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Proposal of a hybrid CHP system: SOFC/microturbine/absorption chiller

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SUMMARY

Distributed generation is becoming an attractive option for industrial and commercial scale customers. The main advantage of this on-site power generation is that it offers a more efficient, reliable and cost-effective power supply. In addition, waste heat can be used for local heating or cooling. This is known as cogeneration or combined heat and power (CHP). In the present work, a hybrid-CHP system for a 230 kWe demand building is proposed and analyzed. The system considers the coupling of:

- A Solid Oxide Fuel Cell stack with an output of 200 kWe
- A Microturbine with an output of 30 kWe
- A single effect Absorption cooling system providing 55 kWt for air conditioning using water chillers

This plant would use natural gas as the primary fuel. The SOFC module is fed with the gas fuel and the whole stack generates the main power while acting as a combustor. The product gases exit the anode at a temperature of 900°C and are directly injected to the Micro Gas Turbine unit to produce additional power. Finally, the waste heat available at the turbine's exhaust fires a single effect Absorption Water-Chiller to provide cooling for air conditioning in the building. This proposed system would generate up to 230 kWe and 55 kWt with high thermal efficiencies of around 70–75%. Currently, Hybrid SOFC/GT and Microturbine/CHP systems are being considered or tested at several facilities. However, a combination of both, which would yield to trigeneration, has not been considered yet. Here we present a conceptual model based on specific proposals and investigations done by other researchers. A theoretical analysis on the proposed model is conducted to evaluate the potential and possibilities of such Hybrid CHP system and further discussions based on the economical considerations is also presented.

KEY WORDS: solid oxide fuel cell; microturbine; absorption chiller; distributed generation; combined heat and power

1. INTRODUCTION

Centralized power generation is still the dominant practice throughout Mexico; state company CFE being the main supplier. However, there is a growing trend of moving toward on-site generation, also known as distributed generation (DG). Currently, about 24% of the total power capacity

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in Mexico belongs to the private sector, but the Mexican law dictates that this power cannot be sold to public users; instead, it must be either self-consumed or sold to the state company. Nevertheless, most of the self-consumption is focused on the industrial sector, leaving the commercial sector vulnerable to the CFE prices and reliability.

The main advantage that commercial-scale DG offers is a higher efficiency on the power production. It also relieves the main power grid, making it more reliable. If carefully planned and evaluated, the DG scheme can also offer a less expensive and cleaner source of electric power. The improved efficiency is achieved by cogeneration or combined heat and power (CHP), which is the simultaneous production and utilization of electricity and heat. The waste heat can be used for heating or cooling purposes in schools, buildings, shopping centers and hospitals.

Of all the available DG technologies, the Micro Gas Turbine is a good option due to its low level of emissions and compatibility for CHP purposes. Yet also, the Fuel Cell technology is becoming a very interesting alternative because it offers the highest efficiency and the lowest level of emissions.[‡] The FC technology has only gained a minor breakthrough in the global stationary power generation market, but practically none in Mexico.

Within the Fuel Cells range, the Solid Oxide Fuel Cell (SOFC) and the Molten Carbonate Fuel Cell are the best candidates for stationary applications because they are considered to be high temperature fuel cells, thus having the highest potential for cogeneration. Also, these fuel cells are gaining strong and special attention because they can be linked with a bottoming cycle (generally turbine cycles) to produce additional electric power.

2. THE SOFC

The SOFC is considered a high temperature fuel cell. In fact, it operates at the highest temperature (between 800 and 1000°C) of all fuel cells. The SOFC is completely a solid-state device that overcomes many of the problems of other lower temperature fuel cells, such as liquid electrolyte management, the need of precious metals as catalysts, corrosive fluids, etc. Also, due to the operational temperature of the SOFC, there is opportunity to utilize the waste heat for a bottoming cycle and/or heating/cooling purposes.

The SOFC module would consist of a stack of several tubular fuel cells. The advantage of using tubular SOFCs is that high temperature gas-tight seals are not necessary. The tubular ceramic fuel cell has the air electrode (cathode) inside the tube and the fuel electrode (anode) outside. In between is the solid electrolyte that is generally zirconia doped with yttria (YSZ). At high temperatures, this electrolyte starts to conduct oxygen ions from cathode to anode. At 800°C, the ionic conductivity of YSZ is $0.02\,S\,cm^{-1}$ while at 1000°C it becomes $0.1\,S\,cm^{-1}$.

The SOFC operates at sufficiently high temperatures to allow direct internal reforming. The anode exhaust gases contain enough high-pressure steam to provide the water necessary for the reforming reaction. The heat that is needed for this endothermic reaction is supplied by the surroundings via convection and radiation. One of the advantages of the SOFC is that either hydrogen or carbon monoxide can be used as fuel. This is particularly convenient because when methane (CH_4) is fed to the SOFC, it gets reformed (producing H_2 and CO) and the cell utilizes both gases to generate power. Carbon monoxide represents no threat to the cell because platinum catalysts are not necessary to promote the main reaction due to the high operational temperature. Only a nickel-based catalyst is needed to enhance the reforming reaction.

3. SYSTEM PROPOSAL

In the present work, a hybrid-CHP system for a 230 kWe demand building is proposed and analyzed. The system considers the coupling of:

- A SOFC stack with an output of 200 kWe,
- A Microturbine with an output of 30 kWe,
- A single effect Absorption cooling system providing 55 kWt for air conditioning using water chillers.

[‡]Except for the zero emissions level of Photovoltaic Cells and Wind Generators but there is little or no CHP opportunity with these technologies.

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This plant would use natural gas as the primary fuel. The SOFC module is fed with the gas fuel and the whole stack generates the main power while acting as a combustor. The product gases exit the anode at a temperature of 900°C and are directly injected to the Micro Gas Turbine unit to produce additional power. Finally, the waste heat available at the turbine's exhaust fires a single effect Absorption Water-Chiller to provide cooling for air conditioning in the building.

A simplified diagram of the system is shown in Figure 1. The natural gas must be compressed and heated externally because a bleed from the turbine's inlet to pre-heat the fuel would significantly diminish the turbine's output power. In any case, the bleed could be extracted from the turbine's exit, before entering the recuperator, but this would lower the temperature of the air at the SOFC's inlet and it would definitely reduce the potential thermal energy necessary for the absorption cooling system. Perhaps this method of pre-heating the fuel would only be convenient when cooling demand is low or during wintertime. The natural gas should be heated at least to a temperature of about 600°C.

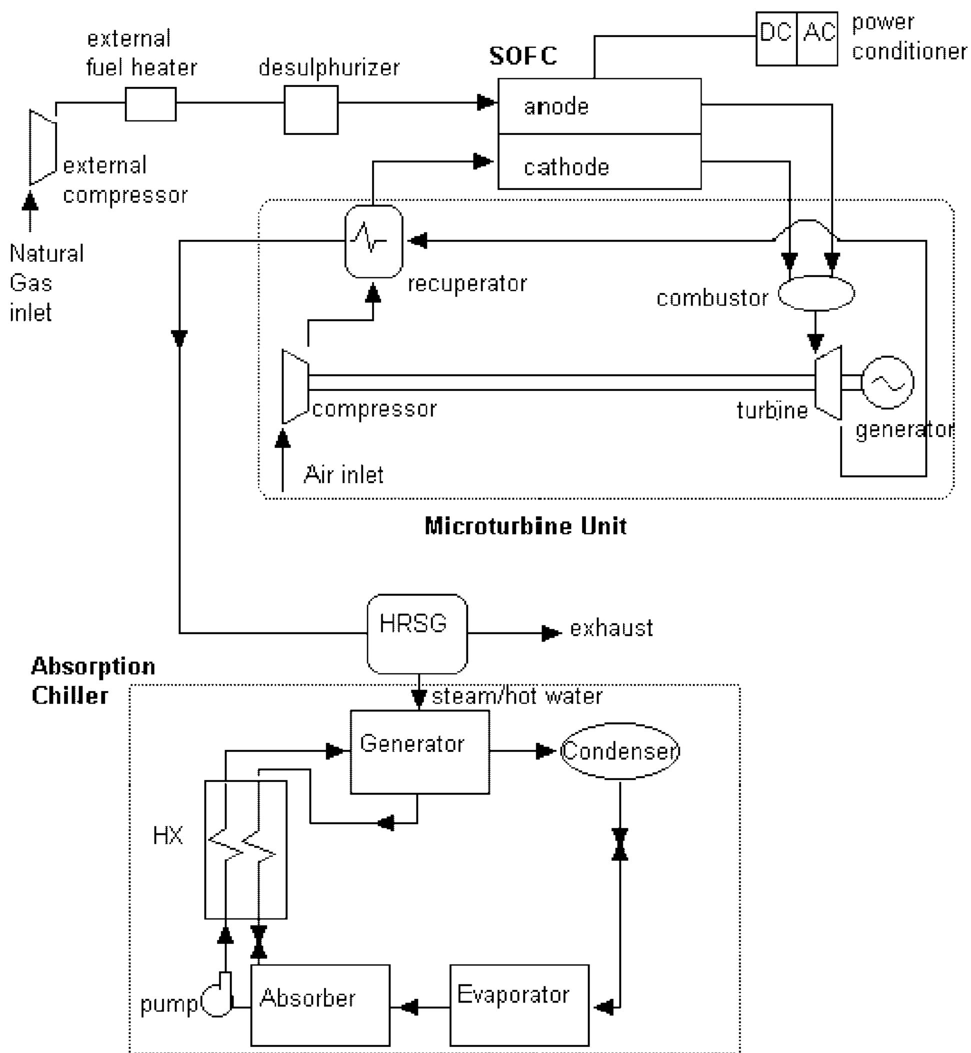

Figure 1. Simplified schematic of a Hybrid SOFC/μT/Absorption Chiller System.

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After being compressed and pre-heated, the fuel passes through a desulphurizer unit (an absorbent) to remove the odorants in the gas before entering to the anode in the SOFC.

Another optional modification could be an additional fuel feeding line to the combustor of the Microturbine. This is because the gas effluent from the SOFC contains a small amount of unutilized fuel, which could account for a non-stoichiometric combustion in the Microturbine (refer footnote ‡). This fact yields to consider the addition of an extra fuel feeding line to the combustor of the Microturbine. However, the additional injection of fuel into the system would certainly affect the efficiency; therefore, it might be only justified when the load demand is higher than usual. In such cases, the Microturbine could supply the extra power needed.

The efficiency of a typical SOFC operating in the 900–1000°C range at the outlet is around 45–50% using the LHV [1,2]. A Microturbine by itself operates with a thermal efficiency of 25–30% [1,3]. When coupling the SOFC with a gas turbine or a microturbine, the efficiency has the potential to be raised to 60–65% [4]. Furthermore, if waste heat is recovered and used for an absorption cooling system, the whole plant thermal efficiency could be well over 70%.

Absorption systems is an alternative to provide air conditioning in buildings since they use waste heat instead of mechanical and/or electric energy to drive a refrigeration cycle. The cooling obtained with the proposed system will not be sufficient to cool the whole building, but it could help the conventional vapor-compression refrigeration system to cover the cooling load at peak hours. This peak shaving effect would positively reflect on the electric power consumed by the conventional system.

4. CYCLE CALCULATIONS

Basic calculations were performed to obtain the approximate efficiencies of the SOFC and the Microturbine as well as the COP of the Absorption system and the whole plant efficiency. Other important parameters such as mass flow rates and cycle temperatures were also computed.

Basic assumptions:

- The input fuel (natural gas) is considered to be pure methane,
- Ambient air is at 25°C and 1 bar,
- The SOFC operates at 900°C,
- No leaks are present in the system,
- The isentropic efficiencies of the compressor and turbine are assumed to be 0.8 and 0.85 respectively,
- The mechanical efficiency in the shaft is considered to be 0.95,
- The recuperator has an effectiveness of 0.8,
- The fuel and oxidant utilization factors in the SOFC are 0.8 and 0.25 respectively.

4.1. SOFC calculations

As mentioned before, both hydrogen and carbon monoxide can act as fuels in the SOFC. The corresponding reactions are presented below:

For hydrogen:

$$2H_2 + 2O^{=} \rightarrow 2H_2O + 4e^- \quad \text{Anode side} \qquad (1)$$

$$O_2 + 4e^- \rightarrow 2O^{=} \quad \text{Cathode side} \qquad (2)$$

For carbon monoxide:

$$2CO + 2O^{=} \rightarrow 2CO_2 + 4e^- \quad \text{Anode side} \qquad (3)$$

$$O_2 + 4e^- \rightarrow 2O^{=} \quad \text{Cathode side} \qquad (4)$$

Since methane will be fed to the SOFC, both gases will be present in the anode. This can be seen from the endothermic reforming reaction of methane:

$$CH_4 + H_2O \rightarrow 3H_2 + CO \quad \text{Reforming reaction} \qquad (5)$$

Anode and cathode reactions can be derived for methane in the SOFC:

$$CH_4 + 4O^{=} \rightarrow 2H_2O + CO_2 + 8e^- \quad \text{Anode side} \qquad (6)$$

$$2O_2 + 8e^- \rightarrow 4O^{=} \quad \text{Cathode side} \qquad (7)$$

However, there is another reaction that takes place in the SOFC. This is the water–gas shift reaction,

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and it differs from the reforming reaction in that it is an exothermic and faster reaction:

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \text{Water-gas shift reation} \tag{8}$$

The fuel and air mass flow rates are calculated using a common method described in [5]. The rated power output and individual cell voltage are given as input data and 200 kW and 0.7 V were used.

Usually, the ideal voltage for the hydrogen fuel cell reaction is calculated using the following expression:

$$E = \frac{-\Delta G_{H_2}}{2F} + \frac{RT}{2F}\ln\left(\frac{a_{H_2O}\cdot\sqrt{a_{O_2}}}{a_{H_2O}}\right) \tag{9}$$

Where a is the activity, and for ideal gases is defined as the partial pressure of a gas over its standard pressure, this is:

$$a = \frac{P}{P_0} \tag{10}$$

However, according to [5], for a methane fueled cell 'the Nernst voltage' is derived from the following equation:

$$E = \frac{-\Delta G_{H_2}}{2F} + \frac{RT}{8F}\ln\left[\frac{p_{CH_4}}{p^2_{H_2O}\cdot p_{CO_2}}\right] + \frac{RT}{8F}\ln(p^2_{O_2}) \tag{11}$$

The effect of pressure on the output voltage for the cell can be calculated from the next expressions:

$$\Delta V_V = 0.027\ \ln\left(\frac{P_2}{P_1}\right) \tag{12}$$

$$\Delta V_{(mV)} = 59\ \log\left(\frac{P_2}{P_1}\right) \tag{13}$$

Both these equations are given for a SOFC operating at 1000°C. According to [6] for Equation (12) and [5] for Equation (13) and they yield similar results.

4.2. Microturbine calculations

A thermodynamic analysis based on a Brayton cycle with regeneration was performed for the Microturbine. A compression ratio of 4 and a Turbine inlet temperature of 1173 K (900°C) were used. The air-standard assumptions (accounting for the variations of specific heats with temperature) and the isentropic efficiencies of the compressor and turbine were also considered in these calculations. The most important parameters obtained through this analysis are the turbine and compressor work and the specific fuel consumption, but the temperature of every point in the cycle was obtained as well.

The compressor real or actual work input is calculated from an energy balance:

$$Wc_R = h_{2R} - h_1 \tag{14}$$

where h_{2R} and h_1 stand for the real enthalpies of air at the compressor outlet and inlet respectively. Multiplying the compressor work times the air mass flow rate obtained in the SOFC calculations gives us the compressor input power, which is taken form the shaft power of the turbine.

The turbine real or actual work output is derived similarly:

$$Wt_R = h_3 - h_{4R} \tag{15}$$

while the turbine net output work is obtained by subtracting the compressor work:

$$Wt_{net} = Wt_R - Wc_R \tag{16}$$

and multiplying this times the total mass flow rate gives us the Microturbine net power output.

4.3. Absorption chiller calculations

For air conditioning purposes, a single effect, and water-fired absorption chiller with a cooling capacity of 20 tons, was considered. The refrigeration cycle operates on the lithium bromide-water system (LiBr-H_2O).

The design of the Heat Recovery Steam Generator unit is beyond the scope of this work and is not presented here. An option could be a double heat exchanger as suggested by [3]. Water at 95°C is assumed to fire the generator.

The complete cycle was calculated using the Engineering Equation Solver (EES) computer program.

The absorbent flows through points 1, 2 and 3. The refrigerant flows through points 7, 8, 9 and 10. The mixed solution (absorbent plus refrigerant) corresponds to points 4, 5 and 6 (Figure 2).

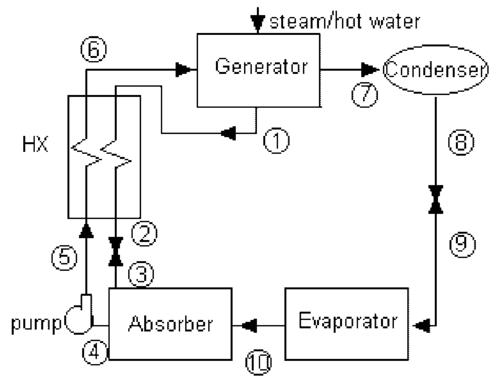

Figure 2. Flow diagram of Absorption System.

The mass balance equations are:

$$\frac{\dot{m}_{ab}}{\dot{m}_r} = \frac{X_S}{X_{ab} - X_S} \tag{17}$$

$$\frac{\dot{m}_S}{\dot{m}_r} = \frac{\dot{m}_{ab} + \dot{m}_r}{\dot{m}_r} \tag{18}$$

The energy balance at the heat exchanger yields:

$$h_6 = h_5 + \left(\frac{\dot{m}_{ab}}{\dot{m}_S}\right)(h_1 - h_2) \tag{19}$$

While the heat balance at the evaporator is:

$$\dot{Q}_e = \dot{m}_r(h_{10} - h_9) \tag{20}$$

And a heat balance at the generator gives us:

$$\dot{Q}_g = \dot{m}_r\, h_7 + \dot{m}_{ab}\, h_1 - \dot{m}_S\, h_6 \tag{21}$$

Finally, the coefficient of performance for the refrigeration system is calculated:

$$\mathrm{COP} = \frac{\dot{Q}_e}{\dot{Q}_g} \tag{22}$$

The Hybrid CHP thermal efficiency of the whole system is calculated using the following expression:

$$\eta = \frac{\dot{W}_{SOFC} + \dot{W}_{\mu T} + \dot{Q}_e}{\dot{m}_{CH_4} \cdot \mathrm{LHV}_{CH_4}} \tag{23}$$

5. ECONOMICAL CONSIDERATIONS

The unitary electric energy cost can be calculated assuming the most critical parameters involved in it as variables, these are gas price and capital cost. The numerical results are shown in Figure 3. Typical CFE tariffs for this capacity range are in the order of 10 USct kWh^{-1} for HM users considering load factors around 50%. This service is in medium voltage (13.8 < kV < 33 kV) and above 100 kW if the user is not residential or less than 100 kW for residential users. The other typical CFE tariff that can be used to compare with SOFC-μT system is the DAC tariff (Domestic High Consumption). This tariff is normally around 20 USct kWh^{-1} for residential users that do not have their own substation to receive the CFE energy. Both tariffs are indicated as horizontal lines in Figure 3 to indicate feasible regions generated by moving gas price and investment.

As shown in Figure 3 the most competitive SOFC-μT system can be reached when the specific investment is in 600 USD kW^{-1} and gas prices below 7.5 USD MMBtu^{-1} if compared with HM CFE tariff. The objective is not real at the moment because specific investment is around 4000 USD kW^{-1} for this system. However the SOFC-μT system is competitive for that investment comparing with CFE DAC tariff and gas prices below 20 USD MMBtu^{-1}. In conclusion, this technology will be more competitive for most users (HM tariff) when getting lower construction costs (in other words lower specific investment).

6. RESULTS AND DISCUSSION

The obtained results are reported in Table I. The data obtained through the presented analysis concur with the experimental results published in the consulted sources. It is also worth mentioning that all of the assumed parameters and reference information is based on real and practical models. For instance, the SOFC and Microturbine data is based on the experimental models of Siemens-Westinghouse and the NFCRC. The results obtained are satisfactory and realistic and they represent the benefit of practicing DG with technologies such as the SOFC and Microturbines. However, fast cost analysis shows feasibility for

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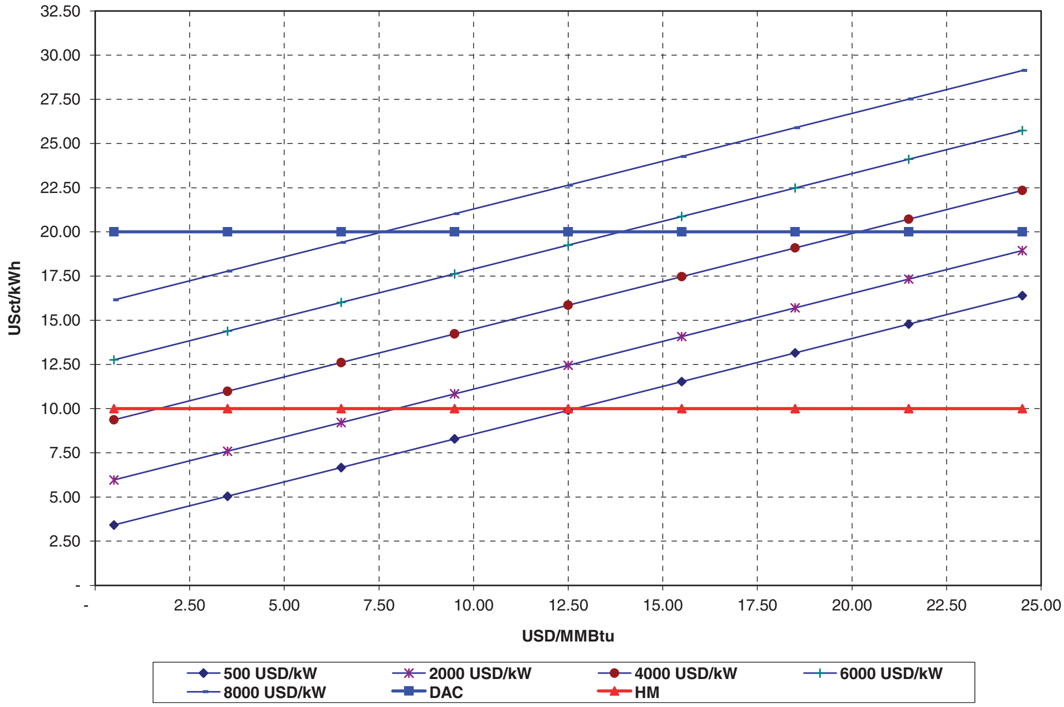

Figure 3. Sensitivity to SOFC-μT energy unitary costs changing Natural Gas Price and Specific Investment.

typical Mexican energy users when the specific investment be around 600 USD kW^{-1}, considering the current gas prices.

7. CONCLUSIONS

A Hybrid CHP system consisting of a SOFC, a Microturbine and an Absorption Chiller has been proposed and analyzed. This system would provide 230 and 55 kWt. The plant is intended to supply power to a commercial-scale facility such as a building, school, hospital, supermarket, etc. The objective of this proposal is to encourage the on-site generation schemes in the commercial sector in Mexico, presenting the Fuel Cell technology as an efficient and clean power generation alternative; as well as the benefits obtained with the combination of other technologies such as Microturbines and Absorption systems. The electric efficiency of a typical SOFC operating independently is around 45%, which is higher than any of the current power generation schemes, including even combined cycle (gas and steam turbine). The high electric efficiency, plus the very low levels of emissions (less than $0.01\,NO \times kg\,MWh^{-1}$) make the SOFC a serious candidate for stationary power generation applications. When combining the SOFC in a bottoming cycle such as a turbine cycle, the electric efficiency rises above 60%. Because of the high operational temperature of the SOFC, cogeneration can be achieved. If waste heat is utilized to provide heating or cooling, the thermal efficiency of the plant can go above 70%. The cycle calculations were performed using common methods described in the diverse fuel cell literature. A thermodynamic analysis of the Micro turbine and absorption chiller was also performed. The EES software was used to calculate the absorption system's parameters. A cost analysis on the proposed system will dictate the feasibility of such a plant. Currently, the installation costs are in the ranges of 400 US$/kWe and 4000–5000 US$/kWe for the Microturbine and SOFC respectively. The high cost of the Fuel Cells represents the main

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Table I. Hybrid CHP system parameters.

Power output of the system (kWe)	231.75
Ambient temperature (°C)	25
Atmospheric pressure (bar)	1
SOFC operational temperature (°C)	900
Pressure ratio	4
Fuel utilization factor in SOFC (%)	80
Oxidant utilization factor in SOFC (%)	25
Average current density ($\mathrm{A\,m^{-2}}$)	3200
Fuel mass flow rate ($\mathrm{kg\,s^{-1}}$)	0.0074
Air mass flow rate ($\mathrm{kg\,s^{-1}}$)	0.204
Steam–carbon ratio	3
SOFC power output (kWe)	200
Turbine inlet temperature (°C)	900
Compressor isentropic efficiency (%)	80
Turbine isentropic efficiency (%)	85
Recuperator effectiveness (%)	80
Compressor power input (kW)	37.2
Turbine gross power output (kW)	70.3
Turbine net power output (kW)	31.75
Mechanical efficiency in shaft (%)	95
Microturbine exhaust temperature (°C)	286
Overall efficiency (%)	62
COP of Absorption chiller	0.762
Temp. of water to fire the generator (°C)	95
Hot water flow to fire the generator ($\mathrm{L\,s^{-1}}$)	4.8
Refrigerant mass flow rate ($\mathrm{kg\,s^{-1}}$)	0.02351
Absorbent mass flow rate ($\mathrm{kg\,s^{-1}}$)	0.2358
Cooling capacity (kWt)	55
Thermal efficicency of Hybrid CHP (%)	77

obstacle for this technology. But, if a breakthrough in manufacturing processes and materials research achieve lower costs, the Fuel Cells will become clearly the best option for stationary power generation, and because of its modular advantages, also the best choice for DG.

NOMENCLATURE

A	= activity
COP	= coefficient of performance
E	= voltage (V)
F	= Faraday constant ($\mathrm{C\,mol^{-1}}$)
G	= Gibbs free energy ($\mathrm{J\,kg^{-1}}$)
H	= Enthalpy ($\mathrm{J\,kg^{-1}}$)
LHV	= Low heating value-specific heat ($\mathrm{J\,kg^{-1}}$)
$\dot{m}$	= mass flow rate ($\mathrm{kg\,s^{-1}}$)
P	= pressure (Pa)
P	= partial pressure
Q	= heat flow (W)
R	= gas constant ($\mathrm{J\,mol^{-1}\,K^{-1}}$)
T	= temperature (K)
V	= voltage (V)
W	= power (W)
X	= concentration

Subscripts

ab	= absorber
c	= compressor
e	= evaporator
g	= generator
R	= real
r	= refrigerant
S	= solution
t	= turbine

Greek

η	= efficiency

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