suther et al. [46]. Finally, they investigated possibility of deployment of SOFC-GT in a mid-size car with capacity of 75 kW and efficiency of 55%. They concluded that the results of their modeling proved the feasibility of utilization of the SOFC–GT hybrid system in unconventional applications which required further and more detailed investigations.

Steffen et al. [99] developed a model of SOFC-GT cycle to provide auxiliary power for a 300 passengers commercial transport aircraft in 2015. They stated that 440 kW was an adequate unit size for this application. Unlike the ground stationary power plants, in aerospace systems, power density (power/volume) and system specific power (power/mass) were the most important parameters to consider. Another remarkable difference in this application was fuel source which was jet fuel. This led to using catalytic partial oxidation (CPOX) for fuel reforming process. Their proposed system resulted in efficiency of about 63% (LHV) which was significantly higher than the efficiency of conventional systems at about 42%. However, the proposed system was much heavier (1396 kg versus 331 kg) mainly because of the metallic interconnect mass in fuel cell stack. They suggested that by applying some innovative techniques (e.g. corrugated flow channels) the system’s mass could considerably be reduced. They completed this study in another paper [100] by considering system partial load operation. In this case, system total mass increased considerably to 1912 kg.

16. TRANSIENT AND OFF-DESIGN CONDITION MODELING

In every energy system, dynamic and part-load behavior and load following characteristic are critical factors to consider. This is especially important for SOFC hybrid systems since they have been considered as forerunner technology in the market of distributed and residential power supply and mobile applications. Since these types of power stations operate in isolated condition, their load demand following characteristic is extremely important. Thus, part-load performance, operational stability and safety are key issues that should be addressed for SOFC based energy systems before they can be commercialized. The main objective of these studies is to design a control strategy that can maintain SOFC and GT inlet temperatures during load changes [27]. These aspects of SOFC hybrid system have been studied extensively in the literature. In this section some of these papers will be reviewed.

Costamagna et al. [101] evaluated design and off-design performance of SOFC and MGT hybrid system. For design-point operation, they found the overall efficiency to be higher than 60% and MGT-to-SOFC work output ratio to be 0.19. In off-design operation, they considered two control strategies: constant and variable turbine rotational speed. In former scheme, the load was controlled by varying the overall fuel flow which resulted in the reduced system efficiency (from efficiency of 61% to 56% at 70% of the power at design-point).

The latter involved variation of the MGT rotational speed. However, operation mode of conventional large size GT plants generally did not provide such opportunity. The rotational speed of these plants was dictated by alternate current frequency required by the end user or electrical grid. Since typical plants were not equipped to an inverter, their rotational speed was fixed and could not be used as control parameter. On the contrary, an inverter was one of the essential components for hybrid SOFC-GT systems to convert electricity generated by SOFC to alternating current (AC) required by electrical grid. Thus, in these hybrid systems, it was possible to operate GT at variable rotational speed (variable frequency).

In variable MGT rotational speed control mode, they found that it was possible to obtain very high overall efficiency (always higher than 50%) even at very low part-load conditions (up to 30% of nominal power). It was interesting that the power ratio of MGT and SOFC dropped for variable rotational speed control and increased for constant speed in comparison to the design-point. They concluded that the hybrid system controlled by variable rotational speed strategy operated with higher efficiency and flexibility. In addition, this scheme could control the tubular SOFC stack temperature more accurately.

Roberts et al. [27] again investigated two control strategies for an atmospheric SOFC-GT hybrid system, variable versus fixed speed gas turbine operation. In the case of constant GT speed, in order to maintain the SOFC stack operating temperature, they considered two mechanisms, cathode exhaust bypass or additional combustor. They found that none of these strategies were satisfactory because former resulted in very high oxygen utilization in the cathode and low recuperator temperature and the latter significantly reduced system efficiency. In contrary, the variable rotational speed gas turbine control design satisfied all operational constraints, including high efficiency and sufficient control of the SOFC stack temperature.

In their next paper [102], they further expanded their work by limiting the gas turbine's minimum operating speed to 65,000 rpm and adding auxiliary combustor to the system. The combustor was used to protect the SOFC from excessive cooling by combusting extra fuel to maintain the cathode inlet temperature, when the GT minimum rotational speed was reached. By applying this control strategy, hybrid system efficiency higher than 60% could be achieved. However, excessive burning of supplementary fuel in auxiliary combustor, particularly at partial load conditions, considerably reduced the system efficiency. Then, they evaluated the dynamic behavior of the hybrid cycle power output when the system was controlled by designed control strategy. They concluded that this strategy was "stable, safe, and robust" over wide range of power output.

Similarly, Kimijima and Kasagi [103] pointed out that variable rotational speed operation strategy was superior to the constant rotational speed operation strategy for 30 kW SOFC-MGT cycle.

Magistri et al. [62], in their previously explained paper (in "Models for comparison of configurations" section), investigated off-design behavior of the hybrid cycle for three system sizes, namely 250 kW, 2 MW, and 20 MW with over 60% to 65% efficiencies at design-point and always over 55% at part-load conditions. They also evaluated fixed and variable gas turbine rotational speed as off-design control strategies. They stated that varying the rotational speed of the gas turbine could be considered as an appropriate control strategy for small and medium size systems. However, for large hybrid systems, it was not possible to apply this strategy. In this case, they suggested bypassing SOFC to maintain stacks operating temperature in an acceptable range. Moreover, they estimated the influence of ambient conditions on cycle performance and noted that due to their significant impact on the system performance, they should be taken into account in system design and operation. Finally, they studied the transient behavior of the system as a result of a fuel step reduction. They concluded that it took about 300 seconds for the SOFC and the heat exchanger to adapt to transient conditions due to their high thermal inertia.

Stiller et al. [104, 105] developed a model to investigate steady state and transient condition for a SOFC and GT hybrid cycle. They used different approaches for modeling of various components, for instance, gas flows were modeled by 1-D scheme, whereas solid structures and recuperator heat exchanger were treated as 2-D components in axial and radial direction, and finally, the burner was simulated non-dimensionally. For off-design steady state operation, fuel and air flow rate (controlled by a flow control valve and GT shaft speed variation, respectively) were used as controlling parameters. They illustrated the steady state off-design behavior of the hybrid system by providing performance map of different parameters, such as net power, net electricity, pressure, and SCR, as a function of fuel flow and air flow relative to their design values. They showed that at high fuel flow and low air flow, there was no steady state condition (unstable regimes) and at high air flow and low fuel flow, SOFC temperature was lower than acceptable range.

In the next step, based on these findings, they designed a multi-loop feedback control scheme for the hybrid cycle with the following objectives: safe and long lifetime operation, high efficiency, fast load following, and "governing external influences". They controlled the system power output by adjusting the SOFC current, fuel utilization, air flow, and the SOFC stacks temperature. They investigated how the system responded to variation in several system parameters, such as load changes, load curve following, ambient air condition changes and system malfunction and degradation. They concluded that by using this control scheme, the system safe and stable operation was guaranteed during all tests. In addition, the system was able to follow small and large load changes in time scale of below 1 and 10-60 seconds, respectively.

Song et al. [73] in previously explained work (in "2-Dimentional models" section) analyzed impacts of the system operating characteristics at part-load conditions on the hybrid system performance. They found that when supplied fuel reduction was utilized as the only load control parameter, efficiency drop in both SOFC (due to the decrease of cell temperature) and GT (due to the decrease in TIT) were unacceptable. Therefore, they suggested simultaneous reduction of supplied air and fuel in order to maintain the SOFC stacks temperature and the TIT as close to the design-point conditions as possible as the best control strategy. The air flow rate could be adjusted by manipulating the angles of the inlet guide vanes (IGVs) located in front of the compressor inlet. The results of this simulation revealed that the performance characteristics of MW-class systems in this study were very close to those of the multi-kW systems with a variable rotating speed of the gas turbine proposed by Campanari [106].

Calise et al. [79] deployed the same approach to test partialization strategies. Similarly, they found that the best partialization strategy could be achieved by maintaining the air to fuel ratio. However, the technique did not demonstrate high flexibility of operating range. By applying this scheme, the plant net electrical power output could be reduced to a minimum of 80% of its rated value. Further reduction in load led the air compressor to approach its surge line. They stated that in such limited range of load change, none of strategies resulted in considerable efficiency penalty. They suggested that using fuel flow rate as load control parameter could result in a better behavior of the off-design operation of the system, provided that the turbomachineries design was optimized.

Chan et al. [107] proposed a strategy for system start-up, part-load and full-load operational control (based on the model developed in [57, 58]). In their control scheme, in order to reduce system electrical load, part of the fuel was directly injected into GT combustor (bypassing SOFC stacks). Although this scheme was safe and simple, it reduced the system total efficiency.

Tanaka et al. [68] developed a model to perform technical and economical sensitivity analysis on a SOFC-GT combined cycle. They studied system performance as well as cost and energy pay-back times (CPT and EPT). In their model, additional combustion in GT combustor, similar to [56], was considered for anode off-gas stream. But, unlike [56], the SOFC to GT power output ratio was controlled by supplementary fuel flow rate. They illustrated electrical efficiency and TIT versus this ratio for different values of operating pressure, temperature, SCR, fuel and air utilization ratios, and load following characteristic (partial load performance). Their finding for latter was interesting. SOFC cycle could operate in part load condition to provide lower power demands without reducing its electrical efficiency below the nominal value. However, in hybrid SOFC-GT system total efficiency dropped. This was due to the compressor constant rotational speed, which meant more air should be compressed than really required resulting in higher compression work and lower TIT. Nevertheless, they concluded that system load following capability was higher than conventional power plants. Moreover, they mentioned similar results as [56] for the influence of TIT on overall efficiency.

Therefore, generally speaking, based on the aforementioned studies we can conclude that a variable rotational speed gas turbine control strategy increases the efficiency and the range of operation of both pressurized and atmospheric SOFC-GT hybrid systems.

Zhang et al. [108] developed a dynamic model to simulate a simple SOFC-GT hybrid cycle. Their model required to define a disturbance variable and then to evaluate the responses of the system vital parameters to this disturbance. They chose current density of SOFC as disturbance and the SOFC air inlet temperature, SOFC outlet temperature, TIT, the output voltage, and the gas species molar fractions at the outlet of SOFC as system parameters. They found that response of the SOFC outlet temperature was positively related to the disturbance. But SOFC air inlet temperature and TIT were reversely proportional to current density. They also compared the response time constant of some system parameters and pointed out that this time for temperature was much higher than that of species molar fraction. They concluded that their model was able to follow the disturbance accurately.

Zhu and Tomsovic [109] developed a slow dynamic model of SOFC-MGT system to analyze the load-following performance of the system. They showed that the system could follow total load increase of 5% of the base load with rate of about 10 kW/s. They concluded that the system's load-following capability was suitable for application in distributed generation (DG) sector.

Another important issue in this type of modeling is protection of the SOFC-GT hybrid system and its components from critical incidents such as anode oxygen exposure, excessive cell temperature gradients and carbon deposition during severe load changes, shut-down or start-up. The simulations that addressed these conditions might be able to provide information for the development of control strategies for operation of the systems in these situations. A few published papers investigated hybrid system behavior in shut-down and start-up trips [110, 111, 112]. They concluded that SOFC stacks sensitivity to thermal stresses resulted in their slow characteristics which limited optimal time required for start-up and shut-down [111]. The start-up time varied from 1.3 [112] to 5.5 hours [110] for different configurations and control strategies.

17. THERMOECONOMIC STUDIES

Riensche et al. [113, 114] developed a model for 200 kW SOFC-CHP plant and conducted a technical and economical sensitivity analysis on the effects of system parameters on efficiency and COE. They assumed a lifetime of 10 years (40,000 hours) for the system. They found that net COE could be reduced by nearly 50%, when external reforming was replaced by internal reforming. Also, the electrical efficiency could be increased up to 50% at fuel utilization factor of about 95%. But for optimal COE, the fuel utilization factor should be set to 65%. They also studied the effects of different plant configurations. They found that with anode off-gas recirculation, stack one pass fuel utilization factor could be reduced to about 60%, while plant's net fuel utilization factor remained fixed at 80%, which resulted in 25% reduction in the cell area. In addition, steam concentration in the system exhaust stream was lower, thus the unrecoverable latent heat was lower and afterburner temperature was higher. Both effects resulted in higher total system efficiency.

Fontell et al. [115] performed a conceptual study of a 250 kW planar SOFC plant for CHP application. They set some performance targets for their design. They were able to meet some of these targets. For instance, their design exceeded the aimed electrical and total efficiency (LHV) of 47% and 80% by achieving about 56% and 85% efficiencies, respectively. However, their system's specific mass, about 49 kg/kW, could not satisfy desired specific mass of 15–20 kg/kW.

Finally, they conducted an economical analysis assuming stack lifetime of 40,000 hours (similar to [113, 114]) and system lifetime of 20 years (similar to [68]). Also, the degradation rate (percentage decline of the cell voltage per 1000 hours) was considered 0.25%/1000h. They listed cost of major components based on total cost as follows: stacks (31%), power electronics (15%), control system (17%), and labor and overheads (15%).

Tanaka et al. [68], in previously explained paper (in “Transient and off-design condition modeling” section), conducted economical analysis to investigate the effect of system parameters on CPT and EPT. Unlike [113, 114], in their model total plant life was assumed to be 20 years and fuel cells and catalyst were replaced every 5 years. They concluded that although the unit initial capital costs were higher than that of a large-scale conventional coal power plant, it was still a competitive alternative technology.

Calise et al. [116] added thermoeconomic evaluations to their previously explained model [59] and used genetic algorithm (GA) for optimization purpose. The model included 19 fixed parameters and 48 synthesis and design decision variables. The system initial investment was selected as optimization objective. The result showed that the optimized plant investment was 45% lower than reference case. However, the system was suffered efficiency loss, from 67.9% to 67.5%. Some system parameters, such as turbomachinery syntheses and designs as well as SOFC geometric parameters, were remarkably adjusted by optimization process. For instance, the number, diameter, and length of the tubes in cell stacks were decreased, resulted in dramatic reduction of the cell’s active area.

18. COMBINATION OF MODELING AND EXPERIMENTAL WORK

Lai et al. [117] introduced a new method to evaluate the performance of SOFC and GT hybrid cycle under various operational conditions without using actual SOFC. They stated that the cost of SOFC experimental equipments were still too high for university researchers. Therefore, the authors designed a SOFC-GT system by replacing SOFC by a traditional furnace to simulate fuel cell off-gas condition. Also, in order to simulate a real hybrid SOFC-GT plant, their system was equipped with another burner (to allow additional hydrogen injection for complete combustion of spent gas from SOFC), a turbocharger and a water injection system. Their system proved that such system could simulate real SOFC-GT behaviors with reasonable approximation. They found that, for example, no particular device was required to combust residual fuel for high temperature SOFC (800–1000 °C). But for a mid and low temperature SOFC (500–800 °C), some devices were required to provide better mixing and holding the flame.

With similar approach, Tucker et al. [118] used the Hybrid Performance (Hyper) hardware simulation facility at the National Energy Technology Laboratory (NETL), U.S. Department of Energy to evaluate possibility of using air flow as process control variable in the SOFC-GT hybrid system. The Hyper facility was able to simulate SOFC-GT system with electricity generation capacity of 300 kW to 900 kW by its hardware and software simulator. The hardware portion consisted of a natural gas burner, a modified GT, an off-gas recuperator, several tanks representing the volumes and flow impedances of real components, and required piping. The purpose of real time fuel cell simulator was to control the burner to resemble the thermal output and temperature of SOFC. Their objective was to test feasibility of using compressor bleed air and cold air by-pass as system control variables through air flow management.

19. DISCUSSION

In order to have a clear idea about the current status of SOFC hybrid systems modeling in the open literature, the summarized characteristics of some selected models are presented in Table 2. In this table, characteristics such as the purpose of the papers (parametric, configuration, partial load, and economical analysis and optimization), the system or cycle which combined with SOFC to form hybrid cycle, fuel type, fuel cell type (tubular or planar, fuel and air flow direction, temperature level), reformer type (taking into the account of anode recirculation), plant capacity, number of geometrical axes through which the flow parameters vary, time dependency of the model, simulation software, and model validation are considered.

Some keys about this table should be mentioned. First of all, when several papers used the same model for different analyses, they are considered as one entry. When none of the boxes is marked, it means that there was no information about that specific parameter in the paper(s). For anode recirculation, Y/N means both cycles (with and without anode recirculation) were investigated. But for validation of the model with experiments, Y/N means the model was partially validated. Most likely this indicates that SOFC model was validated but whole cycle was not. Also, the feasibility studies and conceptual design papers are considered as configuration analysis.

This table shows that many models concentrate on studying the effect of various parameters on system performance as well as examining and comparing different configurations. Also, majority of the models have been on internal reforming SOFC-GT systems fueled by methane or natural gas with vast range of plant capacity from a few hundred kilowatts to multi-hundred megawatts. In terms of SOFC stack, majority of the models were based on high temperature tubular SOFC both with and without anode recirculation. It is possible to find 1-D and 2-D modeling approaches in literature. However, it should be noted that even though authors called their model as 1-D or 2-D, some components such as gas turbine or heat exchangers might be modeled as 0-D. Many models were steady state and they were not fully validated against experimental data. A few of them were partially validated by validating the SOFC part. And finally, many modelers used Aspen Plus® as the simulation software.

Some key findings of this review paper to identify areas that require further studies may be summarized as follows:

1. Most of the studies used well established tubular type SOFC. However, recently, planar type has proved to have more potential for cost reduction. Therefore, future studies should be focused on this type of SOFC, especially low temperature (LT) type.
2. 0-D modeling approach for hybrid systems simulation has been well developed. But further investigation is required to assess the influence of this approach. In other words, the question of how realistic it is to assume SOFC as a box should be investigated. In order to do this, an extensive study to compare 0-D and higher dimensional approach for the same system is required.
3. As Table 2 shows, most of the models were not validated. More demonstration sites and experimental studies are crucial in this respect so that researchers will be able to validate their model according to the results of these experimental works.
4. As mentioned, most of the models emphasized on parametric and configurations analysis. The next logical step is to use different optimization methods to optimize the hybrid system with the objective of system efficiency and cost.
5. Although numerous configurations have been proposed for hybrid systems in literature, well established and accepted configuration is still lacking. Existing proposed configurations should be compared with similar specifications and assumptions so that selection of best configuration for different conditions and applications can be done.
6. Dynamic models are extremely important to study system performance and establish suitable control strategy in transient conditions such as start up, shut down, and severe load changes. Thus, further investigations are required in this area.
7. More studies are needed on the indirect internal reformer to evaluate its effect on system overall performance.
8. Hybrid SOFC with integrated gasification combined cycle is considered as the ultimate SOFC based power generation cycle and its different aspects should be studied in detail.
9. Effect of fuel composition changes on system design and operation of existing system should be investigated.

20. CONCLUSION

Solid oxide fuel cells and energy systems based on them have been receiving more attention these days. Modeling plays an important role in the development of fuel cells especially in hybrid SOFC systems. In this paper, the state-of-the-knowledge of modeling of SOFC hybrid cycles is reviewed. First, it presents key fuel cell model features and their classification to facilitate matching modelers' requirements with selected modeling approach. Also, essential steps to develop a model are presented. In addition, potential problems that may arise with inappropriate assumptions such as 0-D modeling for specific application are discussed.

In the next section, a comprehensive literature survey on different types of SOFC hybrid systems modeling is presented. These models are categorized based on the classification scheme discussed earlier. In this paper, a hybrid cycle could be any combination of SOFC and gas turbine, steam turbine, coal integrated gasification, and application in combined heat and power cycle. In order to make this review comprehensive, wide range of models are considered, including but not limited to, design and off-design, steady state and dynamic, and multi-dimensional models. Also, systems with various applications, fuel types, and configurations are considered. Moreover, models with different objectives such as parametric, exergetic, and thermoeconomic analysis as well as optimization are reviewed.

This review shows that in spite of tremendous improvements in the modeling of SOFC hybrid systems, there are areas that need further studies. They include planar SOFC, transient and off-design condition, and coal and biogas fed hybrid cycle modeling and model validation.

21. ACKNOWLEDGEMENT

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			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Purpose of paper	Parameter analysis			×	×	×	×	×	× (Ex)	×		×	× (Ex)	×	×	×			×				×			× (Ex)			×		×	×		×							
	Configuration analysis			×	×					×	×	×	×	×	×		×	× (Ex)			×	×	×	×	×	×	×	×		×	×										
	Partial load		×						×			×							×													×	×	×	×	×	×	×	×	×	
	Optimization								×											×																				×	
	Economical analysis								×							×	×	×				×																		×	×
Hybrid cycle	GT	HR	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×		×			×	×	×	×	×	×	×	×	×		
		SHR			×	×		×	×		×		×		×			×					×			×		×			×	×			×				×		
	Steam turbine												×										×				×				×										
	CHP						×	×				×								×							×		×	×					×					×	×
	IG																									×	×	×													
	CO_2 capture																			×	×	×		×	×																
Fuel type	Hydrogen										×				×																							×			
	Methane/ NG		×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×					×	×		×	×	×	×		×	×	×	×
	Coal																									×	×	×													
	Biogas/others																												×			×									
FC type	Tubular			×	M	×		×	×	×		I	×	×		×	×	×	×		×	×	×		×	M							×	×	×		×	I			
	Planar	E					×			×	×									×																×			×	×	
		A	×																										×	×		×									×
		C																																							
FC type (temperature)	LT		×																																						×
	IT											×				×													×	×		×									
	HT			×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×				×	×	×	×	×	×	×	×	
Flow configuration	Co-flow		×	×		×		×	×	×			×	×		×	×	×	×		×	×	×		×								×	×	×		×		×		
	Counter-flow																													×											×
	Cross-flow				×		×			×	×	×								×						×												×		×	
Reforming type	Internal		×	×	×	×		×	×	×	×	×	×	×	×	×	×	×	×		×	×	×	×	×	×	×	×		×			×	×	×	×		×	×	×	×
	External				×		×													×		×	×						×	×		×								×	
Anode recirculation			N	Y	N	Y/N	Y	N	Y/N	N	N	Y	Y/N	Y		Y	Y	N	Y	N	Y			Y		N	Y/N		N	Y/N		N	Y	Y	N	N		Y	N	Y/N	Y
Plant Capacity (MW)			0.25	0.22	100		0.5	1.3	1.5		0.3	2					20		11		15	1.5		640	70		50			0.0015		0.44	0.3		1.3		19	0.55	0.25	0.2	0.25
Model Dimension	0-D					×		×	×						×							×	×		×		×	×	×			×	×		×					×	
	>0-D			×			×			×	×	×							×	×										×				×		×		×			
Dependency to time	Steady-state		×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×			×		×	×
	Transient		×									×																						×		×	×	×	×		
Validation with experiments			N	N	N	Y/N	N	N	N	Y/N	N	Y/N	N	Y/N	N	N	N	N	N	N	Y/N	N	N	N	Y	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N
Simulation software			M		AP	AP	AP	M	M	PR	AP				AP					IP	PR	T	T		AP	AP	AP	AP	V			AP	M	g	M	ACM			M	PR	AP

TABLE 2: Summarized characteristics of some selected models in the open literature

Abbreviation:
GT+HR: Gas Turbine + Heat Recuperation
GT+SHR: Gas Turbine + Heat Recuperation + Steam Recuperation
Ex: Exergy analysis
NG: Natural Gas
E: Electrolyte Supported SOFC
A: Anode Supported SOFC
C: Cathode Supported SOFC
M: Monolithic SOFC (MSOFC)
I: Integrated Planar SOFC (IP-SOFC)
AP: Aspen Plus®
M: MATLAB/Simulink®
PR: PRO/II
IP: IPSEpro™
T: Thermo Economic Modular Program (TEMP)
V: VALI™
g: gPROMS
ACM: Aspen Custom Modeler®

Selected papers:
1. Roberts et al. [27] and Mueller et al. [102]
2. Song et al. [32]
3. Harvey and Richter [52],[54]
4. Suther et al. [46] and Zabihian et al. [119]
5. Palsson et al. [56]
6. Chan et al. [57],[58]
7. Calise et al. [59],[79].[116]
8. Stiller et al. [60]
9. Selimovic and Palsson [61]
10. Magistri et al. [62]
11. Granovskii et al. [63],[77],[80]
12. Pangalis et al. [65] and Cunnel et al. [66]
13. Kuchonthara et al. [67],[69]
14. Tanaka et al [68]
15. Lundbergm et al. [70]
16. Rao and Samuelsen [72]
17. Song et al. [73]
18. Möller et al. [75]
19. Riensche et al. [81]
20. Franzoni et al. [83]
21. Massardo et al. [84]
22. Inui et al. [85]
23. Campanari and Chiesa [86]
24. Lobachyov and Richter [88]
25. Kivisaari et al. [89]
26. Kuchonthara et al. [90]
27. Van Herle et al. [93]
28. Braun et al. [97]
29. Winkler and Lorenz [98]
30. Steffen et al. [99] and Freeh et al. [100]
31. Costamagna et al. [101]
32. Stiller et al. [104],[105],[110]
33. Chan et al. [107]
34. Zhang et al. [108]
35. Zhu and Tomsovic [109]
36. Kemm et al. [111]
37. Lin and Hong [112]
38. Riensche et al. [113],[114]
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