Design and Thermoeconomic Analysis of a PEMFC-TEC Cogeneration Plant

A. H. Haddadi [1] ,**A. Ghomian** [2] ,**S. Hassanpour Yosefi** [3] ,**F. Torabi** [4]

[1] B. Sc. Student, Mechanical Eng. Faculty, K. N. Toosi University of Technology *amirhossein.haddadi@gmail.com*
[2] B. Sc. Student, Mechanical Eng. Faculty, K. N. Toosi University of Technology *atefe.ghomian@gmail.com*
[3] B. Sc. Student, Mechanical Eng. Faculty, K. N. Toosi University of Technology *sina.yosefi89@gmail.com*
[4] Assistant Professor, Mechanical Eng. Faculty, K. N. Toosi University of Technology *ftorabi@kntu.ac.ir*

Abstract

Fuel cell systems generate a large amount of heat, so they are considered as an important candidate for CHP systems. However, Proton Exchange Membrane Fuel Cells (PEMFCs) operate in a relatively lower temperature and less pressure compared to those of other fuel cells, and they are not usually considered as a choice for CHP plants. The present research studies the idea of Ocean Thermal Energy Conversion (OTEC), combining it with PEMFC and thermodynamically investigates the effect of combining PEMFC with Thermal Energy Conversion (TEC) system. A combination of PEMFC and TEC systems (PTEC) leads to a remarkable increase in efficiency of PEMFC.

Keywords

Proton Exchange Membrane Fuel Cell, Thermal Energy Conversion, Cogeneration

Nomenclature

A_e	Total heat transfer area of heat exchanger plates, m^2
b	Channel gap, m
c	Velocity, ms^{-1}
C	Cost, \$
c_p	Molar specific heat capacity in constant pressure, $\mathrm{kJkg}^{-1}\mathrm{K}^{-1}$
d_{eff}	Effective diameter, m
d_p	Port diameter, m
e	Specific exergy, kJkg^{-1}
e^{ch}	Specific chemical exergy, kJkg^{-1}
e^{ph}	Specific physical exergy, kJkg^{-1}
$\dot{E}_D$	Destruction exergy, kJs^{-1}
F	Faraday's const., Cmol^{-1}
f_{ch}	Fricton factor
g	Gravitational accelaration, ms^{-2}
G	Mass flow of air to cooling tower, kgs^{-1}
G_c	Channel mass velocity, $\mathrm{kgm}^{-2}\mathrm{s}^{-1}$
G_p	Inlet mass velocity, $\mathrm{kgm}^{-2}\mathrm{s}^{-1}$
h	Specific enthalpy, kJkg^{-1}
HHV	Higher heating value, kJkg^{-1}
i	Annual interest rate
I	Electric current, A
K	Conductivity, $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$
k	Specific heat ratio
L_{ch}	Effective length, m
L_v	Effective plate length, m
L_w	Channel width, m
n	Years of system operation
$\dot{m}$	Mass flux, kgs^{-1}
$\dot{n}$	Molar flux of hydrogen, mols^{-1}
N	Total number of cells
N_{cp}	Channel per pass
N_p	Number of passes
N_t	Number of plates
P	Pressure, Pa
Pr	Prandtl number
Q	Heat, kJ
$\dot{Q}$	Heat transfer rate, kJs^{-1}
Re	Reynolds number
R_u	Universal gas constant, $\mathrm{Jmol}^{-1}\mathrm{K}^{-1}$
s	Specific enthropy, $\mathrm{kJkg}^{-1}\mathrm{K}^{-1}$
T	Temperature, K
V_{cell}	Voltage of the cell, V
$\dot{W}_{\mathrm{cv}}$	Control volume work rate kJs^{-1}
x	Molar fraction, molmol^{-1}
z	Height, m

Greek Symbols

β	Chevron angle
ϵ	Exergetic efficiency, %

η_{cell}	Cell efficiency, %
η_{PTEC}	Overall efficiency of PTEC plant, %
μ	Viscosity, Pas
ρ	Density, kgm^{-3}

Subscripts

0,1,2,...	Locations on the thermodynamic cycle
amb	Ambient
ch	Channel
evp	Evaporator
FC	Fuel cell
in	Inlet
inv	Investment
main	Maintenance
mu	Makeup water
op	Operation
out	Outlet
turb	Turbine
WF	Working Fluid

Introduction

PEMFCs are a type of fuel cells that operate in low temperatures (less than 90°C) and small pressures. According to U. S. Department of Energy, PEMFCs are the primary candidate for vehicles, buildings, and other small applications. Normally due to their low temperature and pressure, PEMFCs are not considered for cogeneration systems [1]; however, a combination of PEMFCs and the OTEC concept helps one to utilize the waste heat rejected by fuel cells and increase their output power as well as their efficiency. Moreover, from an economical standpoint, this combination is more affordable than the initial fuel cell.

From the first law of thermodynamics, the OTEC cycle has a low efficiency thus requires higher initial investment; but there are a number of advantages which make it a very suitable power generation system. The operation costs are very low in a rather large scale and span of time. Besides, since there are no pollutant emitting fossil fuels involved in the power generation cylce, it is known to be environment-friendly plant. Also OTEC can generate power using temperature differences (as low as 20°C), this feature makes it probably the best candidate for combination with PEMFCs that are not capable of generating high temperature differences, but more than enough to feed an OTEC system .

Fuel cells are electrochemical engines that produce electricity from paired oxidation/reduction reactions. One can think of them as batteries with flows of reactants in and products out [2]. Conventional combustion-based power plant typically generates electricity at efficiencies of 33 to 35 percent, while fuel cell systems can generate electricity at efficiencies up to 60 percent (and even higher with cogeneration) [7]. During early 1960s Thomas Grubb and Leonard Niedrach of General Electric invented PEM fuel cells that were used in Gemini space program and this was followed by Apollo space program [3–6]. Lately, various manufacturers including major auto makers have been striving to develop fuel cell technology for use in power generation applications such as fuel cell vehicles (FCV).

OTEC is a system of converting heat energy into electricityby using the temperature difference between water at the surface of the ocean and cold water of the depths [10]. In 1881, D'Arsonval proposed to use relatively warm surface water of the oceans (24°C to 30°C) to evaporate pressured Ammonia in a heat exchanger and use the vapor to drive a turbine-generator, since Ammonia circulates in a closed cycle, this concept has been named closed-loop cycle. Fourty years later, another French inventor named Georges Claude, proposed to use water as the working fluid, this cycle can be configured into a closed loop cycle that produces desalinated water as well as electricity [9].

C. Xie et al. [11] used the idea of OTEC and proposed a hybrid system consisting of a PEMFC and a TEC subsystem to exploit thermal energy of the PEMFC for electricity generation. This system achieves the combined heat and power efficiency and utilizes heat to generate more valuable electricity. In any TEC system, the temperature difference between heat source and sink is the most determinant factor in performance of the system. Combining PEMFC with a TEC subsystem leads to increasing in heat source temperature, while the sink temperature remains the same. This causes considerable enhancement in efficiency of the TEC subsystem. Analytical results show that this combination increases the overall efficiency of PEMFC by 0.4-2.3 %.

Although Xie et al. [11] presented a very interesting, rational and feasible idea in their respective researches, a number of questions remain unanswered regarding their model. Specifically, there is not any indication of cold water source and it is evident that providing 5°C water is an expensive process. No particular economical analysis is carried out and the exergetic analysis is somewhat incomplete.

In the present research, a number of alterations are made to the original design in order to make it a practical power generation plant. This research peruses the PTEC cycle from several different aspects for the first time. A closed-loop cycle is introduced, a thorough thermodynamic analysis is carried out and properties of all states are obtained. The exergy analysis is expanded and corrected for each and every component as well as the overall system. Heat exchangers, cooling towers and other components are designed. Then an economical analysis is implemented with respect to the designed components to guarantee that the proposed model is economical to manufacture and operate.

Proposed Model

The goal of modified PTEC cycle is to design a completely closed-loop system. Fig. 1 shows the suggested design for a modified PTEC cogeneration system. A typical PTEC plant consists of four main following subsystems:

1. Fuel processing subsystem
   The fuel processing subsystem reforms natural gas fuel into a hydrogen rich gas using an auto-thermal fuel reformer, such that the energy released from the exothermic partial oxidation of natural gas is equal to the energy consumed by the endothermic steam reforming of natural gas [20, 21]. Designing the fuel process subsystem is not within the goals of this paper, thus it is not investigated in the present research. The system is assumed to receive pure hydrogen with the desired pressure as fuel.

2. PEMFC subsystem
   PEMFC is a highly efficient electricity generation device which converts the chemical energy of fuel to electricity, water and heat through electrochemical reactions [23]. These systems have several advantages such as low operating temperature, solid electrolyte, reliability, polution-free, high power density [24], two or three times more efficient than traditional combustion, quiet operation, having no moving parts [7], no corrosive fluid, high current density, low weight cost and volume and lower sensitivity to orientation [25]
   These cells utilize hydrogen as fuel and oxygen or air as cathode oxidant [26]. On the anode each hydrogen molecule frees two electrons, and on the cathode each oxygen molecule captures four electrons [2]. The overall fuel cell reaction is as follows:

$$2\,\mathrm{H_2} + (\mathrm{O_2} + 3\cdot 76\,\mathrm{N_2}) \longrightarrow 2\,\mathrm{H_2O}(l) + 3\cdot 76\,\mathrm{N_2} \quad (1)$$

3. TEC subsystem

   TEC is a power generation system that benefits the same design as OTEC, but unlike Ocean Thermal Energy Conversion it may operate elsewhere. Fig. 2 shows T-S diagram of a TEC system. Water flows to the PEMFC, absorbs the generated heat and delivers it to the evaporator in order to generate more valuable electricity from the waste heat, then returns to it's initial temperature and is pumped back to the cell. The heat absorbed by the evaporator is used to evaporate the working fluid in TEC subsystem in order to drive the turbine, and the discharged steam is condensed and pumped back to the evaporator to complete the TEC cycle. The cold water which is used for cooling the discharged steam in condenser, is provided by a common cooling tower.

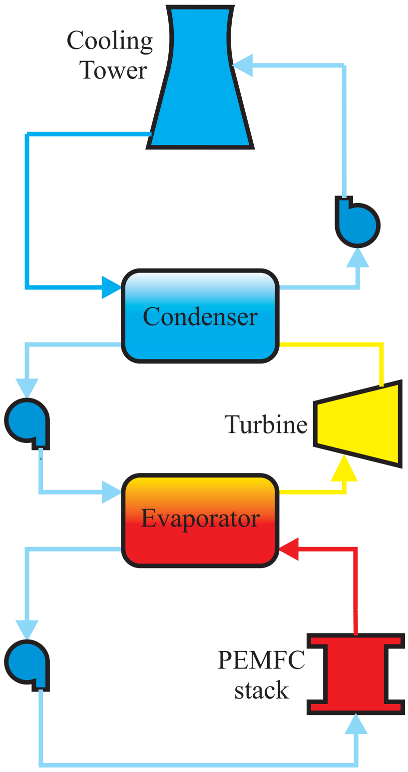

Fig. 1: Configuration of PTEC cycle

4. Cooling water production subsystem
   Providing cold water is very important in power generation. In the present model it is suggested to utilize a cooling tower to provide the required amount of cold water. The cold water provided by cooling tower maintains required temperature of the condenser.

Mathematical Modeling

A. *PEMFC subsystem*

The governing equations for electricity and heat generation in the PEMFC are as following:

$$V_{\mathrm{cell}} = \frac{V}{N} \quad (2)$$

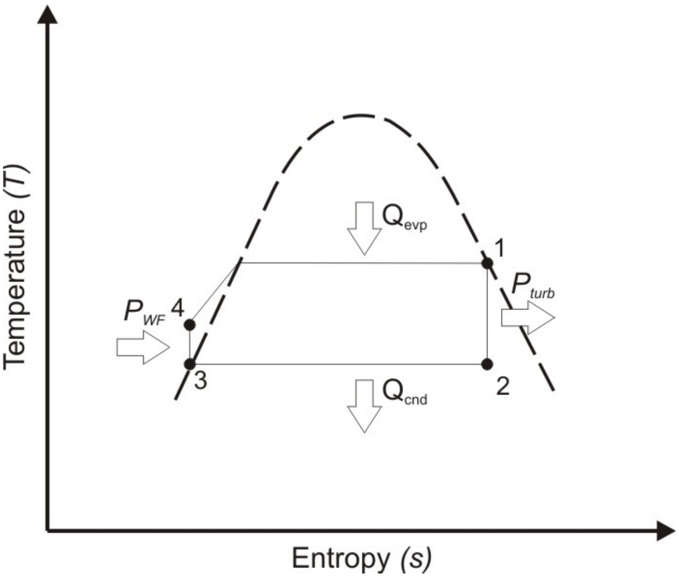

Fig. 2: T-S diagram of a TEC cycle

TABLE I: Typical parameters of the process

Parameter	Property	Value
P	Fuel cell output power	10 kW
V	Fuel cell output voltage	48 V
N	Total number of Cells	70
P_{air}	Fuel cell inlet air pressure	3 atm
P_{H_2}	Fuel cell inlet hydrogen pressure	5 atm

The higher heating value enthalpy can be converted to an equivalent voltage of 1.481 V [27], so the efficiency of the cell is:

$$\eta_{\text{cell}} = \frac{V_{\text{cell}}}{1.481} \tag{3}$$

where V_{cell} denotes the voltage of a single cell.

The electric current of fuel cell is:

$$I = \frac{P}{V} \tag{4}$$

Where P represents power of the fuel cell and V denotes voltage of the cell stack.

According to Faraday's law, hydrogen consumed is directly proportional to current [27], thus the molar flux of hydrogen may be calculated from:

$$\dot{n} = \frac{I}{2F} \tag{5}$$

where I is the electric current and F is Faraday's constant.

With the efficiency defined as (3), the waste heat generated is simply:

$$\dot{Q}_{\text{FC}} = N \times \dot{n} \times HHV \times (1 - \eta_{\text{cell}}) \tag{6}$$

where N is the total number of cells in a fuel cell stack and HHV denotes the higher heating value of hydrogen.

TABLE II: Standard molar chemical exergy of various substances at $T_0 = 298.15°$C and $P_0 = 1.0$ atm

Substance	Chemical Exergy [kJkmol^{-1}]
H_2	236,100
O_2	3970
N_2	720
$H_2O(l)$	900

B. *TEC subsystem*

Total efficiency of PTEC plant is:

$$\eta_{\text{PTEC}} = \frac{(\dot{W}_{\text{turb}} + \dot{W}_{\text{FC}} - \dot{W}_{\text{pump,WF}} - \dot{W}_{\text{pump,FC}})}{(70 \times \dot{n} \times HHV)} \tag{7}$$

where W_{turb} is the output turbine power, W_{FC} is the electricity generated by fuel cell, $W_{\text{pump,WF}}$ and $W_{\text{pump,FC}}$ are power consumption by working fluid and fuel cell side pumps.

C. *Cooling water production subsystem*

The air flow to the cooling tower known as G, may be calculated from [28]:

$$h_{\text{CT,in}} - h_{\text{CT,out}} = \frac{G}{m_{\text{CT}}}[(h_{\text{air,out}} - h_{\text{air,in}}) - (W_{\text{air,out}} - W_{\text{air,in}})h_{\text{mu}}] \tag{8}$$

Where h_{mu} shows the specific enthalpy of make-up water.

Exergy Analysis

Exergy is the maximal work, attainable in given reference state without generalized friction. In the closed system energy is conserved but exergy is destroyed due to generalized friction [22]. Exergy can be destroyed and generally is not conserved, a limiting case is when exergy would be completely destroyed, as would occur if a system were to come into equlibrium with the environment spontaneously with no provision to obtain work [16]. The following expression is used for the total exergy transfer associated with a stream of matter [16,17,30], the total value of exergy can be divided into two different parts, chemical and physical exergy:

$$e = e^{ph} + e^{ch} \tag{9}$$

The physical exergy associated with a stream of matter may be calculated using the following expressions:

$$e^{ph} = (h - h_{\text{amb}}) - T_{\text{amb}}(s - s_{\text{amb}}) + \frac{c^2}{2000} + \frac{gz}{1000} \tag{10}$$

For an ideal gas stream one can utilize the following expression:

$$e^{ph}=c_pT_{\mathrm{amb}}[\frac{T}{T_{\mathrm{amb}}}-1-\ln\frac{T}{T_{\mathrm{amb}}}+\ln(\frac{P}{P_{\mathrm{amb}}})^{\frac{k-1}{k}}] \tag{11}$$

The chemical exergy of the stream is obtained from:

$$e^{ch}=\sum_{i=1}^{n}x_ie_i^{ch}+\bar{R}_uT_{\mathrm{amb}}\sum_{i=1}^{n}x_ie_i^{ch} \tag{12}$$

The exergy balance for a control region from which the irreversibility rate of steady flow process can be calculated, can be derived by combining the steady flow energy equation (first law) with the expression for the entropy production rate (second law) [15]. The following equation can be employed to calculate exergy destruction in a control volume:

$$\dot{E}_D=\sum_j(1-\frac{T_{\mathrm{amb}}}{T_j})\dot{Q}_j-\dot{W}_{\mathrm{cv}}+\sum_i\dot{m}_ie_i-\sum_o\dot{m}_oe_o \tag{13}$$

A. Fuel Cell

The physical exergy values can be computed using equations (10) to (13) and the chemical exergy values are available in table II. Also using equations (1) and (5) mass flows can be determined. Equation (14) shows the total expression for exergy destruction.

$$\begin{aligned}\dot{E}_{\mathrm{D,FC}}&=\dot{m}_{\mathrm{H_2}}e_{\mathrm{H_2}}+\dot{m}_{\mathrm{air}}e_{\mathrm{air}}-\dot{m}_{\mathrm{H_2O}}e_{\mathrm{H_2O}}\\&+\dot{m}_{\mathrm{FC}}(e_{\mathrm{FC,in}}-e_{\mathrm{FC,out}})-\dot{W}_{\mathrm{FC}}\end{aligned} \tag{14}$$

B. Condenser and Cooling Tower

Exergy destruction in cooling tower can be calculated as follows:

$$\begin{aligned}\dot{E}_{\mathrm{D,CT}}&=G(e_{\mathrm{air,in}}-e_{\mathrm{air,out}})+m_{\mathrm{mu}}(e_{\mathrm{mu}}-e_{\mathrm{air,out}})\\&+m_{\mathrm{CT}}(e_{\mathrm{cnd,in}}-e_{\mathrm{cnd,out}})\end{aligned} \tag{15}$$

C. Turbine

Exergy destruction in turbine can be calculated as follows:

$$\dot{E}_{\mathrm{D,turb}}=\dot{m}_{\mathrm{WF}}(e_1-e_2)-\dot{W}_{\mathrm{turb}} \tag{16}$$

D. Pump

Exergy destruction in pump can be calculated as follows:

$$\dot{E}_{\mathrm{D,pump}}=\dot{m}_{\mathrm{WF}}(e_3-e_4)+\dot{W}_{\mathrm{pump}} \tag{17}$$

Heat Exchanger

Gasketed plate heat exchangers find wide industrial application today, but their largest single application has been that of central cooling in a petrochemical, metallurgical and power plants [13].

The equations are stated in two parts: first, for pressure loss and second, for heat transfer coefficient [12, 13].

A. Pressure loss equations

The channel equivalent diameter can be calculated from:

$$d_{\mathrm{eff}}=\frac{2b}{\mu} \tag{18}$$

Where b is the channel gap and μ denotes the enlargement factor which varies from 1.1 to 1.25.

N_{cp} or the number of channels per each pass is:

$$N_{cp}=\frac{N_t-N_p}{2} \tag{19}$$

Where N_t is the total number of plates and N_p represents the number of passes

The channel mass velocity is as follows:

$$G_c=\frac{\dot{m}}{N_{cp}bL_w} \tag{20}$$

Where L_w is the channel width.

ΔP_{ch} is the total channel pressure loss:

$$\Delta P_{\mathrm{ch}}=4f_{\mathrm{ch}}\frac{L_{\mathrm{ch}}N_p}{d_{\mathrm{eff}}}\frac{G_c^2}{2\rho}(\frac{\mu_b}{\mu_w})^{-0.17} \tag{21}$$

Where f_{ch} is the friction factor which relates to single-phase frictional loss inside tubes:

$$f_{\mathrm{ch}}=\frac{k_p}{Re^z} \tag{22}$$

values of k_p and z versus *Reynolds* for various chevron angles are given in tables in references [12, 13].

$$L_{\mathrm{ch}}=\text{number of passes}\times\text{flow length in one pass}$$

and $(\frac{\mu_b}{\mu_w})^{0.17}$ is the viscosity correction factor.

The total port loss can be calculated by:

$$\Delta P_p=1.4N_p\frac{G_p^2}{2\rho} \tag{23}$$

Where Gp is the total flow in port opening and is computed from:

$$G_p=\frac{\dot{m}}{\frac{\pi D_p^2}{4}} \tag{24}$$

B. Heat transer coefficient

The Nusselt number can be calculated from:

$$Nu=C_hRe^yPr^{0.33}(\frac{\mu_b}{\mu_w})^{0.17} \tag{25}$$

Values of C_h and y versus Re for various chevron angles are given in tables from references [12, 13].

The overall heat transfer coefficient have been determined from:

$$\frac{1}{U_c}=\frac{1}{h_h}+\frac{1}{h_c}+\frac{t}{k_w} \tag{26}$$

Where film heat transfer coefficients (h_h and h_c) are gained from the Nusselt number, and t and k_w are thickness and conductivity of plates.

$\dot{Q}_c$ is the total heat transfer in heat exchanger and can be calculated from:

$$\dot{Q}_c = U_c A_e \Delta T_{\mathrm{lm}} \tag{27}$$

Where A_e is the effective heat transfer area and:

$$\Delta T_{\mathrm{lm}} = \frac{\Delta T_1 - \Delta T_2}{\ln \dfrac{\Delta T_1}{\Delta T_2}} \tag{28}$$

Thermoeconomic Analysis

Thermoeconomics deal with the value of the energy within a plant, where heat and work conversion finds place [31]. Raising the efficiency cost-effectively (Thermoeconomics) is a multi-disciplinary problem in which thermodynamics interfaces other disciplines of knowledge which in this particular case are design, manufacture and economics [32].

Total Annual Cost (TAC) of a system consists of two main terms, investment and operation costs.

$$TAC = C_{\mathrm{inv}} + C_{\mathrm{op}} \tag{29}$$

Cost of investment is the total purchase cost of main system components multiplied by Capital Recovery Factor (CRF).

$$C_{\mathrm{inv}} = CRF \times (C_{\mathrm{cnd}} + C_{\mathrm{evp}} + C_{\mathrm{turb}} + C_{\mathrm{FC}} + C_{\mathrm{CT}}) \tag{30}$$

Where CRF is computed from the following equation:

$$CRF = \frac{i}{1 - (i+1)^{-n}} \tag{31}$$

i denotes the annual interest rate and n is the years of system operation.

The cost of operation is a combination of fuel and and maintenance costs.

$$C_{\mathrm{op}} = C_{\mathrm{fuel}} + C_{\mathrm{main}} \tag{32}$$

Results

A. Proposed Model

In this paper, a 10 kW PEMFC with a temperature of 55°C was used as a basis for PTEC cogeneration system. The presented PTEC cycle is a closed cycle as opposed to that of Xie et. al. [11], there are a number of advantages to a closed-loop cycle which were mentioned before.

The efficiency of the initial PEMFC with the given parameters is known to be 46% before addition of the TEC subsystem. Outcome of the thermodynamic analysis indicates that a combination of PEMFC and TEC increases efficiency of the overall plant to 51.5%. Results mentioned in Table III indicate that the presented closed-cycle PTEC acquires the same increase in efficiency as that of the model proposed by Xie et. al., taking into account that the cold water issue is solved and a relatively higher temperature water is utilized compared to that of the original model.

TABLE III: Typical parameters of the process

Subsystem	Efficiency Xie et. al.	 Modified PTEC
PEMFC	40%	46%
TEC	4.4 %	9%
Overall (PTEC)	45.3%	51.5%

TABLE IV: Temperature of various system states

Parameter	Property	Value [°C]
T_{amb}	Ambient temp.	25
T_{FC}	Fuel cell operating temp.	55
$T_{\mathrm{evp,i}}$	Evaporator inlet temp.	55
$T_{\mathrm{evp,o}}$	Evaporator outlet temp.	24
T_1	Turbine inlet temp.	52
T_2	Turbine outlet temp.	17
T_3	Working fluid pump inlet temp.	17
T_4	Working fluid Pump outlet temp.	17
$T_{\mathrm{cnd,i}}$	condenser inlet temp.	15
$T_{\mathrm{cnd,o}}$	Condenser outlet temp.	25

Table IV lists the temperature of each state within the closed loop PTEC cycle.

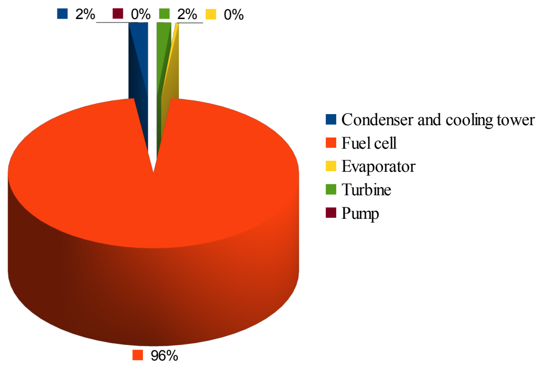

Fig. 3: Exergy destruction percentage within individual components of the system

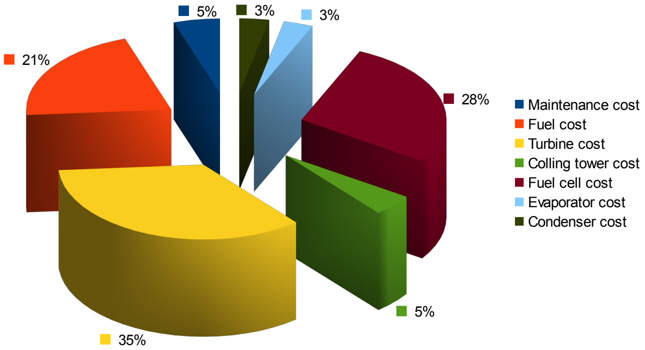

Fig. 4: Total annual cost of individual system components and consumables

B. Exergy Analysis

Figure 3 illustrares exergy destruction within each component of the plant. The PEMFC is the main source of exergy destrucion and irreversibility and is held accountable for 96% of exergy destruction as it is the only component of the system that receives fuel directly from an outside source and is responsible for converting chemical exergy of fuel to useful work. Although exergy loss takes place within different components of this system, their value is negligible compared to those of exergy destruction term as the working temperature of system components are not much deviated from ambient temperature.

C. Thermoeconomic Analysis

The system may be analyzed from an economical standpoint using the equations expressed within the Thermoeconomic Analysis section. Using the diagrams from Reference [33], the cost of each component or consumable is estiamted. Figure 4 shows the TAC percentage of different segments. As illustrated, Turbine, PEM fuel cell and fuel are of the most economic significance respectively.

After a significantly low time span of six and a half months this plant is able to cover TAC expenditures by selling the generated electricity and within three and a half years, it is able to return the total costs of investment and operation.

Conclusion

In the present work, a closed loop PTEC cogeneration plant is proposed which consists of three subsystems. The system is analyzed form themodynamical, exergical and economical points of view. The results show that the proposed model is able to increase the efficiency of the whole system about 5%. The increase in efficiency requires extra initial and operational cost. The calculation shows that this extra cost can be covered in a significantly low time span of six and a half months. Moreover, after three and a half years, the proposed model is able to return the total costs of investment and operation.

The exergical calculations show that the PEMFC is the main source of exergy destruction in the system. About 96% of exergy destruction happens in the PEMFC due to the electrochemical processes. This fact reveals that optimization of this system is very crucial.

Economical analysis shows that turbine (35%), PEMFC (28%) and fuel (21%) are the most cost determining parts of the system in TAC. These results show that this model has a very good potential for further optimisation.

References

[1] T. Kaarsberg, R. Fiskum, J. Romm, A. Rosenfeld, J. Koomey, W. P. Teagan, "Combined Heat and Power (CHP or Cogeneration) for Saving Energy and Carbon in Commercial Buildings," Sustainable Development, Climate Change, Energy Planning and Policy, Paper 482, Panel 9, 1998.

[2] B. Lin *Hydrogen fuel cell scooters for urban Asia,* Princeton University, 1999.

[3] B. C. Hacker and J. M. Grimwood *On the Shoulders of Titans: a history of Project Gemini,* 1st Edition, NASA: Washington D.C, 1977.

[4] T. Schmeister *Determining the quality and quantity of heat produced by proton exchange membrane fuel cells with application to air cooled stacks for combined heat and power,* University of Victoria, 2010.

[5] http://en.wikipedia.org/wiki/PEMFC

[6] http://www.sae.org/fuelcells/fuelcells-history.htm

[7] http://www.hydrogen.energy.gov

[8] F. Barbir *PEM Fuel Cells: Theory and Practice,* 1st Edition, Elsevier Academic Press, 2012.

[9] L. A. Vega, "Ocean thermal energy conversion primer," Marine Technology Society Journal, pp. 25-35, Winter, 2003.

[10] T. Nakaoka, H. Uehara, "Performance test of a shell–and–plate–type condenser for OTEC," Journal of Power Sources 191, pp. 433-441, 2009.

[11] Ch. Xie, Sh. Wang, L. Zhang, S. J. Hu, "Improvement of proton exchange membrane fuel cell overall efficiency by integrating heat–to–electricity conversion," Journal of Power Sources 191, pp. 433-441, 2009.

[12] S. Kakaç, H. Liu *Heat exchangers: selection, rating, and thermal design,* 1st Edition, CRC Press, 2002.

[13] E. A. D. Saunders *Heat exchangers: selection, design*

and construction, 1st Edition, Longmanman Scientific & Technical, 1988.

[14] S. R. Turns, *An introduction to combustion concept & application,* 2nd Edition, McGraw Hill, 2000.

[15] T. J. Kotas, *The exergy method of thermal plant analysis,* reprint edition Edition, Kreiger Publishing Company, 1995.

[16] A. Bejan, G. Tsatsaronis , M. Moran *Thermal Design & Optimization,* NewYork: John Wiley and Sons Inc, 1996.

[17] P. Perrot, *A to Z of Thermodynamics,* Cambridge, Oxford University Press, 1998.

[18] L. Barelli, G. Bidini, F. Gallorini, A. Ottaviano, "An energetic–exergetic comparison between PEMFC and SOFC–based micro–CHP systems," International Journal of Hydrogen Energy 36, pp. 3206–3214, 2011.

[19] A. Ishihara, S. Mitsushina, N. Kamiya, K. Ota, "Exergy analysis of polymer electrolyte fuel cell using methanol," Japan Science and Technology

[20] P. S. Goulding, A. Gough, M. deegan *Compact Reformer for the Solid Polymer Fuel Cell,* Department of Trade and Industry (DTI), London, UK, 1998.

[21] W. G. Colella, "Modelling results for the thermal management sub-system of a combined heat and power (CHP) fuel cell system (FCS)," International Journal of Hydrogen Energy 36, pp. 3206–3214, 2011.

[22] E. Yantovski, "What is exergy," Proc. Int. Conf. ECOS 2004, Ed. Mexico, pp 801-817, 2004.

[23] G. Hoogers *Fuel Cell Technology Handbook,* CRC Press, New York, 2003.

[24] C. Rayment, S. Sherwin *Introduction to fuel cell technology,* Department of Aerospace and Mechanical Engineering, University of Notre Dame, 2003.

[25] J. C. Amphlett, M. Farahani, R.F. Mann, B. A. Peppley, P. R. Roberge, "Parametric modelling of the performance of a 5kW proton–exchange membrane fuel cell stack," Proc. of the 26th Intersociety Energy Conversion Engineering Conference, 1991.

[26] A. A. Kulikovsky, *Analytical Modeling of Fuel Cells,* 1st Edition, Elsevier, 2010.

[27] EG&G Services, *Fuel Cell Handbook,* 5th Edition, Parsons, Inc. Science Applications International Corporation, October 2000.

[28] P. K. Nag, *Power Plant Engineering,* 2nd Edition, McGraw-Hill, 2003.

[29] B. A. Qureshi, S. M. Zubair, "Application of exergy analysis to various psychrometric processes," International Journal of Energy Research 27, pp 1079-1094, 2003.

[30] A. Yilanci, H. K. Ozturk, O. Atalay, I. Dincer, "Exergy Analysis of a 1.2 kWp PEM Fuel Cell System," Proceedings of 3rd International Energy, Exergy and Environment Symposium, 2007.

[31] P. Valdimarsson, "Basic Concepts of Thermoeconomics," Presented at Short Course on Geothermal Drilling, Resource Development and Power Plants, organized by UNU-GTP and LaGeo, in Santa Tecla, El Salvador, January 16-22, 2011.

[32] Y. M. El–Sayed, "Thermodynamics and Thermoeconomics," International Journal of Applied Thermodynamics 2 pp.5–18, March, 1999.

[33] M. S. Peters, K. D. Timmerhaus, R. E. West *Plant Design and Economics for Chemical Engineers,* 5th Edition, McGraw-Hill, 2003.