QATAR UNIVERSITY

COLLEGE OF ENGINEERING

ADVANCED TECHNOLOGY FOR LOW ENERGY COMMERCIAL BUILDING IN QATAR

BY

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ABSTRACT

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Title: Advanced Technology for Low Energy Commercial Building in Qatar

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There is no doubt that it is critical and beneficial for Qatar to start utilizing alternative energy efficient solutions to reduce the energy consumption and sustain its natural resources. In particular, commercial buildings consume about 5,000 GWh, which accounts for 19% of the total energy consumption in Qatar, more than 65% of that is consumed by HVAC. To reduce this significant amount of energy, a promising technology can be used: Solid Oxide Fuel Cell Combined Heat and Power (SOFC CHP) with natural gas as fuel. This thesis is focused on studying the feasibility and viability of using SOFC CHP system to supplement energy use in office buildings in Qatar.

An office building model has been created in eQuest energy modeling software package with an area of 7000 m^2. ASHRAE 90.1-2010 standard, Qatar Construction Specification (QCS) 2014, Kahramaa policies were considered in developing the energy consumption model in the office building. Moreover, utility costs as per local market have been introduced to the model. Based on that, energy consumption profiles and annual energy costs results were calculated. Then, (Chiappini & et al., 2011) SOFC cogeneration models were integrated in the model to investigate the performance of the SOFC CHP system in the office building. Two climate zones were considered: Qatar and Kuwait in this study. Several baseline cases were considered to optimize the HVAC system and loading profile that could utilize the SOFC to its full extent. These baselines are: electric chiller, absorption chiller, and combined electrical-absorption chiller systems were analyzed.

Performance curves were analyzed for a range of SOFC CHP system capacities (25-250 kW) in terms of energy produced, utilized thermal energy and overall efficiency. Moreover, annual energy costs for the office building were calculated with and without SOFC CHP system to assess potential cost savings. Results showed that using SOFC CHP system will lead to promising savings in annual energy costs reaching a reduction up to 67% from the baseline case. Moreover, optimum overall efficiency reached up to 73%.

In the optimum case scenario in Kuwait, the payback period was found to be 7.8 years, while the net present value was 209,005 $ at SOFC capacity of 250 kW. Applying the same system to Qatar had also led to promising results of payback period of 11.0 years and net present value of 57,742 $ at 200 kW.

Finally, an environmental impact assessment was evaluated in terms of CO2, NOx, and SO2 emissions. It was found that application of SOFC CHP system had led to a maximum reductions in CO2 emissions of 30%, NOx of 90%, and SO2 of 90%.

In conclusion, based on literature review, background information, and analysis developed in this project, it is clear that SOFC CHP system is very promising energy technology for Qatar. It is recommended to establish more researches in this subject to furnish the infrastructure of solid oxide fuel cell technology in Qatar. Future researches shall be directed towards solid oxide fuel cells material selections to enhance lifetime and durability. Moreover, researches to find the optimum exhaust thermal energy utilization systems for hot climate zones are highly demanded to enhance the overall efficiency of the system.

DEDICATION

I dedicate this work to my parents, wife, brothers and sisters, friends, colleagues and professors who had motivated me in all means. Moreover, I dedicate this work to Qatar's government and people who had furnished this opportunity for me to continue my Master Degree.

ACKNOWLEDGMENTS

My first and foremost thanks are to Dr. Ahmad Sleiti who had the patience and motivation to teach, guide, motivate, and supervise me to complete my Thesis work. Thereafter, my thanks shall reach all the people who had helped me in either professional or motivational means mainly including my mother, wife, and friends.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ASHRAE	American Society of Heating, Refrigeration, and Air Conditioning Engineers
BEM	Building Energy Modelling
CCHP	Combined Cooling, Heating and Power
CHP	Combined Heat and Power
COP	Coefficient of Performance
GCC	Gulf Cooperation Council
HVAC	Heating, Ventilating, and Air Conditioning
MINLP	Mixed Integer Non-linear Programming
PNNL	Pacific Northwest National Laboratory
QCS	Qatar Construction Specifications
RT	Refrigeration Ton
SOFC	Solid Oxide Fuel Cell

Chapter 1: INTRODUCTION

1.1 Motivation

Qatar economic played a major role of increasing the population in Qatar to more than 2.65 million people (Permanent Population Committee, 2017), with an increment multiple factor of 4.6 since 1999. Hence, the growth in economy and population in Qatar has been accompanied by an increased number of industrial entities as well as construction of industrial and commercial buildings. As a result, electricity production in Qatar, between 1999 and 2011, increased by about 3.7 times as shown in Figure 1 (Ayoub, Musharavati, Pokharel, & Gabbar, 2014). Therefore, Qatar is considered as the second highest energy consumer per capita among Gulf Cooperation Council (GCC) countries (Ayoub, Musharavati, Pokharel, & Gabbar, 2014). Moreover, energy consumption in Qatar also results in 44.0 tons per capita of CO_2 emissions (Oak Ridge National Laboratory, 2014), which contributes to almost 0.3% to the total world's CO2 emissions. These emissions have warranted Qatar, as part of the Kyoto Protocol, to commit to reducing energy-related CO2 emissions. With depleting fossil fuel sources worldwide, developing controversy over Qatar-based fossil fuels such as Natural Gas, and a growing awareness of the environmental impacts of fossil fuel combustion, it is critical for Qatar to find ways to reduce energy consumption and to develop sustainable energy sources.

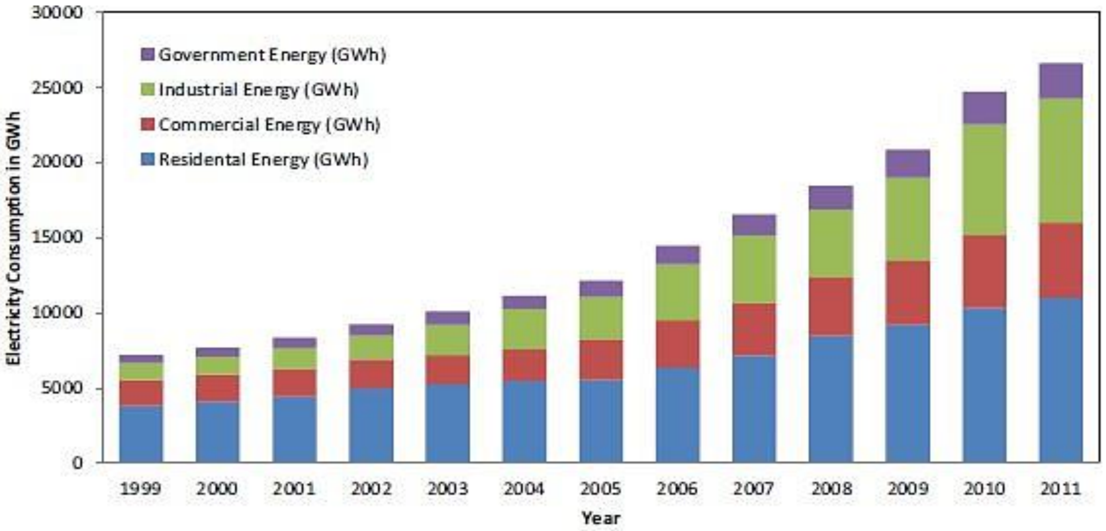


Figure 1: Electricity consumption by sector in Qatar from year 1999 to year 2011 (Ayoub, Musharavati, Pokharel, & Gabbar, 2014)

Buildings account for more than 60% of the total energy consumed in Qatar (Ayoub, Musharavati, Pokharel, & Gabbar, 2014). Since buildings play such an important role in Qatar energy consumption portfolio, this sector must see dramatic changes in energy efficiency in order to create a more sustainable future for the country and the world. Developing low energy buildings, or buildings which consume significantly less energy than an average building, therefore, is paramount to achieving this goal.

The building sector can be divided into two distinct sub-sectors: residential and commercial buildings. The commercial building stock in Qatar, due to its sheer size and scope, holds the most promise for generating significant energy savings through: (1) achievements in energy efficiency and (2) renewable energy technologies. These buildings alone account for almost 19% of the total Qatar energy consumption and CO2 emissions (Ayoub, Musharavati, Pokharel, & Gabbar, 2014). As such a significant energy consumer, the commercial building sub-sector has begun to demand significant interest and resources from the government, industry, and academia alike.

1.2 Commercial Building Energy Consumption in Qatar

Among the different types of commercial buildings, office buildings in particular consume the most energy and produce the most CO2 emissions. This can be understood due to nature of office buildings which usually built to be mid-rising to high-rising buildings. Moreover, office buildings requires sufficient air conditioning, cooling, heating, water pumping, and lighting accompanied with computers, printers, and elevators loads within a limited area which increases intensity. Therefore, office buildings should be considered as the single most significant market for applying energy-efficient technologies in the commercial sector.

If building energy consumption is viewed in terms of end-use consumption, more than half of energy consumed in commercial buildings is typically used by heating, ventilating, and air conditioning (HVAC) systems, as shown in Figure 2 (Ayoub, Musharavati, Pokharel, & Gabbar, 2014).

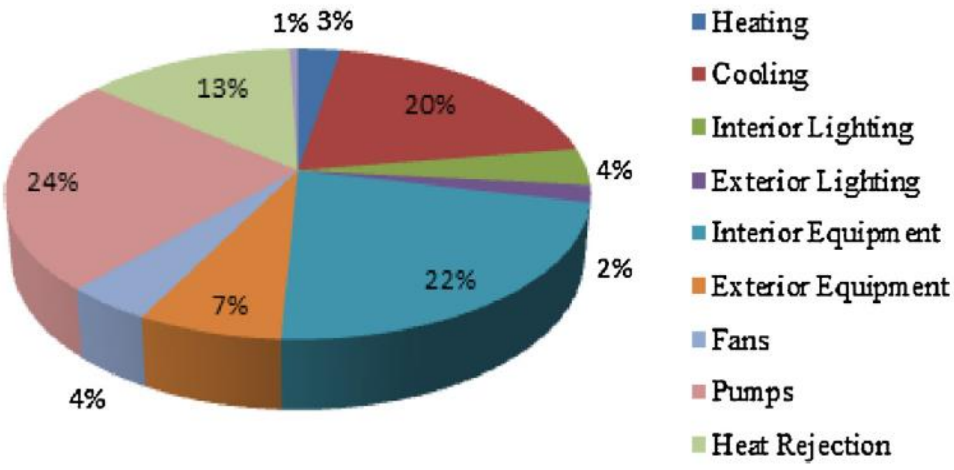


Figure 2: Hotel Building Energy Consumption in terms of end-use in Qatar (Ayoub, Musharavati, Pokharel, & Gabbar, 2014)

Since the HVAC system consumes more than 65%, on average, the focus on reducing building energy consumption and increasing energy efficiency should start with this system. Lowering the HVAC energy consumption is a priority for developing low energy consuming buildings.

1.3 Advanced Energy Efficiency Strategies for Commercial Buildings

There are numerous advanced energy efficiency technologies for developing low energy consuming buildings, however, this project focuses solely on a novel concept which is the usage of fuel cell. The usage of fuel cell is considered as a promising strategy for reducing the HVAC loads, more specifically, solid oxide fuel cell (SOFC), combined heat and power (CHP) systems. A fuel cell produces electrical energy directly from energy stored in chemical bonds, without any mechanical work, which leads to electrical efficiencies as high as 60% (Demin & Tsiakaras, 2001). A fuel cell CHP system uses the exhaust gas thermal energy of a fuel cell stack to heat the hot water loop in a building or even operate a small gas turbine, thereby increasing the overall efficiency of the system (Fontell & al., 2004). The fuel cell, therefore, provides both thermal energy and electrical energy (heat and power) for the building. Since both the electrical and thermal energy of the fuel cell are utilized, overall system efficiencies approaching 90% can be achieved (Srivastava, 2006). SOFCs are the most useful type of fuel cell for CHP systems as they operate at high temperatures (600-1000 ^{O}C) and can use a variety of readily-available fuels, such as natural gas or biogas, through internal reforming (Bove & Ubertini, 2008).

The goal of this project is to investigate the potential advanced energy-efficient building technology for the development of low energy commercial buildings by application of SOFC CHP systems. Hence, a numerical model of SOFC CHP system from literature was utilized and applied for a case of an office building using a building energy simulation program called eQuest. Moreover, the ultimate objective of this study is to evaluate the feasibility and viability of applying SOFC CHP system for office buildings in Doha which serves 2030 vision of Qatar.

Chapter 2: BACKGROUND INFORMATION

Alternative Energy Sources have become one of the main subjects for all majors of engineering. Building Energy Modeling (BEM) has been approached from different prospectives recently and with different solutions. To reduce the energy consumption, BEM can be used to simulate different material of construction which can reduce cooling or heating requirements. Moreover, BEM can be used to simulate different advanced renewable or non-renewable energy sources to investigate its potential and viability compared to conventional sources of energy. In this study, eQuest software has been used as BEM software which can simulate the energy consumption of a building, the source of energy, and also run a cost analysis to check viability of the applied technology. Following section provides a brief description about the software.

Building energy simulation programs (BESP) provide users with a reliable estimate of the energy use and system related costs of commercial, residential and other types of buildings. Architects, engineers and others in the building design trade are using BESP to compare various designs and select the design that is both efficient and cost justified. BESP can be used to compare several kinds of scenarios including different material of construction, technologies, and sources of energy.

2.1 eQuest Software.

eQUEST, or the QUick Energy Simulation Tool, is an enhanced graphical user interface program for DOE-2.2, a well-validated BESP that was first developed in the late 1970’s (eQUEST: Introductory Tutorial, Version 3.64, 2010). Lawrence Berkeley National Laboratory (LBNL) with the collaboration from James J. Hirsch had developed eQuest and DOE-2.2 programs (eQUEST: Introductory Tutorial, Version 3.64, 2010). In purpose, eQuest was developed on the basis of DOE-2 in order to provide a graphical useful interface of DOE-2.2 that can be used by building professionals from various levels and disciplines such as Engineers, Architects, or building operators. Moreover, eQuest has further extended the functionality of DOE-2.2 by including an interactive operation and dynamic defaults in accordance to the building type.

Function wise, eQuest, on the basis of DOE-2.2, simulates hour-by-hour the energy consumption of a building through the entire year based on several parameters such as occupant schedules, lighting schedules, weather data, building construction, and thermostat settings. Moreover, eQuest includes the selection of the HVAC system to be applied, lighting lux levels, and whether grid electricity, generator power supply, or both together is applied. Finally, eQuest also provides an easy tool to calculate the utility cost in terms of electricity or fuel consumption over the entire year.

A basic program flowchart for DOE-2.2 is shown in Figure 3.

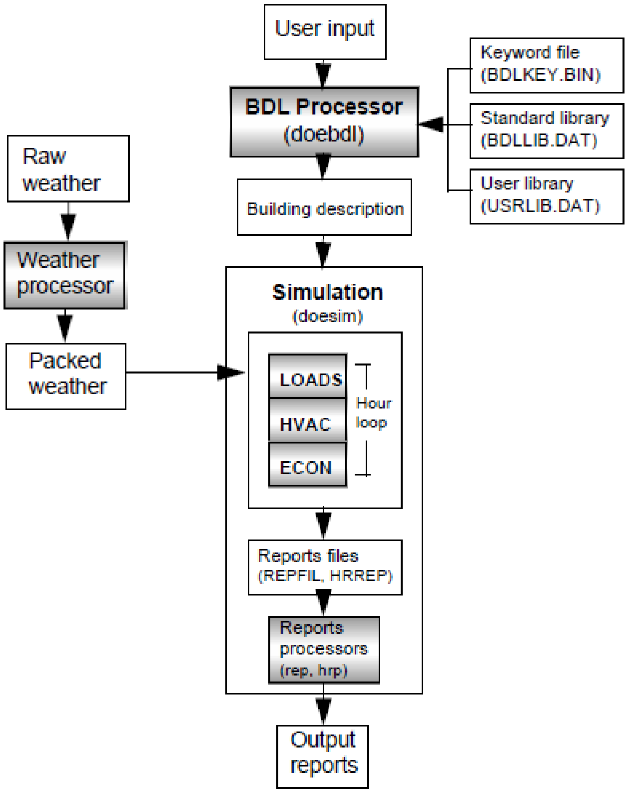


Figure 3: DOE-2.2 program flowchart (Overview of DOE-2.2, 1998)

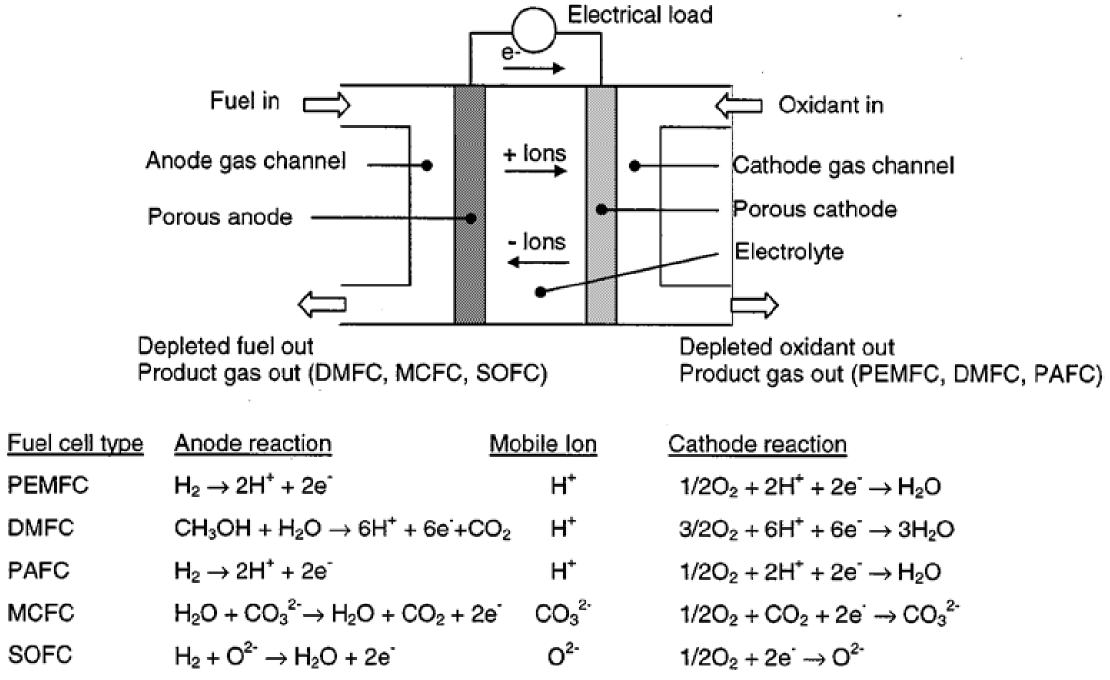
In general, for most programs which simulate the energy of a building, the major calculations would include (1) Loads calculations for internal and external lighting, water pumping, and miscellaneous equipment, (2) HVAC loads calculations, and (3) Economic viability calculations. Those calculations are performed based on hourly weather data and building specifications.

eQuest software, version 3.65, was used in this project to simulate the baseline office building model. Furthermore, further development to the baseline model was performed by creating and attaching the SOFC CHP system to baseline case HVAC system.

Although the database of the software doesn't include the SOFC system, it has the ability to create it under the category of Generators.

2.2 SOFC Basics

Fuel Cells, in general, are electrochemical devices that produce electrical power through reduction and oxidation (redox) chemical reactions occurring at its electrodes (Thomas & Zalbowitz, 2002). Unlike turbines, Fuel Cells don't require mechanical work to generate the electrical power. Moreover, Fuel Cells electrical efficiencies can reach up to 60% (Demin & Tsiakaras, 2001). Five basic types of fuel cells and their associated chemical reactions are shown in Figure 4:



Fuel cell type	Anode reaction	Mobile Ion	Cathode reaction
PEMFC	$H_2 \rightarrow 2H^+ + 2e^-$	H^+	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
DMFC	$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$	H^+	$3/2O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
PAFC	$H_2 \rightarrow 2H^+ + 2e^-$	H^+	$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O$
MCFC	$H_2O + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$	CO_3^{2-}	$1/2O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
SOFC	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$	O^{2-}	$1/2O_2 + 2e^- \rightarrow O^{2-}$

Figure 4: Fuel Cell Types and Chemical Reactions (Ellis & et al., 2001)

Naming of each type of fuel cells is based on their electrolyte. For example, the solid oxide fuel cells have a solid oxide or ceramic as an electrolyte. Unlike conventional fossil-fuel combustion technologies, Solid Oxide Fuel Cells are not limited by Carnot Efficiency. This is due to the fact that fuel cells can generate electricity when all components are at the same temperature driven by the chemical reaction between the cathode and anode, whereas, the combustion technologies require thermal energy to be converted to Work to produce electrical power. The advantage of Solid Oxide Fuel Cells being not limited to Carnot Efficiency is that its overall efficiency combining thermal and electrical efficiencies can reach more than 90% (Stambouli & Traversa, 2002). A schematic of the basic operation electrochemical reactions of a SOFC with a hydrocarbon fuel, such as natural gas, is given in Figure 5

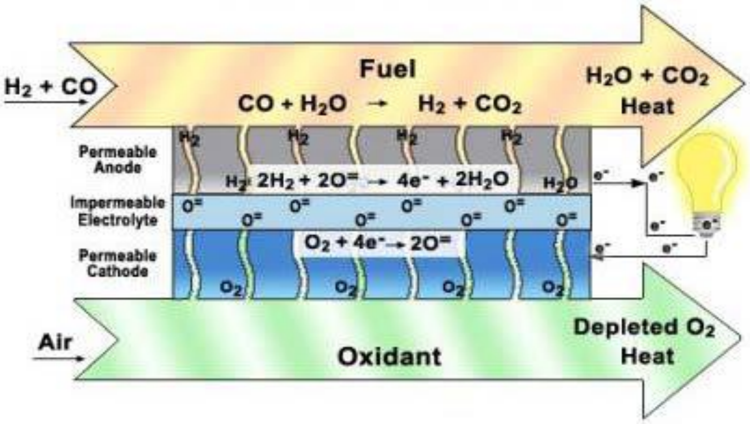


Figure 5: SOFC Basic Electrochemical Reactions (Czech, Main, & Kaplan)

As shown above, a reduction of the Oxygen from air was occurred at the interface between the cathode and the electrolyte by the presence of free electrons to produce oxygen ions, O2-. Then, the Oxygen ions are moved by ionic conduction through the electrolyte to the interface between anode and electrolyte. At anode-electrolyte interface, Oxygen ions and Hydrogen molecules get combined, H2, through an oxidation reaction. Thus, this reaction releases electrons to an external circuit for generating useful electricity. Electrons released are then introduced into the fuel cell cathode for sustained electrochemical operation. If pure hydrogen is used, the final by-product of the SOFC will be only H_2O. However, if natural gas was used instead, then CO_2 would also be produced.

As shown in following Figure 6, a single cell SOFC is typically only a few millimeters thick.

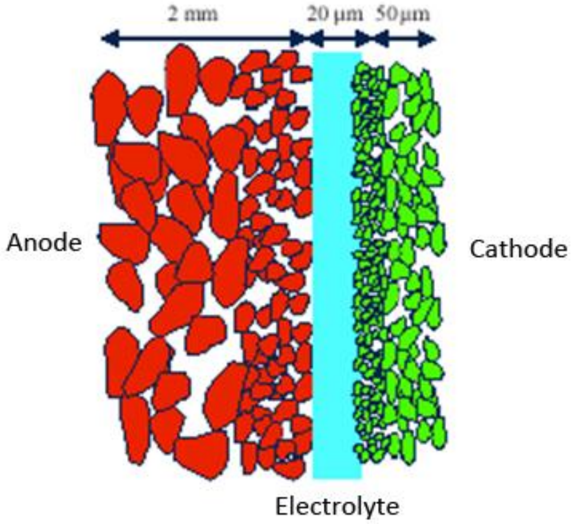


Figure 6: Dimensions of SOFC cell

Fundamentally, a single cell can only produce about 1 W/cm^2. Hence, a single cell with an average surface area of 20 cm^2 will be able to produce only 20 W of electricity. Therefore, in order reach up to kW- or even MW- scale power, thousands of single cells need to be stacked together and connected in series, as demonstrated in Figure 7.

Figure 7: Solid Oxide Fuel Cell Stack

One of the main advantages of SOFC stacks is that they are well-suited for applications in localized stationary, or distributed generation (DG) power applications, as the high operating temperature (600 – 1,000 ^{o}C) allows for operation on conventional hydrocarbon fuels (e.g. natural gas) with the production of high-quality exhaust waste heat for cogeneration and internal reforming. [30]. Running the SOFC with natural gas as fuel can eliminate almost all SOx, NOx, and particulate matter emissions, along with reduction of CO2 emissions by up to 54% in comparison to the conventional fossil-fueled power plants (Stambouli & Traversa, 2002). Mentioned properties of SOFCs make them essential for power generation scenarios where high power production is needed, emission minimization or elimination is required, or biological waste gases are available for fuel (Stambouli & Traversa, 2002). In addition, SOFC stacks have been successfully tested in long-term stationary power applications up to the MW-scale, typically for use in commercial CHP applications (Singhal, 2002).

The current cost of Solid Oxide Fuel Cells is still expensive compared to the conventional power generation systems. However, researchers around the world are trying to eliminate the challenges accompanied with operating at high temperature (e.g. 900-1000^{o}C) such as thermal shocks and incompatibilities between cell materials, electrode sintering and interfacial diffusion during operation, sealing degradation, the need for exotic interconnect and housing components, and long start-up and cool down-times, according to (Huang & al., 2007) and (Wachsman & Singhal, 2009). This can be done by operating the SOFC on intermediate temperature range such as 600-800^{o}C.

Several estimations have been developed for the capital and installation costs of the SOFC systems in residential and commercial buildings, which had led to values ranging from an optimistic value of $500/kW up to $1,000/kW according to US DOE Solid State Energy Conversion Alliance (SECA) program’s 2010 goals, according to (Fontell & al., 2004), (Hawkes & Leach, 2005) and (Zink & al., 2007).

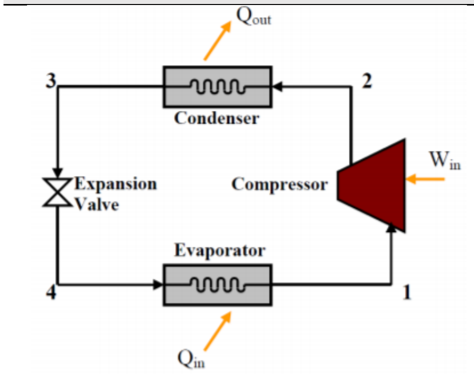
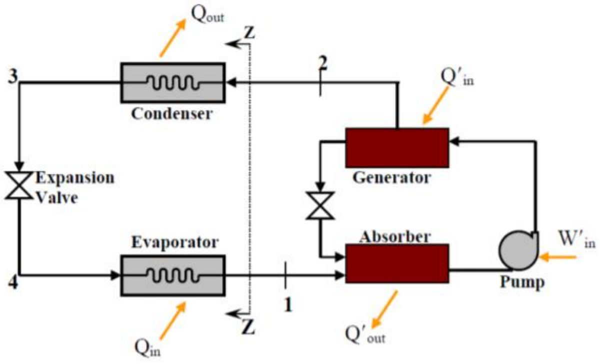
2.3 Absorption Chiller Basics

Absorption Chillers are machines which utilize heat to produce cooling effect through refrigeration cycle. One simple machine which uses the absorption concept is the residential refrigerator with ice cubes at the top and gas flame at the bottom, without involvement of electricity. The absorption chiller is the development of the same concept with more complications.

The concept of absorption cycle is almost the same as the Vapor compression cycle with a main difference of replacing the compressor with a chemical cycle taking place between the absorber, pump, and regenerator. Hence, absorption cycle doesn’t require much usage of electricity; however, it requires heat supply from an external source. Fundamentally, instead of compression of the refrigerant Vapor, the absorption cycle dissolves the refrigerant Vapor in a liquid (absorbent), which is then pumped to the generator. At the generator, the heat will be supplied from an external source increase the solution (absorbent + refrigerant) temperature and pressure which will lead to evaporation of the refrigerant inside the solution. Hence, the refrigerant Vapor is then leaves the generator to the condenser where it follows the same procedures in the Vapor refrigeration cycle with respect to condenser, expansion valve, and evaporator. In the condenser, the refrigerant Vapor is cooled by a coolant to condense it. Then, it gets expanded in the expansion valve which allows reducing its pressure and temperature. Following that, the refrigerant passes through the evaporator where it absorbs heat from the space to be cooled providing a cooling effect to the space. Hence, the Vapor refrigerant leaves the evaporator to the absorber again to get absorbed by the absorbent there to start a new cycle.

Table 1

Vapor Compression Cycle vs. Vapor Absorption Cycle Schematic (Absorption Cooling, 2012)

Vapor Compression Cycle	**Vapor Absorption Cycle**
	

2.4 Solid Oxide Fuel Cell – Absorption Chiller Cogeneration

As Solid Oxide Fuel Cells require very high temperature in order to utilize the Natural Gas in its operation with a minor loss in the heat, an excessive heat is produced in the exhaust. On the other hand, absorption chillers utilize heat rather than electricity for its operation. Hence, In order to utilize this excessive exhaust heat, a Cogeneration option of utilization of exhaust heat into an absorption chiller can be considered.

1) The fuel get heated and introduced in the anode side of the SOFC. Air get heated and introduced in the cathode of the SOFC. Oxygen’s negative ions get transferred from cathode side to the anode through the electrolyte to get reacted with the fuel there. In this reaction, electrons get released and circulated through an electrical circuit attached to the system. In the exhaust, CO2 and H2O will be the product of the reactions with a temperature reaches up to 1000 oC.

2) Hence, the high temperature exhaust products get introduced in the generator (evaporator) of the absorption cycle where it heats the solution (e.g. lithium bromide + water) to release water Vapor which is the refrigerant. Hence, the Vapor water will follow the cycle described above in Absorption Chiller Basics section.

The main purpose of this cogeneration is to utilize the excessive heat produced from the SOFC to get as much as possible from the system in terms of fuel utilization and energy production. This will increase the overall efficiency of the system up to more than 60%.

2.5 LITERATURE REVIEW

According to (E. Riensche & et al., 1998), an analysis of both energy and economics was conducted for a thermo-dynamical model of a 200 kW natural gas sourced Solid Oxide Fuel Cell system including the balance of plant components. Energy consumption and cost of equipment used for fuel processing units, heat exchangers, fuel supply, air supply, removal of exhaust gas, and power conversion were included in their model, shown in Figure 8.

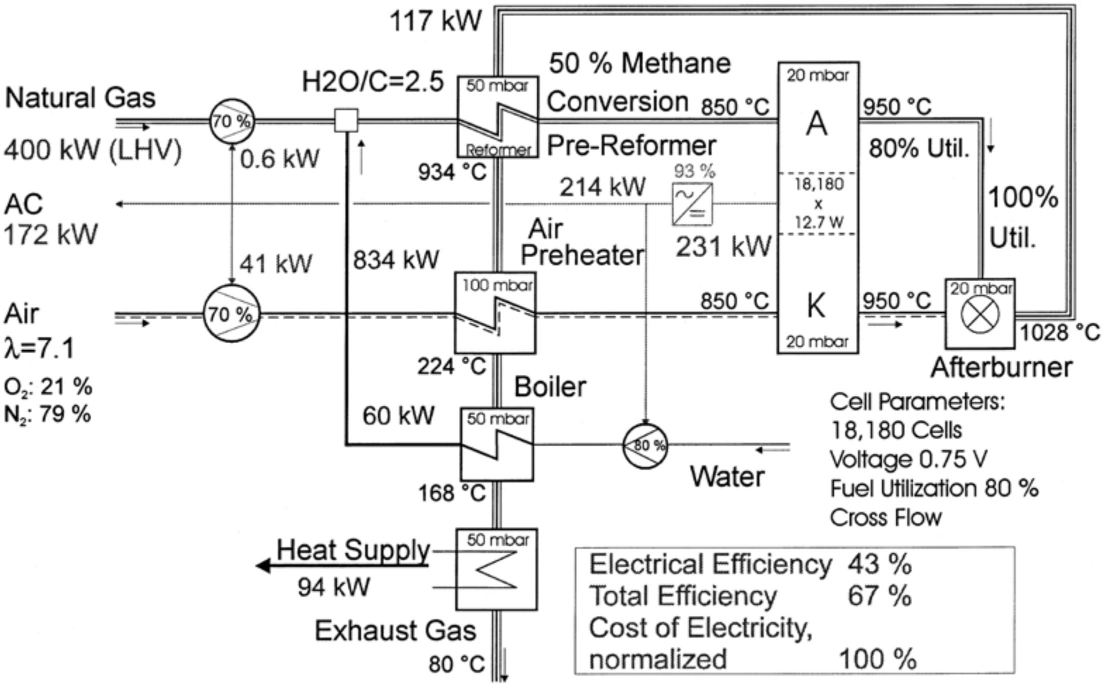


Figure 8: SOFC/BoP model of (E. Riensche & et al., 1998)

In their analysis, (E. Riensche & et al., 1998), the SOFC stack module was operated at a fuel utilization factor of 80% along with a temperature of 850°C, considering an internal fuel reforming of 50%. Considering no part load performance for the SOFC stack module, the electrical and electro-thermal efficiency values were calculated to be 43% and 67% respectively for the SOFC CHP system. In addition, a parametric analysis was developed to investigate the main parameters affecting SOFC performance and economics such as fuel utilization, fuel reforming technique, and operating temperature. Hence, the following results were obtained:

1) Reducing the fuel utilization from 80% to 65% had reduced the electricity cost by 5%.
2) Internal fuel reforming had led to 50% less electricity cost than external reforming.
3) Increasing operating temperature by 150 K from 1123 K resulted in electricity cost reduction of about 20%, as shown in Figure 9.

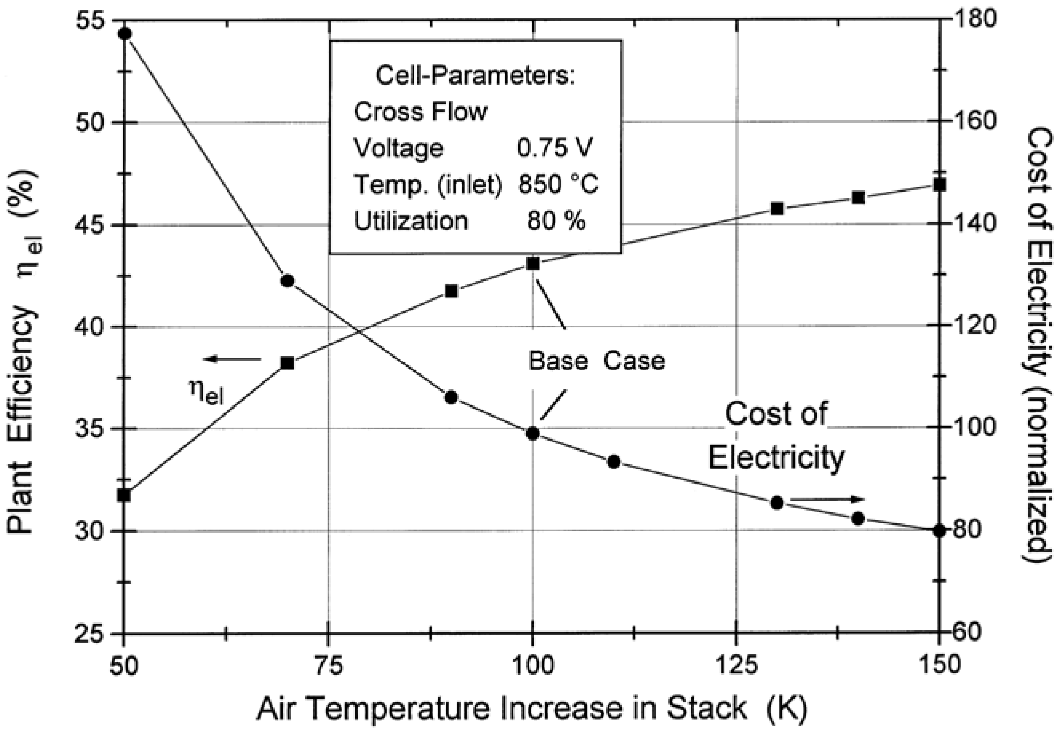


Figure 9: Impact of varying operating temperature on the SOFC system (E. Riensche & et al., 1998)

In (R.J. Braun & et al., 2006), a study has been conducted to evaluate several SOFC-CHP systems for Residential Appliances. Five different designs for system were considered to check the optimal thermal to electric ratio (TER) including domestic hot water (DHW), distinct fuel types and fuel reforming techniques. The SOFC-CHP system was optimized by their TER, but no building loads were taken into consideration. The optimal TER ratio to match DHW thermal load was found to be between 0.7 and 1.0.

The stack model used in (R.J. Braun & et al., 2006) is extrapolated case of a validated steady-state, 1-D, single cell energy balance model which is shown in Figure 10.

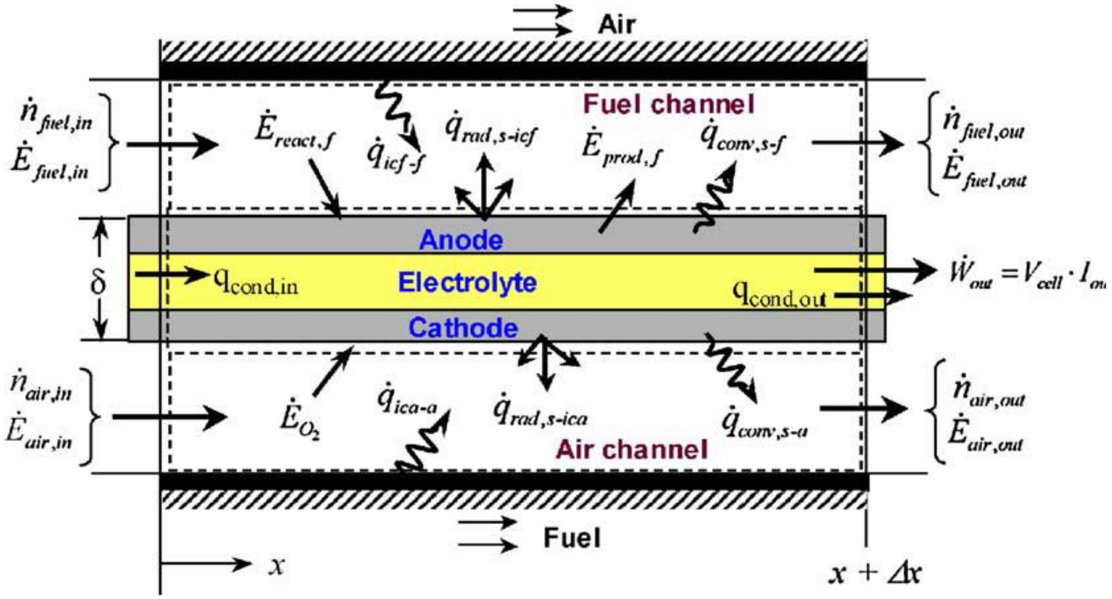


Figure 10: 1-D, steady-state single cell energy balance model (R.J. Braun & et al., 2006)

The operation conditions implemented and assumptions considered in (R.J. Braun & et al., 2006) were (1) 800^{o}C for SOFC temperature, (2) 85% of fuel utilization, (3) BoP components were simulated in the study of and (4) no SOFC part load performance was considered. Hence, it was found that there are no electrical efficiency benefits observed when hydrogen fuel was used instead of natural gas fuel. This finding was resulted in both internal and external reforming cases. This is because of utilizing exhaust thermal energy to reform a hydrocarbon fuel such that the total chemical energy of delivered fuel to the fuel cell stack is increased, while the amount of fuel fed to the system remains lower than hydrogen-based systems. Moreover, they found that internal reforming of methane gas inside the system has reduced the required cathode air mass flow rate by 50% as well as maximizing the electrical efficiency.

(A. D. Hawkes & et al., 2007) studied the viability of several strategies of operating a 5 kW SOFC micro-CHP system for residential application in United Kingdoms. Different operating procedures were evaluated due to the fact that constant loading is preferable for operating SOFC system, while cyclical heat requirement profile in morning and night is the case in the UK. The system which was studied has included a direct internal reforming SOFC stack with BoP model, as shown in Figure 11.

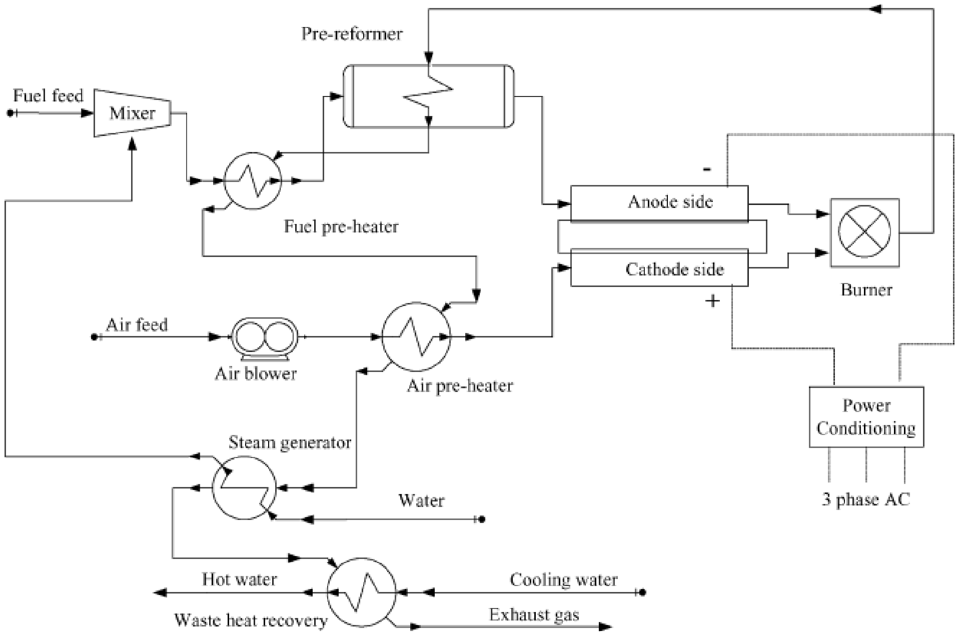


Figure 11: (A. D. Hawkes & et al., 2007) SOFC micro-CHP system

Part load efficiency curves, shown in Figure 12, were developed using gPROMS ModelBuilder from a previous research on studying 1-D, steady-state single cell SOFC model by energy and mass balance (P. Aguir & et al., 2004).

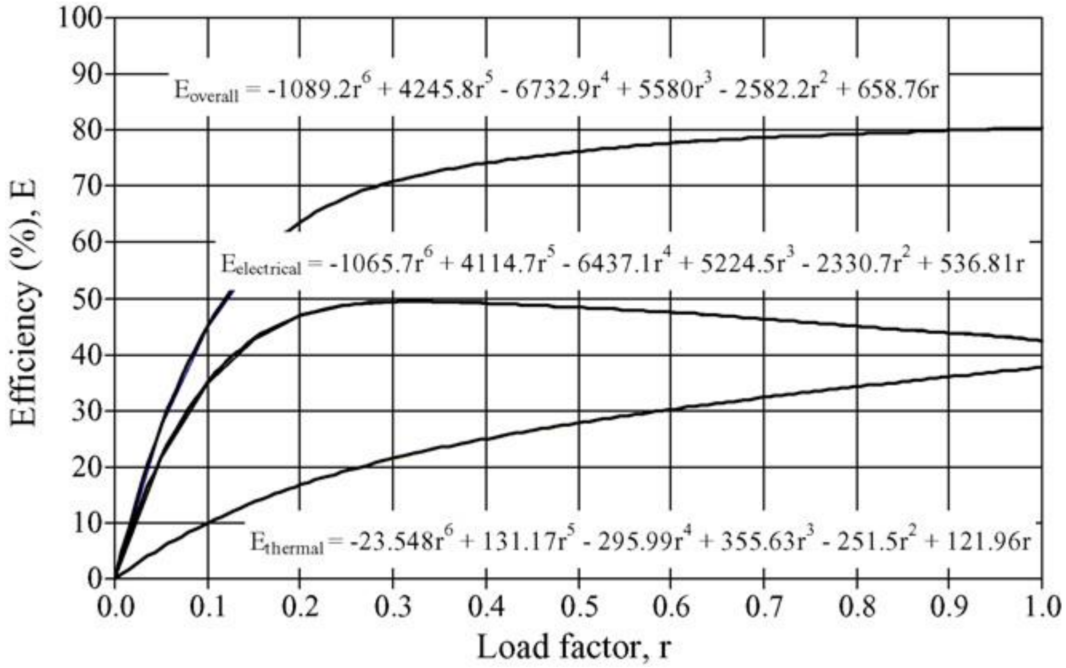


Figure 12:SOFC CHP part-load efficiency curves (A. D. Hawkes & et al., 2007)

The fuel utilization factor was assumed to be 70%. The heat load was simulated using Environmental Design Solutions Limited (EDSL) Tas software. Distinct heat load profiles were studied, and the optimal concept found was when a space heating was applied by a 3 kW under floor heating system that is operating constantly during the winter. The optimal concept was found to lead to a reduction of 1,300 kg/year of CO2 emissions. The study has highlighted the importance of finding the best application that has TER that is well suited with SOFC electro-thermal efficiency.

According to (Frimodt & Mygind, 2010), Frimodt et al. had investigated the potential of integrating SOFC system with Absorption Cooling Units. The integrated system consists of an absorption chiller driven by the heat exhausted from the SOFC system. Initially, a market investigation was conducted based on rough economical calculations for application of SOFC-ABS in energy distributed generation of hotels. Following assumptions were taken into consideration which are (1) COP of absorption chiller is 1.3, (2) Efficiency of SOFC system is 0.5, (3) COP of electric chiller is 4.0, (4) Gas and Electricity prices are 0.032 $/kWh and 0.12 $/kWh respectively, (5) SOFC capital cost is 500$/kW, (6) Absorption chiller capital cost is 590 $/kW, (7) Electric chiller capital cost is 287 $/kW, (8) discount rate is 5%, and (9) system lifetime is 10 years. Based on the assumptions considered, three cases were considered which are (1) Grid electricity with electric chiller, (2) SOFC electricity with electric chiller, and (3) SOFC with both electric and absorotion chillers. For case (3), it was noted that the SOFC-ABS system could generate quarter of the cooling demand due to the low COP of absorption chillers, while the remaining cooling demand was generated by electric chillers. In another words, quarter of the cooling demand was generated by a free energy source. Moreover, by application of SOFC only in case (2), a reduction in total cost, which includes capital and utility (fuel or electricity) costs, was calculated to be around 45% of the original cost. In case (3), a further reduction of almost 3.7% out of the original cost was observed. Hence, it was concluded that the system could fit DG application in hotels and can generate economical profits.

Furthermore, a theoretical zero-dimensional steady state thermodynamical model (shown in Figure 13), supported by experimental data from industry, was performed for the SOFC-ABS system to assess its feasibility. The SOFC-ABS system was simulated fully to find out the energy production in comparison to the fuel input. Moreover, main design parameters were varied in a sensitivity analysis to find out the each parameter effect on the general performance.

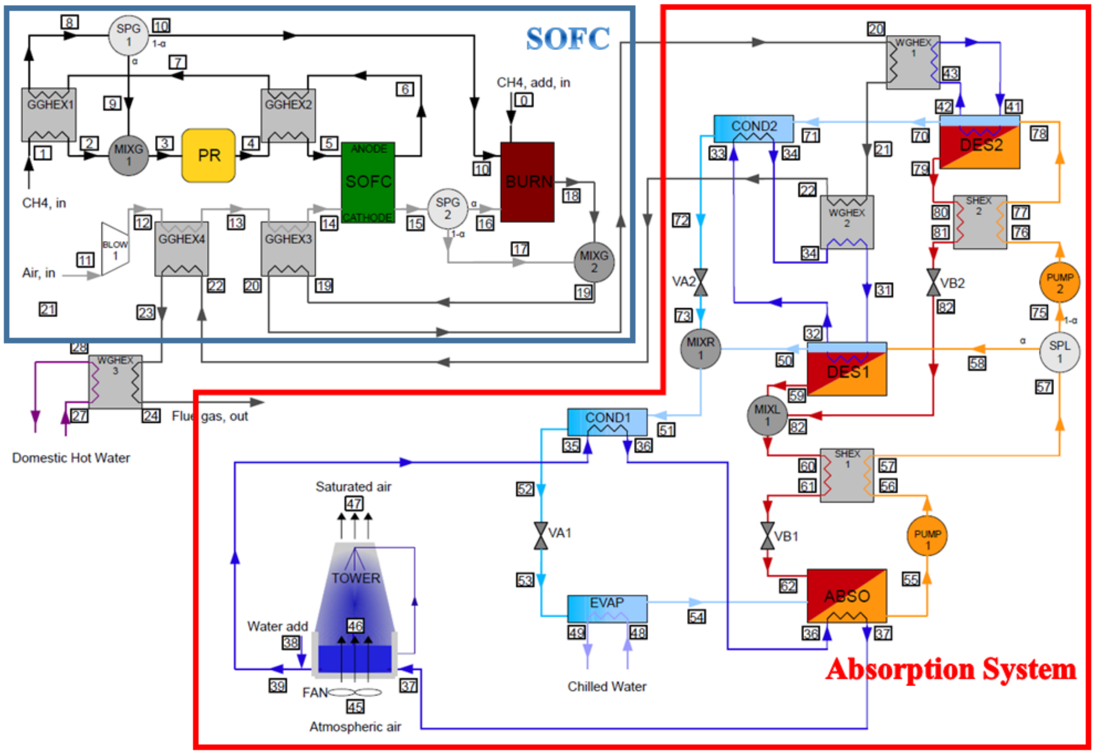


Figure 13: Thermodynamical model of SOFC-ABS System (Frimodt & Mygind, 2010)

The results showed that the double stage absorption cycle is the optimum alternative if the SOFC inlet air was additionally preheated by the heat remaining from the exhaust gas of the absorption chiller. More specific, it was found that the double stage absorption chilling system could produce a cooling effect of around 59kW per 100kW of fuel input, while the single stage absorption chilling system could only give a cooling effect of 26kW. Moreover, if an additional air preheating was introduced in the SOFC system by the exhaust gas from the ABS system, an increment of 14kW of extra cooling could be produced for the double stage absorption chilling system.

Optimizing the model in respect to various temperatures and effectiveness of heat exchangers had result in producing 50 kW of electricity, 59 kW cooling effect, and 3 kW of heating for heat water production out using 100 kW of fuel. Otherwise, if the waste heat from SOFC was used only for producing hot water, the system would have given a total output of 95 kW distributed as 50 kW for electricity and 45 kW for hot water production with the same amount of fuel.

Furthermore, the results have shown that a wet cooling tower is required in case if the surrounding temperature is above 20^{o}C. Otherwise, the normal limit of 150^{o}C for the desorber temperature could be exceeded which could require different material selection.

Referring to (Sleiti A. K., 2010), a computation fluid dynamics model was developed for a tubular SOFC system to investigate the effect of decreasing cathode's porosity and inlet temperature on the performance of the system. One air channel and one fuel channel were modeled to simulate the electrochemical effects. Conduction and convection modes of heat transfer were analyzed in the model. The model was developed with three cases of each parameter such that 700^{o}C, 600^{o}C, and 500^{o}C for inlet temperature, and 30%, 20%, and 10% for cathode porosity. The results showed that the system can run more efficiently at simulated inlet temperature with low cathode porosity compared to higher temperature taken into consideration that properties of cathode, anode and electrolyte were kept the same.

In (Sleiti & Naimaster, 2010), the impact on intermediate temperature SOFC by electrode microstructure and electrolyte parameters was investigated by a one dimensional SOFC model based on PNNL. By analysing the exchange current density term, (which takes into consideration several parameters such as cathode activation energy, pore size, cathode porosity, and grain size at the cathode triple phase boundary), the activation overpotential was calculated. As PNNL model doesn't integrate cathode pore size, grain size, and porosity, an analytical exchange current density solution was utilized from (Deng & Petric, 2005). Hence, by a parametric and optimization analysis, 29% decrement in activation overpotential was achieved. In addition, the maximum power density for the intermediate temperature SOFC was increased by 400% from the case in PNNL benchmark.

According to (Chiappini & et al., 2011), Chiappini et al. had conducted a study to investigate the management of Solid Oxide Fuel Cell in Distributed Generation applications. He has developed a model of Solid Oxide Fuel Cell stack with its associated Balance of Plant components in order to simulate electrical and thermal energy production. Simulations have considered the effect of various parameters such as loading factor, temperatures, and fuel utilization rates on the energy production. The Solid Oxide Fuel Cell system studied is an externally reforming natural-gas fuelled with cogeneration option.

All Balance of Plant components have been simulated as black boxes where they were characterized according to their primary design data in order to study the performance of solid oxide fuel cell system in isolation. Two main models were considered in the combined heat and power Solid Oxide Fuel Cell model which are (1) an electrochemical model and (2) a thermal model [ref]. In order to develop a steady-state, one dimensional Solid Oxide Fuel Cell electrochemical model, the following conditions were taken into consideration:

1) All the gases flowing in the system are ideal.
2) The output voltage is constant from each cell in the stack.
3) Perfect Mixation is applied to all gases inside the stack.
4) Uniform Distribution of supplied air and fuel into each individual cell in the stack.
5) Water-gas shift reaction occurs at equilibrium.

Hence, based on the assumptions above, Chiappini has considered that there are three types of losses that occur in Solid Oxide Fuel Cell electrochemical model which are mainly (1) the Ohmic Losses (η_{ohm}), (2) Activation Losses (η_{act}), and (3) Diffusion Losses (η_{diff}). In principle, the ohmic losses are the losses associated with the ohmic resistances of cathode, anode, and electrolyte. Secondly, the activation losses are more related to the activation barriers available at the electrodes. Lastly, the diffusion losses are calculated with regards to concentration variations between different critical species used in the system such as hydrogen and oxygen. Hence, these losses consists of complex functions affected by several parameters such as temperature, pressure, electronic and ionic conductivities, current, and number of moles available for fuel and oxidant. Moreover, gas flow rates, methane reforming reaction rates, and water-gas shift reaction rates are all also variables that were considered in losses functions. The electrical voltage available for each cell after consideration of losses listed above can be calculated using equation below. In Equation 1, E_{nernst} is the ideal Nernst voltage

Equation 1: Energy losses in SOFC

$$E_{FC} = E_{Nernst} - \eta_{Ohm} - \eta_{act} - \eta_{diff}$$

With regards to the thermal model, the driver of managing the heat is the air mass flow rate at the cathode. The air flow rate through the system has two main objectives which are (1) to provide the oxygen on cathode side to completer the electrochemical reactions and (2) cooling the cell to guarantee that the temperature difference between inlet and outlet is lower than the threshold temperature difference which is usually 50^{o}C. This temperature difference restriction is required to avoid any thermal stresses in the system. Although, those functions for air within solid oxide fuel cell system are crucial, there is one essential major function of this air which is the delivery of the thermal energy into useful exhaust gases to produce further electrical power or to supply it for heating applications. In order to calculate the air mass flow rate required, the solid oxide fuel cell energy balance was used:

Equation 2: SOFC Energy Balance

$$\begin{aligned}\dot{m}_{an,in}h_{an,in} + \dot{m}_{ca,in}h_{ca,in} + \dot{Q}_{reac} - \dot{Q}_{loss} \\ = \dot{m}_{an,out}h_{an,out} + \dot{m}_{ca,out}h_{ca,out} + V_{FC}iA\end{aligned}$$

In Equation 2, “h” stands for enthalpies at anode and cathode calculated as a function of inlet or outlet temperatures. Moreover, $\dot{Q}$ stands for heat flux either generated by the reactions or lost during the reactions. Below is a flowchart (Figure 14) showing the list of required input parameters to the model as well as the expected output parameters from the model.

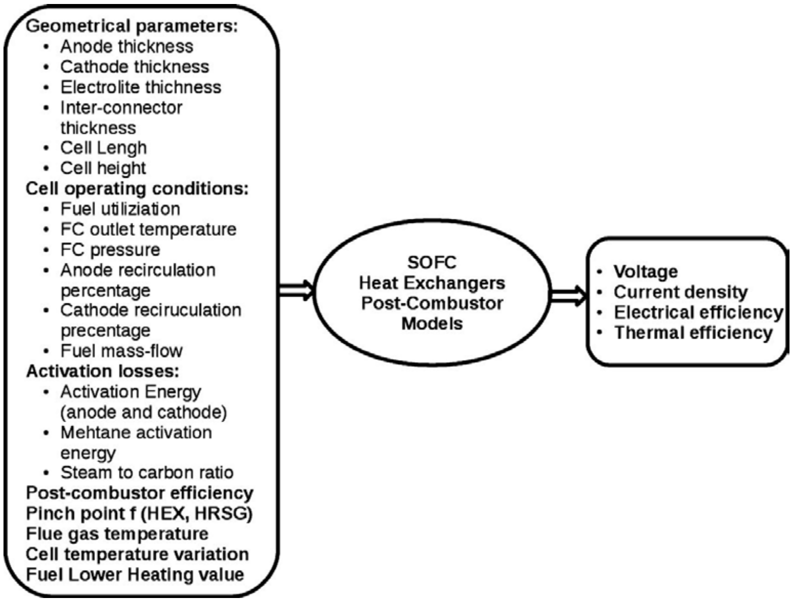


Figure 14: Chiappini et al. SOFC system model input-output scheme (Chiappini & et al., 2011)

Moreover, a general schematic for the Solid Oxide Fuel Cell cogeneration system model is shown below (Figure 15):

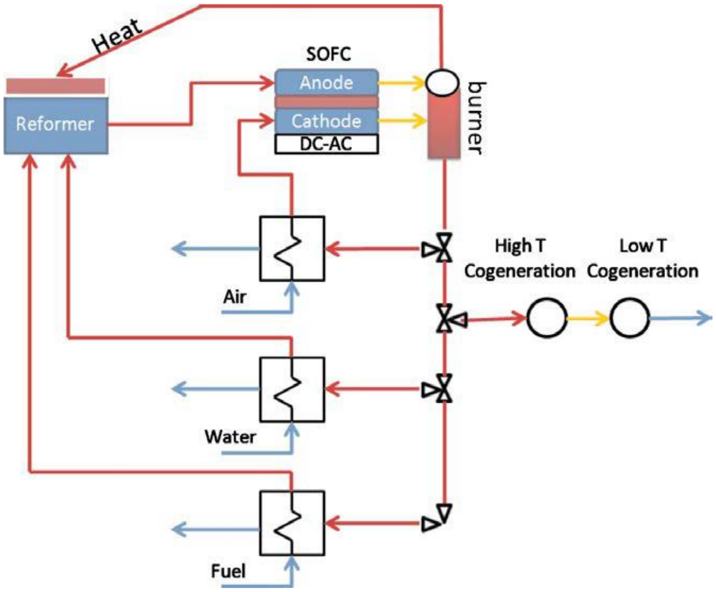


Figure 15: Chiappini et al. SOFC cogeneration system model (Chiappini & et al., 2011)

In order to develop a part load electrical and thermal efficiencies curves for the Solid Oxide Fuel Cell cogeneration system under various operating conditions, Chiappini et al. had established the following procedure:

(1) Both electrochemical and reforming characteristics were used to develop an approximate polarization curve (relation between cell output voltage and current produced) of the SOFC stack for the given operating parameters. Furthermore, after obtaining the polarization curve from the model by Chiappini, he compared the numerical polarization curve with an experimental developed one by (Lim & et al., 2008) in order to employ a reliable electrochemical model. The comparison is shown in Figure 16.

(2) Evaluation of design section where the design conditions, characteristics, and dimensions of the Solid Oxide Fuel Cell is set and calculated.

(3) Variation of three characteristics factors such as fuel flow rate, fuel utilization, and fuel cell temperature in off design conditions to evaluate the performance of the power system with respect to those factors.

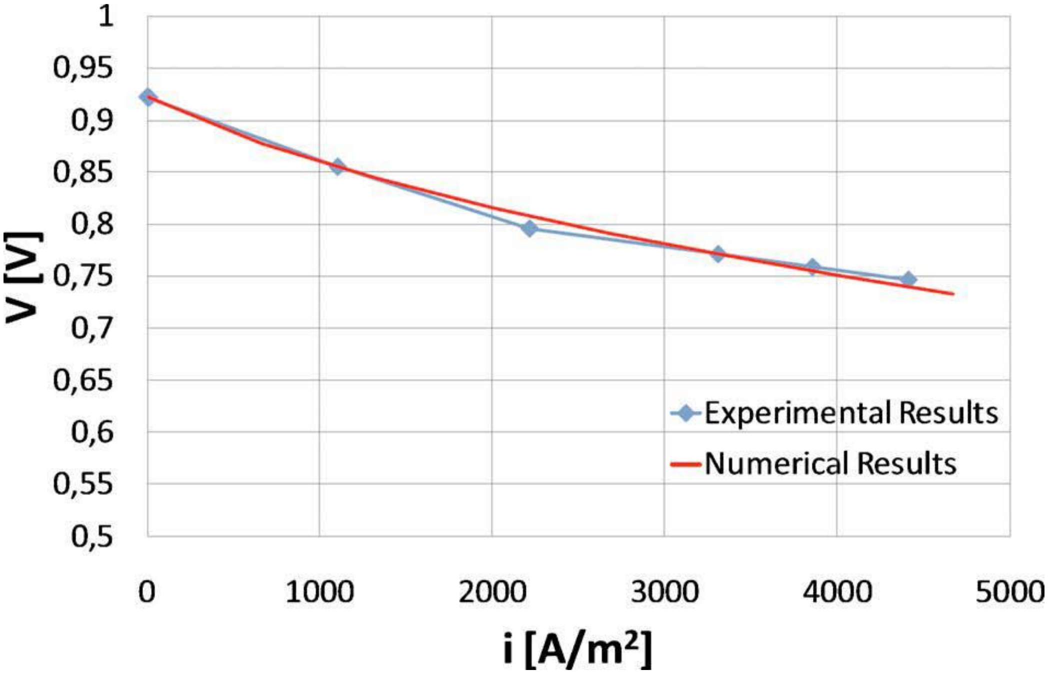


Figure 16: Chiappini et al. 5 kW SOFC stack model validation (Chiappini & et al., 2011)

Referring to (Sleiti & Naimaster, 2013), Naimaster et al. had studied the potential of Solid Oxide Fuel Cell combined heat and power system for energy-efficient commercial buildings in United States of America. The study considered three locations inside United States that have different weather conditions in order to investigate the best application of Solid Oxide Fuel Cell (heating, cooling, etc..), which are (1) Charlotte, NC (warm and humid), (2) Miami, FL (very hot and humid), and (3) Minneapolis, MN (cold and humid). A medium sized office building of 7000 m^2 was modeled in eQuest software, as shown in Figure 17, for each location to obtain the required energy consumption. Hence, to investigate the effect of integration the Solid Oxide Fuel Cell, a standard HVAC system was initially simulated to be considered as a baseline case. The case was developed on the basis of ASHRAE 90.1-2010, Appendix G, for the given building type and size where the HVAC system is a rooftop variable air volume (VAV) with reheat and the cooling is provided by direct expansion coils (DX), while heating is provided by hot water natural gas boilers. Moreover, the VAV fans were set on a minimum flow point of 30% and the DX coils have an energy efficiency ratio of 9.845. All equipment were auto sized by eQuest based on the considered building loads and climate.

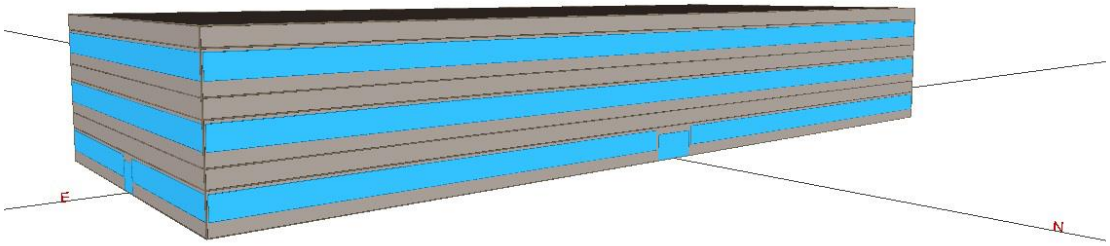


Figure 17: Office Building 3D view in eQuest (Sleiti & Naimaster, 2013)

In the other case, a Solid Oxide Fuel Cell combined heat and power system was simulated as an electric generator into eQuest software with connected exhaust heat to the hot water loop. In addition, all equipment remained the same as the baseline case. The electrical power generated by the Solid Oxide Fuel Cell system was used for loads like cooling, lighting, ventilation, etc.., while the exhaust heat was used in hot water loop to provide heating through heating coils, and in case there is no enough waste heat, a natural gas driven boiler was operated.

As there is no Solid Oxide Fuel Cell system database built-in eQuest software, the performance characteristics of the Solid Oxide Fuel Cell combined heat and power was introduced through the utilization of validated performance curves published in

(Chiappini & et al., 2011) for both electrochemical and thermal models, see Figure 18 and Figure 19.

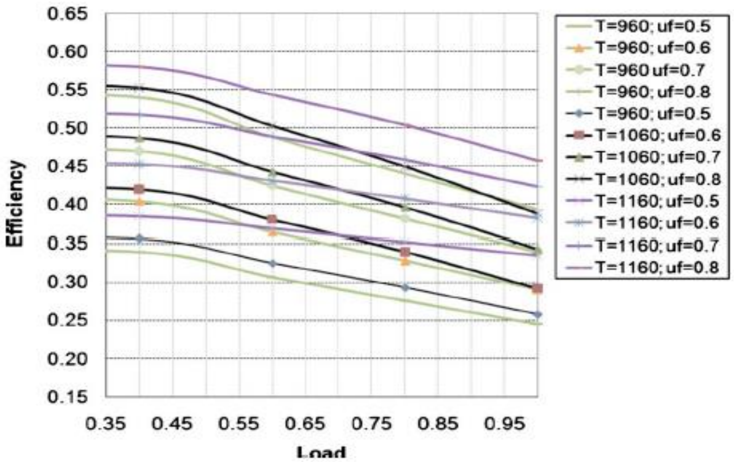


Figure 18: Chiappini et al. SOFC cogeneration model part-load electrical efficiency (Chiappini & et al., 2011)

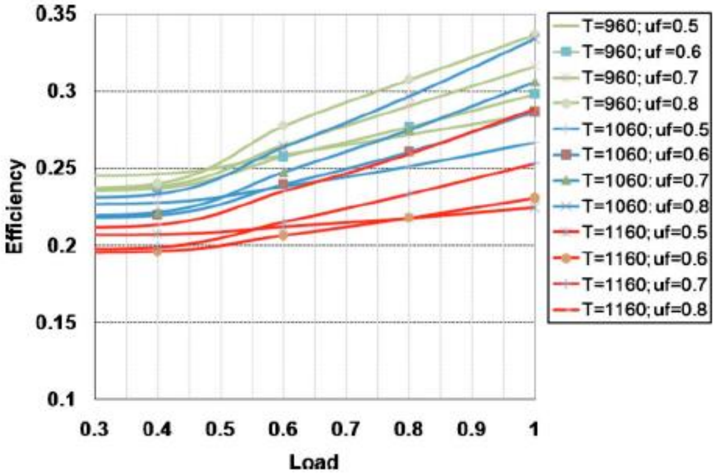


Figure 19: Chippini et al. SOFC cogeneration model part-load thermal efficiency (Chiappini & et al., 2011)

Moreover, the Solid Oxide Fuel Cell fuel consumption was introduced to the software through the heat input ratio (HIR), as given in Equation 3:

Equation 3: SOFC Heat Input Ratio

$$HIR = \frac{\Delta\dot{H}_{HHV\ fuel}}{P_e}$$

In Equation 3, *ΔHHHV fuel* is the design fuel consumption at the higher heating value (HHV) and P_e is the design electrical power. The HIR was considered as the inverse of the electrical efficiency for the Solid Oxide Fuel Cell stack [ref]. The electrical efficiency considered by (Sleiti & Naimaster, 2013) was at full load with an operating temperature of 890^{o}C and a fuel utilization factor of 80%, which corresponds to and electrical efficiency of 46% (refer to Figure 18). Based on that, the HIR for the given model was calculated as 2.17.

As stated above, the exhaust heat was connected to the hot water loop as a heat recovery system. The thermal energy was introduced to the software as a fraction of the input design fuel consumption. The fraction of recoverable heat relative to fuel consumption used was 0.38. In case of Miami location, the thermal energy available at exhaust was introduced into domestic hot water (DHW) loop instead of boiler hot water loop, as there is higher demand in DHW loop.

The rated power (capacity) of Solid Oxide Fuel Cell stack was varied from 25 to 250 kW to check the best system for the simulated cases. The Solid Oxide Fuel Cell combined heat and power system was set to track the electric load of the building, with a minimum operation ratio of 0.3, which means that the system will not work at less than 30% of its rated power.

By simulating building energy with the HVAC standard system described above, the annual energy consumption by end-use for each simulated location is shown in Figure 20. As expected, the maximum energy demand in office buildings is either space cooling or heating which is ranging between around 35% for Miami, and more than 55% for Minneapolis. For typical energy end-uses such as lighting, miscellaneous equipment, and exterior usage, Naimaster et al. have considered it the same as it is function of building type (Sleiti & Naimaster, 2013).

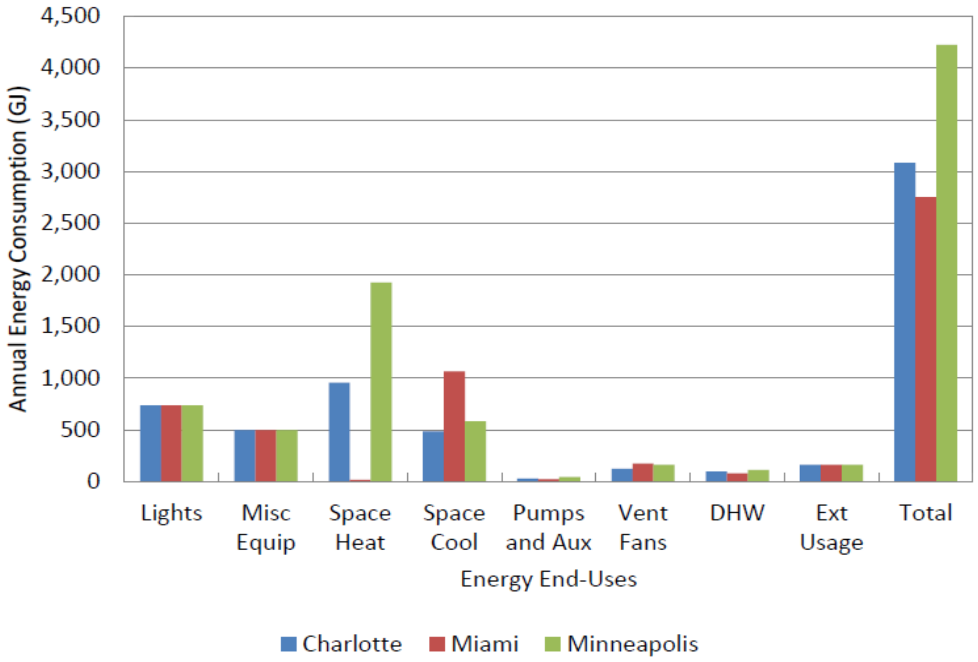


Figure 20: Baseline office building model annual energy consumption (Sleiti & Naimaster, 2013)

For most of the end-uses prescribed above, the energy is provided as a direct usage of electricity, while for heating and domestic hot water, the energy is provided through the consumption of natural gas. In order to have an initial sensation of the results, Naimaster et al. had compared the thermal to electrical ratio (TER) of energy consumption for each location to the one can be produced by the Solid Oxide Fuel Cell combined heat and power system. The TER calculated for each is (1) 0.52 for Charlotte, (2) 0.03 for Miami, and (3) 0.93 for Minneapolis. Since TER for SOFC CHP system is 0.61 at full load, Charlotte and Minneapolis were considered as having favourable energy consumption profiles because it will utilize the exhaust heat as well as the electricity produced by SOFC in more efficient way. Beside the better utilization of thermal energy produced by SOFC, and in terms of cost reduction, both Charlotte and Minneapolis have low percentage of cost per gigajoule between natural gas and electricity which is 40.5% and 42.5%, respectively. Since SOFC will utilize natural gas to produce electricity as well as heat, there is a possibility to have cost savings even when higher energy consumption is required by the building due to lower cost of fuel compared to electricity.

Thereafter the initial assessment described above, simulations have been conducted considering the SOFC CHP system into eQuest software. The results showed that there is a decrease of electricity consumption as fuel consumption increases, as shown in Figure 21. Moreover, it was found that the optimal system capacity to be used is 175 kW as there will be the lowest annual utility cost. In case of Minneapolis, and compared to the baseline cost, there was an annual utility cost saving of 14.5%, corresponding to $7,725/year, at 175 kW SOFC capacity. The performance of the SOFC CHP system in relative to its capacity with respect to heat recovery, energy production, and cogeneration efficiency is presented in Figure 21. The cogeneration efficiency has decreased with increasing system capacity from 63% at 25 kW to 42% at 250 kW, and 50.5% for the optimal system capacity which is 175 kW.

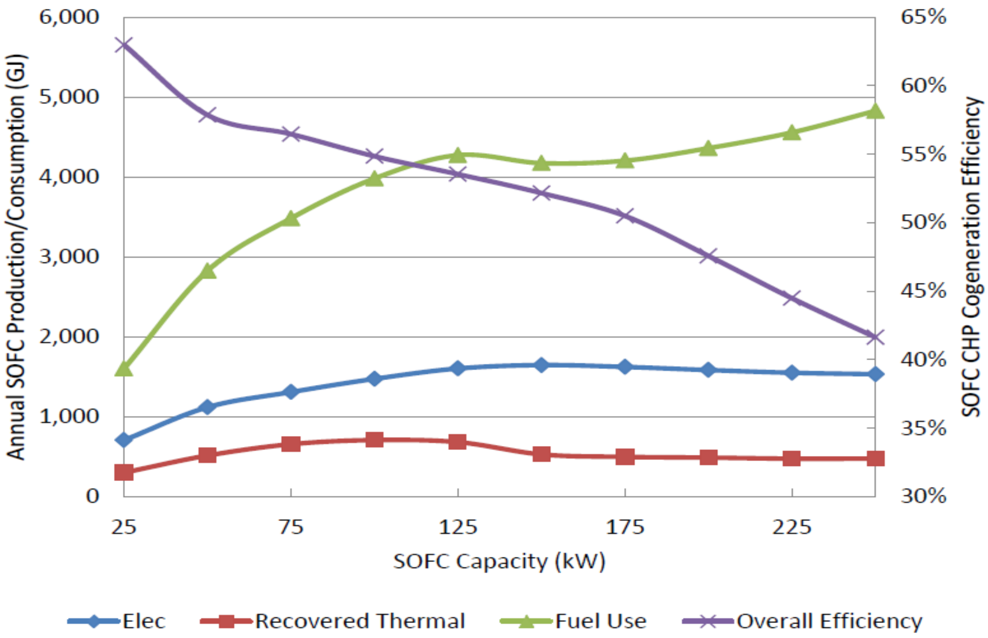


Figure 21: SOFC CHP system performance in Minneapolis (Sleiti & Naimaster, 2013)

Naimaster et al. has also checked three more performance factors with respect to SOFC CHP system which are (1) Utilization Factor, (2) Capacity Factor, and (3) Heat Recovery Factor. Both SOFC Utilization Factor (1) and Heat Recovery Factor (3) were defined by (Medrano & et al., 2008) as the (1) percentage of hours the SOFC system was utilized annually, and (3) the ratio of actual heat recovered to the optimum possible heat recovered in a year, respectively. Lastly, SOFC capacity factor is the annual amount of hours at which the system was running at full load (Sleiti & Naimaster, 2013). A summary of SOFC performance factors calculated for Minneapolis location is presented in the following table:

Table 2

Minneapolis SOFC CHP System Performance Factors (Sleiti & Naimaster, 2013)

Performance Factors	**Value**
Annual utility savings	14.5%
SOFC Utilization Factor	38.4%
SOFC Capacity Factor	76.8%
SOFC Heat Recovery Factor	9.0%
SOFC CHP efficiency	50.5%

Regarding the environmental aspect, CO2 emissions calculations were performed to investigate the effect of using SOFC CHP system on emission reduction. The CO2 calculations for the electricity usage directly from the grid were in accordance to US DOE eGRID2010 electric grid CO_2 emission values by state (eGRID2010 Version 1.1: Year 2007 Summary Tables, 2007). On the other side, calculations for CO_2 emitted by natural gas-combustion inside the boilers were performed with values given in Table 1 of the US EIA's Voluntary Reporting of Greenhouse Gases Program (Voluntary Reporting of Greenhouse Gases Program, 2011). In the case of SOFC CHP system, CO2 emission calculations for the energy consumption of the office building were based on Table 14.2 found in (O'Hayre & et al., 2009). Hence, the 175 kW SOFC CHP system simulated in

Minneapolis has shown a reduction of 62% of CO2 emissions compared to the baseline system.

The cost of the Solid Oxide Fuel System was calculated by means of simple payback period taking into consideration that the capital and installation costs are \$1000/kW, maintenance cost is 0.36 \$/GJ of electricity produced, and lifespan of 40,000 hours. Even in the best case for Minneapolis which has the best utility cost saving (14.5%), the payback period didn't fall within the lifespan of the system. The minimum saving required with the given assumptions were calculated to be 29% in order to get a break even time within system's lifespan.

In (Al-Qattan, ElSherbini, & Al-Ajmi, 2014), an analytical study was conducted to evaluate the performance of combined SOFC system with district cooling. The case study considered is a low-rise residential district which requires around 27,300 RT. The electric energy from SOFC system was introduced to district cooling and exhaust heat was introduced to gas turbines and absorption chillers. A thermal energy storage was also used to lower capacity of the system. Part-load operation was considered to maximize efficiency of the system. The system was able to reduce the peak power by 57% (24 MW) and the fuel consumption by 54% (750 TJ/year). In addition, emissions were reduced by more than 50% compared to baseline case. Economically, the cost study of the system components and operation showed that 53% reduction in the cost per RT-hr of cooling compared to traditional system.

According to (Chen & Ni, 2014), an economic analysis was conducted to evaluate viability of SOFC-absorption cooling cogeneration/tri-generation system for a hotel in Hong Kong. The energy consumption profiles for ICON Hotel were adopted for this study. An existing absorption chiller (Broad Group in China) and SOFC server (Bloom Energy in US) were chosen from the market and utilized for the study in terms of performance and cost. In tri-generation system configuration was such that the SOFC exhaust will be utilized first in absorption cooling and then in the domestic hot water. It was found that the payback period will be limited to less than 6 years taking into consideration 50% government subsidy of the overall system cost.

Referring to (Zare & Gholmian, 2016), a comparative study was conducted on implementing Organic Rankin Cycle and Kalina Cycle in SOFC/Gas Turbine System for exhaust heat recovery. The system was fuelled by methane; internal and external reforming with anode gases recirculation was checked. A thermodynamical model was developed to study the parameters affecting such system and its performance; following points summarize the most important parameters and their noted effects.

- Current density increment had led to decrement in exergy efficiency due to required high fuel consumption by the SOFC.
- Optimizing inlet pressure of the bottom cycle led to maximizing both exergy efficiency and total output power.
- Compressor pressure ratio at which exergy efficiency is optimum is different for SOFC/GT-ORC and SOFC/GT-KC, and is higher in SOFC/GT-ORC.
- Although increasing fuel utilization had led to higher exergy efficiencies, it was noted that net output power was decreased.

On the other hand, an environmental impact assessment has been carried out. The results had proved that implementing Organic Rankine Cycle can enhance the exergy efficiency to reach a value of 62.35%. On the other side, employing Kaline Cycle had led to exergy efficiency up to 59.53%. Figure 22 shows study results in terms of thermal efficiency, exergy efficiency, CO2 emissions, and output power.

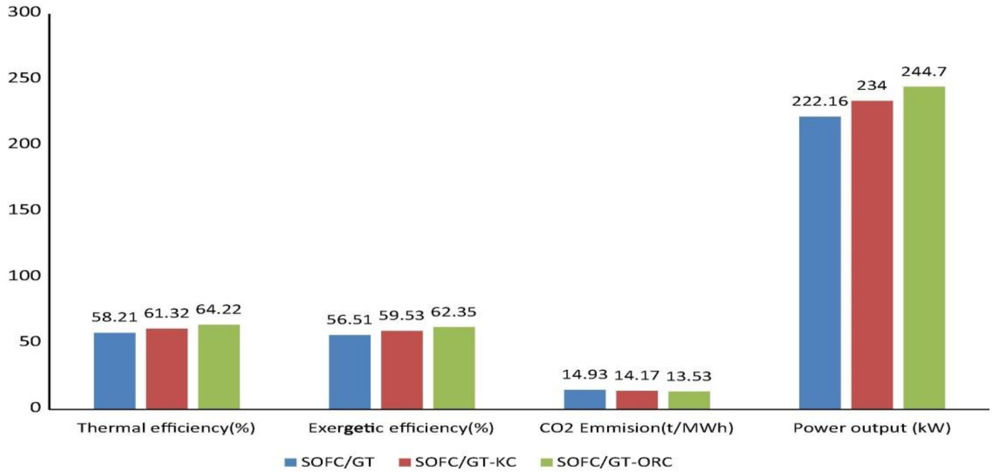
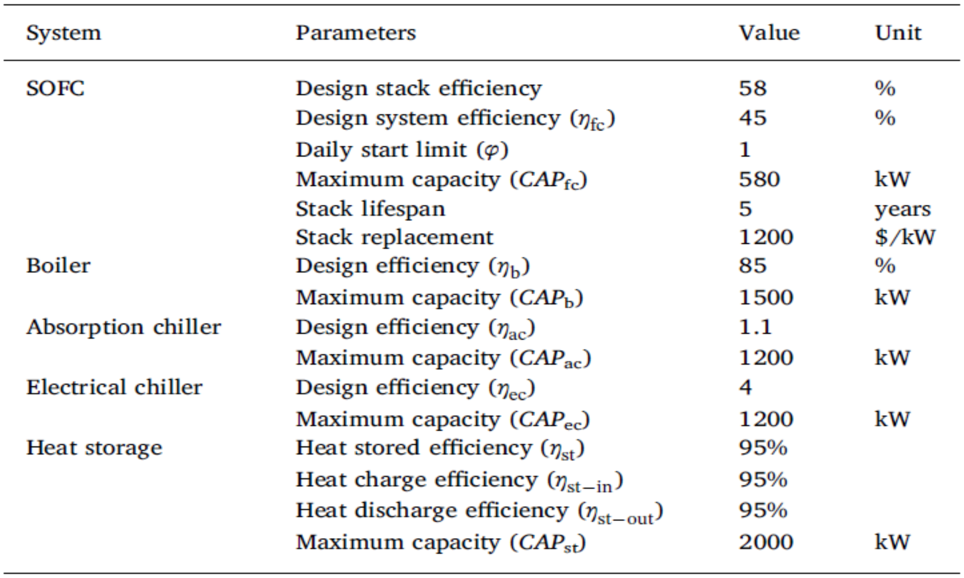


Figure 22: Comparative study results figure obtained from (Zare & Gholmian, 2016)

In (Jing, et al., 2017), a model of SOFC based CCHP system was developed using MINLP approach to optimize the design and operation of the system. User specified sizing and optimal sizing options were utilized in the model. Moreover, the proposed model can be studied by four operation forms which are full load, day/night, base load, and following electrical load. Real operation constraints such as equipment number of starts, equipment on/off, and part load efficiency were considered. Three scenarios were studied using the optimal sizing option.

The proposed SOFC CCHP system was applied on a case study of a Hospital in Shanghai which has a hot climate during summer (hottest in July) and cold climate during winter (coldest in January). The ground floor area of the hospital is 35,100 m^2. Energy demand is relatively stable as the hospital would operate for 24 hours/day. A Project lifetime of

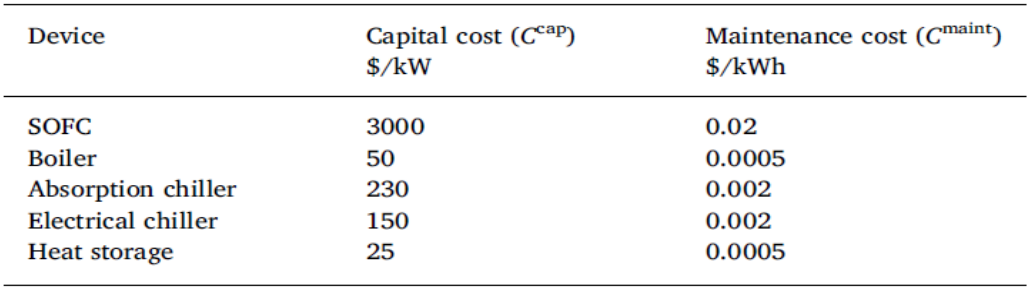
10 years was considered. In addition, a 6% interest rate was assumed in the calculations. SOFC natural gas and grid electricity assumed emission factors were 0.18 and 0.95 kg/kWh respectively. Systems design input parameters are listed in Figure 23.



System	Parameters	Value	Unit
SOFC	Design stack efficiency	58	%
	Design system efficiency (η_{fc})	45	%
	Daily start limit (φ)	1	
	Maximum capacity (CAP_{fc})	580	kW
	Stack lifespan	5	years
	Stack replacement	1200	$/kW
Boiler	Design efficiency (η_b)	85	%
	Maximum capacity (CAP_b)	1500	kW
Absorption chiller	Design efficiency (η_{ac})	1.1	
	Maximum capacity (CAP_{ac})	1200	kW
Electrical chiller	Design efficiency (η_{ec})	4	
	Maximum capacity (CAP_{ec})	1200	kW
Heat storage	Heat stored efficiency (η_{st})	95%	
	Heat charge efficiency (η_{st-in})	95%	
	Heat discharge efficiency (η_{st-out})	95%	
	Maximum capacity (CAP_{st})	2000	kW

Figure 23: Equipment Sizes and Efficiencies considered in (Jing, et al., 2017)

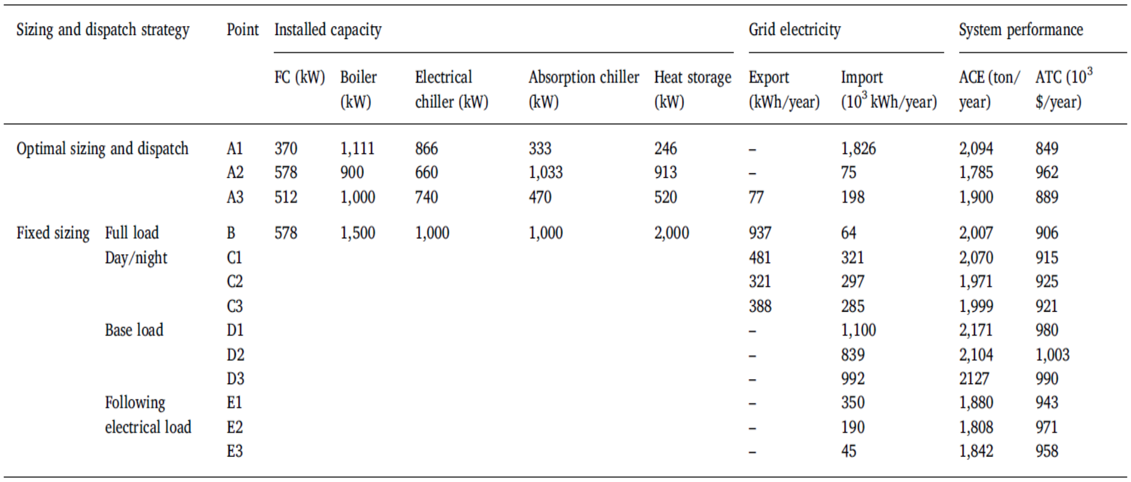
Furthermore, the capital and maintenance costs for the major components of the SOFC CCHP system are listed in Figure 24. It is worth mentioning that a replacement cost of 1200 $/kW was considered for the SOFC stack every five years.



Device	Capital cost (C^{cap}) $/kW	Maintenance cost (C^{maint}) $/kWh
SOFC	3000	0.02
Boiler	50	0.0005
Absorption chiller	230	0.002
Electrical chiller	150	0.002
Heat storage	25	0.0005

Figure 24: Equipment Capital and Maintenance Costs considered in (Jing, et al., 2017)

All design scenarios and their performances are presented in Figure 25. As tabulated in Figure 25, the lowest annual total cost was found at scenario A1 which utilized low capacity of SOFC stack module, higher electric chiller capacity than absorption chiller, and low heat storage capacity. On the other side, the lowest annual carbon emission was found at scenario A2 as it is utilized high SOFC stack module capacity, higher absorption chiller capacity compared to electric chiller, and high thermal storage. Hence, both SOFC stack modules and Absorption chillers supports lowering annual carbon emissions. This is due to the fact that SOFC stack module utilizes the natural gas without combustion requirement. In addition, absorption chillers utilize the exhaust heat available at SOFC stack module. However, for lower costs, electric chillers are dominant due to much higher coefficient of performance compared to absorption chillers. Therefore, it can be noticed that an intermediate scenario (A3) was developed in between scenario A1 and A2 which had led to electricity export of 77 kWh/year to the grid. Finally, a LCOE of 0.17 $/kWh was achieved by the optimal design compared to 0.21 $/kWh in baseline case.



Sizing and dispatch strategy		Point	Installed capacity					Grid electricity		System performance	
			FC (kW)	Boiler (kW)	Electrical chiller (kW)	Absorption chiller (kW)	Heat storage (kW)	Export (kWh/year)	Import (10^3 kWh/year)	ACE (ton/year)	ATC (10^3 \$/year)
Optimal sizing and dispatch		A1	370	1,111	866	333	246	–	1,826	2,094	849
		A2	578	900	660	1,033	913	–	75	1,785	962
		A3	512	1,000	740	470	520	77	198	1,900	889
Fixed sizing	Full load	B	578	1,500	1,000	1,000	2,000	937	64	2,007	906
	Day/night	C1						481	321	2,070	915
		C2						321	297	1,971	925
		C3						388	285	1,999	921
	Base load	D1						–	1,100	2,171	980
		D2						–	839	2,104	1,003
		D3						–	992	2127	990
	Following electrical load	E1						–	350	1,880	943
		E2						–	190	1,808	971
		E3						–	45	1,842	958

Figure 25: Different Scenarios Systems Design and Performance (Jing, et al., 2017)

(Palomba, et al., 2018) investigated the performance of SOFC-CHP system with adsorption and hybrid chillers for telecommunication applications. They had conducted an experimental analysis to characterize the main components of system, specially SOFC-CHP and thermal driven units, under a wide range of operating conditions. Then, the experimental results were employed in TRNSYS dynamic model to numerically analyze the overall system performance. Two design cases were considered at which one is employing SOFC-CHP system with adsorption chiller only, while the other one is employing adsorption/vapour compression cascade hybrid. On the other side, the reference case considered was utilizing grid electricity with vapour compression chiller. Based on simulations, it was noticed that multi-generation approach which utilizes a cascade hybrid chiller with SOFC-CHP system can achieve higher energy savings when compared to both adsorption chiller and reference case. It was found that the hybrid system was able to save up to 110 MWh annually. The overall efficiency of the system reached a value up to 66%.

From literature review aforementioned, it can be concluded that the system has a promising potential to save energy and costs in Qatar. The studies showed that the exhaust heat recovery system selection is very essential to fairly enhance the system efficiency and potential savings. Due to low number of studies or projects in the region with respect to SOFC system, the database of its performance and costs is not available. Therefore, the performance parameters utilized in this thesis for SOFC system were taken from (Chiappini & et al., 2011) validated models. Moreover, for HVAC systems characteristics, typical values implemented in eQuest software were used with latest performance characteristics. Economically, system components costs were retrieved from most recent studies to evaluate the viability of the system.

Chapter 3: MODEL DESCRIPTION

In this chapter, the office building model created in eQuest software will be described. In specific, model location and weather data, considered construction specification and assumptions considered for baseline and SOFC CHP system cases. Moreover, methodology followed for economic analysis and emissions calculations will be presented.

3.1 Office Building Model in eQuest

To investigate the effects of a SOFC CHP system on annual building energy consumption and utility costs, a 3-story, 7000 m^2 rectangular office building model was designed and simulated using eQUEST software. A schematic of the building model is shown below in Figure 26.

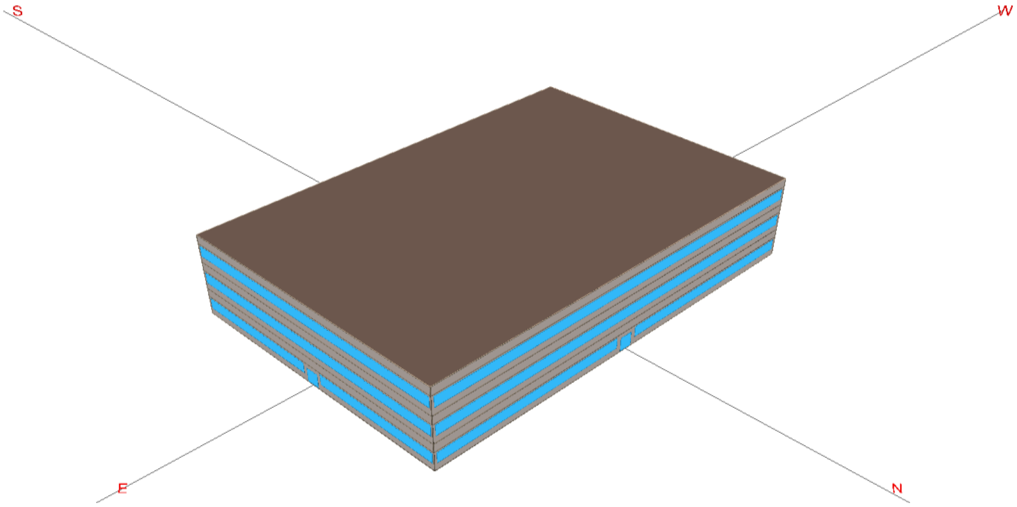


Figure 26: eQuest 3D view of the Office Building Model

Before using the model for Qatar applications, it was validated against results provided in (Sleiti & Naimaster, 2013) for Minneapolis location. The validation process showed matching percentage of 98% with the above cases, please refer to Figure 27. The design data for validation model were matched as much as possible to the model description in (Sleiti & Naimaster, 2013), and any mismatches in results could be due to different conditions considered.

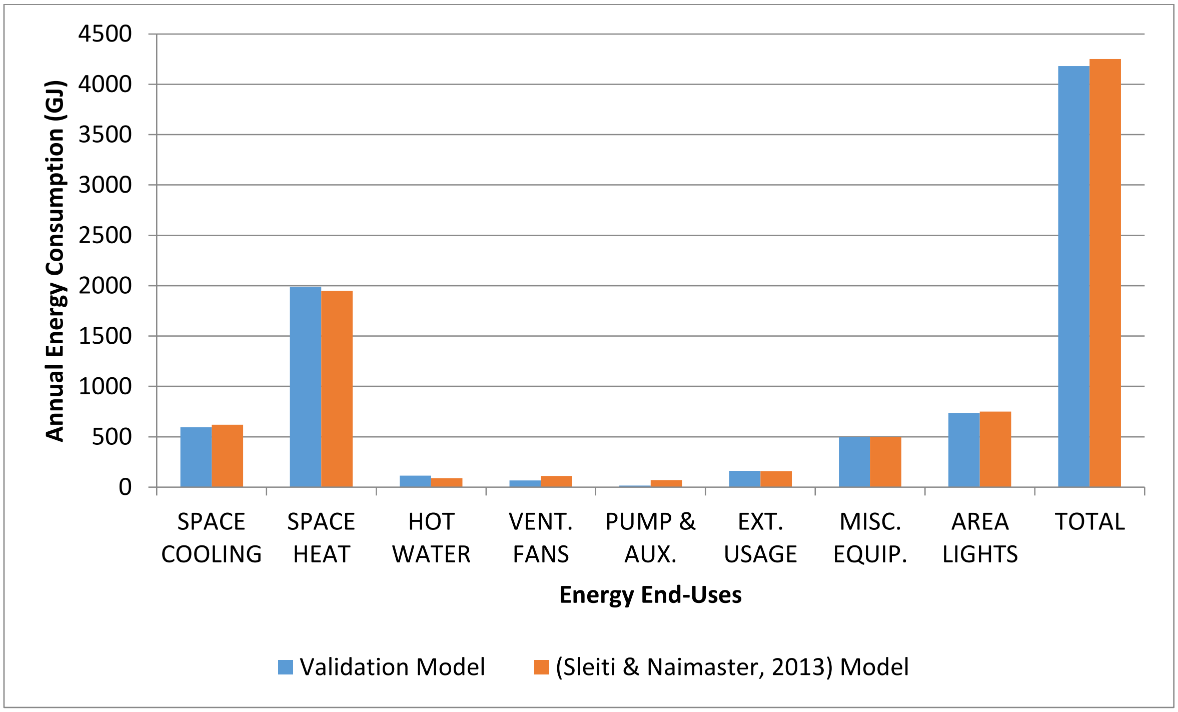


Figure 27: Validation Model Results against (Sleiti & Naimaster, 2013) Model

For Qatar, the construction of the building, including the building envelope materials was designed to meet Qatar Construction Specifications and Kahramaa standards where possible. On the other hand, lighting loads, and HVAC equipment and controls, was designed to meet the ASHRAE 90.1-2010 standards. According to Kahramaa best practices for conservation of electricity and water which was published in 2012, the overall heat transfer coefficient value (U Value) for the building roofs and external walls must not exceed values tabulated below:

Table 3

Kahramaa Standards overall heat transfer coefficient values for roofs, walls and windows

Building Item	**U-value**
Roof	0.437 W/m2 °C
External Wall	0.568 W/m2 °C
Windows	3.30 W/m2 °C (for 5-40% window wall ratio) 2.10 W/m2 °C (above 40% window wall ratio)

Based on the criteria stated above, the applied construction U values for the office building envelope are:

Table 4

Applied overall heat transfer coefficient values for roofs, walls and windows

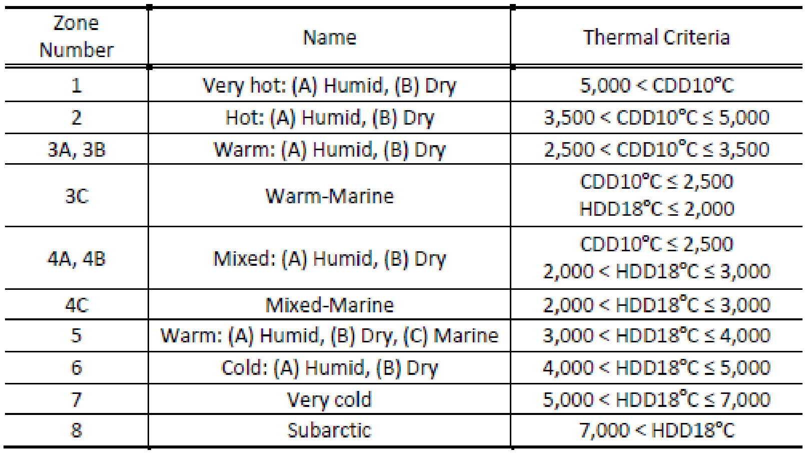
Building Item	**U-value**
Roof	0.3915 W/m2 °C
External Wall	0.4994 W/m2 °C
Windows	3.30 W/m2 °C (40% window to wall ratio)

The percent of window to wall, considering the wall from floor to ceiling, is around 57.3%, corresponding to 40% total window to wall percentage.

3.2 Office Building Model Locations

In order to understand the distribution of energy consumption expected in the office building, the location of the study should be assessed. Climate zones for building simulation and modeling supported by most energy standard groups, such as ASHRAE, are defined by the International Energy Conservation Code (IECC) (International Climate Zone Definitions, 2008).

The climate zones, numbered 1 through 8, are defined by their heating and cooling degree-days, as shown in.



Zone Number	Name	Thermal Criteria
1	Very hot: (A) Humid, (B) Dry	5,000 < CDD10°C
2	Hot: (A) Humid, (B) Dry	3,500 < CDD10°C ≤ 5,000
3A, 3B	Warm: (A) Humid, (B) Dry	2,500 < CDD10°C ≤ 3,500
3C	Warm-Marine	CDD10°C ≤ 2,500 HDD18°C ≤ 2,000
4A, 4B	Mixed: (A) Humid, (B) Dry	CDD10°C ≤ 2,500 2,000 < HDD18°C ≤ 3,000
4C	Mixed-Marine	2,000 < HDD18°C ≤ 3,000
5	Warm: (A) Humid, (B) Dry, (C) Marine	3,000 < HDD18°C ≤ 4,000
6	Cold: (A) Humid, (B) Dry	4,000 < HDD18°C ≤ 5,000
7	Very cold	5,000 < HDD18°C ≤ 7,000
8	Subarctic	7,000 < HDD18°C

Figure 28: Zones defined by Thermal Criteria (Sleiti & Naimaster, 2013)

Doha, the capital city of Qatar, is located in the mid region of the earth, in Middle Eastern Gulf, where it is surrounded by sea water from almost all sides. Gulf countries are in general very hot, and in addition, Qatar is very humid. Therefore, Qatar can be considered under zone 1 since its climate is very hot and very humid most of the year.

For comparison purposes, Kuwait city was also modeled in eQuest. Kuwait is one of the gulf countries located at the eastern side of the gulf peninsula. Its weather is close to Qatar but less humid. Kuwait weather data was already available in the Department of Energy software (eQuest), and the same was used.

The weather data for Qatar was obtained using Meteonorm software which is a software that contains global climate database as well as friendly interface tools to deal with it (Meteotest, 2018). Meteonorm software contains Qatar weather data obtained from Doha International Airport. This weather data was then inserted in eQuest software to analyze it in terms of required energy consumption. It is worth mentioning that the maximum dry bulb temperature as per the weather data was 46.6 ^{o}C during the month of July, while the minimum temperature was 10.9 ^{o}C in January. Moreover, the maximum recorded relative humidity is reaching up to 100% during January, while the minimum relative humidity was 15% in September. Therefore, HVAC system is expected to be the most energy consumption utility in the office building with a consumption percentage more than 50%.

3.3 Baseline Case

Generally, the office building energy use was designed in accordance with ASHRAE 90.1-2010, Appendix G, standards which are already set as default in eQuest software. Typical values for lighting, miscellaneous equipment, and exterior usage energy requirement per area or per person were utilized into the software. A default hourly profiles that are built-in the software for lighting, fans, cooling, etc. were also utilized.

Three baseline cases were modeled for each location considering different HVAC systems. First one is the actual implemented system which is (1) centrifugal electric chillers, while the other one is (2) combination of double stage absorption and centrifugal electric chillers. It was considered that electric chiller COP is 4.20 and absorption chiller COP is 1.42 (U.S. Department of Energy, 2017). For the second case, the best combination was assessed to get the best performance and minimum cost. One more baseline case was simulated for absorption chiller only where it was found that it is not feasible and viable due to its very low COP.

In first case, one medium electric chiller was auto sized by eQuest software. Two water loops were connected to the electric chiller which were (1) condenser water loop, (2) chilled water loop. The condenser water loop is circulated through a cooling tower for condensing purposes; the chiller water loop is directed to the cooling coils to provide space cooling as required for each zone. The schematic diagram of the system is shown in Figure 29.

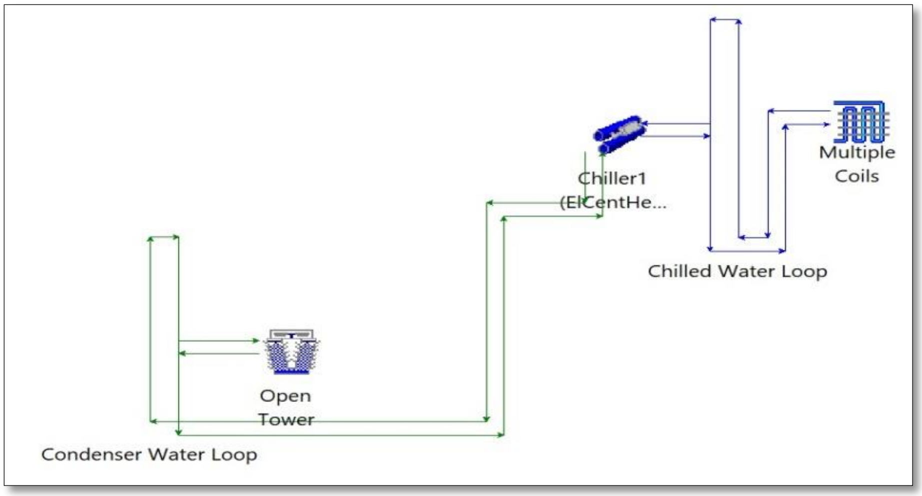
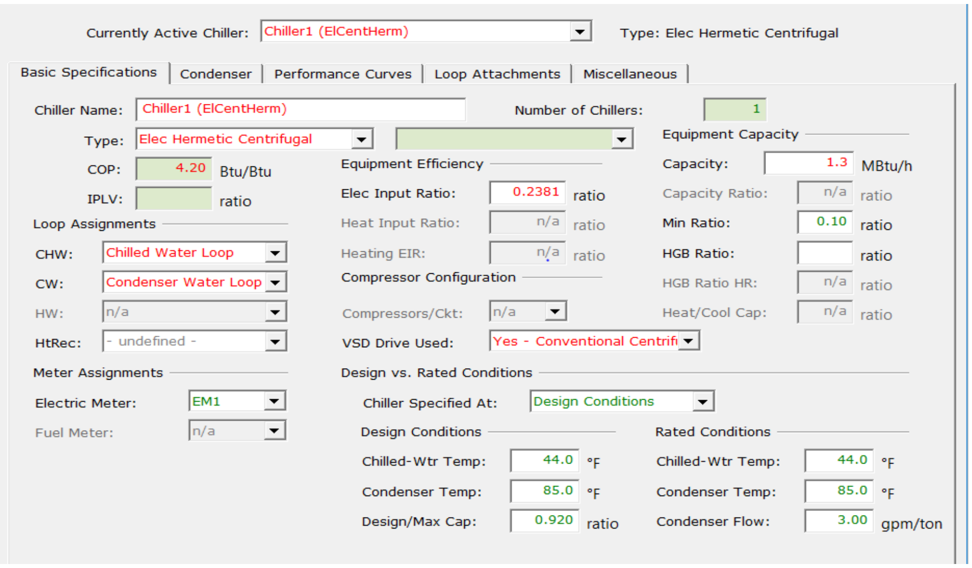


Figure 29: Baseline Case (1): Electric Chiller HVAC system Schematic Diagram in eQuest



Currently Active Chiller: Chiller1 (ElCentHerm)
Type: Elec Hermetic Centrifugal

Chiller Name: Chiller1 (ElCentHerm)
Number of Chillers: 1
Type: Elec Hermetic Centrifugal
COP: 4.20 Btu/Btu
IPLV: ratio

Loop Assignments
CHW: Chilled Water Loop
CW: Condenser Water Loop
HW: n/a
HtRec: - undefined -

Meter Assignments
Electric Meter: EM1
Fuel Meter: n/a

Equipment Efficiency
Elec Input Ratio: 0.2381 ratio
Heat Input Ratio: n/a ratio
Heating EIR: n/a ratio

Compressor Configuration
Compressors/Ckt: n/a
VSD Drive Used: Yes - Conventional Centrifi

Equipment Capacity
Capacity: 1.3 MBtu/h
Capacity Ratio: n/a ratio
Min Ratio: 0.10 ratio
HGB Ratio: ratio
HGB Ratio HR: n/a ratio
Heat/Cool Cap: n/a ratio

Design vs. Rated Conditions
Chiller Specified At: Design Conditions

Design Conditions
Chilled-Wtr Temp: 44.0 °F
Condenser Temp: 85.0 °F
Design/Max Cap: 0.920 ratio

Rated Conditions
Chilled-Wtr Temp: 44.0 °F
Condenser Temp: 85.0 °F
Condenser Flow: 3.00 gpm/ton

Figure 30: Electric Chiller Characteristics and Operating Conditions

For the second case, one electric chiller and one absorption chiller were combined. The best proportion for each system was assessed and entered in specific in the software.

Three water loops were connected to the system which were (1) hot water loop (allocated for the absorption chiller), (2) condenser water loop, (3) chilled water loop. Both condenser water loop and chilled water loop were combined for the respective chillers. The schematic diagram of the system is shown in Figure 31.

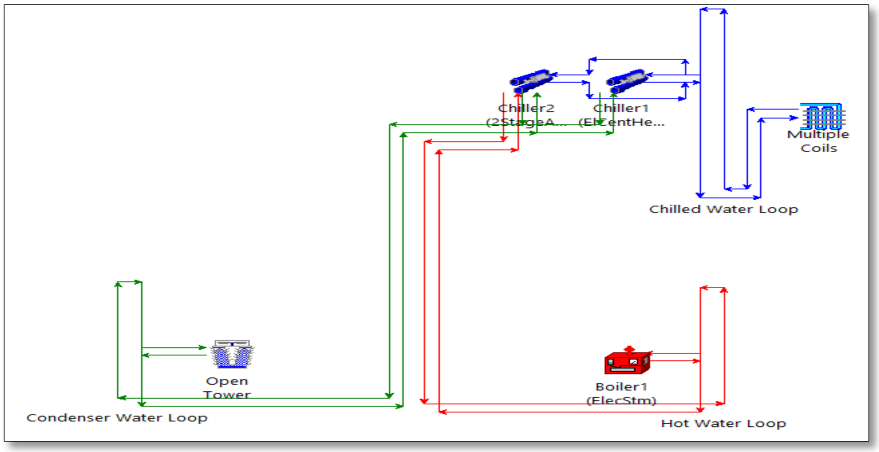
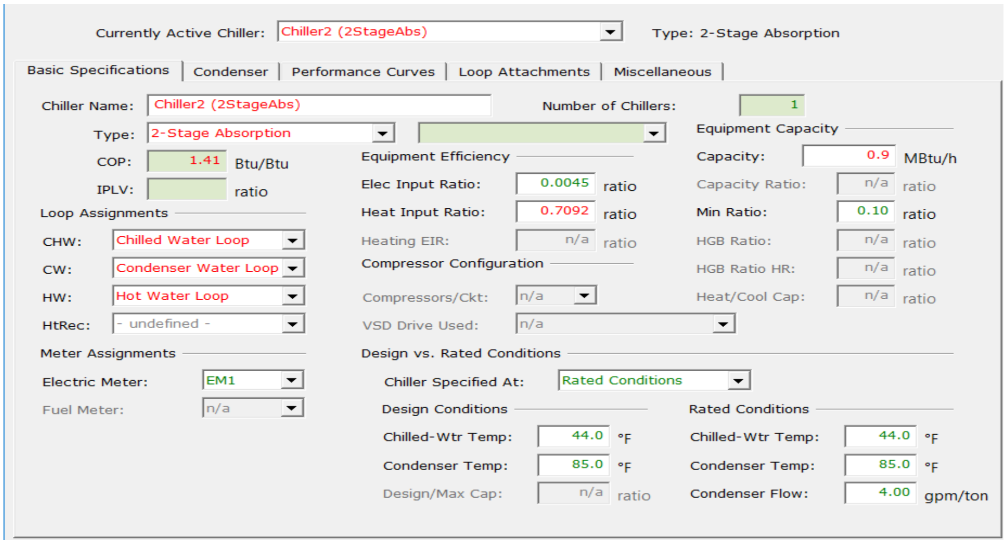


Figure 31: Baseline Case (2): Combined Electric/Absorption HVAC system Schematic Diagram (eQuest)



Currently Active Chiller: Chiller2 (2StageAbs)
Type: 2-Stage Absorption

Chiller Name: Chiller2 (2StageAbs)
Number of Chillers: 1
Type: 2-Stage Absorption
COP: 1.41 Btu/Btu
IPLV: ratio

Loop Assignments
CHW: Chilled Water Loop
CW: Condenser Water Loop
HW: Hot Water Loop
HtRec: - undefined -

Meter Assignments
Electric Meter: EM1
Fuel Meter: n/a

Equipment Efficiency
Elec Input Ratio: 0.0045 ratio
Heat Input Ratio: 0.7092 ratio
Heating EIR: n/a ratio

Compressor Configuration
Compressors/Ckt: n/a
VSD Drive Used: n/a

Equipment Capacity
Capacity: 0.9 MBtu/h
Capacity Ratio: n/a ratio
Min Ratio: 0.10 ratio
HGB Ratio: n/a ratio
HGB Ratio HR: n/a ratio
Heat/Cool Cap: n/a ratio

Design vs. Rated Conditions
Chiller Specified At: Rated Conditions

Design Conditions
Chilled-Wtr Temp: 44.0 °F
Condenser Temp: 85.0 °F
Design/Max Cap: n/a ratio

Rated Conditions
Chilled-Wtr Temp: 44.0 °F
Condenser Temp: 85.0 °F
Condenser Flow: 4.00 gpm/ton

Figure 32: Double Stage Absorption Chiller Characteristics and Operating Conditions

3.4 SOFC CHP System Case

As there is no SOFC system database module inside eQuest software, the SOFC CHP system was introduced into the model by the mean of an Electric Generator. Three cases were simulated following baseline cases which are (1) SOFC with Electric Chiller and (2) SOFC with combined system of Electric and Absorption Chillers. The second case of combining electric chillers with absorption chillers was proposed based on following logics: (1) electric chillers are more efficient so they supply most of the cooling energy (2) SOFC exhaust thermal energy can be utilized to run the absorption chiller to provide extensive cooling energy. As there is no heating load considered other than domestic hot water, this case can optimize the usage of SOFC system as it utilizes the thermal energy available at the exhaust of SOFC system for the hot water loop, which shall match the building TER to the SOFC TER. All other energy consuming services such as lighting, exterior usage, etc. were kept the same as in baseline case.

Defining SOFC CHP system performance in terms of heat input ratio was done as per Equation 3 stated in the literature review of this thesis in order to calculate the fuel consumption associated with energy produced for the building. Moreover, two performance curves were used to profile the behavior of the SOFC with part load ratio in terms of electricity and thermal energy produced by the stack. These curves were developed based on Figure 18 and Figure 19 mentioned in the literature review of this thesis. The performance curves considered in this thesis were based on operating temperature of 890 ^{o}C and fuel utilization of 0.8.

3.5 Economic Analysis

As known, for any energy alternative system analysis to be feasible and attractable for customers, it needs to have economic advantages upon the conventional systems. Hence, electricity and natural gas utility costs as per local market in Qatar and Kuwait were obtained in order to compare it to the utility cost provided by SOFC system. For Qatar, electricity cost was retrieved from Kahramaa website (Kahramaa Electricity Tariff, 2018), while the natural gas cost for bulk customers was obtained from WOQOD customer service department; utility cost values are shown in Table 5. On the other side, for Kuwait, the electricity utility cost was found in Kuwait times newspaper website (New Electricity Tariffs, 2017); the natural gas utility cost was found to be following the global pricing as per (Alhouli, 2017); utility cost values are tabulated in Table 5.

Table 5

Utility Cost for Natural Gas and Electricity ($/GJ)

	Natural Gas	Electricity
Qatar - Cost ($/GJ)	2.85	15.22
Kuwait – Cost ($/GJ)	2.62	23.06

In this study, capital and installation costs of 1000 $/kW for SOFC stack system was considered with reference to (Sleiti & Naimaster, 2013). In addition, capital and installation costs of 150 $/kW and 270 $/kW for electric and absorption chillers, respectively, in accordance to (Jing, et al., 2017) and (Iodice, d’Accadia, Abagnale, &

Cardone, 2016), were included in the study to estimate the economical key indicators such as payback period (PBP) and net present value (NPV). To be more accurate, a marginal amount was added to absorption chiller capital/installation cost mentioned above to take into consideration the cost for SOFC exhaust heat exchanger. Maintenance cost for SOFC stack is 0.36 $/GJ produced with reference to (Sleiti & Naimaster, 2013), while for electric and absorption chillers, maintenance cost is 0.25 $/GJ referring to (Jing, et al., 2017). The lifetime of the SOFC system was assumed to be 60,000 hours as targeted by (International Energy Agency, 2007). Finally, one of the factors which affect viability of the system is the discount rate applied in the location of the study. In case of Qatar, the discount rate was considered as the interest rate announced by Qatar Central Bank (QCB), which was found to be 1.5% (Qatar Central Bank, 2017).

3.6 CO2 emissions calculations

In order to evaluate if the SOFC CHP system adds any value in terms of CO2 emissions reduction, a comparison shall be conducted between the base load scenario and the SOFC CHP scenarios. The CO2 emissions associated with usage of electricity from Grid was obtained from (Ayoub, Musharavati, Pokharel, & Gabbar, 2014) by dividing the amount of CO2 emissions in baseline scenario over the electricity utilized, which has led to a value of 0.5957 kg-CO2/kWh.

On the other side, CO2 emissions can also be calculated by utilization of the concept followed by (Sleiti & Naimaster, 2013) which is retrieved from (eGRID2010 Version 1.1: Year 2007 Summary Tables, 2007), however, it was updated on 2016 by US Environmental Protection Agency and the updated one was found in (eGRID Summary

Tables 2016, 2016). Hence, following table lists the average values emissions associated with electricity production in kg/kWh:

Table 6

Emissions rates (kg/kWh) (eGRID Summary Tables 2016, 2016)

CO_2	NO_x	SO_2
0.452886	**0.000327**	**0.000362**

On the other side, SOFC system associated CO2 emissions quantity was compared to SOFC supplier information. BloomEnergy is a SOFC systems manufacturer based in United States of America. The company had supplied several Kilowatts/Megawatts scale projects for Adobe, AT&T, Walmart, and Yahoo. From company's website, the datasheet for SOFC 200 kW system was obtained in order to visualize an actual tested data as well as utilize it for CO2 emissions estimation. In (Bloomenergy, 2017), it is stated that the associated SOFC CO2 emissions quantity is ranging between 679 to 833 lbs/MWh, which stands for 0.3079 to 0.3778 kg-CO2/kWh. Moreover, the emission fraction factor for other emissions such as NOx, and SOx are $4.53e^{-6}$, and negligible amounts, respectively.

Moreover, as per literature review discussed on (Sleiti & Naimaster, 2013), the emission factor was calculated to be 0.24 kg-CO2/kWh based on results observed in the paper of study.

Chapter 4: RESEARCH FINDINGS

4.1 Baseline Cases Results

As mentioned in section 3.3 of this thesis, a baseline case of the office building was simulated considering a conventional HVAC system which is Electric Chiller system. Moreover, as mentioned, two locations were considered which are Qatar (Doha City) and Kuwait (Kuwait City). The annual energy consumption in relation to each energy end-use for Qatar was determined by eQuest software, and it is shown in Figure 33:

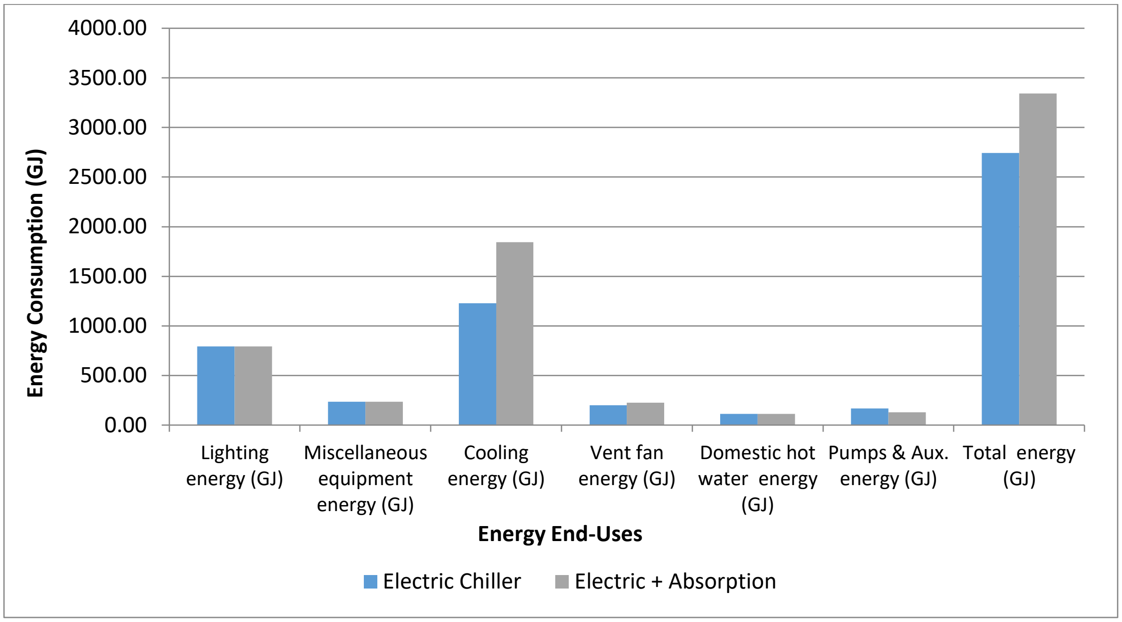


Figure 33: Qatar Baseline Cases (1-2) Energy Consumption by End-Uses

As expected, cooling energy is approximately ranging between 50% and 70% out of the total energy consumption in the office building depending on the HVAC system applied. As the absorption chiller system COP is very low compared to electric chiller COP, and requires energy for water heating, the cooling energy required was reaching high levels such as 70% of the total annual energy consumption. The total annual energy consumption for Qatar baseline cases was calculated to be 2741.67 GJ in electric chiller case (1) and 3341.82 GJ in combined electrical/absorption chillers system case (2). There was no heating load applied to the space of office building as this is rarely applied or required in Qatar. In case (1), all end-uses get its required energy from electricity except domestic hot water which requires thermal energy. Hence, the thermal energy requirement is very low compared to the electrical energy. The TER is calculated to be 0.034 at which the only thermal load is the domestic hot water. As the TER is very low compared to the TER of the SOFC CHP system studied by (Chiappini & et al., 2011), it is not expected to have a sufficient use of the Exhaust Thermal Energy available in SOFC CHP system. However, in case 2, the addition of absorption chiller resulted in higher thermal energy requirement at which part of it can be supplied by SOFC exhaust. Moreover, the overall TER (0.3) can then be closer to SOFC TER as energy production.

Since the thermal energy available at the exhaust of the SOFC CHP system cannot be utilized to its full extent, it is required to look for other parameters which might support in getting better performance from the system as well as decrease the cost. Taking into account the costs of natural gas and electricity, it is expected to have high cost savings as the cost of energy for natural gas is almost 21% of the one for electricity.

Similarly, the annual energy consumption in relation to each energy end-use for Qatar was determined by eQuest software, and it is shown in Figure 34.

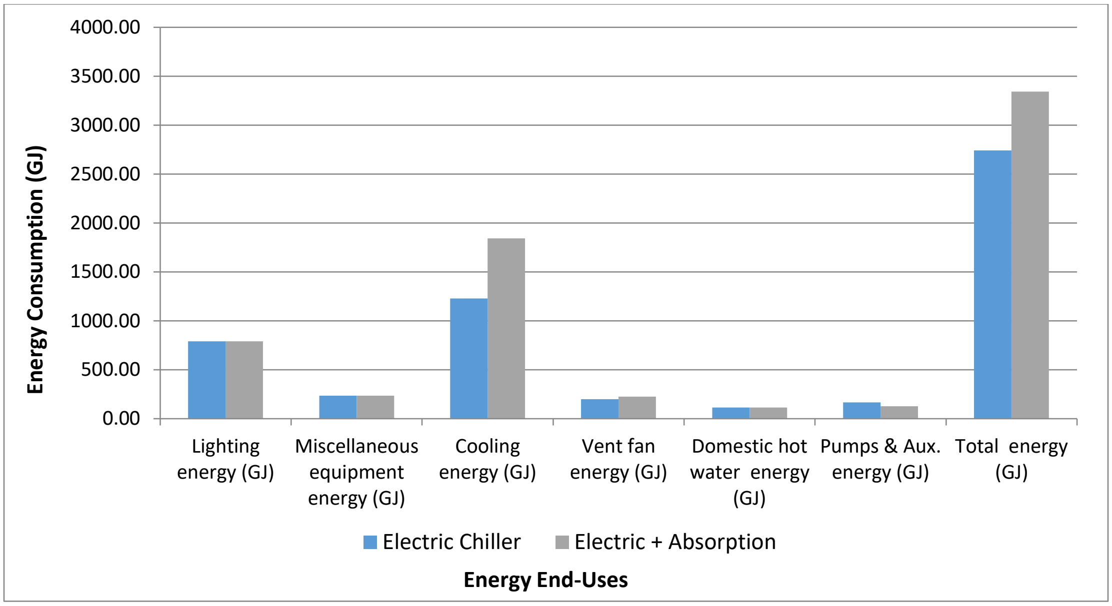


Figure 34: Kuwait Baseline Cases (3-4) Energy Consumption by End-Uses

As expected, Kuwait energy profile in the simulated cases is in the range of similarity to Qatar’s cases. The total annual energy consumption for Kuwait baseline cases was calculated to be 2841.57 in electric chiller case (3) and 3442.62 GJ in combined electrical/absorption chillers system case (4). However, following the same energy profile doesn’t mean to have similar cost split.

Finally, in order to compare Qatar and Kuwait baseline cases simulated, Figure 35 was developed. This figure would give an initial expectation on the results that would be obtained by applying the SOFC CHP concept; also it would validate that the results are in line to each other for the countries in the same region.

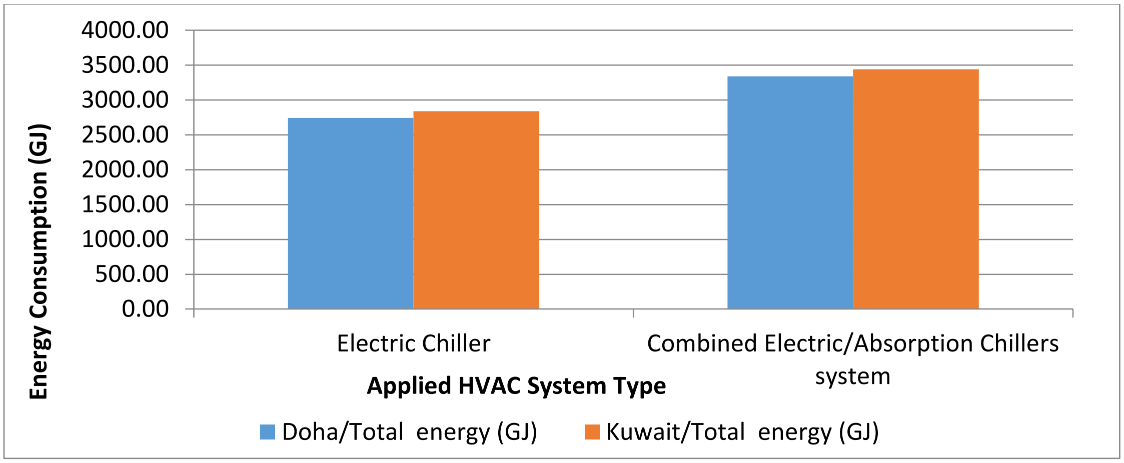


Figure 35: Qatar vs. Kuwait Baseline cases (1-4) Annual Energy Consumption Comparison

Results of Kuwait baseline cases are generally showing higher values. This could be due to higher cooling demand required. However, similarity of energy demands doesn't mean that their costs are the same. Therefore, following is Figure 36 which shows the values of Annual Energy Cost ($) for each baseline case (1-4).

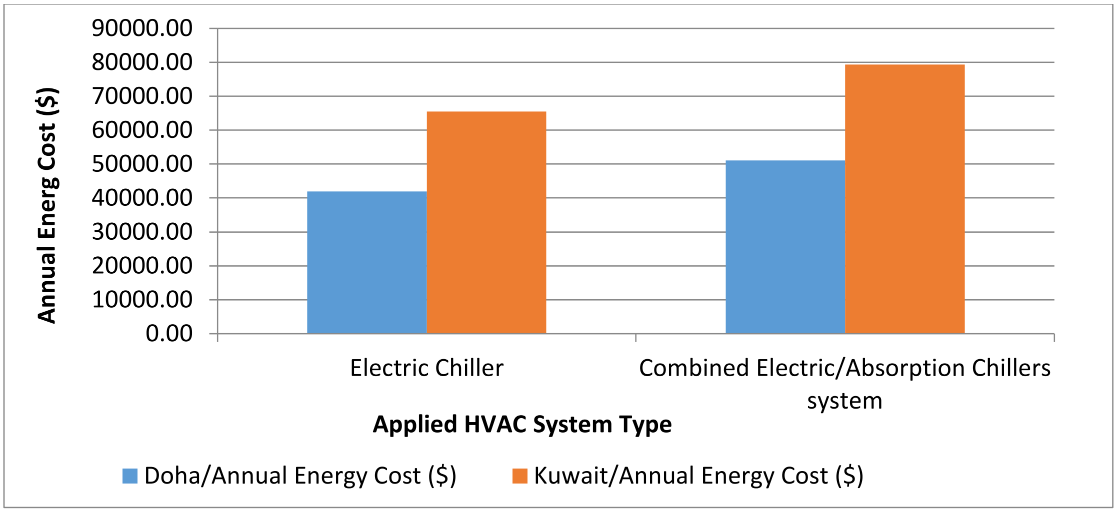


Figure 36: Qatar vs. Kuwait Baseline Cases (1-4) Annual Energy Costs Comparison

As shown, Kuwait baseline annual energy costs for the same conditions are higher due to higher grid electricity utility costs. However, this is an advantage for SOFC CHP system as it runs on natural gas which has much lower value in both locations.

4.2 SOFC CHP System Case

For each location, the SOFC system capacity was sized in a range from 25 kW to 250 kW with intervals of 25 kW to come up with the optimum capacity that fits the application. Consumption of fuel and electricity from grid along with their annual costs were analyzed and recorded for each capacity. Moreover, SOFC CHP system performance was analyzed in terms of energy production for the same range stated above; electrical energy produced, utilized thermal energy, and cogeneration efficiency were observed and recorded for each SOFC capacity in the range studied. In continuation to baseline cases (1-4), the SOFC CHP system was applied on each baseline case to find the optimum cogeneration option. Therefore, four cases results will be presented in this section, and will follow the following sequence: (1) Qatar – SOFC with Electric Chiller HVAC system, (2) Qatar – SOFC with Electric/Absorption Chillers combined system; the same sequence will be repeated for Kuwait location as cases (3-4).

4.2.1 Qatar

The first case simulated in eQuest software to monitor the performance of SOFC CHP system was by integrating the system into baseline case (1). In this case, the SOFC CHP system electricity was introduced to the building, while the thermal energy was introduced into the domestic hot water loop. Figure 37 shows the performance of SOFC CHP system in terms of fuel consumption, reduction in grid electricity consumption, and building total cost of energy.

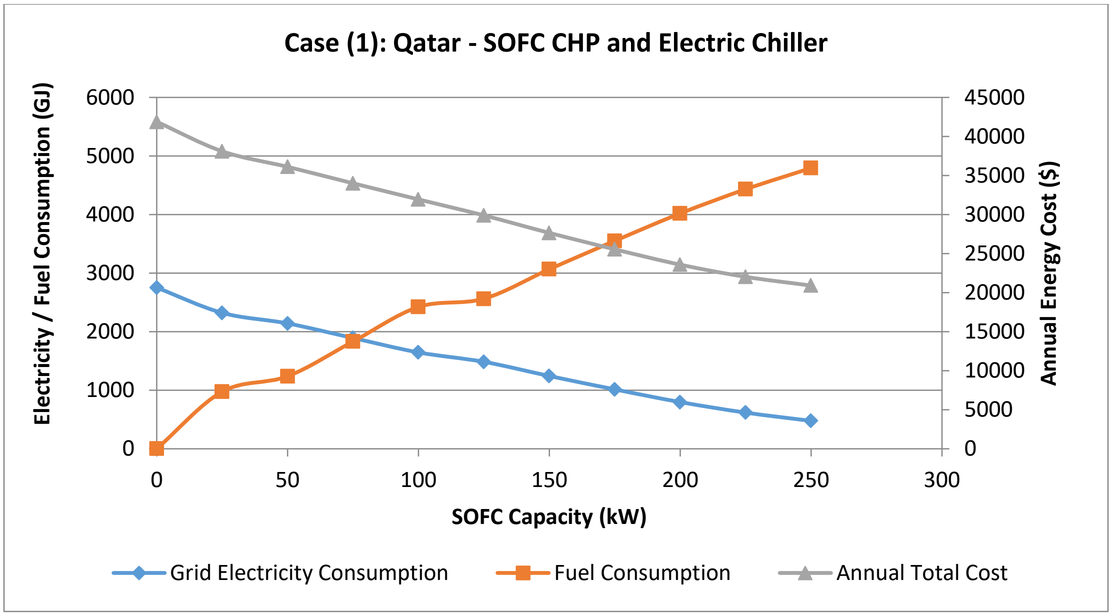


Figure 37: Case (1): Building energy requirement with SOFC CHP and Electric Chiller - Qatar Results

It is clear that as the fuel consumption increases, the electricity consumption decreases due to the fact that the SOFC is natural gas fuelled. The electricity consumption continues in decreasing till the SOFC system reaches its full potential in supplying electricity efficiently to the building as the minimum part load ratio simulated was 30%. Moreover, the total cost of energy is reducing as the capacity of the SOFC system is increasing. This reduction in cost is due to the high difference between the costs of electricity and natural gas consumptions. The optimal SOFC capacity at which the minimal annual utility cost was recorded was at 250 kW which corresponded to a value of 20,907 $/year compared to 41,887 $/year in baseline case. However, this doesn't indicate precisely whether the system is optimal or not as it doesn't take into account the capital cost of the system.

On the other hand, in order to investigate the performance of the SOFC CHP system in terms of energy produced, Figure 38 was developed. It shows the electrical energy produced by SOFC, utilized thermal energy from SOFC exhaust, fuel consumption, and cogeneration efficiency.

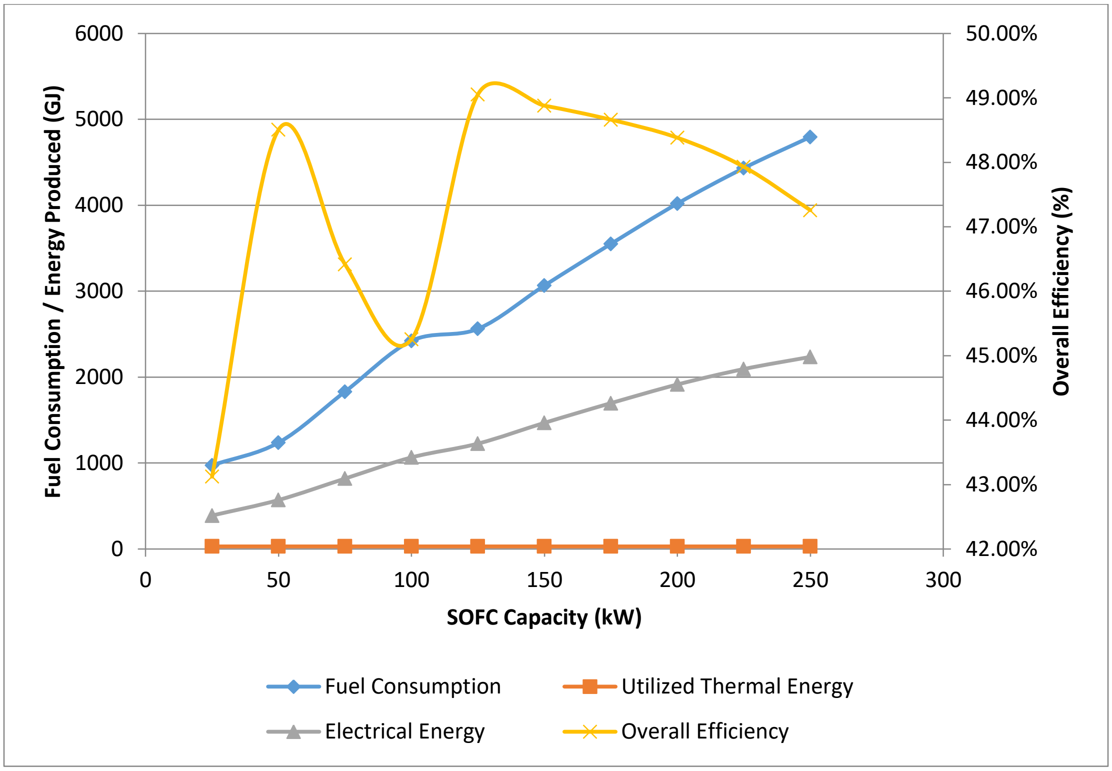


Figure 38: Case (1): SOFC CHP / Electric Chiller system performance - Qatar Results

As expected, the utilization of SOFC CHP system in this case will not reach its full extent as there is no heating load required rather than the domestic hot water which is minor in Qatar. Hence, it can be noticed from Figure 38 that the maximum overall efficiency obtained was around 49% at 125 kW SOFC capacity. On the other hand, there is a sharp decrement in the overall efficiency at SOFC capacity of 100 kW; this is because different part load ratio lead to different system efficiency. As the study is hourly basis, with the setting of minimum load ratio of 0.3, some minor loads which are around 30 kWh could require SOFC system to start if its capacity is up to 100 kW, however, 75 kW system has higher efficiency as it has less part load ratio as per Figure 18. Moreover, it is clear that the utilized exhaust thermal energy is very minor at which 25 kW SOFC capacity was able to cover it, and it continued steady for remaining simulated capacities.

Case (2) was simulated by integrating an absorption chiller to case (1) to utilize the higher efficiency of Electric Chillers as well as utilizing the exhaust heat released by SOFC system to the Absorption Chiller. Moreover, the proportion of each chiller was optimized in a way to provide the best energy savings. Taking into consideration that the building cooling load requirement is 155.75 refrigeration tons; the system was sized to meet a multiplier of 1.2 which results in 186.9 refrigeration tons. Hence, it was found that the optimum proportions for electric chiller and absorption chiller are 108.33 (58%) and 78.57 (42%) refrigeration tons respectively.

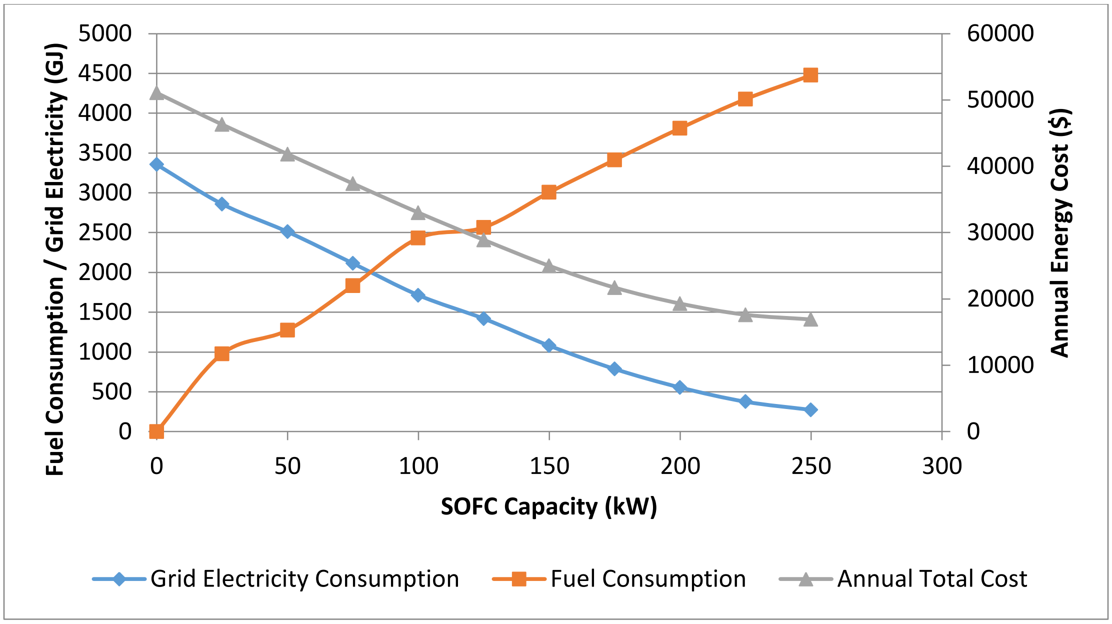


Figure 39: Case (2): Building energy consumption with SOFC CHP/Electric /Absorption Chillers - Qatar Results

Figure 39 shows the performance of SOFC CHP system in terms of fuel consumption, reduction in grid electricity consumption, and building total cost of energy. As presented, the annual total cost has decreased rapidly by applying the SOFC system on the combined electric/absorption chillers system, which had led to cost savings up to 67% at 250 kW SOFC capacity, reaching an annual energy cost value of 16,911 $ annually. It is worth mentioning that the least annual energy cost obtained from cases (1 and 2) is in case (2).

For SOFC CHP system performance with respect to energy production and overall efficiency, it is recorded in Figure 40.

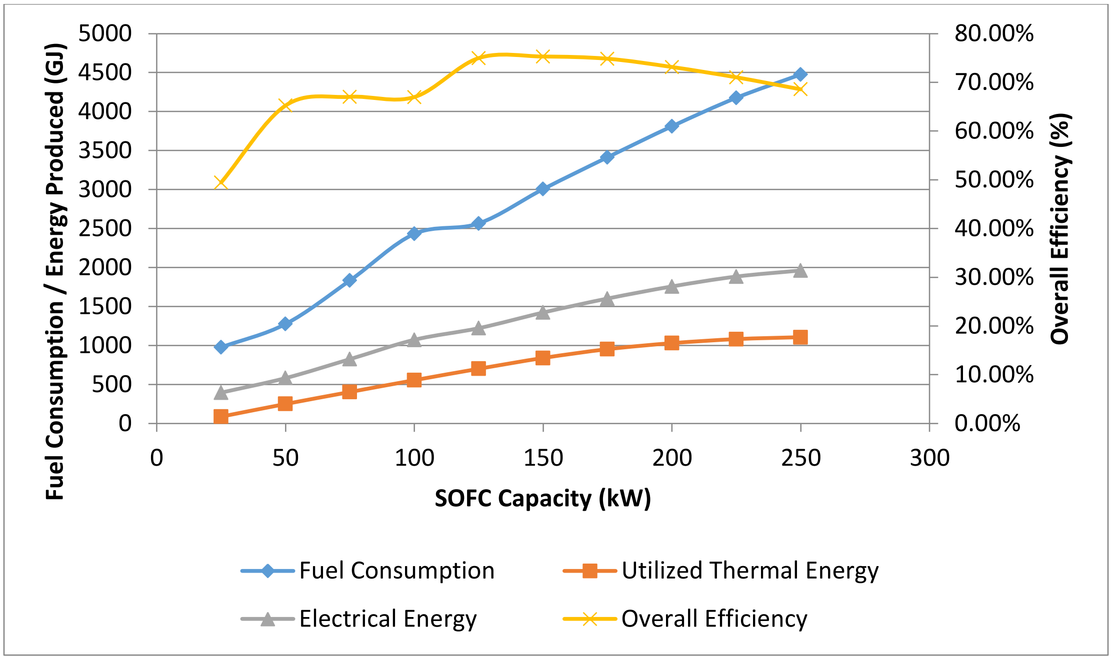


Figure 40: Case (2): SOFC CHP / Electric / Absorption Chillers system performance - Qatar Results

Both curves for electrical energy production and utilization of exhaust thermal energy are moving positively as the SOFC stack capacity is increased. Moreover, it can be observed that the maximum overall efficiency of SOFC CHP system in this case (2) touched a percentage of 75.29%. This is also considered as a promising value for cogeneration energy efficiency which can lead to fair reduction in costs and fuel consumption.

4.2.2 Kuwait

Similar to Qatar cases (1-2), simulation results will be presented in this section for cases (3-4) investigating the SOFC CHP system performance in Kuwait city. The differences between the two countries in simulation input files were in weather data, fuel utility cost, and electricity utility cost. As in case (1), the SOFC CHP system electricity was introduced to the building, providing cooling load by electric chiller, while the thermal energy was introduced into the domestic hot water loop. Figure 41 shows the performance of SOFC CHP system, in Kuwait city, in terms of fuel consumption, reduction in grid electricity consumption, and building total cost of energy.

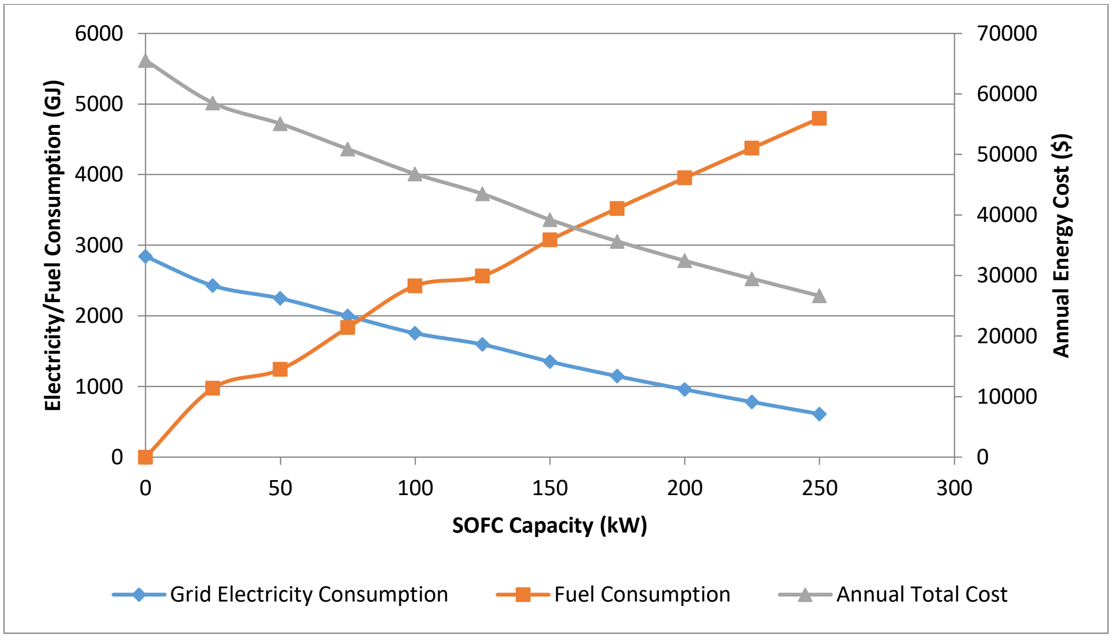


Figure 41: Case (3): Building energy requirement with SOFC CHP and Electric Chiller - Kuwait Results

From Figure 41, it shall be addressed that the annual total cost curve is decreasing more rapidly compared case (1) for Qatar. This could be due to the higher difference between natural gas and electricity utility costs in Kuwait city; this gives an initial indication that SOFC CHP system will account more savings in energy cost in Kuwait. The optimal SOFC capacity at which the minimal annual utility cost was recorded was at 250 kW which corresponded to a value of 26,648 $/year compared to 65,515 $/year in baseline case (3). However, this doesn't indicate precisely whether the configuration of the system is optimal or not as it doesn't take into account the capital cost of the system.

On the other hand, in order to investigate the performance of the SOFC CHP system in terms of energy produced, Figure 42 was developed. It shows the electrical energy produced by SOFC, utilized thermal energy from SOFC exhaust, fuel consumption, and cogeneration efficiency.

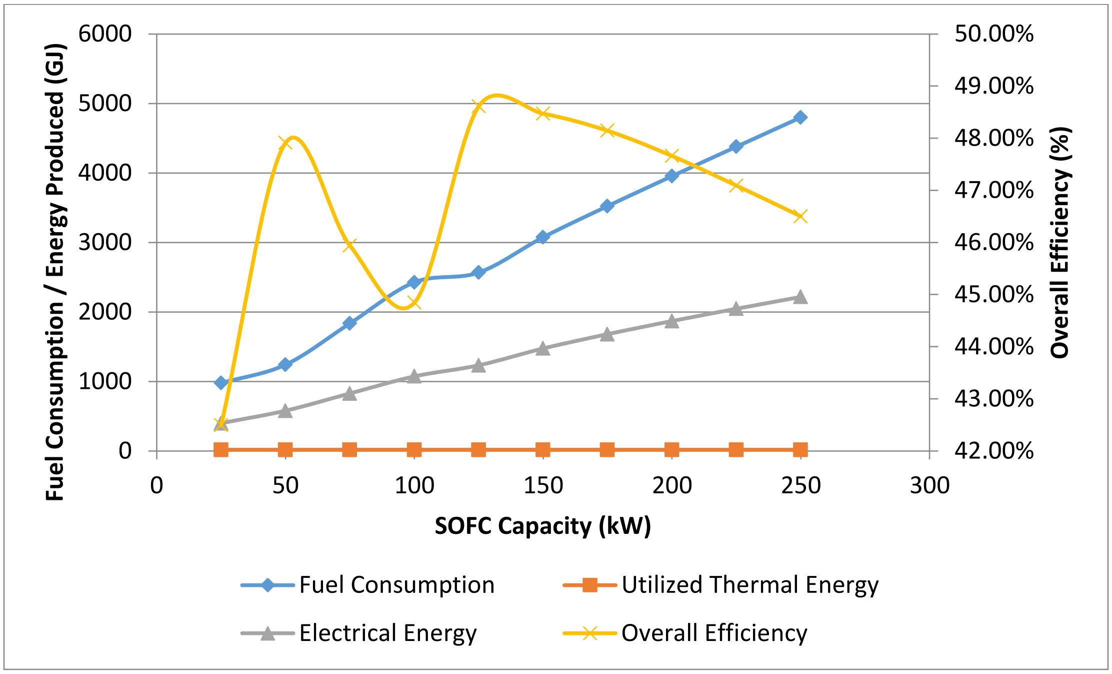


Figure 42: Case (3): SOFC CHP / Electric Chiller system performance - Kuwait Results

As expected, the utilization of SOFC CHP system in this case will not reach its full extent as there is no heating load (for Kuwait) required rather than the domestic hot water which is even less than case (1) for Qatar. Hence, it can be noticed from Figure 42 that the maximum overall efficiency obtained was around 48.61% at 125 kW SOFC capacity (similar to case (1) in Qatar). Moreover, it is clear that the utilized exhaust thermal energy is very minor at which 25 kW SOFC capacity was able to cover it, and it continued steady for remaining simulated capacities.

As similar building size was considered in all cases of both locations, the proportions of electric and absorption chillers were kept the same as case (2) in this case (4). Hence, 108.33 (58%) and 78.57 (42%) refrigeration tons were used for electric and absorption chillers respectively.

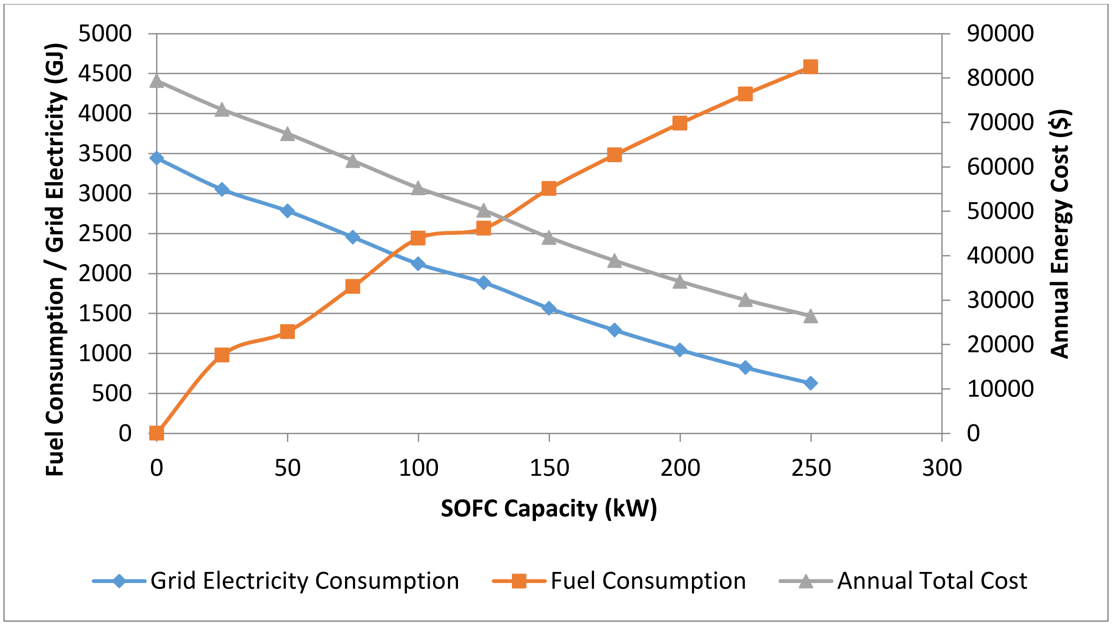


Figure 43: Case (4): Building energy consumption with SOFC CHP/Electric/Absorption Chillers-Kuwait Results

Figure 43 shows the performance of SOFC CHP system in terms of fuel consumption, reduction in grid electricity consumption, and building total cost of energy. As shown, the annual total cost has decreased rapidly by applying the SOFC system on the combined electric/absorption chillers system, which had led to cost savings up to 67% at 250 kW SOFC capacity, reaching an annual energy cost value of 26,442 $ annually. It is worth mentioning that the least annual energy cost obtained from cases (3 and 4) is in case (4).

For SOFC CHP system performance with respect to energy production and overall efficiency, it is presented in Figure 44.

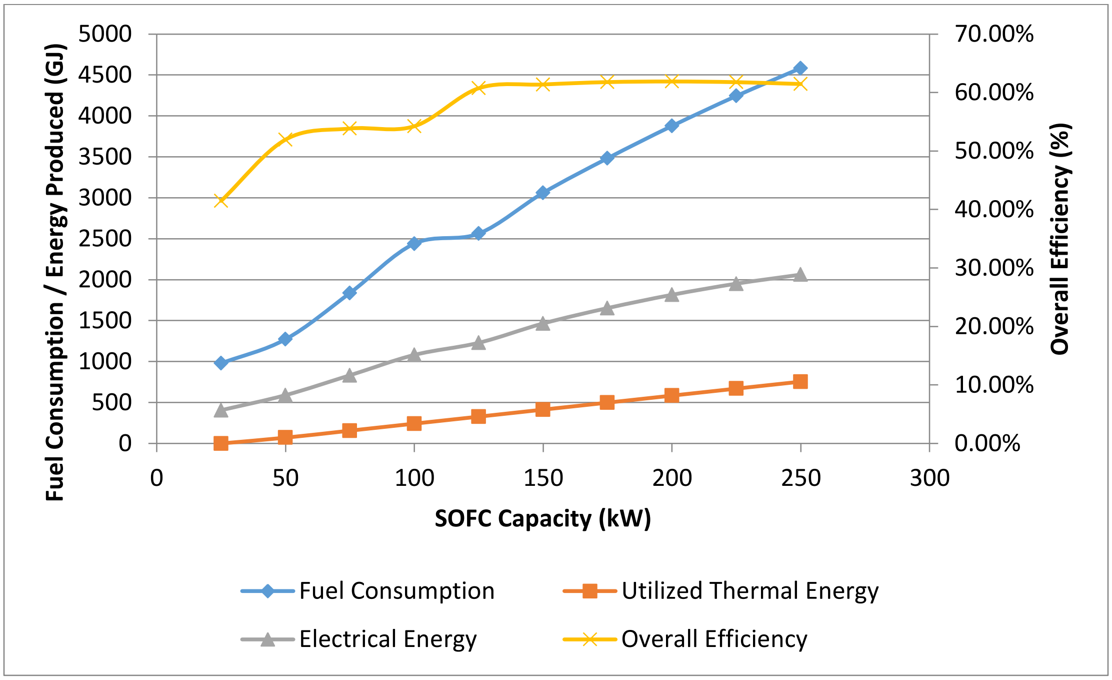


Figure 44: Case (4): SOFC CHP / Electric / Absorption Chillers system performance - Kuwait Results

Both curves for electrical energy production and utilization of exhaust thermal energy are moving positively as the SOFC stack capacity is increased. Moreover, it can be observed that the maximum overall efficiency of SOFC CHP system in this case (6) reached a percentage of 61.88%. This is also considered as a promising value for cogeneration energy efficiency which can lead to fair reduction in costs and fuel consumption.

4.3 Economic Analysis

After discussion of SOFC CHP performance results which shows whether the system is feasible or not, it is worth discussing the results of the economic analysis conducted for the system. This analysis shall help investors or office building owners, in Qatar and Kuwait, in deciding preliminarily whether the system is viable and worth detailed study or not. As mentioned in section 4.5 of this study, three indicators were used to determine the viability of the SOFC CHP system which are payback period and net present value.

4.3.1 Qatar

In cases (1-2) for Qatar location, the savings in annual energy costs were calculated considering the best baseline case (1) which had annual energy cost of 41,887 $/year. Based on savings in utility costs per year, discount rate, maintenance costs, and capital cost of SOFC stack system, the net present value was calculated. On the other side, the payback period was calculated based on annual cash flow and capital cost of SOFC stack system. Following figures are showing the results for net present value and payback period with respect to SOFC capacity (25-250 kW).

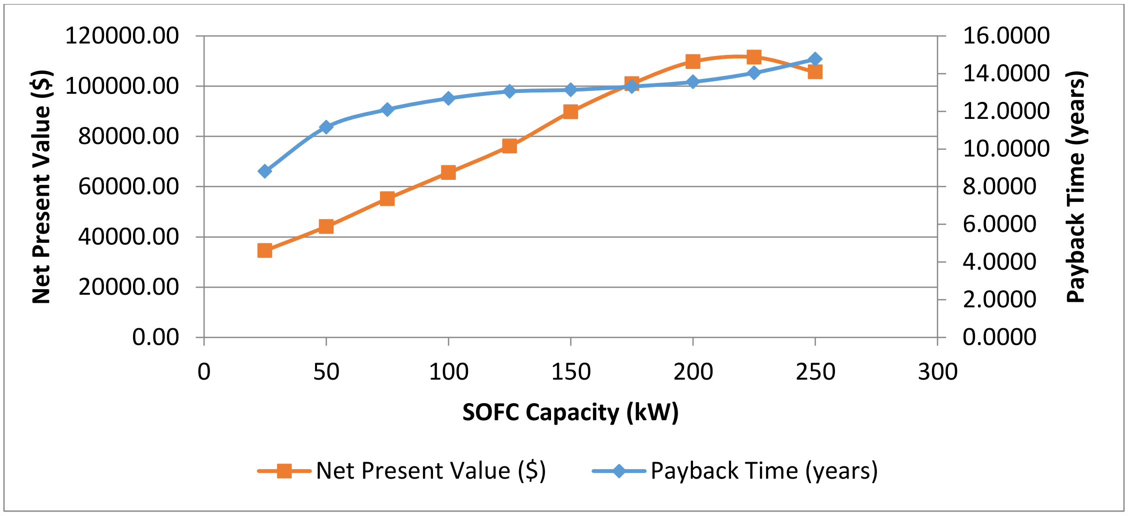


Figure 45: Case (1): Net Present Value and Payback period for SOFC CHP / Electric Chiller system – Qatar

From Figure 45, it can be seen that the maximum net present value reached a value of 18,402 $ which corresponds to SOFC capacity of 175 kW. However, the optimum payback period is at 25 kW SOFC capacity which stands for almost 8.4 years. This could be due to constant exhaust thermal energy utilization in case (1) which had permitted for high utility savings with low capital cost when SOFC stack capacity of 25 kW was used. Hence, this gives a feedback that it is better to use small SOFC stack capacities in office building for small scale appliances such as water supply while connecting exhaust thermal energy to the domestic hot water loop.

In case (2) for Qatar location, the system had showed very promising and interesting economic results for large SOFC capacities. It can be seen from Figure 46 that the system had given the optimal net present value at SOFC capacity of 200 kW. The values of net present value and payback period at 200 kW SOFC stack capacity are 57,742 $ and 11 years, respectively.

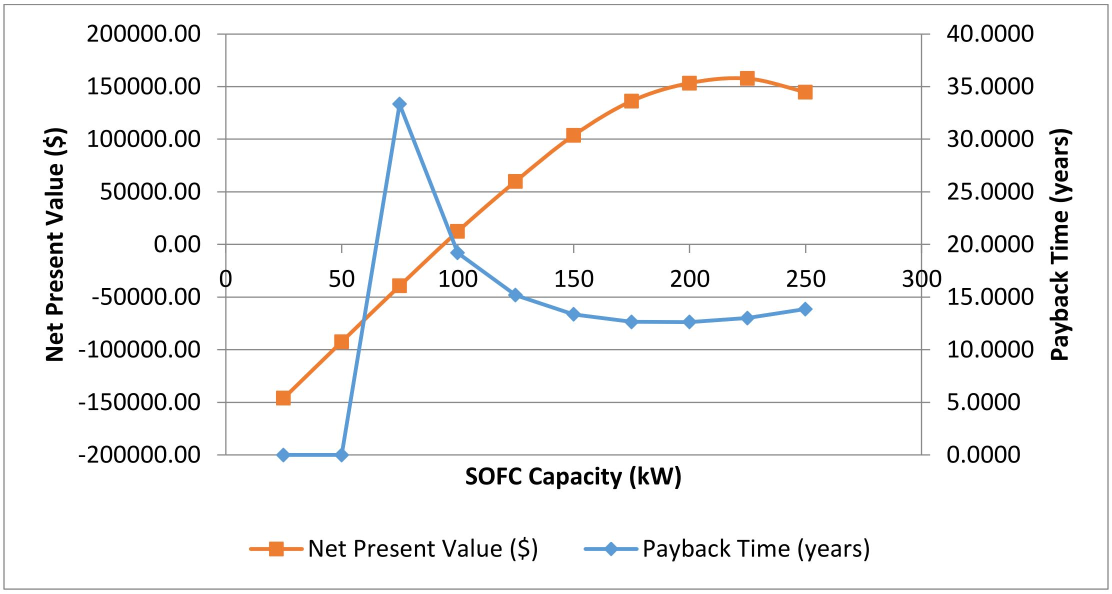


Figure 46: Case (2): Net Present Value and Payback period for SOFC CHP/Elec-Absorp Chillers system – Qatar

4.3.2 Kuwait

Similar to cases (1-2) for Qatar, the same methodology was followed for Kuwait cases (3-4) at which the economic analysis savings calculations considered baseline annual energy cost of 65,515 $/year. Following figures are showing the results for net present value and payback period with respect to SOFC capacity (25-250 kW). In general, Kuwait economic results were more promising and positive. This is mainly due to the larger difference between the electricity utility cost from grid and natural gas utility cost compared to Qatar location.

Similar to case (1), Figure 47 shows that the best SOFC capacity in terms of payback period is 25 kW which corresponds to payback period of 4.3 years. On the other hand, optimum net present value was found to be 223,577 $ at SOFC stack capacity of 250 kW with a payback period of 7.4 years.

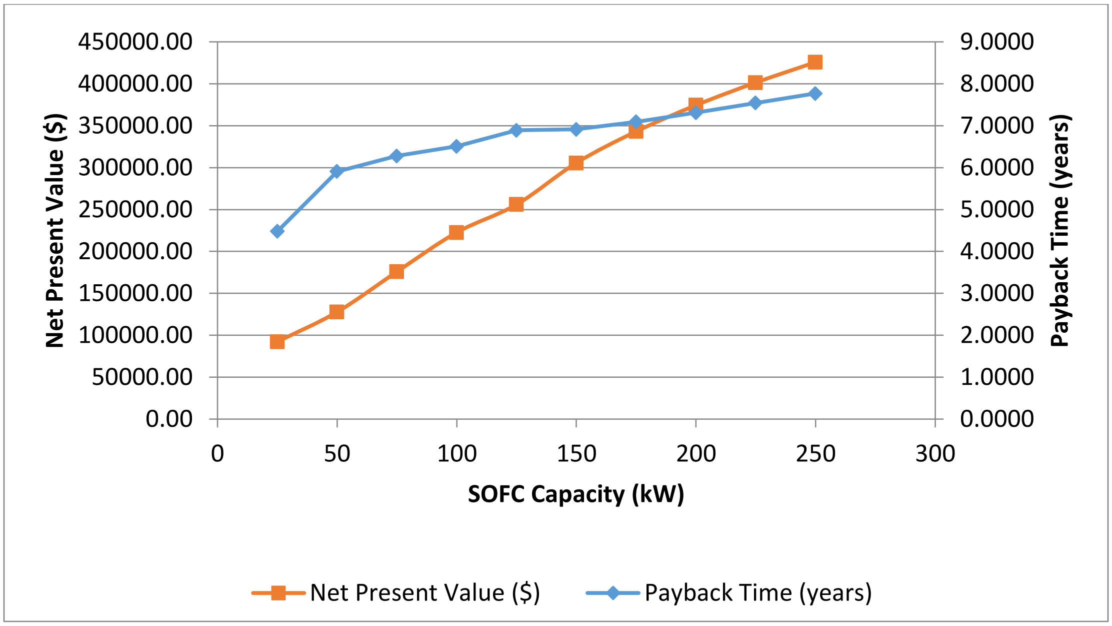


Figure 47: Case (3): Net Present Value and Payback period for SOFC CHP / Electric Chiller system – Kuwait

Finally, Figure 48 presents the economic results for case (6). It is noticed that the optimum payback period is about 8 years at SOFC stack capacity of 250 kW, with a net present value of 209,005$.

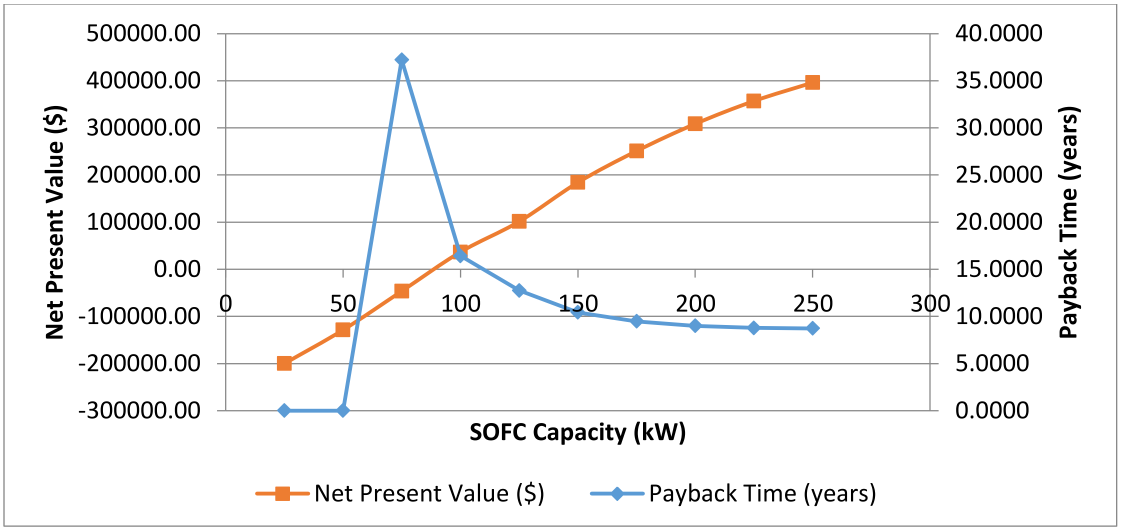


Figure 48: Case (4): Net Present Value and Payback period for SOFC CHP/Elec-Absorp Chillers system – Kuwait

4.4 Environmental Impact Assessment

In this section, emissions analysis results will be presented. Based on the values discussed in section 4.6 of this report, the emissions for the best scenarios were calculated. In general, results in range between 175 to 250 kW for SOFC stack capacity were found to be the optimum for cases (2 & 4) and were selected for emissions calculations. As (eGRID Summary Tables 2016, 2016) and (Bloomenergy, 2017) show measured and tested values for CO2, NOx, and SO_2, the results were analyzed based on their values.

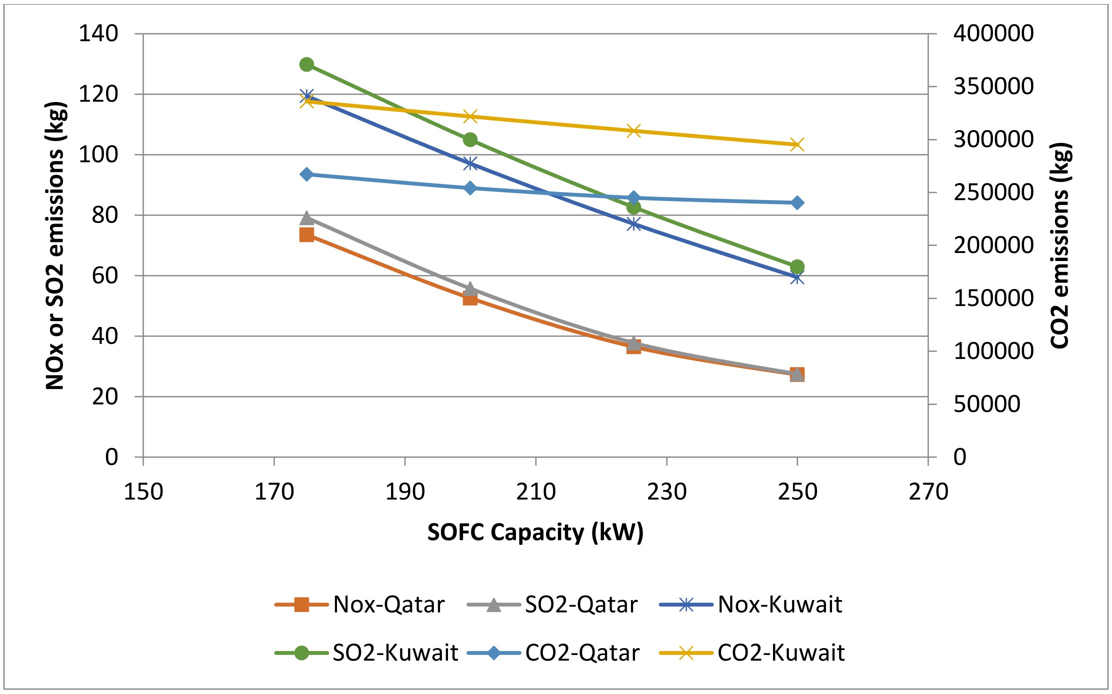


Figure 49: Emissions amounts for best scenarios - Qatar vs. Kuwait

From Figure 49, it can be seen that there is fair reduction in harmful emissions as SOFC capacity increases. Moreover, a maximum reduction of 30% in CO2 emissions can be observed in case (2) for Qatar at 250 kW, while the maximum reduction in CO2 emissions reach 17% for case (4) in Kuwait at the same SOFC capacity. For NOx and SO2, reduction of 70-90% and 53-77% was recorded for Qatar and Kuwait cases (2 & 4), respectively. Finally, other harmful emissions were found to be negligible in case of applying SOFC CHP system. Hence, there is a clear indication that SOFC CHP system is dominant in environmental terms.

4.5 Summary of results

In this section, two summary tables shall be presented that contains the best scenarios tabulated results. Table 7 shows the performance of the Office Building by application of SOFC CHP / Electric / Absorption Chillers combined system in terms of annual energy consumption (kWh/year), utilized thermal energy (kWh/year), energy obtained from Grid (kWh/year), maximum electrical energy produced by SOFC system (kWh/year), and overall efficiency with respect to the location. The best overall scenario for each location was highlighted in bold which shows the best performance of the SOFC CHP system from both financial and performance points of view.

Table 7

SOFC CHP System Performance results for Best Scenarios Summary Table

Capacity	**Location**	**Annual Energy Consumption**	**Utilized Thermal Exhaust Energy**	**Energy Obtained from Grid**	**Maximum Electrical Energy Produced by SOFC**	**Overall Efficiency**	**Electricity Cost**	**Fuel Cost**	**Annual Total Cost**
kW	-	kWh/year	kWh/year	kWh/year	kWh/year	%	$/year	$/year	$/year
175	Qatar	663580	264710	218546	445034	74.84%	11975	9730	21705
	Kuwait	817780	138510	358581	459199	61.78%	29762	9126	38888
200	**Qatar**	**642180**	**286110**	**154031**	**488149**	**73.14%**	**8440**	**10861**	**19301**
	Kuwait	794020	162270	289810	504210	61.88%	24054	10159	34213
225	Qatar	627730	300560	104336	523394	71.02%	5717	11903	17620
	Kuwait	770250	186040	228231	542019	61.77%	18943	11119	30062
250	Qatar	620880	307410	75829	545051	68.57%	4155	12756	16911
	Kuwait	**746610**	**209680**	**173881**	**572729**	**61.45%**	**14432**	**12010**	**26442**

Finally, Table 8 presents summary of the economic results of the best scenarios simulated for the office building with application of SOFC system; electricity and fuel costs, savings in annual energy costs, capital and maintenance cost for SOFC system, yearly cash flow, payback period, revenue after SOFC lifetime, and net present value are all shown in Table 8.

Table 8

SOFC CHP System Economic Analysis results for best scenarios Summary Table

Capacity	**Location**	**Savings in annual energy cost per year**	**Capital Cost of SOFC**	**Maintenance Cost of SOFC**	**Yearly Cash Flow**	**Payback period**	**Revenue after SOFC lifetime**	**Net Present Value**
kW	-	$/year	$	$/year	$/year	years	$	$
175	Qatar	20182	190700	730	19452	10.9	81622	53289
	Kuwait	26627	190700	1081	25546	8.3	360959	129736
200	**Qatar**	**22586**	**215700**	**786**	**21800**	**11.0**	**89496**	**57742**
	Kuwait	31302	215700	1139	30163	8.0	400592	162645
225	Qatar	24267	240700	832	23435	11.5	87390	53254
	Kuwait	35453	240700	1188	34265	7.8	433020	189097
250	Qatar	24976	265700	860	24116	12.3	71923	36796
	Kuwait	**39073**	**265700**	**1228**	**37845**	**7.8**	**458143**	**209005**

Chapter 5: CONCLUSIONS AND RECOMMENDATIONS

In this thesis, a 7000 m^2 office building was modeled in eQuest energy modeling software package. The model was created in accordance to ASHRAE 90.1-2010 standard, Qatar Construction Specification (QCS) 2014, Kahramaa policies. Moreover, electricity and natural gas utility costs as per local market have been introduced to the model. By simulation of the model in terms of energy and cost, energy consumption profiles and annual energy costs results were calculated. Then, (Chiappini & et al., 2011) SOFC cogeneration models were integrated in the model to investigate the performance of the SOFC CHP system in the office building. Two climate zones were considered: Qatar and Kuwait in this study. Several baseline cases were considered to optimize the HVAC system and loading profile that could utilize the SOFC to its full extent. These baselines are: electric chiller, absorption chiller, and combined electrical-absorption chiller systems were analyzed.

Performance curves were analyzed for a range of SOFC CHP system capacities (25-250 kW) in terms of energy produced, utilized thermal energy and overall efficiency. Moreover, annual energy costs for the office building were calculated with and without SOFC CHP system to assess potential cost savings. It was found that the using SOFC CHP system had led to promising savings in annual energy costs reaching a reduction up to 67% from the baseline case. Moreover, optimum overall efficiency reached up to 73%.

In the optimum case scenario in Kuwait, the payback period was found to be 7.8 years, while the net present value was 209,005 $ at SOFC capacity of 250 kW. Applying the same system to Qatar had also led to promising results of payback period of 11.0 years and net present value of 57,742 $ at 200 kW.

An environmental impact assessment was evaluated in terms of CO2, NOx, and SO2 emissions. It was found that application of SOFC CHP system had led to a maximum reductions in CO2 emissions of 30%, NOx of 90%, and SO2 of 90%.

In conclusion, based on literature review, background information, and analysis developed in this project, it is clear that SOFC CHP system is very promising energy technology for Qatar. As of results obtained, it can be considered as viable and feasible for the environment of Qatar. However, detailed studies shall be established to further investigate the performance of the SOFC CHP system more practically. Moreover, following are points of recommendation which could help future research in this subject especially for Qatar:

- It is recommended to implement a prototype SOFC system in Qatar to accommodate further researches on the subject and validate feasibility and viability of the system. Moreover, it will facilitate any required parametric studies affecting both performance and cost of the system.
- It is required to work on designing a system which could utilize the exhaust thermal energy available from SOFC CHP system because this will enhance extensively the performance of the system. A study can be implemented to combine SOFC system with district cooling in Qatar for further optimization.
- More researches shall be done to find alternative materials for SOFC system to enhance the durability and lifetime of the system.
- It is recommended to use software which is capable of running SOFC system with built-in database to take into consideration the real time problems.

- Currently, no studies were established in Qatar to find out the actual installed cost of the system. Therefore, it is highly recommended to conduct those studies based on real vendor information and quotations to reach a firm conclusion.

REFERENCES

A. D. Hawkes, & et al. (2007). Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating. *Journal of Power Sources, 164*, 260-271.

Absorption Cooling. (2012, February). Retrieved 2017, from Chartered Institution of Building Services Engineers: http://www.cibse.org/getmedia/5c9a9e15-5103-4b70-8aa1-1b7456fdf9a5/Datasheet-7-Absorption-Cooling.pdf.aspx

Alhouli, O. (2017). *Using solar energy in Kuwait to generate electricity instead of natural gas.* Retrieved 2018, from Kansas State University: https://krex.k-state.edu/dspace/bitstream/handle/2097/35558/OmarAlhouli2017.pdf?sequence=5

Al-Qattan, A., ElSherbini, A., & Al-Ajmi, K. (2014). Solid oxide fuel cell application in district cooling. *Power Sources, 257*, 21-26.

Ayoub, N., Musharavati, F., Pokharel, S., & Gabbar, H. A. (2014). Energy Conumption and conservation practices in Qatar - A case study of a hotel building. *Journal of Energy and Buildings, 84*, 55-59.

Bloomenergy. (2017, March). *Energy Server 5 200kW datasheet.* Retrieved 2018, from Bloomenergy Company: https://www.bloomenergy.com/sites/default/files/es5-200kw-datasheet.pdf

Bove, R., & Ubertini, S. (2008). Modeling Solid Oxide Fuel Cells: Methods, Procedures, and Techniques: Springer.

Chen, J. M., & Ni, M. (2014). Economic analysis of a solid oxide fuel cell cogeneration/trigeneration system for hotels in Hong Kong. *Energy and Buildings, 75*, 160-169.

Chiappini, D., & et al. (2011). SOFC Management in Distributed Energy Systems. *Journal of Fuel Cell Science and Technology, 8*.

Czech, T., Main, R., & Kaplan, K. (n.d.). *Fuel Cells.* Retrieved 2017, from Visual Encyclopedia of Chemical Engineering: http://encyclopedia.che.engin.umich.edu/Pages/Reactors/FuelCells/FuelCells.html

Demin, A., & Tsiakaras, P. (2001). Thermodynamic Analysis of a Hydrogen Fed Solid Oxide Fuel Cell Based on a Proton Conductor. *Internation Journal of Hydrogen Energy, 26*, 1103-1108.

Deng, & Petric. (2005). Geometric Modeling of the Triple-Phase Boundary in Solid Oxide Fuel Cells. *Journal of Power Sources, 140*, 297-303.

E. Riensche, & et al. (1998). Optimization of a 200 kW SOFC cogeneration power plant: Part I: Variation of process parameters. *Journal of Power Sources, 73*, 251-256.

eGRID Summary Tables 2016. (2016). Retrieved 2018, from United States Environmental Protection Agency: https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

eGRID2010 Version 1.1: Year 2007 Summary Tables. (2007). Retrieved 2014, from US Environmental Protection Agency: http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_SummaryTables.pdf

Ellis, M. W., & et al. (2001). Fuel cell systems: efficient, flexible energy conversion for the 21st century. *Proceedings of the IEEE, 89,* pp. 1808-1818.

eQUEST: Introductory Tutorial, Version 3.64. (2010, August). Retrieved 2017, from US Department of Energy: http://doe2.com/download/equest/eQ-v3-64_Introductory-Tutorial.pdf

Fontell, E., & al., e. (2004). Conceptual study of a 250 kW planar SOFC system for CHP application. *Journal of Power Sources, 131*, 49-56.

Frimodt, C., & Mygind, K. F. (2010, July 5). *Integration of Solid Oxide Fuel Cells and Absorption Cooling Units.* Retrieved 2017, from Ea Energy Analyses Company:

http://www.ea-energianalyse.dk/reports/student-reports/integration_of_solid_oxide_fuel_cells_and_absorption_cooling_units.pdf

Hawkes, A., & Leach, M. (2005). Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers. *Journal of Power Sources, 149,* 72-83.

Huang, B., & al., e. (2007). Performance of Ni/ScSZ cermet anode modified by coating with Gd0.2Ce0.8O2 for a SOFC. *Materials Research Bulletin, 42,* 1705-1714.

International Climate Zone Definitions. (2008). Retrieved 2017, from American Society of Heating, Refrigeration, and Air-Conditioning Engineers: https://www.ashrae.org/File%20Library/.../20081111_CZTables.pdf

International Energy Agency. (2007). *IEA Energy Technology Essentials.* Retrieved 2018, from International Energy Agency: https://www.iea.org/publications/freepublications/publication/essentials6.pdf

Iodice, P., d'Accadia, M. D., Abagnale, C., & Cardone, M. (2016). Energy, economic and environmental performance appraisal of a trigeneration power plant for a new district: Advantages of using a renewable fuel. *Applied Thermal Engineering, 95,* 330-338.

Jing, R., Wang, M., Wang, W., Brandon, N., Li, N., Chen, J., & Zhao, Y. (2017). Economic and environmental multi-optimal design and dispatch of solid oxide fuel cell based CCHP system. *Journal of Energy Conversion and Management, 154*, 365-379.

Kahramaa Electricity Tariff. (2018). Retrieved 2018, from Kahramaa: https://www.km.com.qa/CustomerService/Pages/Tariff.aspx

Lim, T., & et al. (2008). Operating characteristics of a 5 kW class anode-supported planar SOFC stack for a fuel cell/gas turbine hybrid system. *International Journal of Hydrogen Energy, 33*, 1076-1083.

Medrano, M., & et al. (2008). Integration of distributed generation systems into generic types of commercial buildings in California. *Energy and Buildings*, 537-548.

Meteotest. (2018). *Meteonorm Software*. Retrieved 2018, from http://www.meteonorm.com/en/

New Electricity Tariffs. (2017, August 23). Retrieved March 2018, from Kuwaittimes News: http://news.kuwaittimes.net/website/new-electricity-tariffs/

Oak Ridge National Laboratory. (2014). *CO2 Emissions*. (The World Bank) Retrieved 2017, from The World Bank Website: https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

O'Hayre, R., & et al. (2009). *Fuel Cell Fundamentals* (2nd ed.). John Wiley & Sons.

Overview of DOE-2.2. (1998, June). Retrieved 2017, from US Department of Energy: http://www.doe2.com/download/docs/22_oview.pdf

P. Aguir, & et al. (2004). Anode-supported intermediate temperature direct internal reforming solid oxide fuel cell. I: model-based steady-state performance. *Journal of Power Sources, 138*, 120-136.

Palomba, V., Ferraro, M., Frazzica, A., Vasta, S., Sergi, F., & Antonucci, V. (2018). Experimental and numerical analysis of a SOFC-CHP system with adsorption and hybrid chillers for telecommunication applications. *Applied Energy, 216*, 620-633.

Permanent Population Committee. (2017, March). Sukkan. *Population Newsletter*(35), p. 5.

Qatar Central Bank. (2017). *Rates & Ratios : QCB Interest Rates*. Retrieved 2018, from Qatar Central Bank: http://www.qcb.gov.qa/English/pages/interestrates.aspx

R.J. Braun, & et al. (2006). Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications. *Journal of Power Sources, 158*, 1290-1305.

Singhal, S. C. (2002). Solid oxide fuel cells for stationary, mobile, and military applications. *Solid State Ionics, 152-153*, 405-410.

Sleiti, A. K. (2010). Performance of tubular Solid Oxide Fuel Cell at reduced temperature and cathode porosity. *Journal of Power Sources, 195*(17), 5719-5725.

Sleiti, A. K., & Naimaster, E. (2010). Effects of Electrode Microstructure on Intermediate Temperature Solid Oxide Fuel Cell Performance. *Journal of Fuel Cell Science and Technology*, 051015.

Sleiti, A., & Naimaster, E. (2013). Potential of SOFC CHP systems for energy-efficient commercial buildings. *Energy and Buildings*, 153-160.

Srivastava, N. (2006). Modeling of Solid Oxide Fuel Cell / Gas Turbine Hybrid Systems.

Stambouli, A. B., & Traversa, E. (2002). Solid oxide fuel cells (SOFCs): a review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews, 6*, 433-455.

Thomas, S., & Zalbowitz, M. (2002). *Fuel Cells: Green Power.* Retrieved 2017, from Dartmouth Thayer Engineering College: https://engineering.dartmouth.edu/~d30345d/courses/engs171/FuelCells-article.pdf

U.S. Department of Energy. (2017, May). *Combined Heat and Power Technology Fact Sheet Series.* Retrieved 2018, from U.S. Department of Energy: https://www.energy.gov/sites/prod/files/2017/06/f35/CHP-Absorption%20Chiller-compliant.pdf

Voluntary Reporting of Greenhouse Gases Program. (2011). Retrieved from US Energy Information Administration: http://www.eia.gov/oiaf/1605/coefficients.html

Wachsman, E., & Singhal, S. C. (2009). Solid Oxide Fuel Cell Commercialization, Research, and Challenges. *The Electrochemical Society Interface*, 38-43.

Zare, V., & Gholmian, E. (2016). A comparative thermodynamic investigation with environmental analysis of SOFC waste heat to power conversion employing Kalina and Organic Rankine Cycles. *Journal of Energy Conversion and Management*, 150-161.

Zink, F., & al., e. (2007). A solid oxide fuel cell system for buildings. *Energy Conversion and Management, 48*, 809-818.