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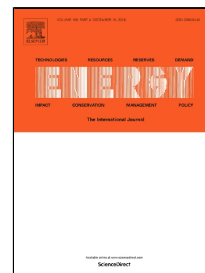
Solid oxide fuel cell hybrid system: a detailed review of an environmentally clean and efficient source of energy

U.M. Damo, M.L. Ferrari, A. Turan, A.F. Massardo

PII: S0360-5442(18)32302-8  
DOI: 10.1016/j.energy.2018.11.091  
Reference: EGY 14189  
To appear in: *Energy*  
Received Date: 03 July 2018  
Accepted Date: 21 November 2018

Please cite this article as: U.M. Damo, M.L. Ferrari, A. Turan, A.F. Massardo, Solid oxide fuel cell hybrid system: a detailed review of an environmentally clean and efficient source of energy, *Energy* (2018), doi: 10.1016/j.energy.2018.11.091

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## **Solid oxide fuel cell hybrid system: a detailed review of an environmentally clean and efficient source of energy**

U.M. Damo<sup>1,\*</sup>, M.L. Ferrari<sup>2</sup>, A. Turan<sup>1</sup>, A.F. Massardo<sup>2</sup>

<sup>1</sup>School of Mechanical, Aerospace and Civil Engineering, The University of Manchester, UK

<sup>2</sup>Thermochemical Power Group, University of Genoa, Genoa, Italy

\*Corresponding author      dk\_damo@yahoo.com, usman.damo@manchester.ac.uk

This paper reports a review of an environmentally clean and efficient source of energy such as solid oxide fuel cell hybrid systems. Due to climate concerns, most nations are seeking alternative means of generating energy from a clean, efficient and environmental-friendly method. However, this has proven a big hurdle for both academic and industry researchers over many years. Currently, practical and technically feasible solution can be obtained via an integration of a microturbine and a fuel cell (hybrid systems). Combining the two distinct systems in a hybrid arrangement the efficiency of the microturbine increases from 25-30% to the 60-65% range. Hence, this paper outlines an engineering power generation solution towards the acute global population growth, the growing need, environmental concerns, intelligent use of energy with attendant environmental and hybrid system layouts concerning arising problems and tentative proposed solutions. Furthermore, advantages of a solid oxide fuel cell hybrid systems with respect to the other technologies are identified and discussed rationally. Special attention is devoted to modelling with software and emulator rigs and system prototypes. The paper also reviews the limitations and the benefits of these hybrid systems in relationship with energy, environment and sustainable development. Few potential applications, as long-term potential actions for sustainable development, and the future of such devices are further discussed.

### **Keywords**

Solid oxide fuel cell; hybrid system; prototypes; modelling with software and emulator rigs; environmentally clean energy; high efficiency.

## 1. Introduction

An estimate carried out by United States Census Bureau (USCB) states that the world population exceeded 7 billion on March 12, 2012 [1,2]. Another prediction by the United Nations Population Fund (UNPF) claims it reached this milestone on October 31, 2011, with the median age of the world's population estimated to be 29.7 years old in 2014 [3-5].

Hence, the future of the world with regards to energy demand/generation seems critical as most nations, including the developed nations, depend almost exclusively on conventional energy sources such as oil, coal, and gas to generate their power. This not only results in global warming, but also leads to increased fuel prices [6]. In addition to this, due to the exponential increase in energy demands, there is increased reliance on conventional fossil fuels [7]. As these conventional sources are finite and rapidly depleting, altering the course of the balance of future energy demand/generation in risk naturally ensues [8]. The global dependence on conventional energy sources of fuel for energy production is at a critical level. This is further intensified considering the inability of renewable sources to completely replace conventional sources due to their low energy density and variability issues.

To provide a sustainable energy supply, the solid oxide fuel cell (SOFC) hybrid system appears to be a rational and pragmatic alternative, offering a sustainable, efficient and effective solution for intermediate term power generation [9-11]. The potential of SOFC based hybrid systems has been researched and reported by many authors since the 1990s [12-14]. Table 1 presents a summary of the advantages and disadvantages of this type of plant. Combining the two distinct systems increases the efficiency in comparison with current generation standalone microturbines from 25-30% to values close to 65% (LHV fuel to electricity). This increase in efficiency is primarily due to the very favourable thermodynamic contribution of the fuel cell to power generation based on electrochemical conversion and is thus not subjected to the limitations of the Carnot cycle [15-19].

**Table 1- Advantages and disadvantages of SOFC/mGT coupling [19].**

<b>Advantages</b>
Size and air flow values consistent with SOFC stack size
Pressure value consistent with pressurised existing SOFC stacks
Turbine inlet temperature values close to stack discharge conditions
Available air temperature values close to acceptable SOFC cathode inlet temperature range if the microturbine is based on the recuperated cycle and/or including recirculation devices
Possible electrical integration at continuous current level
<b>Disadvantages</b>
Commercial microturbines not specifically designed for SOFC issues
Significant influence of ambient temperature value
Plant exhaust flow temperature cannot be decreased to values lower than 200-250°C (however, this disadvantage could be a positive aspect in case of co-generation)
Controllability of dynamic phenomena
Integration of components with different dynamic time scales

The aim of this review paper is a presentation of the SOFC hybrid system technology (avoiding discussions on such kinds of fuel cells, due to too much texts devoted to SOFCs) focusing special attention on its potential benefits, problems and limitations for market penetration. The main innovative aspects of this review paper are: (i) a comprehensive presentation of the SOFC hybrid system layouts, (ii) a complete discussion on the plant development activities, (iii) a detailed analysis on the main issues (from costs to control system, reliability and degradation problems), and (iv) aspects about the future of these SOFC systems. Moreover, the authors would like to highlight the innovative presentation (in a comprehensive review paper) of development devices devoted to SOFC hybrid systems: software-based modelling activities, emulator test rigs (cyber-physical approach) and prototypes.

The paper is organized as shown in the following list: (i) presentation and discussion on SOFC hybrid system layouts, (ii) presentation of development steps for these innovative plants (from software modeling, experiments with emulator rigs to prototype building activities), discussion on

specific issues that are limiting their market penetration, and future perspectives of these hybrid systems.

## **2. Configurations of SOFC hybrid systems**

As stated earlier, matching of a high-temperature fuel cell, like SOFC, with a microturbine (mGT) can yield a highly efficient (in the 60-65% range) power generating system and hence reducing harmful pollutants to the environment [20-25]. However, the mGT-SOFC coupling it is not as simple as replacing the combustor with a fuel cell, additional design and development constraints arise when integrating the two components.

When operating a fuel cell (FC) under high pressure conditions (as between the compressor and the turbine of a microturbine) an increase in the fuel cell power output (for the same fuel cell stack) and a reduction in various electrochemical losses results in a greater obtainable efficiency (most notably improving electrochemical kinetics) [26, 27]. Hence, these synergistic aspects of hybrid gas turbine fuel cell systems are of interest and justify how analyses and testing to-date have determined that such hybrid systems have great promise [26].

### **a) SOFC hybrid systems layouts (recuperator configurations).**

Figure 1(1) presents a simple layout for a gas turbine. This can be a suitable choice for hybrid systems by replacing the conventional combustor with a high-temperature fuel cell like SOFC. This simple gas turbine consists of a compressor, a combustor and a turbine. The Brayton cycle provides the basic power cycle for the gas turbine. The compressed gas (between 3-30 bar) is mixed with the fuel to provide isobaric combustion. The resulting hot gas (800-1300°C) is then allowed to expand in the turbine which is mechanically coupled to a generator and to the compressor. Because of the expansion in the turbine, the exhaust gas temperature decreases to 250-600°C. The exhaust temperature becomes lower when there is a rise in pressure ratio between the turbine inlet and exhaust [20]. Figures 1(2)-1(6) present several layouts for conventional gas turbines, which can

easily be coupled with a high-temperature fuel cell for a hybrid system technology. However, the replacement of the turbine conventional combustion chamber with the high-temperature fuel cell (the SOFC [20]) is not a straightforward engineering undertaking due to several constraints and control issues.

**Layout 1:**

Usually the simple cycle is not considered as ideal for the SOFC/mGT coupling, due to insufficiently high temperatures at the fuel cell inlet and not optimal efficiency (missing recovery of the exhaust thermal content).

**Layout 2:**

Micro gas turbines operating with a recuperator increases the electrical efficiency. This device recovers some of the heat from the exhaust stream and transfers it to the incoming air stream, enhancing the temperature of the air stream supplied to the combustor. Further exhaust heat recovery can be used in a combined heat and power combination. Nevertheless, this makes the hardware costlier and increases the complexity of the system. In addition to this, there will be a slight loss in the maximum power available due to the pressure losses in the recuperator [20]. This is a promising layout for SOFC hybrid systems due to the high efficiency coming from the heat recovery and the air pre-heating (reaching operative conditions close to SOFC inlet temperature).

**Layout 3:**

This turbine layout is not normally considered for standard machines. However, the replaced SOFC directly connected to the turbine at atmospheric pressure confers a great advantage by avoiding expensive pressurisation of the generator and a more complicated control system [20]. On the other hand, this solution requires a heat exchanger operating at too great a temperature, increasing cost and reliability issues.

**Layout 4:**

The intercooler and compressor staging are used to decrease the work consumption of the compression section of the system. An instance of performing the compression with just one machine, two or more compressors are used, and the gas is cooled in between each compressor pair. Although this approach could be useful also for hybrid system performance increase, no real applications of the intercooled cycle are considered to date. This is primarily due to the necessity to operate with larger compression ratios requiring multi-stage microturbines. The related cost increase is not an impediment concerning the application of this layout for hybrid systems.

**Layout 5:**

Reheating and turbine staging involve the addition of multiple burners and turbine pairs. This also provides the same advantage as in Layout 4, meaning a higher initial investment [20] that is currently not justified in hybrid systems.

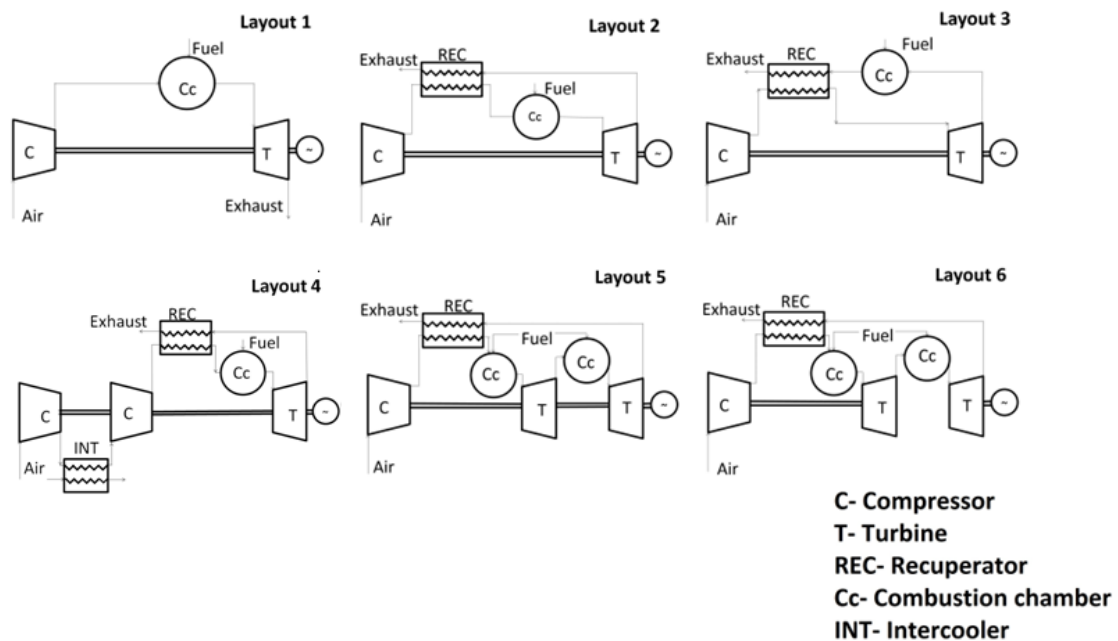
**Layout 6:**

To attain a more flexible part-load behaviour, a possible solution involves using separate power turbines, as shown in Figure 1(6). Usually, the part-load efficiency is higher in the case of a twin spool gas turbine than a single shaft gas turbine [20]. However, this gas turbine flexibility must be carefully investigated considering the coupling with the SOFC with a detailed off-design analysis.

To avoid risky operational conditions (thermal shock and possible damage to the stack) of the SOFC, it is necessary to consider significant air pre-heating [21, 25] upstream of the cathodic inlet. Consequently, it is necessary to consider heat recuperation and/or further pre-heating solutions, such as a cathodic recirculation.

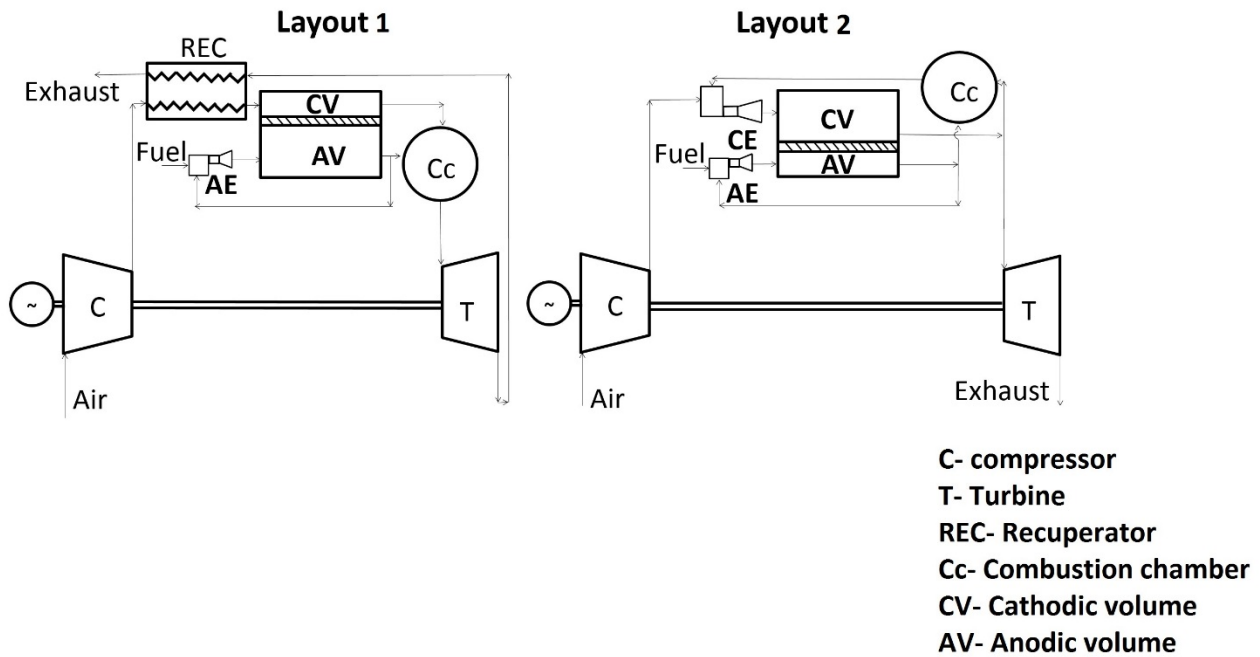
The efficiency of a SOFC-mGT Hybrid system depends largely on the system size, the type of layout considered, Figures 1(2)-1(6), the use of supplementary heating for the combustor and the

performance of the SOFC and gas turbine technologies used [20]. Efficiencies may range from 55 to 60% for a small, simple SOFC-mGT system in the 250 kW to 1 MW range to almost 68% for a 5-10 MW SOFC-mGT system when coupled with an intercooler and reheat by a separate SOFC generator. A total efficiency (thermal and electrical combined) of 85-90% can be reached. Emissions of NO<sub>x</sub> depend largely if a combustor is used in the hybrid system; however, in such cases it is remarkably lower than that for a comparable conventional gas turbine [20].



**Figure 1- Examples of gas turbine engine layouts, layout 1(2) to 1(6) can be a choice for hybrid systems by replacing the conventional combustor with a high-temperature fuel cell such as in an SOFC (re-plotted based on [20]).**





**Figure 2- Hybrid systems general layouts: Cathode–anode side interaction in SOFC hybrid systems [28].**

**b) SOFC hybrid systems different layouts (anodic, cathodic recirculation configurations).**

In a hybrid system, the fuel cell module is usually located between the compressor and the turbine (pressurised solution). Although the steam necessary for reforming reactions could be supplied externally, an efficient solution involves the development of anodic recirculation. Due to the high temperature conditions, a recirculating system based on blowers are usually considered critical from the reliability point of view. For this reason, several researchers [9,20,28] proposed ejector technologies due to low cost and high reliability (such a device has no moving parts). However, ejector performance is crucially related to prevalent geometry and the fluid dynamic coupling with specific boundary conditions. As no control margin is available, the application of these devices generates a significant complexity increase for the part-load and transient management of the hybrid system. In systems including an anodic ejector, fuel is supplied into the primary duct (Figure 2 presents general layouts of the hybrid system (HS)) and a part of the SOFC anodic exhaust is recirculated into the secondary duct. Moreover, in SOFC systems equipped with flattened-tube or

planar fuel cells, a cathodic recirculation is necessary for air pre-heating (since the recuperator is expensive and unable to reach the required high temperature conditions, in some layouts this device was not included [28]). As shown in Figure 2, the cathode and anode sides have different volume sizes depending on the fuel cell technology [28]. The tubular cell of the "Layout 1" has an anodic volume larger than that of the cathodic side (cathode/anode volume ratio around 0.5 [28]), but in the other scheme ("Layout 2") the configuration is almost opposite (cathode/anode volume ratio around 4 [28]). This is due to a fuel cell layout without high-temperature air preheating systems (e.g. flattened-tube or planar SOFCs) attached to it [28]. Furthermore, the two layouts have different values for pressure losses in the cell sides. So, even if cathode and anode flows are mixed in the "Cc" (the off-gas burner) in both layouts, different pressure values are possible in the upstream ducts between cathode and anode sides, especially during hybrid system part-load and time-dependent operations [28].

As can also be seen from the layout, a reforming arrangement may be hosted upstream of the anode inlet [28] or positioned internally in the fuel cell [28]. "Layout 1" shows a typical recuperator added to preheat the air flow upstream of the fuel cell inlet utilising turbine exhaust thermal energy [28]. This layout is an interesting and a potential dynamic solution for a SOFC stack equipped with an air preheating heat exchanger (or tube), like the tubular fuel cells designed and developed by Siemens Westinghouse [28, 29].

**c) SOFC hybrid systems different layouts (internal/external reforming configurations).**

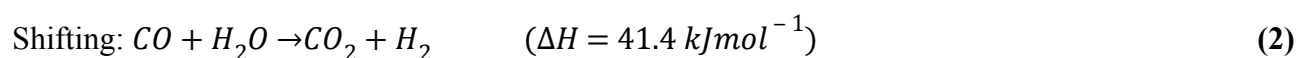
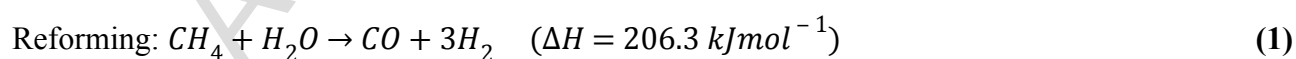
Since the early 1990s when the initial theoretical studies on the combination of high-temperature fuel cells and gas turbine took place, many researchers and research institutions have carried out extensive research activities concerning this promising technology to improve energy generation [30].

However, several unresolved problems are still being analysed, including issues related to the SOFC coupling with the microturbine, control system aspects and cost-related problems. In addition, from the SOFC design point of view, different options are under discussion, such as the reforming method for generating hydrogen from conventional fuel (natural gas) to feed the SOFC of the HS. Fuel cell and hybrid system performance depends greatly on the reforming method used [30-33].

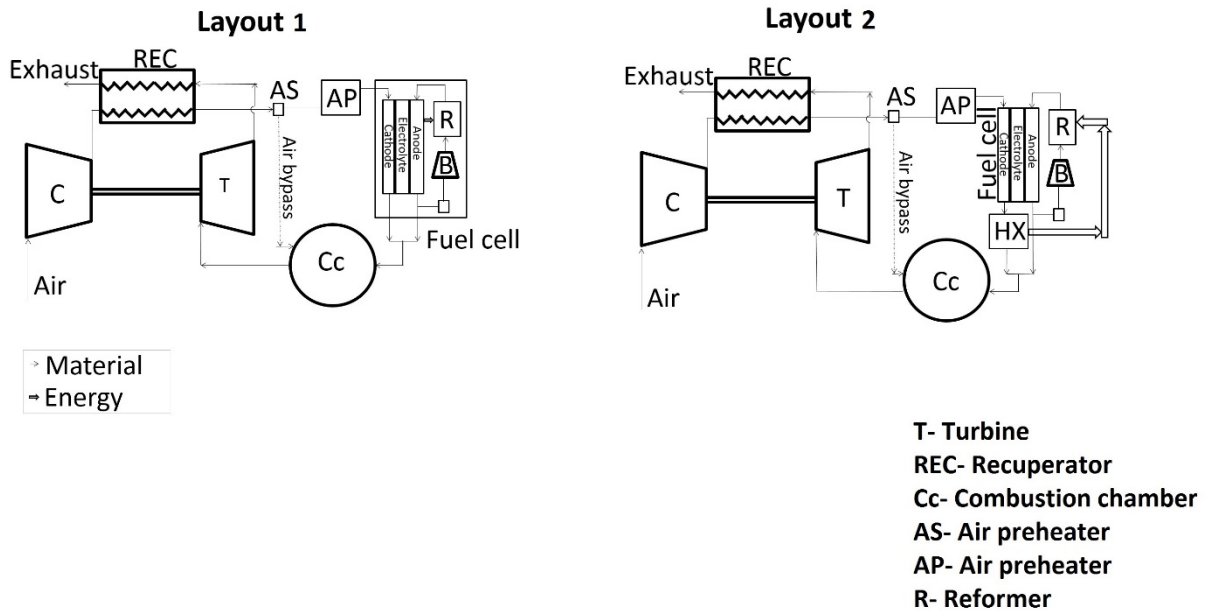
For a natural gas-fuelled hybrid SOFC–mGT system, a variant of the internal or external reforming methodologies are required. To avoid the extra cost for an external reformer and to provide additional ‘cooling’ for the SOFC stack, the use of an internal reformer is usually a wiser choice [31].

### Reforming reactions

Although some fuel cells can accept fuel compositions different from pure hydrogen, in SOFC systems a significant amount of hydrogen is necessary. Even if there are different ways to extract hydrogen from commercial fuels, a typically adopted engineering practice is to use a steam reforming process for hybrid plants fed by natural gas. Considering this process, methane is reacted catalytically with steam at high temperatures. The basic reaction for internal reforming can be written as Eq.1.



Reaction 2 shows the water-gas shift mechanism that occurs during the steam reforming process to yield additional hydrogen. More details about the reforming processes are presented in [31, 33], including internal-reforming SOFC stacks, a technology that the HS critically relies on.



**Figure 3- Pressurized SOFC/mGT hybrid systems: (a) layout 1—internal reforming and (b) layout 2—external reforming [30].**

### Layout (1):

This option (Figure 3 - Layout 1) uses the internal reformer, where the steam reforming takes place. Recirculation of the anode exit gas, containing adequate steam, supplies the reforming steam. The reformer is in thermal contact with the fuel cell to provide the reform heat. This concept of the reforming process is similar the one currently under commercial development [32]. Nonetheless, the recirculation is modelled to be performed by a blower rather than an ejector as outlined in the references.

**Layout (2):**

This option utilises the external reformer technique. The recirculation of the anode exit gas is also used for supplying the reforming steam. Numerous techniques can be used to provide heat to the external reformer [32]. The reforming heat is then transferred from the cathode exit gas at an adequately high temperature. Although this technique has a greater higher performance than other external reforming schemes [32], the heat exchange could be critical due to high temperature conditions.

**3. Hybrid system analyses with mathematical models**

When modelling any combination of a fuel cell and a heat engine i.e. HS, it is necessary to describe the primary reasons and outputs required of the model and establish the main attributes. The most appropriate modelling technique and the characteristics of the model depend in most cases on the application. Even though this is an important step to bear in mind, there are usually many assumptions considered during this process that will give rise to inaccuracies and sometimes produce incorrect trends. More details about the model can be subsequently determined after finalizing such criteria. As with modelling of other thermal systems encountered in the literature, the first step in the modelling of an SOFC HS is to understand the system and translate it into mathematical equations and statements [33]. The common steps for model development are summarised as follows:

1. specifying a control volume around the desired system,
2. writing general laws (including conservation of mass, energy, and momentum; second law of thermodynamics; charge balance; and so on),
3. specifying boundary and initial conditions,

4. solving governing equations by considering boundary and initial conditions (analytical or numerical solution),
5. validating the model [33].

Although the modelling of a fuel cell is a three dimensional (3-D) and time-dependent problem, using appropriate assumptions, it can be reduced in complexity to a steady-state, 2-D, 1-D, or 0-D problem for specific applications and objectives [33]. As discussed earlier, most SOFC HS simulations in the open literature are 0-D models. In this type of modelling, a series of mathematical formulations are utilized to define output variables based on input values [33]. In this technique, the fuel cell is processed as a dimensionless box, hence the term employed by some authors as box modelling [33]. Despite the large number of assumptions and simplifications in this method, it is vital to examine the effects of various operational parameters on the cycle performance overall, perform sensitivity analysis, and compare different configurations. When the goal of modelling is to study the inner working of an SOFC, a 0-D approach is not suitable because it is based on global balances. In case it is necessary to evaluate the property distribution inside the components a proper domain discretisation is mandatory, considering 1-D, 2-D or 3-D approaches depending on the geometry, the phenomena and the problem type to be analysed. Nonetheless, for HS system simulation, where the emphasis is placed on the interaction of the fuel cell and the rest of the system and how the fuel cell can affect the overall performance of the system, this approach is usually appropriate. In this level of system modelling, there are a variety of assumptions and simplifications. For example, Winkler et al. [34] developed a hybrid fuel cell cycle and assumed that the fuel cell was operated reversibly, (representing any fuel cell type) and the heat engine employed a Carnot cycle, to represent a generic heat engine. Various software packages and programming languages have been used in SOFC HS simulation. Commercial models for SOFC stacks are not yet available and hence all modellers usually devise their own tool with proper details and assumptions [33]. In view of such considerations, what differentiates models is how they

simulate the remaining components of the system. Usually, they can be grouped together into two primary classes. In the first category, comprehensive models can be developed using programming languages such as FORTRAN or high-level software such as the MATLAB/Simulink® platform to solve the governing equations for the system, while the second approach enables the modellers to use commercial software such as Aspen Plus® to model the conventional components of the cycle.

Due to the nature of the assumptions and simplifications invariably involved with numerical modelling approaches, resulting predictions should be used cautiously. In every modelling activity, physical attributes of the system should be translated into mathematical equations and solutions of these equations are used to express the behaviour of the system [33]. In the case of fuel cells, the operational realities comprise highly complex physicochemical processes embodying fine subtle details which might not be available. Therefore, to extract and subsequently solve these governing equations, many assumptions and simplifications are usually employed. This is necessary for predictions of what should strictly be assessed considering practices that provide for the rigorous assessment and the predictive aspects of the sub-models for use in comprehensive engineering design and development tasks. It is worthwhile remembering that fuel cell models are a “simplified representation of real physics” and even with appropriate validation, the accuracy of their results cannot be guaranteed [33].

For example, one should be aware of possible problems that can arise when local equations are considered as global. Bove et al. reported such a problem [35,36], outlining the main problems of using a 0-D technique for modelling lacking variations in fuel, air, and exhaust gas compositions through the fuel cell. Therefore, when the inlet, outlet or an average value of the gas composition was used in the modelling, different results may be obtained. It was shown that it was impossible to evaluate effects of fuel utilization variation through the fuel cell when inlet gas composition was considered. Furthermore, considering different output stream compositions could result in underestimating the cell voltage and power output.

Magistri et al. [37-39] studied both simplified and detailed SOFC models and how these affected the predictions of the design-point performance of hybrid systems. They emphasised the usefulness of the simplified model for hybrid system design and off-design analysis. Whilst the detailed model should be used for the complete description of the SOFC internal behaviour. Judkoff et al. [39] reported and classified the sources of simulation errors into three groups (these were provided for building simulation programs, but they were equally applicable to SOFC HS simulations):

1. errors introduced due to assumptions and simplifications,
2. errors or inaccuracies in solving mathematical equations,
3. coding errors.

They also proposed a pragmatic, three-step approach to identify these errors. In the first approach involving comparative testing, the results of the model should be compared with the results of other models of a benchmark quality for the same problem with similar initial and boundary conditions. If the results of the models match within an acceptable error, this further implies the implementations are acceptable. However, this does not guarantee the validity of the results because they can all be in error. In the second approach based on analytical validation procedures, the results of the model for a simple case are compared with the results of an available analytical solution if one exists. In the empirical validation approach, the results of the simulations are compared with real data from the actual system under laboratory or field conditions [38].

Finally, the validation of a model is necessary for it to be a credible tool. Appropriate data is needed for validation. With limited resources, this can be difficult as most data is not freely available in the open literature. Even though performance data from an entire hybrid power generation system is usually proprietary and not available in the literature, information for a single system is easier to find. Consequently, 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 [38].

Even though the SOFC is considered as the "heart" of these hybrid cycles, its detailed mathematical modelling and simulation methodology is not included in this review. The focus here is on the evaluation of overall system performance and not on its component performance. One can refer to reference [38] for review papers on SOFC modelling. In addition, some good examples of such simulations can be found in [39,40] for steady-state and [40,41] for transient and dynamic modelling.

Furthermore, several computational models were developed by various authors and presented in the literature to analyse the performance, including off-design behaviour of hybrid systems, both at component and system levels. For component calculations detailed approaches are employed, particularly for the fuel cells covering many design and development variables including various loss mechanisms, enabling technologies, and optimization procedures. For instance, material related aspects concerning electrode design as well as electrolyte selection and performance issues require very complex chemical models involving micro-kinetic descriptions. Studies have been presented in the literature employing complex 3-D CFD tools incorporating detailed electrochemical reactions to describe the relevant fluid dynamic and transport aspects of the design involving relevant variable/property field distributions for SOFCs. The model complexity is usually reduced in cases of axisymmetric geometry (2-D approaches) or due to the necessity for fast performance (1-D approaches). At a plant level, however, suitable model simplifications are vital; it is for such reasons that macro-engineering models based on control volume analyses are generally used for obtaining performance level predictions including system dynamics. If real-time performance is required, however, modelling approaches invariably due to necessity, must be extremely simplified while capturing most of the engineering considerations of interest. These usually involve interpolation between performance maps when the physical aspects are too

complicated. Real-time modelling approaches are also considered vital for plant monitoring and diagnostic reasons, as a model running in real time parallel with the plant can be used for fault detection.

#### **4. Analyses with emulators for tests on hybrid systems**

Due to the high cost of fuel cell production, particularly the stacks component [19], and because these cells are very liable to both thermal and mechanical stresses, emulator test rigs are regularly being used for experimental activities [19]. Therefore, these rigs can produce the most beneficial engineering design and development results [19] without the risk to or the need for the most critical components, and hence reducing the development cost. Hybrid system emulators are designed for specific plant component performance and operational modes. However, they are not able to produce performance results covering all critical operational and off-design aspects. For example, if the fuel cell is not included in the rig, it is not possible to study the electrochemical performance [19] of the reactor. Hybrid system emulators are especially useful during the component and control system design stages of the development process, where an appropriate emulator rig is ideally suited to produce the necessary experimental data [19].

Over the past two decades, many academic research activities have been carried out in relation to modelling activities of hybrid systems based on the cyber-physical approach. It is a unique technique usually used during experimental activities for studying the interface and communication and integration issues between seemingly distinct technologies. This gives the flexibility of designing simulated models and hardware components to communicate with one another. This technique is usually based on the coupling of hardware and real-time software for the components not physically present in the rig. The following text highlights some of the major research activities on such systems.

An important research activity coordinated in the early 1990s by U.S. DOE-NETL laboratories of Morgantown (WV, USA) focused on hybrid systems. The experimental activities were based on the cyber-physical technique incorporating an emulator test rig including a recuperated microturbine. This physical emulator for tests on SOFC hybrid systems consists of a turbomachine, recuperators, a fuel cell vessel (without ceramic material) and an off-gas burner vessel [32, 42]. Downstream of the cell volume, the plant is provided with a combustor controlled by a fuel cell real-time model (cyber-physical mode [42]).

At the University of Genoa, Italy a cathode-anode emulator test rig based on microturbine technology (a T100 machine) was developed. The cathode and anode sides of this emulator is based on vessels (without ceramic materials) designed considering a similitude approach with the stack by Rolls-Royce Fuel Cell Systems [43-45]. In this layout, the recuperator and the combustor have been kept inside the turbine cabinet, and the pipes related to the simulation of the hybrid volume have been connected to the original turbine. The commercial microturbine has been modified for the connections to the vessels, but not as drastically as at NETL. The machine uses its commercial control system to consider the minimum possible changes for adaptation of a commercial machine avoiding any risk related to the development of a new control logic [44, 28]. In comparison with the NETL's facility, this emulator rig includes anodic recirculation to study the anode side of the fuel cell system, including assessment of the cathode/anode pressure difference [43, 28] and thermal coupling, as well as the use of an ejector for anode recycle. Thus, to gain an acceptable emulation of a real plant, part of the anodic loop was included into the cathodic volume to partially heat the anodic flow [43, 28]. Also, the TPG's facility can be operated in cyber-physical mode for tests in conjunction with a real-time model [44,45].

The German Aerospace Centre (DLR) has built a similar hybrid system test rig. This test rig comprises a modified and detailed instrumented T100 PH microturbine, connection pipes, and an SOFC emulator. The latter component consists of a pressure vessel, a natural gas lean premix

burner, and a water heat exchanger [46,47]. In comparison with the previous setups, the DLR rig can provide realistic SOFC temperatures in the vessel. Moreover, thanks to the mentioned heat exchanger, it is possible to emulate also the SOFC outlet chemical composition (more fuel is injected with the aim of obtaining the right composition, while the right temperature value is obtained cooling the flow with the heat exchanger).

Ref. [48,49] reported an SOFC-mGT Hybrid model that consists of a microturbine, with a power range of 30 kW Permanent Magnet Synchronous Generator (PMSG), a 90 kW SOFC, a reformer, which converts methane into the hydrogen rich gas feeding the SOFC and a steam generator modelling the time delay required for the methane conversion into hydrogen. However, the emulation part (carried out with hardware) is solely related to electrical components. The system was analysed using computational models. Therefore, it is very different from the SOFC/mGT emulator including a real gas turbine as reported in previous studies [32,43-47]. The differences and the limitations in emulation activities in the model are that only the mGT can operate at partial load [49]. The SOFC operates at its nominal power value (90 kW). The other assumptions incorporated in the model are described in [48].

## **5. Prototypes based on the SOFC-mGT Hybrid systems (Siemens-Westinghouse, Rolls-Royce Fuel Cells Systems, Mitsubishi Heavy Industries, GE Energy etc.)**

This section describes various prototypes concerning hybrid systems that have been effectively tested in research programs of different companies. The following plants can be divided in two main categories: complete hybrid system prototypes operating in the mentioned companies (prototypes: 1, 2 and 3), and research programs under development involving, now, just tests on components (prototypes: 4, 5, 6 and 7).

**Prototype 1-** Westinghouse (W) has been actively involved with SOFC development for more than 3 decades. In 1998 it merged with the Germany Company which later became Siemens

Westinghouse Power Corporation (SWPC). This new company concentrates on research and development (R&D) of SOFC-mGT hybrid systems for the emerging distributed power market. A full scale 100 kW plant, without integrated micro gas turbines, was tested, running more than 15000 hours. All the observed parameters i.e. the design parameters and operation behaviour have been achieved or even exceeded [50].

Another prototype was tested, with a total output of 200 kW composed of an output roughly 180 kW from the SOFC and roughly 40 kW from the microturbine generator. The system consists of a stack: a Siemens Westinghouse tubular SOFC and a microturbine generator supplied by Ingersoll Rand Company. This system was the first demonstrator of the SOFC-mGT hybrid technology. This was able to reach a fuel-to-electricity conversion efficiency of approximately 53% for this size class. These systems continue to undergo further development at the National Fuel Cell Research Centre (NFCRC) to determine performance characteristics and operational parameters, to gain experience for the design of prototypes and commercial products. The research centre predicts to run a system capable of fuel-to-electricity conversion efficiencies of 60-70%. NFCRC was established at the University of California Irvine by the U.S. Department of Energy (D.O.E.) and the California Energy Commission (CEC). Subsequent plants over the years have been designed, developed and tested accumulating hours of operation. Another development by Siemens–Westinghouse achieved a power range of 300-1000 kWe pressurized SOFC/mGT system offering 55-60% electric efficiency and 75+% total efficiency [51].

**Prototype 2** - Rolls-Royce Fuel Cell Systems (RRFCS), a subsidiary company of Rolls- Royce plc has been developing SOFC technologies since 1992 with some significant breakthroughs over the years. Further activities carried out since 2004 by this company were in the areas of SOFC-mGT hybrid technology for power application. The concept behind the development of an RRFCS 1 MW stationary power Solid Oxide Fuel Cell (SOFC) system has been designed, tested and put into operation in 2008. For more on the 1 MW power generation product development programme please see the discussion in [52-58]. This system consists of a generator module (which includes the

fuel cell stack), turbogenerator (TG), fuel processor, and power electronics subsystems. Moreover, each subsystem is based on supporting a 240 kW fuel cell stack and together they form the basis of the 1 MW power plant. At the design point, a 240 kW fuel cell stack and TG are operated to generate 250 kW [54]. However, the overall RRFCs scheme is relatively simple, due to the limited number of components, the interaction between the components, which is complex and the system behaviour, which is determined by many parameters [55]. The second-generation device is planned to have a higher electrical power output and higher electrical thermal efficiency compared with the first-generation device [52].

**Prototype 3** - Mitsubishi Heavy Industries, Ltd. is among the early manufacturers of SOFC as a component of large-scale power generation systems and has promoted both component and system/integration development since the 1980s [59]. Since 2004, Mitsubishi Heavy Industries has designed and manufactured a 200 kW class SOFC-MGT hybrid system, integrating tubular SOFCs and a micro gas turbine (mGT). In 2007 this system underwent a performance test. This test demonstrated world's highest-class gross power output of 229 kW-AC (SOFC: 204 kW-DC/188 kW-AC; mGT: 41 kW-AC). The system has also achieved a power efficiency of 52.1%-LHV at the operating point with a net power output of 204 kW AC, giving the highest level in its class [59]. The company's main goal was a full-scale development of a triple combined-cycle system that integrates a gas turbine combined cycle (GTCC) and SOFCs. As of 2010, Mitsubishi Heavy Industries, Ltd. and Tōhoku Electric Power Co. started a joint research programme for the development of a maximum-efficiency power generation system [59].

In February 2014, Mitsubishi Heavy Industries and Hitachi jointly established Mitsubishi Hitachi power systems Ltd [60]. This new company has developed a plant of small-scale triple combined system under the project name 'Elemental Technology Development for Utility Generation System Using SOFC' by February 28th, 2015. This small-scale triple combined cycle system will be a further improvement to the former 250kW-class SOFC-MGT hybrid system developed by the NEDO Project in 2012 [60].

**Prototype 4** - G. Schiller reported in ref [61] the study by SOFCo-EFS Holdings LLC (2015) of a hybrid SOFC for an auxiliary power unit (APU) replacement for an airplane platform: Boeing 777-200 ER-sized aircraft (pure enough source of H<sub>2</sub> for proton exchange membrane (PEM) fuel cell is impractical due to the complex nature of jet fuel). This new system will have 440 kW of electrical power in flight as well as on the ground. The SOFCo-EFS Holdings LLC design will be a 440 kW hybrid APU using: - a planar SOFC, single stage turbo-compressor, auto-thermal reformer (ATR). The SOFC fuel cell APU estimated performances are at cruise – (Total Power- 440.4 kW, Fuel Cell DC Power- 404.9 kW, Turbine AC Power, and 35.5 kW). On the ground: Total Power- 432.1 kW, Fuel Cell DC Power- 347.0 kW, Turbine AC Power, and 84.2 kW. Aircraft specific tasks are: development of a kerosene reformer and means to prevent detrimental sulphur effects, development of reformer and cells with higher impurity tolerance, study of low temperature and cold-start influence on fuel cells, study of influence of oxygen pressure reduction on performance, study of product water quality, design, tests and optimization of the system with the components reformer, fuel cell, micro gas turbine and air compression.

**Prototype 5** - B. Geyer of US Fuel Cell Council presented a report at Brazil SOFC Network [62], of the North American companies that are involved in SOFC development. Amongst these companies is the ZTEK Corporation, a company engaged in the business of developing, manufacturing, selling and servicing fuel processing and Solid Oxide Fuel Cell (SOFC) based energy systems, reforming natural gas and generating electricity cleanly via electrochemical reactions [62-64]. A 200 kW SOFC gas turbine system is currently under construction at ZTEK facility in Woburn, Massachusetts, US. ZTEK technology claim their device will consume half as much fuel to generate the same amount of electricity as conventional fossil fuel combustion technologies. In doing so, this has the potential to cut fuel costs in half and drastically reduce emissions by over 90%, including the greenhouse gas CO<sub>2</sub>, which can be sequestered [64].

**Prototype 6** - Delphi is a major developer of electronics for automotive technologies. The company has been involved in the development of a solid oxide fuel cell unit for over a decade, focusing their R&D towards powering vehicles, stationary power generation and military applications [65]. Part of a project by Solid State Energy Conversion Alliance (SECA) Coal-Based Systems Project the United States Department of Energy has contributed \$22 million towards simulations where United Technologies Research Centre (UTRC) has verified SOFC-ST (with a steam turbine) and SOFC-GT-ST (with a gas turbine and a steam turbine) hybrid plants, in atmospheric or pressurized operating configuration and towards the building of a 50 kWe experimental facility. The goal is to develop Integrated Gasification Fuel Cells Power Plant (IGFC) power plants with power ratings above 100 kW at an overall electrical efficiency of at least 50%, excluding coal gasification and carbon separation processes [65].

**Prototype 7** - Fuel Cell Energy (FCE) and Versa Power Systems participate in the FE Program Adv. Power - Fuel Cells, Solid Oxide, relating to the SECA Coal-Based Systems Program for the study and development of SOFC-GT systems. The agreement (worth almost \$57 million) began in 2006 and ended in 2015. The agreement refers to the study and testing of a hybrid system powered by coal syngas. The three stages of development are the scale-up of the cell and stack base and the creation of a 16 kW and a 30 kW stack; further scale-up of the fuel cells and stack to 60 kW, followed by the making of 250 kW modules and, finally, the realization of a proof-of-concept multi-MW system, with integrated coal gasification, a high efficiency turbine and moreover a treatment system for CO<sub>2</sub> separation.

## **6. Hybrid system problems for market penetration**

This section discusses the main problems that are negatively affecting these systems, with special attention on issues to be solved for market penetration.



## 6.1 Hybrid systems cost challenges

Even though this system has attracted significant interest in the last decade from the research community and industry it is still not ready to enter the commercial market due to several problems that can be classified primarily in two groups: economic and technological. Furthermore, the thermo-economic analysis of this hybrid SOFC fuel cell system is absolutely required. This is because such considerations highlight additional issues concerning component manufacturing, maintenance cost and the potential solutions to reduce the cost of this technology for wider market penetration.

Considering the microturbines, different works on their cost aspects are available [67,68]. Focusing the attention on the data reported in [68], the analysis was carried out for 6 machines in the 30-1,000 kW range. Their equipment costs range from 1,251 \$/kW (1,000 kW machine) to 1,896 \$/kW (30 kW machine) for just the generation package. If the machine also includes the heat recovery and the gas compression systems, the total equipment costs reach the 1,710 \$/kW-2,289 \$/kW range. Moreover, the installation costs must be added considering labour, materials, installation project/management, engineering activities, project contingency, financing and other costs. This estimation is not easy due to significant variation depending on the scope of the plant, local emission requirements, and other specific aspects related to the installation site. Considering the results reported in [68] for an USA scenario, an estimation shows the following installation costs: 787 \$/kW for the 1,000 kW case to 1,611 \$/kW for the 30 kW machine.

However, when considering the fuel cells, the primary concern that comes to one's mind is the cost, fuel production and infrastructure, and materials and manufacturing. This is regarded as the three major impediments hindering the speedy deployment of fuel cell systems [66]. These objections are examined below in the context of ongoing research and development, with attempts to overcome them. Figure 4 represents the cost of the fuel cell in different application areas [67]. For

the stationary application, SOFC and MCFC are the most suitable fuel cell types for distributed power supply (output >10 kW) [67].

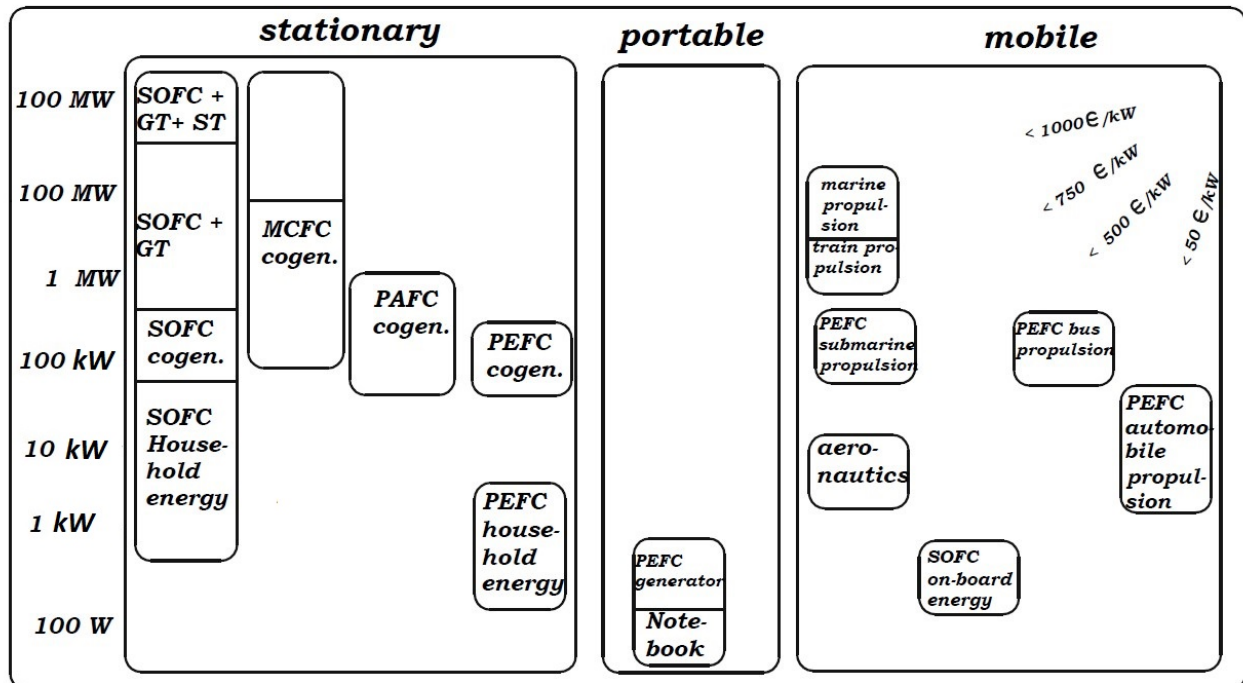


Figure 4- Cost of the fuel cell in different application areas (re-plotted based on [67]).

Different cost values can be available in literature [69] due to different plant configurations. For instance, a very detailed cost analysis is shown in [70]. Focusing the attention on a 100 kW planar SOFC operating with 0.4 A/cm<sup>2</sup> current density, the global cost of the SOFC system was calculated equal to 2,275 \$/kW for a production of 100 units/year. This cost can be broken down considering the following data: 31.8% for the stack, 6.7% for fuel and air supply components, 5.4% for fuel processing components, 13.9% for heat recovery components, 34.9% for power electronic, control, and instrumentation components and 7.3% for assembly activities of components and additional works. However, due to lower values of current density (in some works close to 0.25 A/cm<sup>2</sup>) and additional stack costs for pressurized operations, in hybrid systems the SOFC stack could be close to 3,000 \$/kW. Moreover, appropriate considerations should be made for raw material costs for

hybrid SOFC fuel cell system components, as these often overshadow the whole system costs. It is foreseen, notwithstanding, that mass production and economies of scale will unequivocally lower system costs [66]. In details, a significant cost decrease for large mass production is forecasted: [70] shows about 37% cost decrease considering a production of 50,000 units/year instead of 100 units/year.

Ref. [71] presents a study that compared the thermodynamic and economic analyses of distributed power generation plants; thermo-economic models of three hybrid systems plants with and without fuel decarbonization and carbon dioxide sequestration were successfully constructed and reported. The results show that the thermodynamic analysis efficiency loss is created by the fuel pre-treatment and CO<sub>2</sub> separation and compression [71].

Ref [72] reported a study on the coupling of the SOFC reactor with a small gas turbine based on economic issues within this system (SOFC-mGT). For this study a detailed 2D numerical model of a tubular SOFC reactor was integrated into a thermo-economic modular program (TEMP). This is a validated power plant simulation tool which allows thermodynamic, exergetic, economic, environmental analyses and optimization [72]. They presented the thermodynamic and electrochemical results obtained for the system at the design point. In conclusion of their work, they reported a thermo-economic investigation of the cost of electricity (COE) of the SOFC-mGT, which was based on the new SOFC cost equation [72].

Research activity was also presented by A.F. Massardo, L. Magistri in refs [73,74] showing both an exergy and a thermo-economic analysis of the Internal Reforming Solid Oxide Fuel Cell (IRSOFC) and Gas Turbine (GT) systems using the TEMP code developed by the authors of ref [75], also studied in ref [72]. A suitable equation for IRSOFC cost evaluation based on cell geometry and performance was proposed and employed to evaluate the electricity generation cost of the proposed combined systems. Results were presented, and the influence of several parameters were discussed,

such as external reformer operating conditions, fuel to air ratio, cell current density, and compressor pressure ratio [74].

Many researchers have reported detailed economic analyses to estimate cost contributions of different HS system components and manufacturing processes, with conflicting and sometimes incompatible conclusions. The reader is therefore directed to accessible government-contracted reports and other documents for more consultations on hybrid SOFC fuel cell systems cost and cost reduction approaches [66-75].

## **6.2 Hybrid systems reliability/availability challenges**

Reliability is the probability of a device performing its purpose adequately for the period intended under the operating conditions encountered [76,77]. The aim of this section ranges from the presentation of a general concept of the reliability in engineering systems to reliability in SOFC systems. A reliability evaluation technique is a very wide topic and important part of any design and development of a new engineering system. This concept has been applied to aerospace, military and nuclear industries, to provide vital answers to the questions of how safe or reliable will the resulting system be during its entire future operation life. However, this question can be answered, in part, using quantitative reliability evaluation [76,77].

As a result, notable attention has developed towards the application of such techniques to the design and operation of simple and complex systems together with an increasing number of legal requirements, including product liability aspects and statutory directives [76]. Types of systems when considering reliability study can be easily divided into two groups as reported in [76]: the mission-oriented systems and continuously operating systems.

The SOFC hybrid gas turbine system (which is a continuously operated system) can have a significant number of system failures (due to component failures that might affect the customer supply of electricity) that are allowable provided they do not occur too frequently or are of

prolonged duration. A system adjustment or restoration processes is carried out during these failures. Hence, the understanding of this revival process is a necessary part of the required techniques [76]. The reader is directed to [76,77] for more further details on the reliability/availability approaches of a continuously operating system which SOFC gas turbine hybrid system (methods of assessing the reliability of the system).

### **6.3 Integration challenges for mGT/SOFC systems**

The major setback regarding the SOFC/GT coupling is related to the fact that the microturbines in such systems are not optimised for coupling with SOFCs. Moreover, their designs are based on general market requirements in terms of size and performance. Thus, the adaptation of a commercial GT for use in a fuel cell coupling application can introduce an important constraint on the stack size or can generate a significant efficiency reduction resulting from the need for an air bleed or bypass approach [29].

Several additional property constraints must be considered to avoid component damage [28, 29] or significant lifespan degradation. The following factors have a strong influence on these constraints: plant layout, component layout and constraints, property ranges and controlling devices. Another important constraint relates to chemical composition and kinetics-related aspects since the efficient stack operation requires maintaining flow compositions within very narrow limits [29]. For example, even if methane can be directly used as a fuel in SOFCs, the electro-kinetic considerations regarding specific consumption issues reveal a slow reaction rate, implying that maintaining a significant amount of hydrogen in the anode is always vital (to be produced by steam reforming and shifting reactions). Also, any variations in the fuel cell thermal effluent (which is the thermal energy of the SOFC exhaust streams) due to transients in fuel composition, can affect the stability of the turbine cycle, which can be a significant problem to the fuel cell stacks [28, 29].

#### 6.4 Hybrid system control and diagnostic challenges

Another challenge concerning hybrid system development is the control system. Due to the complexity and issues related to systems integration, it is necessary to carry out intensive research activities exclusively devoted to system dynamics and to the appropriate design of adequate control hardware and algorithms [19, 78-85]. Some major challenges that have been identified and investigated previously by different research groups include the following: compressor surge, transient control, designing a proper heat engine for integration with the fuel cell, off-design performance including multi-spool gas turbine configurations and difficulty of matching gas turbine pressure ratio and mass flow rate (with the SOFC pressure ratio and mass flow rate [85]). Therefore, a summary of such activities related to control system design are outlined below for both steady-state and transient operation conditions.

- *Microturbine commercial control system*

Normally, all available mGT commercial control devices or approaches are designed without considering integration with a third component system. Therefore, the integration with external additional hardware (for example, a SOFC) is a critical issue. The resulting layout must be controlled via an integrated control system for the whole plant [19].

- *High temperature valves avoidance*

It is necessary to design and avoid installation of several valves in the high temperature ducts to avoid reliability decay and significant cost increase. Controlling the required flows from the low temperature zones causes a significant complexity to increase in the control system design [19].

- *Problems related to measurement of important properties*

Some control specific process and/or component variables cannot be easily measured without excessive costs [19]. Therefore, these important variables can be calculated via extensive simulations (with validated models) for control system design.

- *Simple PID controllers are not adequate to satisfy all system operational constraints*

Because of the slow thermal response of the stack and given the constraints related to temperature gradients [19], simple PID controllers are not able to avoid oscillations of temperature during transient operations. Hence, other approaches are necessary to avoid such problems. The following are possible solutions: feed-forward approach, model predictive control, h-infinity or other innovative control solutions [19].

A further important aspect to be considered for hybrid systems regards the diagnostic issue. While different research groups presented innovative approaches on diagnostics for SOFC components (e.g. for carbon deposition issue [86], for the SOFC performance [87], and for the reformer [88]), these kinds of activities on the entire hybrid system are quite limited. As an example, of possible preliminary activities the University of Genoa developed an apt real-time model to be used in parallel with the hybrid system to be monitored [89] (significant mismatches could be related to faults). Moreover, other activities on compressor surge prevention [90] or hybrid system degradation [91] are preliminary works for diagnostic purpose.

### **6.5 SOFC degradation issues on hybrid plants**

For successful commercialisation of SOFC systems [91-97], the degradation of cells and stacks is regarded as one of the most important criteria because of their strict lifetime requirements, e.g. over 40,000 hours with power losses of less than 10% for stationary applications [97]. The performance degradation at high temperature is caused by various problems and proceeds through complicated pathways, which include deterioration of individual materials, mutual interaction of multiple components and response to contaminants introduced from external sources [97]. For the past few decades, extensive research efforts have been devoted to clarifying degradation mechanisms, and various roots of the performance deterioration have been identified [91-97]. It is important to state that SOFC degradation has an important impact on the possible market penetration of hybrid systems, as achieving longer lifetime (accompanied by high performance) could eventually compensate for higher component costs in comparison with traditional plants. Indeed, despite the

SOFC having a high efficiency and being flexible in terms of fuel usage, making them an attractive technology for the future energy generation, their economic un-competitiveness issues is still a major drawback. This is particularly true for the problems related to their short lifetime, due to the multiple degradation phenomena [91]. Concerned about such considerations, U.S. Department of Energy, National Energy Technology Laboratory (NETL) carried out research activities [91] on the key fuel cell parameters during cell degradation using a distributed model. Degradation was considered as an increment in ohmic resistance, as a function of the following operating parameters: current density, fuel utilization, and temperature. The choice of these parameters was because they have an effect on the cell degradation, and because they can be measured and controlled during the operations to minimize degradation effects. The use of a simple algebraic expression allows to maintain real-time performance of the model [91].

## **7. Future of hybrid systems**

Although several authors previously predicted commercialisation of these hybrid systems in 5-7 years according to plans presented in the initial decade of 2000s (e.g. [54,55]), significant issues (related to technology, maturity, complexity and costs) affected the development speed. However, validated solutions for some research issues (cost decrease, SOFC/mGT matching problem and control system) have since been developed [28,47,52]. Hence, an increase of studies and funding resources on SOFC hybrid systems would be essential to provide realistic solutions for the problems [28,44,45,47,60,76,80]. A promising positive trend concerning these systems is shown by Mitsubishi, due to the first order they have received to start energy generation in 2019 [98]. So, these plants remain as forecasted central pillars for future power generation, especially considering the hydrogen economy development [99,100,101].



## 8. Conclusions

A detailed review of an environmentally clean and efficient source of energy, solid oxide fuel cell (SOFC) hybrid systems has been provided in this paper. These research activities were focused on the whole hybrid system evolution from the early concept design in the early 2000s to the prototypes of such systems by research laboratories like DOE-NETL, TPG-Genoa, DLR-Germany and industries such as Rolls-Royce Fuel Cell Systems, Mitsubishi Heavy Industries, Siemens Westinghouse. However, to date, there has been no detailed review of the entire system starting from some combined details of SOFC hybrid systems layouts, analyses with emulators, hybrid system emulators, prototypes based on the SOFC-mGT hybrid systems reliability/availability challenges and other major challenges facing this technology before fully being commercial. The overview of different topics has been provided in the paper with an update on several current fundamental and applied engineering issues. Combined and detailed literature of the state-of-the-art and further recommendations on where this technology is heading with regards to commercialisation and its challenges have also been provided. The authors are very optimistic that the hybrid system will surely be commercialised and be used as an alternative for power generation in the future.

## 9. Acknowledgements

The author would like to recognise and thank the entire Thermochemical Power Group (TPG) from the University of Genoa, Italy for their contribution to the research materials and for the courtesy shown during the collaboration. The authors also acknowledge the assistance of two of their MACE colleagues, Mr. J. L. Blackall and Mr. Dale Smith, for proofreading of the manuscript.

**10. NOMENCLATURE****Acronyms:**

RRFCS .....	Rolls-Royce Fuel Cell Systems Limited
SOFC .....	Solid Oxide Fuel Cell
DOE .....	Department of Energy
NETL .....	National Energy Technology Laboratory
TPG .....	Thermochemical Power Group
DLR .....	German Aerospace Centre
HS .....	Hybrid System
UNFCCC .....	United Nations Framework Convention on Climate Change
UNPF .....	United Nations Population Fund
USCB .....	United States Census Bureau
mGT .....	micro-gas turbine
REC .....	recuperator
TEMP .....	Thermo-Economic Modular Program

**Subscripts:**

an.....anodic

cat.....cathodic

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## 12. Figure captions

Figure 1- Examples of gas turbine engine layouts, layout 2 to 6 can be a choice for hybrid systems by replacing the conventional combustor with a high-temperature fuel cell such as in an SOFC.

Figure 2- Hybrid systems general layouts: Cathode–anode side interaction in SOFC hybrid systems [28].

Figure 3- Pressurized SOFC/mGT hybrid systems: (a) layout 1—internal reforming and (b) layout 2—external reforming [30].

Figure 4- Cost of the fuel cell in different application areas (re-plotted based on [67]).

- Environmentally clean and efficient source of energy.
- Integration of a microturbine and a fuel cell (hybrid systems).
- Fuel cell modelling and SOFC hybrid cycles.
- Limitations and the benefits of these hybrid systems in relationship with energy, environment and sustainable development.
- Few potential applications, as long-term potential actions for sustainable development, and the future of such devices.