CHAPTER 2

LITERATURE REVIEW

2.1 Fuel Cells

According to the World Energy Outlook Fact sheet 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 around 65%. Electric Power generation is responsible for half of the increase in global greenhouse gas emissions over the period of time. Due to these problems energy sustainability considerations should be involved in all major energy development plans all over the world. Energy sustainable activities are the activities which help existing generation to meet their needs without destroying the ability of future generations to meet their requirements [18].

Fuel cells are very promising alternative for conventional power generation technologies because of their very low environmental effects and high electrical efficiency. Operation of the Fuel Cell is based on electro chemical reactions and not like fuel combustion in conventional power systems, however their efficiency is limited by the ratio of released Gibbs free energy to the inlet fuel calorific value. Also since there is no combustion in the cell, none of the pollutants is emitted into atmosphere.
2.2 Modeling of the fuel cells

Simulation and mathematical modeling of different alternate power generation systems is certainly used for, however it is more important for the fuel cell based combined cycle power plants due to their complexity and difficulty in experimental characterization of internal operation. This complexity is involved in the simultaneous process of electro chemical reactions, ionic conductions, electrical conduction and heat transfer. Therefore it requires a multidisciplinary approach. Modeling can help us to understand the internal operation of the fuel cells [19].

It is difficult to understand the internal chemistry and physics of fuel cells. This is because of difficulty in independent controlling of the fuel cell parameters, large number of physical and chemical processes in the cells and inadequate accessibility to inside of the fuel cells [20].

Also, simulation of fuel cells can help to focus on experimental research and to improve accuracy of extrapolations and interpolations of the evaluated results. Mathematical models can be used as valuable tools to design and optimize fuel cell hybrid systems. Furthermore, dynamic models can also be used to design and test fuel cell power systems control algorithms. Models can be developed to estimate whether characteristics of particular type of fuel cell can meet the requirements of an application and its cost-economy [19].
Due to their importance, in the past two decades there has been significant progress on numerical and computational tools for fuel cells based and hybrid systems and very large number of papers has been published on fuel cells modeling and simulation. For few review papers on modeling and simulation of SOFCs [21,22,23,24,25] and MCFCs [26].

2.3 GT-SOFC Hybrid Cycles

High temperature fuel cells, SOFC and MCFC can be integrated in the conventional power generation system because of their high operating temperature.

The advantages of SOFC Hybrid Systems are:

- High electrical energy conversation efficiency due to high rate of chemical reaction kinetics.
- High oxide – ion conductivity through the cell components.
- Ability to the casted into various shapes, such as tubular, planar or monolithic.
- Suitable and accurate design of the three phase boundary
- No constraints for the electrolyte management.

An elaborate historical and technical review of SOFCs can be found in [27,28,29,30&31] Dokiya [32] studied SOFC materials and fabrication technologies used for manufacturing of different components, evaluated the performance of the fuel cells manufactured by using these materials, and also reviewed efforts to reduce SOFC
Rajashekara [13] classified the fuel-cell and hybrid systems as Type-1 and Type-2 systems. These are mainly suited for combined cycles power generation and stand by or peak load power system respectively. An example of Type–1 hybrid systems is fuel cell and Gas Turbine cycle, where high temperature of fuel cell gas is used in Gas Turbine to increase the overall efficiency of combined system. Another example of this type of combined cycle are fuel cell with internal combustion engine and designs that combine different fuel cell technologies.

Examples of Type-2 hybrid systems are designs which combine a fuel cell with solar or wind power generation systems that integrate the best operating characteristics of the individual units such the duration of the availability of power.

Winkler et al [33] defined the fuel cell hybrid system as the combination of the fuel cell and a heat engine. In this, the heat energy of the fuel cell off-gas is used to generate further electricity in the heat engine. However, we can extend this definition to include combined heat and power systems. Therefore, a hybrid cycle can be any combination of GT-SOFC, GT-MCFC, steam and gas turbine combined cycle (CC), steam turbine, coal integrated gasification (IG), and integrated gasification combined cycle (IGCC).

If the fuel cell is operated at atmospheric pressure, the exhaust gases can be passed through series of heat exchangers to generate
either low-pressure steam for industrial applications or hot water [34] or high-pressure steam for a Rankine power plant [35].

The fuel cell system can also operate at high pressure. In this the high pressure and high temperature combustion gases discharging combustion chamber at the bottom of SOFC can be used to drive a gas turbine without or with a bottoming steam cycle. This case was proposed in 1991 [36].

Among the different hybrid systems proposed for pressurized fuel cells, mostly GT-SOFC hybrid cycles are the most popular systems being studied theoretically and experimentally. There are two main designs to combine GT and SOFC. The difference between the two designs is how they extract heat from SOFC exhaust. In the first case fuel cell off-gas directly passes through Gas Turbine. That means fuel cell stack replaces the gas turbine combustor. But in the second system, the fuel cell off-gas passes through high temperature recuperator which in turn replaces the gas turbine combustor [37].

In the operation of the above systems, the designs of systems are differentiated by the operating pressure of the fuel cell. In the first design operating pressure is equal to the operating pressure of the gas turbine and in the second case it is slightly above atmospheric pressure. It should be noted that in all cases CHP Plants and a steam cycle [38] can be integrated to the hybrid system to recover more energy from exhaust gases.
There have been few demonstrated GT-SOFC power plants in the world. Siemens claimed it has successfully demonstrated its two pressurized GT-SOFC hybrid systems of 220kW and 300kW at the University of California, Irvine and in Pittsburgh [39, 40]. Also, in 2006 Mitsubishi Heavy Industries, Ltd. (MHI, Japan) claimed that they have tested 75kW SOFC-MGT hybrid system power cycle [41].

Although both MCFC and SOFC can be used in hybrid cycles, due to the cell reactions and the molten nature of the electrolyte and lower efficiency of MCFC [42], many research articles are available in the area of SOFC hybrid systems. There are few steady state [43,44,45,46] and dynamic [47] modeling on the GT-MCFC cycles. Suther et al. [48] presented a steady state thermodynamic model of a hybrid GT-SOFC cycle using commercial process simulation software Aspen Plus. Their GT-SOFC hybrid cycle model incorporated a zero dimensional macro level SOFC model. As observed, there is no built-in SOFC model available in this software package. 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 which can be used for more realistic steady state simulation of thermodynamic cycles. In this software, user defined and built-in models can be connected with material, work, and heat streams to form a model of an actual system [49]. 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 evaluations [49].

The model was consisted of two main parts; the cycle model with various components and the SOFC model. The cycle model included all required system equipments such as heat exchangers, fuel reformer, compressors, combustor, 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 relations of thermodynamics, chemical reactions, and electrochemistry. For Fuel Cell chemical reactions, they assumed three reactions taking place within the SOFC: reaction of H2 with O2 forming H2O, methane steam-reforming reaction, CO shift reaction. They used electrochemical reaction calculations to evaluate 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 over potentials namely, the concentration, activation and ohmic losses were deducted. The thermodynamics equations were also used to evaluate the heat output from the stack and the outlet temperature.

The basic technology and dynamic modeling and characterization of solid oxide fuel cell integrated in a gas turbine cycle have been presented by Thorud [10] and he observed that with the use of fuel cell, the efficiency of the gas turbine plant increases.

Nernst has developed Zirconia (ZrO2) as an oxygen ion conductor in the late 1890s. Nowadays, a century later, Zirconia is
still the most common electrolyte material in SOFC’s with the addition of small percentage of Yittria ($Y_2O_3$). However, manufacturing methods and design have been improved to give higher reliability, efficiency and power density.

Viswanathan and Scibioh [50] had explained the detailed working principles and applications of the fuel cells. Bang [51] research work includes the design and optimization of an integrated biomass gasification and solid oxide fuel cell system. Detailed design procedure and chemical reactions takes place in the utilization of fuel cell. This has been explained by Williams [19]. Haseli et al. [52] have experimentally analyzed the gas turbine power plant without using the fuel cell and obtained 40% efficiency, by integrating solid oxide fuel cell, obtained 56-76% efficiency. Exergy analysis of various components of the hybrid power system has been explained by Cocco and Tola [53], Rao and Samuelsen [54] and Bavarsad [55]. Cassnova et al. [56] presented the Siemens-Westinghouse Power Company developed the tubular SOFC’s by integrating with gas turbine and obtained the 70-75% efficiency.

Chan et al. [57, 58] modeled a simple GT-SOFC power plant and presented that an internal reforming hybrid SOFC/GT system could get electrical efficiency of more than 60%. Song et al. [59] studied the possible extension of a SOFC/GT hybrid system to multi MW power generation system based on a commercially available gas turbine and thermo economic analyses of SOFC/GT hybrid systems. Single-level
optimization of a hybrid SOFC/GT power plant has been analyzed by Calise et al. [60]. Zhang et al [61] has done the critical review on integration strategies of solid oxide fuel cells. Douvartzides et al. [62, 63] presented an energy-exergy analysis to optimize the operational conditions of a SOFC/GT power plant, by considering only the hydrogen oxidation within the fuel cell and rejecting the effect of the cell losses instead of methane reforming and carbon monoxide conversion. The optimal condition was obtained for a SOFC fuel utilization factor of 79.85%, an ethanol conversion of 100%, water to ethanol ratio 3:1 and no energy integration was observed. Granovskii et al. [64] compared the performance of two combined GT-SOFC systems. A thermodynamic analysis of a combined gas turbine power system with a solid oxide fuel cell was carried through exergy by Haseli et al. [65]. Larminie [8] and Companari [66] explained the application of Yttria Stabilised Zirconia anodes in SOFC systems allow the conversion of methane into hydrogen and carbon monoxide on their surfaces.

Granovskii et al. [67] and Saidi et al. [68] evaluated the cogeneration efficiencies of fuel cell systems and compared with exergy methods. Zhu and Kee [69] studied the impact of the fuel utilization factor on SOFC efficiency using a detailed electrochemical model and generated efficiency maps which give the range of methane-steam mixtures for maximum efficiency.
2.4 Early Models

The SOFC development has started in the late 1950s and continued longest period and various types of fuel cells [19]. However the results of first simple SOFC models were published in the open literature in 1980s. For SOFC hybrid cycle, the first papers were being presented in early 1990s.

Dunbar and Gaggioli have been considered as beginners in the field of SOFC modeling and their integration with Rankine cycle. They presented their first paper on the results of mathematical modeling of the performance of solid electrolyte fuel cells as early as 1988 [70]. In 1990 [35], they suggested 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 [35]. They determined 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 [71]. They also studied [72] the exergetic effects of the major plant components as a function of fuel cell unit size. The results showed that specific fuel consumption deceased by as much as 32% in hybrid cycle.

Harvey and Richter, who presented a hybrid thermodynamic cycle combining a gas turbine and a fuel cell, are the pioneers in this area. Harvey et al. [73] first proposed the idea in 1993 by analyzing one of the earliest modeling works in GT-SOFC hybrid power cycle.
They developed a model [74] to simulate monolithic SOFC (MSOFC) combined with intercooled GT in Aspen Plus and a fuel cell simulator developed by Argonne National Laboratory [75]. They observed 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 exergy analysis noted the large exergy destruction in combustor, SOFC and air mixer. They proposed that internal reforming could improve both system efficiency and its simplicity.

In their paper [76], they modified and improved the model by incorporating internal reformer to the cycle and taking into account all major cycle overpotentials. Then the cycle efficiency was 68%. Moreover, they mentioned that the system efficiency increased with cycle pressure. They evaluated that maximum efficiency could be achieved at system operating pressure equal to 15 bar while satisfying the system constraints. They compared efficiency of cycle with external and internal reforming and surprisingly found that their efficiencies were almost identical. The exergy analysis showed that exergy destructions in internal reforming cycle were marginally higher than those of external reforming cycle (275 versus 273 MJ/s).

2.5 Parametric Studies of GT-SOFC Hybrid Systems

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

Palsson et al. [77] proposed a steady state model for a combined GT-SOFC 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 system components modeled as standard unit operation models. In order to model SOFC, they adopted two dimensional model of planar electrolyte-supported SOFC.

The finite volume method was used to discretize cell geometry by considering activation and resistance polarization. Their system size was 500kW because they thought this was proper size for demonstration and market entry purposes. It should be noted that they added primary fuel to increase Turbine Inlet Temperature but they maintained constant fuel flow. 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°C). They studied various system parameters, including the electrical efficiency, specific work, Turbine Inlet Temperature, and SOFC temperature with respect to the Pressure Ratio. They observed that increasing Turbine Inlet Temperature did not improve system efficiency and specific work. In order to increase Turbine Inlet Temperature, more fuel should be combusted at GT combustion chamber, thus less fuel remained to be consumed in SOFC unit. Their
analysis depicted that system operating pressure had great impact on hybrid system performance. At lower Pressure Ratios (CRs), the efficiency increased slightly to an optimum point and then sharply decreased for higher CRs. A maximum efficiency of 65% could be achieved at a Pressure Ratio of 2. At this point the Gas Turbine output was almost zero; therefore, this efficiency of the system was equal to SOFC efficiency. The slight improvement in system efficiency influenced in increased efficiency of SOFC. At higher CRs, more power output from the gas turbine and less from the SOFC decreased system overall efficiency. Also they observed that cell voltage had no impact on system performance. Similarly, they studied 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, especially for the reheat case.

Chan et al. [57,58] proposed a model of simple GT-SOFC-Combined Heat and Power system and performed the first law of thermodynamics energy analysis on the model. Their model obtained electrical and total efficiencies of over 62% and 83%, respectively. Then, they investigated the effects of fuel flow rate and system operating pressure on the system overall performance.

Calise et al. [78] studied the impacts of current density, system operating pressure, fuel-to-oxygen ratio, fuel utilization factor and water-to-methane ratio on the electrical efficiency of a hybrid GT-
SOFC system and found the electrical efficiency.

2.6 Models for Comparison of GT-SOFC Configurations

An important objective of hybrid GT-SOFC systems modeling is to predict system performance for different configurations. There have been huge number of proposed hybrid GT-SOFC power systems in the open literature that combined SOFC stacks with heat exchangers, compressors, GTs, pre-reformers, mixers, heat recovery steam generators (HRSGs), CO2 capture, combustors and so on (such as Campanari et al. [38]). However, there have been no universally accepted configuration(s) yet and researches are still trying to propose innovative cycles for the SOFC hybrid systems.

Stiller et al. [79] proposed 2-D planar and 1-D tubular SOFC models to simulate GT-SOFC hybrid cycle. They investigated effects of different operating parameters such as Pressure Ratio, air inlet temperature and so on to compare performance of two cycles. It was observed that hybrid systems could achieve efficiencies above 65% with both planar and tubular SOFC. The main difference between the tubular and planar GT-SOFC Hybrid 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 SOFC stack, due to its higher ohmic loss.
Selimovic and Palsson [80] investigated the effect of using two smaller fuel cells stacks in series (in terms of fuel and air flow) instead of conventional one stage stack. They used same model as [78], with minor modifications. They presented 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.

Magistri et al. [81] developed a model to study the performance of a hybrid system consisting of integrated planar SOFC (IP-SOFC), GT, and district heating. They evaluated that overall efficiency of atmospheric hybrid system was 10% lower than that of pressurized system.

In 2007, Granovskii et al. [64] showed 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 [82]), cycle with anode exhaust recirculation and cycle with HRSG for steam generation. They also included a Rankine steam cycle at the bottom of GT for the configuration with anode exhaust recirculation. They performed energy and exergy analysis on the models and determined that the suitability of these schemes depended on the application of the power generation system.

Pangalis et al. [83] and Cunnel et al. [84] modeled and compared six different configurations of hybrid GT-SOFC power systems by considering variety of features in each system, including
intercooler, reheat SOFC stack, combustion chamber and recuperator. They determined that the optimal configuration in terms of efficiency could be achieved when Gas Turbine with intercooler and recuperator were integrated to primary SOFC (ahead of the combustor) and reheat SOFC (between high- and low- pressure Gas Turbine) with efficiency of 76%. Also, they presented that in configuration with intercooler and recuperator integrated to primary SOFC, the net specific power was maximized. Again, they showed that the most important factor for selecting hybrid SOFC power system configuration was the application of power plant. For example, SOFC based recuperated Gas Turbine, ahead of combustor with thermal efficiency of 64% at relatively low Pressure Ratio of 14 and the specific power of 520kW/kg was probably the most suitable configuration for medium and small scale power generation.

Kuchonthara et al. [85] proposed their GT-SOFC hybrid model by writing a Fortran code for SOFC and running it in Aspen Plus. They preformed a parametric analysis on two hybrid SOFC system configurations: hybrid GT-SOFC with heat recuperation system and hybrid GT-SOFC with heat and steam recuperation (HSR) system. In the former, heat from the Gas Turbine exhaust was recovered by an air preheating system whereas, in latter, an air preheating system and a HRSG were used for this purpose. In Heat and Steam Recuperation system, in order to increase net mass flow and power output of Gas Turbine, the generated steam was directly supplied into the
combustor. They observed that Gas Turbine power output and system overall thermal efficiency were higher in Heat and Steam Recuperation configuration, due to higher energy recuperation rate in this configuration. Also, they presented that higher pressure ratios increased the synergetic effect of steam recuperation.

They evaluated the overall efficiency of the cycle against Turbine Inlet Temperature (TIT) for different Pressure Ratios (CRs). They found that, at low Turbine Inlet Temperatures the thermal efficiency decreased when Pressure Ratio increased. This was due to lower fuel utilization factor in SOFC for higher CRs. In contrast, higher CRs led to thermal efficiency improvement at high Turbine Inlet Temperatures due to larger Gas Turbine power output. It seemed that their results completed previous investigations [48, 77, 86] on the effect of Turbine Inlet Temperature on cycle’s overall performance. As a result, they suggested that optimal system (both high efficiency simultaneously and high power output) could be achieved when system operated at high Turbine Inlet Temperature with an optimal Pressure Ratio.

Similarly, they published another research paper [87] to evaluate performance of hybrid systems when SOFC cycle integrated with different 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 evaluated effects of operating conditions, such as TIT and CR, on the overall efficiency and specific work output of the system. They
suggested 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 GT-SOFC hybrid systems development is to find a gas turbine that suits the requirements of hybrid cycle. Lundbergm et al. [88] investigated 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, reliability, modular design and low cost of maintenance. They found 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 obtained 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).

Sieros and Papailiou [89] studied the optimal fitting of a small GT in a hybrid GT-SOFC for both design-point and part-load operation conditions. They suggested variable geometry components, namely variable nozzle turbine and variable diffuser compressor to avoid compressor surge and increase part-load efficiency.

Rao and Samuelsen [54] started SOFC cycle coupled with intercooled-reheat GT as reference power generation system for their
thermodynamic modeling. Then, they framed their alternative cases by incorporating HAT system to their reference case and also replacing reheater with second SOFC (dual SOFC-HAT). They determined that efficiency of the reference case and its alternatives were 66%, 69%, and 76%, respectively. In addition, they presented that the second scenario could achieve lowest cost of electricity (COE).

Song et al. continued their previously published work [42] in another investigation [59]. They extended their model to find optimal matching between a commercially available gas turbine (Mercury 50) and a SOFC unit. The parameters to be matched were included: pressure and operating temperature 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 presented in Veyo et al. [40], the power ratio of this system was very low. Their results agreed with results obtained by Lundbergm et al. [88].

2.7 Optimization of GT-SOFC Hybrid Systems

A survey of the literature in the modeling of hybrid SOFC power systems shows that little has been done for optimization of the systems. In most of those few works, such as [90], sensitivity analysis of various parameters was performed to develop an optimal SOFC
hybrid power generation system. However, due to the large number of parameters involved and complex nature of their correlation and interrelation, suitability of this optimization method is controversial. In Optimization of a typical GT-SOFC hybrid cycles 5 to 10 (or even more) [91] independent variables should be considered, depending on how complex the model and system are. Therefore, it is important to search for methods that can optimize these non-linear multi-dimensional systems [91].

In a significant development in the optimization of GT-SOFC systems, Moller et al. [91] developed genetic algorithm (GA) to optimize GT-SOFC hybrid configuration with and without a CO₂ separation plant. In order to model the SOFC stack, they adopted the same model as in [77]. In their optimization, the electrical efficiency of the plant was selected as the objective function. Also, the air flow, fuel flow, fuel cell stack voltage, air temperature at the stack inlet, reformer duty, and Pressure Ratio were selected as decision parameters. The optimization procedure adopted in the GT-SOFC power system with above 60% efficiency can obtained, when equipped with CO₂ capture. The results showed that the system electrical efficiency was greatly influenced by SOFC temperature. Also, a low air flow and no or little supplementary fuel could improve the system overall efficiency.
2.8 Exergy Analysis

According to Dincer and Rosen [92] exergy analysis is a technique that can be applied to design, improve, and analyze the energy systems. This method considers the second law of thermodynamics as well as the conservation of mass and energy, simultaneously.

Granovskii et al. [93] presented the importance of exergy analysis in applying the “principles of industrial ecology” for integrating different technologies. For instance, they performed exergy analysis on a GT-SOFC hybrid system and observed that the depletion number of standalone SOFC and GT were much higher than that of hybrid system. This concluded that the GT-SOFC hybrid system was more environmental friendly.

The depletion number, proposed by Connelly and Koshland [94], is a method to describe the efficiency of fossil fuel consumption according to exergy analysis and is defined based on how an irreversibility within a system is related to total exergy input to the system.

Calise et al. [78 & 95] (with a few modifications in system configuration) performed the second law of thermodynamics analysis on a gas turbine cycle integrated with SOFC. Their exergy analysis showed 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 influenced in inefficiencies of chemical reactions occurring in those
equipments. Despite the high electrical efficiency of SOFC, fuel cell stacks are the greatest source of exergy losses due to the number of electrochemical and chemical reactions, such as electrochemical oxidation and steam reforming, taking place simultaneously. Similarly the catalytic burner, where anode off-gas stream was combusted, showed a significant exergy destruction rate. On the other hand, exergy destruction rate of compressors and turbines were not remarkable because of their high isentropic efficiencies and low energy flows. They also performed exergy analysis on partial load operation and determined that although exergy destruction generally increased, its rate depended on the selected control method. Finally, they suggested that in hybrid energy systems design, particular emphasizes should be placed on component with highest exergy losses, i.e. SOFC stacks.

Granovskii et al. [96] presented exergetic performance analysis of a SOFC-GT hybrid cycle. They determined 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 combustion chamber and SOFC stack was less than 5%.

CO₂ Capture:

Although SOFC hybrid power plants are considered to be the cleanest technology to generate electrical energy 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 power plants is an active field of research.

In 1999 Riensche et al. [97] presented a model to simulate a near zero CO$_2$ emission hybrid GT-SOFC combined cycle power plant. Their adiabatic tubular air electrode supported solid oxide fuel cell model was based on one of the earliest planar SOFC model [98]. There are two methods to separate CO$_2$ in the exhaust stream of power plants. In one of these methods, the spent fuel is combusted with pure oxygen, instead of air, to avoid introducing nitrogen to the plants off gas stream. In their developed model, they made use of one of the unique characteristics of SOFC cycle is that other technologies cannot easily compete. They modeled a bank of oxygen ion conducting tubes (very similar to SOFC tubes) and supplied the unused fuel over them. They determined 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 GT-SOFC combination were obtainable in this configuration.

Franzoni et al. [99] proposed a model to simulate 1.5 MW GT-SOFC hybrid power system based on the model explained in [100]. They compared performance of the hybrid power 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 first method, they
observed 17% efficiency penalty, from 62% to 45% with 0.15 kgCO₂/kWh of CO₂ in exhaust. In second the method, the system was equipped with an air separation unit to provide oxygen for gas turbine combustor. The generation efficiency loss in this case was much lower at 3.6% with near-zero CO₂. The thermoeconomic analysis found that the cost of second plant was significantly lower.

With the same procedure, Inui et al. [101] used second method (pure oxygen as the oxidant gas in gas turbine combustion chamber) for CO₂ capture. They evaluated that the generation efficiency of cycle could reach as high as 71% (LHV) indicating that the developed system could satisfy both expectations of high efficiency and ultra clean power generation.

Campanari and Chiesa [102] compared performance of GT-SOFC hybrid cycle with two configurations for CO₂ capture process. In the first approach, steam and CO₂ in the anode exhaust was separated by condensation and chemical absorption, respectively. Then, 30% of remaining fuel combusted in gas turbine combustor and the rest was recycled to anode to be consumed in SOFC. In second approach, CO in anode exhaust was converted to H₂ in shift reactor. Then, existing CO₂ was chemically absorbed, and hydrogen rich gas combusted in gas turbine combustion chamber. The GT-SOFC model for this plant was explained in [67]. The results depicted that both plants exceed 71% (LHV) efficiency and removed 90% of CO₂ in exhaust stream. Although utilization of the shift reactor increased
complexity of second method, 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 CO₂ sequestration.

2.9 Fuel Flexibility of GT-SOFC Hybrid Systems

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

In one of the earliest works in this area, Lobachyov and Richter [103] presented the results of their analytical study on the system that integrated a coal gasification process into hybrid SOFC- GT cycle, which the latter was proposed by Harvey and Richter [74] in 1994. They proposed recycling of part of the hot cathode off-gas to provide the amount of heat required for gasification. They performed energy and exergy analysis on the model. They observed that the cycle could achieve up to 60% energy efficiency. Exergy analysis showed that the SOFC, gasifier, and steam generator were responsible for most of exergy destruction. In addition, the integration of a two- stage gas turbine with reheater and steam turbine at the bottom of the gas turbine resulted in 0.5% and 3.2% improvement in the system overall efficiency, respectively.

Kivisaari et al. [104] conducted 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 (combined heat and power plant). They considered a thermal input of 50 MW capacity with and without anode off-gas recirculation for SOFC. They used a one-point model to reduce evaluation times and model complexity. They observed 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 the fuel utilization. These values, however, could not be trusted completely because, their one-point model did not consider reduction in the concentration of the reacting streams. They noted 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 the system of about 47% and 85%, respectively.

Another research on combination of coal gasification and fuel cell for power generation was presented by Kuchonthara et al. [105]. They adopted the integrated power generation cycle combining with thermo chemical recuperation, brown coal gasification and a fuel cell. In order to model the SOFC they considered the same model as in [89, 91]. Their simulation predicted that the cycle efficiency could be increased from 39.5% (higher heating value, HHV) without the SOFC to about 45% with the integration of SOFC.

Rao et al. [106] evaluated thermo economic analysis of
integrated gasification fuel cell (IGFC) power plant and compared it with an integrated gasification combined cycle (IGCC). They presented that the cost of electricity of IGFC plant was compatible with that of the IGCC plant.

Sucipta et al. [107] used similar type of model as Song et al.’s [42] and added different biomass gasification processes, namely, oxygen, air, and steam-blown, to analyze the effect of biomass fuel composition on GT-SOFC hybrid system performance. They presented that efficiencies level for all three cases were reasonably high (although lower than the reference case fueled with pure methane as fuel) and concluded that the biomass fueled SOFC–MGT hybrid power system was suitable alternative for conventional power plants. They stated that air and steam-blown biomass fuel had the lowest and highest efficiency, respectively, for both SOFC module and for the entire hybrid power system.

Van Herle et al.[108] studied the energy balance analysis on an existing biogas production unit, equipped with a 1kW SOFC demonstrational stack as a small combined heat and power system. They obtained almost 34% and 58% electrical and combined thermal efficiency, respectively. The predictions were validated by the natural gas fueled Sulzer Hexis 1kW systems with an electrical efficiency of 35% (direct current (DC), LHV) [109]. They also compared two reformer techniques, i.e., partial oxidation reforming with air (POX) and steam reforming. They also found the impacts of water addition for steam
reforming process and noted that cogeneration thermal efficiency
significantly decreased with the addition of water. This was due to the
reason that there was no condensation in the exhaust to recover the
evaporation heat absorbed 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, air excess rate, reforming conditions, SOFC stack temperature
and pressure. They presented the variation in electrical efficiency,
when varying the CO$_2$ composition in the biogas feed between extreme
composition limits. Probably, they stated that efficiency increased
when more fuel (methane) was replaced by carbon-dioxide. In other
words, the system performance improved when fueled with low
concentration biogas (richer in CO$_2$). They showed that higher
methane content in inlet biogas fuel resulted in higher input LHV,
which led to higher current, thus to higher loss (ohmic overpotential)
and lower SOFC operating voltage.

They also pointed out that electrical efficiency reduced when
system was pressurized. So, this was in contrast with other
investigations such as Suther et al. [48] and Chan et al. [57]. This
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 gas turbine
and improved mass transfer which led to lower electrode over
potentials. Whereas, more compression work to pressurize inlet
streams reduced net work output from the system.

2.10 Thermoeconomic Studies of GT – SOFC Hybrid Systems

Riensche et al. [110,111] investigated a model for 200kW SOFC-CHP plant and conducted a technical and economical sensitivity analysis on the effects of system parameters on efficiency and cost of electricity. They assumed a lifetime of 10 years (40,000 hrs) for the system. They evaluated that net cost of electricity (COE) could be reduced by nearly 50%, when external reforming was replaced by internal reforming. And also, the electrical efficiency could be increased up to 50% at fuel utilization factor of about 95%. But for optimal cost of electricity, the fuel utilization factor should be set to 65%. They also analysed the effects of different plant configurations. They determined 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 constant at 80%, which resulted in 25% reduction in the fuel cell area. Also, steam concentration in the system exhaust stream was lower, thus the latent heat loss was lower and afterburner temperature was higher. Both the effects resulted in higher total efficiency of the system.

Fontell et al. [112] studied a conceptual study of a 250kW planar SOFC plant for combined heat and power application. They aimed at some performance targets for their design, so that they could able to meet some of these targets. For instance, their design exceeded
the targeted electrical and total efficiency (LHV) of 47% and 80% by achieving about 56% and 85% efficiencies, respectively. But, their system’s specific mass, about 49 kg/kW, could not satisfy desired specific mass of 15–20 kg/kW.

Finally, they performed an economic analysis assuming stack lifetime of 40,000 hrs (similar to [110,111]) and system lifetime of 20 years (similar to [90]). Also, the degradation rate of the cell voltage was considered 0.25%/1000h. They found 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. [86] conducted economical analysis to investigate the effect of system parameters on cost payback time (CPT) and energy payback (EPT). Unlike [110,111], in their model total power plant life was assumed to be 20 years and fuel cells and catalyst were replaced every 5 years. They presented that although the unit initial capital costs were higher than that of a large-scale conventional coal thermal power plant, it was still a competitive alternative energy technology.

Calise et al. [113] extended thermo economic evaluations to their previously investigated model [78] and used genetic algorithm (GA) for optimization purpose. The model considered 19 fixed parameters and 48 synthesis and design decision variables. The system initial investment was identified as optimization objective. The result illustrated that the optimized plant investment was 45% lower than reference case. However, the system efficiency was decreased
from 67.9% to 67.5%. Some system parameters, such as SOFC geometric parameters, turbomachinery syntheses and designs, were considerably adjusted by optimization procedure. For this case, diameter, the number and length of the tubes in fuel cell stacks were decreased, resulted in the reduction of the cell’s active area.

### 2.11 Combination of Modeling and Experimental Work

Lai et al. [114] developed new method to evaluate the performance of SOFC and GT hybrid cycle under various operational conditions without using actual SOFC. They presented that the cost of SOFC experimental equipments were still too high for university researchers. Therefore, the authors designed a GT-SOFC system by replacing SOFC by a traditional furnace to simulate the fuel cell exhaust gas condition. Also, in order to simulate a real GT-SOFC hybrid power plant, their system was equipped with another burner (to allow additional fuel injection for complete combustion of spent gas from SOFC), a water injection system and a turbocharger. Their system proved that such system could simulate real GT-SOFC system behaviors with reasonable approximation. They presented that, no particular device was required to combust residual fuel for high temperature SOFC (800–1000°C). But for a low and medium temperature SOFC (500–800 °C), some devices were required to provide better mixing and holding the flame.

With similar approach, Tucker et al. [115] used the Hybrid
Performance (Hyper) hardware simulation facility at the National Energy Technology Laboratory (NETL), U.S. Department of Energy to estimate the possibility of using air flow as process control variable in the GT-SOFC hybrid power system. The Hyper facility was able to simulate GT-SOFC hybrid system with electricity generation capacity of 300kW to 900kW by its hardware and software simulator. The hardware portion consisted of a natural gas burner, a modified GT, an off-gas recuperator, flow impedances of real components, several tanks representing the volumes and required piping. The main 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 cold air by-pass and compressor bleed air as system control variables through air flow management.

2.12 Molten Carbonate Fuel Cells

Molten Carbonates Fuel Cells (MCFC) are currently being demonstrated in several areas around the world. The typical power size is of several hundreds of kW, however, a 40-125kW MCFC system for medium size commercial, industrial and municipal applications was developed by Gen Cell Corporation, and multi-MW systems are demonstrated in Europe [116], USA [117] and JAPAN [118].

Though there are demonstration projects all around the world, a strong R&D activity is also undertaken by R&D organizations,
Universities and industrial companies. In fact, there are still technical issues to solve before MCFC can compete with traditional energy systems. In particular, increasing useful service life and reducing costs represent two important priorities upon which R&D is focused.

Durability is limited by corrosion within the cell components, dissolution of the cathode into the cell matrix and electrolyte loss. While increasing the stack durability also results in decreasing the system operating and maintenance costs, including that of stack replacement, other cost reduction activities are needed. These include increasing power density and exploring less expensive manufacturing processes. In addition, mass production will contribute significantly to cost reduction.

The Molten Carbonate Fuel Cells (MCFC) offers high electric energy conversion efficiency (around 50% based on the Lower Calorific value of natural gas) in a simple cycle configuration, so that it can substantially reduce exploitation of non-renewable as well as renewable energy sources. Also for equal power production, a high efficiency is translated into reduce CO₂ emissions.

The Molten Carbonate Fuel Cell (MCFC) operates at about 650°C, thus it is different from low temperature fuel cells, and no precious metal is required as the fuel catalyst. Together with production cost saving, the main consequence of this is that CO is not a poisoning element, but on the contrary, that it can be sued as a fuel. This allows the utilization of a variety of fuels which contain CO, such
as hydrocarbons, landfill gas, syngas derived from biomass or coal, gas contained from agricultural or industrial by products.

Molten Carbonate Fuel Cell can operate on a variety of fuels, thus supporting a better security of power supply. Hydrogen is one of the fuels that the MCFC can use, but it is not the fuel alone. Actually, MCFCs have primarily been developed to be operated on natural gas fuel. At present, for environmental and economical reasons, there is a strong interest towards the use of secondary fuels, such as biogas produced from biomass. Due to the lack of hydrogen infrastructure, no company is currently planning any demonstration of MCFC power plant on hydrogen. In the ultimate case of an hydrogen economy, however the MCFC can efficiently convert hydrogen into electricity, like all other fuel cell types.

2.13 Status of Molten Carbonate Fuel Cell Systems

Fuel cell systems based on Molten Carbonate Fuel Cell technology are under development in Italy, Japan, Korea, USA and Germany. Since the 1990s, Molten Carbonate Fuel Cell systems have been tested in field trials in the range between 40kW and 1.8 MW.

Characteristics of Molten Carbonate Fuel Cell Systems:

- Use of nickel as an inexpensive catalyst material.
- High temperature, high efficiency, power plants for the base load industrial and commercial applications.
- High value waste heat by product for cogeneration and combined systems.
- Possibility of internally reforming readily available fuels such as natural gas.
- Silent operation: no moving parts incorporated in the generating mechanism of the power.
- Low emissions (NOx<0.3 ppm, Sox<0.01 ppm, CO<10 ppm, VOC<10 ppm)

The general nominal current density of Molten Carbonate Fuel Cell is 140-160 mA cm\(^{-2}\) at about 0.7 V. The actual operating current density depends on a number of factors, including the requirements of a specific application, the choice of fuel and operating conditions and the economics of the installation. In case of pressurized conditions the stack can operate at a current density upto 200 mA cm\(^{-2}\).

The major Molten Carbonate Fuel Cell technology [119] developers in the world are:

1. Fuel Cell energy (FCE) and GenCell Corporation (USA)
2. CFC Solutions (Germany)
3. Ansaldo Fuel Cells (AFCo, Italy)
4. Ishikawajima-Harima Heavy Industries (IHI, Japan)
5. POSCO / KEPCO consortium and Doosan Heavy Industries (Korea)
2.14 Applications of Fuel Cells in world.

2.14.1 Fuel Cell Energy (USA) and CFC Solutions (Germany)

A significant global operational experience has been accumulated with 250kW power plants on different fuels and various types of applications.

Fuel Cell Energy’s products, also known as Direct Carbonate Fuel Cells (DCFC) can be considered ready for distributed power generation applications. However, efforts for further cost reduction of the systems are strongly needed and are a continuing part of the company’s strategy. Fuel Cell Energy is also looking at other possible applications such as hybrid power systems and markets such as marine applications.

Specifically, the achievements of the about two developers sharing the same Fuel Cell stack technology can be summarized as follows:

- Over 60 systems demonstrated at customer sites in the Us, Japan and Europe
- Over 200 millionkWh of Power generated at customer sites
- Expanded testing and manufacturing facilities.
- Initiated field trail of DFC1500 and DFC3000.
- Continued development of the hybrid systems like DFC/T, marine/diesel DFC power plant and DFC/H₂ hydrogen generation plant.
Identified and implemented cost reductions, completed product standardization and achieved certifications.

It is observed that, although FCE and CFC systems were originally developed for being operated on natural gas and other fuels such as coal gas, propane, diesel, mine methane, landfill gas and biogas, were considered as optional fuel feedstock. In particular the sue of anaerobic digester gas emerged as an important commercial fuel during early field trial program and 40% of all installations have used anaerobic digester gas (ADG).

2.14.2 Ansaldo Fuel Cell (Italy)

The demonstration program indicates a key part of the present phase of development of AFCo. It mainly aims, through feedback from the field, at extending durability, simplifying manufacturing processes, reducing costs, improving availability and reliability. The final aim of the program is to demonstrate the technology viability for different types of fuels and applications, with a total power of 4 MW.

AFCo’s main achievements are as follows:

- Demonstrated sub-scale (100kW) power systems
- Demonstrated 500kW (TWINSTACK) power systems
- Validated integration of stack-micro turbine under static and dynamic conditions (hybrid power cycle)
- Validation of control systems, grid connection and power condition system
• 12000 hrs of operation grid connected
• Validated the use of alternative fuels such as simulated coal gas, simulated biogas and diesel oil
• Validated the start-up of the power plant without need for significant electric power (no grid required)

2.14.3 Ishikawajima-Harima Heavy Industries (Japan)

Ishikawajima-Harima Heavy Industries MCFC technology was strongly recommended by the Japanese New Energy and Industrial Technology Development Organization (NEDO), which started MCFC systems testing activity in 1984, with a 10kW capacity stack. Later a 100kW capacity MCFC system was successfully tested from 1987 to 1992. The results provided the information to realize the first Japanese 1 MW power plant, in Kawagoe, which operated for about 5000 hours and produced 2103 MWh.

For the short and midterm the goal is to operate 7 MW MCFC/GT hybrid power system, while the final aim is to replace large-size thermal power plants with MCFC-based systems.

Fuel flexibility is another important consideration of the demo program in Japan. Recently, for the 2005 EXPO in Aichi, a hybrid GT-MCFC with nominal capacity of 300kW and a 250kW MCFC systems were installed both using fuels derived from waste and natural gas. In particularly, Chubu Electric Powered the first unit on anaerobic digester gas (ADG) produced from waste operating a low temperature
methane fermentation reactor. The second one was operated by Toyota Motors with waste plastics and gasified wooden waste.

The two MCFC power systems were also connected in a network of demonstration installations, including four PAFCs, each with a nominal capacity of 200kW, a 50kW SOFC system and solar panels.

Ishikawajima-Harima Heavy Industries / NEDO power plants results include as follows:

- 1 MW, pilot plant installed in Kawagoe and operated for about 5000 hours, produced 2103 MWh
- Development of commercialization system focused on compactness, high reliability and low cost.
- High performance Fuel cell stack realized (250 cells, 1 m² active area, >1.5kW/m², 350kW)
- 11 systems installed and operated for a total capacity of 2.1 MW
- Longest operational duration 16000 hrs.
- Demonstration of 750kW high performance module period as building block for a MW scale power plant (7-8 MW)
- Installed two 300kW power systems at the Aichi International Exposition, operated on ADG produced from waste collected within the exhibition area.
- Achieved 51% gross generation efficiency on Toyota Motor Corporation power plant during Aichi Expo.
2.14.4 KEPCO (KEPRI) and Posco Power (Korea)

The demonstration phase started in 1993, when a 100kW stack was installed and tested. This successful phase was followed by tests of fuel cell stacks of different sized and system design and construction.

Main plants in Korea are:

- Installed and operated small fuel cell stacks
- Installed and operated a 25kW stack with high performance and long term operation, accumulated 4500 hrs.
- Completed a 100kW fuel cell stack and system design
- Complete system design for a 250kW system and prototype of the power conditioning systems

POSCO, one of the top steel companies in the world and already a strategic partner of Fuel Cell Energy (FCE), has tied a partnership with KEPCO in August 2007 to develop and jointly market power plants integrating fuel cell stack modules manufactured by Fuel Cell Energy. POSCO also provided a 2.4 MW power plant to KEPCO affiliate Korea South East Power Company (KOSEP) in 2009 as a part of aggregated 7.8 MW ordered by POSCO in the year 2008.

2.14.5 GenCell Corporation (USA)

Commercial scale prototype of capacity 40-125kW are built and operated successfully. GenCell completed operation of a system of capacity 40kW unit at the University of Connecticut Campus. The
power system operated on natural gas and produced electricity to the Connecticut Global Fuel Cell Center of the University of Connecticut.

2.15 Potential Customers and Market for MCFC Power Systems

The potential market of the current MCFC available products in the power range of 40kW-2 MW exceeds the current manufacturing capacity, as presented in [120]. This fact is mainly due to the high cost and low durability of the power systems, which prevents the technology from influencing the market adequately. However, despite the durability and cost issues, at present there are some niche markets of particular interest for early adoption of MCFC technology and for bearing non-technical issues such as compliance with standards and regulation codes. These applications include most of the Distributed Generation applications where by-product heat can be recovered in a Combined Heat and Power configuration, including the integration with a steam injection chiller or a high temperature fed absorption cooler.

CFC and FCE have installed most power systems in combined heat and power configuration in particular University campuses, hotels and hospitals were found to be the ideal sites for first market introduction. An example of financial feasibility of a fuel cell-based network operating in combined heat and power mode was presented by Colella et al. [121] for 200kW PAFC systems. Although results are obtained to the PAFC technology, the analysis presents the important
role of thermal recovery in stationary power applications, where the fuel cell power systems are in the some 100kW range. It is predicted that similar results are obtained if MCFC technology is considered in the analysis.

The early models of MCFCs consist in applications where by-products can be exploited as fuel and replace natural gas. There are systems installed or planned to be demonstrated at wastewater treatment facilities, breweries and landfill sites. The European Commission funded the EFFECTIVE project, with two main objectives 1) to develop gas processing systems for upgrading biogas to MCFC quality requirements and 2) to run MCFC stacks at different places (Spain, Germany, Austria and Slovakia) with different types of biogas (from agricultural and co-fermentation facilities, waste water and landfill). As a result of this project an MCFC was operated on biogas for more than 15000 cumulative hours in different places, thus demonstrated the technical feasibility of the system and in particular of the clean-up system and of the fuel cell. During these fields test the stack achieved 50% of electrical efficiency [122-123].

Molten Carbonate Fuel Cell Systems are considered in the range of 250kW-2 MW [120], which reflects most of the applications available today. As shown in the table above, in 2022 MCFCs could achieve more than 15 GW. Although the study considers a destructive market penetration scenario, it does not take into account possible evolution of the technology towards multi-MW power systems [116-]
The number of fuel cell systems developed in the market is given in the Table 2.1.

Table 2.1 : Estimation of Fuel cell Systems in the Market [120]

<table>
<thead>
<tr>
<th>Year</th>
<th>200-250kW SOFC</th>
<th>200-2000kW MCFC</th>
<th>200kW PEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>118</td>
<td>192</td>
<td>166</td>
</tr>
<tr>
<td>2012</td>
<td>893</td>
<td>1464</td>
<td>1262</td>
</tr>
<tr>
<td>2022</td>
<td>5594</td>
<td>15029</td>
<td>4897</td>
</tr>
</tbody>
</table>

During the 1980s, several studies presented considerable potential of MCFC systems in terms of low emission, high efficiency and the possibility of separating Carbon dioxide for the exploitation of clean coal. However, conventional coal-based power plants have rated power of the order of several hundreds of MW. Because of the large size of these conventional power plants, no real-scale demonstration of MCFC coal-based hybrid power system has been realized. The focus for most companies, in fact, is still within the range of 100-500kW based on natural gas. However, in recent years, after many technical issues have been solved the option of using MCFC for coal based plants has regenerated much interest.

Ansaldo Fuel Cells is also showing the interesting role that MCFC systems could have the short midterm for carbon dioxide separation. The MCFC cathode required a mixture of oxygen and
carbon dioxide. The combination of these two gas species produces CO$_3^{2-}$ ions, which allows the operation of the MCFC. As a result of this operation, carbon dioxide is continuously transferred from the cathode to the anode. This particular feature could be exploited for separating carbon dioxide originating from a conventional thermal power plant.

2.16 STATE OF THE ART OF GT-FC TECHNOLOGIES:
Sadegh Motahar and Ali Akbar Alemrajabi et al [125] presented the exergy analysis of a hybrid system in comparison with retrofitted system with steam injection. It has been proposed to use hot exhaust gases from gas turbine, in a heat recovery steam generator produce steam and inject it into gas turbine. Alexandros Arsalis et al [126] studied the thermo economic Modeling and parameter study of hybrid GT – SOFC- ST power plants ranging from 1.5 MW to 10 MW. The models have been developed to function both at full load (Design) and partial load (off – design) conditions. M. Williams et al [127] developed an equation for thermal efficiency as a product of exegetic efficiency and maximum possible thermal efficiency for the integrated GT – FC hybrid systems. Christian Wachter and Franz Joos [128] investigated the behavior of a GT – SOFC hybrid power plant of capacity 25 MW, at steady state off Design and transient conditions. Additional firing of GT combustor was also investigated for the load range from 40% part load to 105% over load.
Francesco Ghiglizzata et al [129] presented the generic real time modeling of SOFC hybrid system using MATLAB – SIMULINK. Sanchez, et al [130] proposed carbon dioxide as the working fluid for a closed supercritical bottoming cycle in the high temperature Fuel cell hybrid systems. Colson, et al [131] evaluated the efficiency of SOFCs in combined cycle operations. Thermodynamic analysis has been conducted to develop SOFC dynamic model and operating fuel heating values have been determined by utilizing the semi empirical gas phase heat capacity method. Tsourapas, et al [132] investigated the feasibility of a hybrid GT – SOFC system for mobile power production. Transient analysis and system optimization are performed based on the system model to determine load following limitations and the desired operating conditions. Dincer, et al [133] conducted the exegetic performance analysis of a gas turbine cycle integrated with SOFCs. The energy and exergy efficiencies of the integrated system reach 70 – 80%, which compress well to the conventional combined cycle power generation efficiency of 55%. Al. Sulaiman, et al [134] studied a hybrid system that combined a SOFC and an Organic Rankin cycle for cooling, heating and power (CHP) production through exergy analysis. The study presents that there is a improvement in exergy efficiency of 3 -25% when CHP (tri-generation) is used compare with the power cycle only. Also, the analysis shows that the exergy efficiencies of power cycle and CHP production decreases with the increase in power density of SOFC. Shelton, et al [135] presented the
modeling of the start-up of FC-GT hybrid systems. This study explains a process modeling method based on a commercial modeling package PROTRAX selected by National Energy Technology Laboratories (NETL) as one of the simulation tools to be used for the Hybrid performance (HYPER) research project. Roberts, et al [136] studied 1.15MW pressurized GT – SOFC hybrid system control for daily load profile scenario and changing ambient conditions. Vansdol, et al [137] developed scaling of a GT – SOFC hybrid system to meet a range of power demand using the APENPLUS simulation software. This system was fed with hydrogen rich coal based syngas. Jiang, et al [138] explained the control strategies for start up and past load operation of GT – SOFC hybrid system. The various control variables are rotational speed of shaft of a compressor, air flow rate, fuel flow rate, turbine inlet temperature and steam – carbon ratio.

Bhargava et al [139] studied the parametric thermodynamic analysis of high performance cycles include recuperated water injection cycle, inter cooled steam injected gas turbine cycle, cascaded humidified advanced turbine cycle, humidified air turbine cycle, Brayton cycle with high temperature fuel cells (SOFC & MCFC) and their combinations with the modified Brayton Cycles.

Brown, [140] investigated the Techno economic optional design of SOFC for micro combined heat and power applications in the U.S. Mueller F [141] proposed the design, simulation and control of a 100 MW class planer GT – SOFC hybrid system. The system contained 70
functional fuel cell modules, each consisting of 10 fuel stocks, a depleted fuel oxidizer, a blower to recirculate depleted cathode air and a cathode inlet air recuperator with bypass. Parametric steady state design analyses conducted on the system revealed that the overall fuel to electricity generation efficiency of the system increases with the increased cathode exhaust recirculation. Watcher, et al [142] focused on the usage of linear control theory for the parameterization of a controller for a 25 MW GT-SOFC hybrid power system. Brear, and Dunkley, et al [143] studied the effect of size on optimization of GT-SOFC hybrid power cycles. The results of this study recommended that hybrid power cycles with total capacity of the order of MW or higher are preferable.

Trasino, et al [144] presented the modeling and performance of the 1MW hybrid power plant designed and developed by Rolls Royce Fuel Cell Systems Limited. This model shows all the operating parameters of plant at each characteristic state and a complete application of thermodynamics and chemical parameters inside the reformer and SOFC stack. Its operating envelope has been calculated considering the effect of ambient temperature and pressure, to characterize the system behavior. Colella, et al [9] optimized the design and deployment of stationery CHP Fuel Cell systems for minimum emissions and costs. The research provides the most effective ways to use stationery distributed Fuel Cell power systems, to reduce the Green house gas emissions at reasonable cost, through an
optimization tool called MERESS (Maximizing Emission Reduction and Economic Saving Simulator). Ferrari., et al[145] investigated the micro gas turbine high temperature fuel cell hybrid power system emulator test rig based on the anodic recirculation system. The recirculation factor value has been measured at steady state conditions for different operative conditions to avoid carbon deposition in the reformer, fuel cell stack and anodic circuit. Zhang, et al [146] studied the control performance to regulate the net electrical power output from the molten carbonate fuel cell hybrid system for different operating conditions such as the differential pressure between the anodic and the cathodic side, the temperatures within the fuel cell, the turbine rotational speed and the steam to carbon ratio.

Based on the literature review, it has been observed that only few researchers have focused on the exergy analysis of the GT-SOFC and GT-MCFC hybrid power generation systems. Also they have done the analysis (both energy and exergy analysis) by considering the single fuel. Therefore, the present research work focused on the thermodynamic analysis of Fuel Cell based Gas turbine combined cycle power plant for different fuels.

2.17. OBJECTIVES OF THE PRESENT WORK

The main aim of this research work is to study the performance of the Fuel Cell based Gas turbine power plants for different fuels. This type of hybrid systems with different fuel options, could play important role
in future decentralized combined heat and power plants. The research work is focused on studying the thermodynamic analysis of the system.

More particularly, the study aims to

I. Investigate the potential performance of SOFC – Gas Turbine combined cycle power plant for different fuels.

II. Evaluate the potential performance of MCFC – Gas Turbine combined cycle Power Plants for different fuels.

III. Evaluation of exergy efficiencies of each component of Fuel Cell – Gas Turbine hybrid power system.

IV. Find irreversibilities in each component of the system, by doing the energy and exergy analyses.