

Exergoeconomic Model of a PEM Fuel Cell

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Abstract:

This paper presents an exergoeconomic model of a proton-exchange membrane (PEM) fuel cell stack. The model was calibrated using data from experiments performed in a 1.2 kW PEM fuel cell with varying load, operated at steady state. The exergy analysis was performed with fuel cell operation in the air stoichiometry range between 2 to 4. The results showed the system exergy efficiency varied from 26% to 39%, while the energy efficiency ranged between 37% and 56%. This range is slightly above the fuel cell data sheet from the manufacturer, which declares a rated energy efficiency of 48%. High pressure, temperature and cell voltage give better exergy efficiency. Variation of system temperature showed no significant impact on the exergy cost, as the PEM fuel cell operates at relatively low temperature in its load range not exceeding 174°C. The exergy cost of the system can be improved by adopting any combination of higher operating pressure, inlet air stoichiometry or cell voltage, which demonstrates a significant improvement in the exergy cost. By reducing the hydrogen cost from 6.7 \$/kg to 1.9 \$/kg, a 15 \$/GJ decrease in exergy cost can be achieved.

Keywords:

Fuel Cells; Hydrogen; Mathematical Modelling; Numerical Simulation; Exergoeconomic Analysis.

1. Introduction

The importance of using clean fuels is acknowledged by the need to reduce emissions caused by fossil fuels. The current geopolitics in Europe and the energy crisis related to it made the demand for renewable energy even more appealing. In this respect, hydrogen-fed energy systems such as proton-exchange membrane (PEM) fuel cells can positively affect the future energy sector [1]. PEM fuel cells is a promising renewable power generation system that solves some of the existing and future energy shortages [2]. Low or zero emissions is the main advantage of PEM fuel cells as they convert chemical energy directly into electricity by combining hydrogen with oxygen from the air without combustion thus providing higher thermodynamic efficiency than heat engines and turbines.

After decades of research and development, practical PEM fuel cell systems became available and are expected to attract a growing share of automotive and electricity markets as costs decrease to competitive levels. Low-temperature PEM fuel cells can be used for aeroplanes, trains and passenger vehicles. PEM fuel cells use an electrolyte to conduct hydrogen ions from the anode to the cathode. The electrolyte is, in most cases, composed of a solid polymer film consisted of a form of acidified Nafion membrane. The membrane is treated on both sides with highly dispersed metal alloy particles, mainly platinum or platinum alloys, that are effective catalysts. Hydrogen is supplied to the anode side of the fuel cell where, due to the impact of the catalyst, hydrogen atoms discharge electrons and turn into hydrogen ions (protons). The electrons move in the form of an electric current that can be utilised before it returns to the cathode, where oxygen is fed from the ambient air. The protons disperse across the membrane to the cathode, where the hydrogen atom is re-joined and reacted with oxygen to produce water, thus completing the overall process [3].

Two primary performance analyses are usually applied: energy-based analysis and exergy-based analysis. Several authors [4-6] emphasise that the energy-based analysis can be misleading because it does not identify deviations from ideal situations. In contrast, the exergy of an energy form or substance is a measure of its usefulness, quality, or potential to cause change. However, a better understanding of exergy and the insights it can provide into the efficiency, environmental impact and sustainability of energy systems are required for researchers working in energy systems and the environment. Further, as energy policies play an increasingly important role in addressing sustainability issues and a broad range of local, regional and global environmental concerns, policymakers must also appreciate the exergy concept and its ties to these concerns.

During the past decade, the need to understand the connections between exergy and energy, sustainable development and environmental impact has become increasingly significant. Indeed, the universe's energy content is constant, just as its mass content is. On the other hand, exergy is not conserved; once the exergy is wasted, it can never be recovered. When energy is used for heating homes or public places, it is not destroyed but merely converted to a less proper form, a form of less exergy. The exergy of a system can be

defined as its work potential compared to an exergy reference environment. The work potential is intimately related to the maximum work obtainable when the analysed system interacts with the reference environment and simultaneously reaches equilibrium. The term exergy is also related to the thermodynamical availability of a system [7]. The exergy analysis complements the energy analysis and allows including the effect of the temperature level at which the analysis is being carried out [8].

The concept of exergy has also been explored in the area of fuel cells [9]. A thermodynamic and exergoeconomic assessment of the PEM Fuel Cell system was conducted at steady-state operation conditions [10]. The study found that, by increasing the current density, power density, exergy destruction rate, hydrogen consumption and the cost rate of power generation increases. An exergy analysis was carried out on a hybrid system consisting of 64 photovoltaic modules, a 5.5 kW fuel cell and an electrolyser [11]. The study concluded that the average annual exergy efficiency of the fuel cell is 32.8%.

Energy and exergy analyses were performed for a 1.2 kW Nexa PEM Fuel Cell unit in a solar-based hydrogen production system [12]. The study used a model and experimental setup of the system with different operating conditions and found that the increase in current density reduces the energy and exergy efficiencies by 14%. Varying pressure, temperature and anode stoichiometry, the research concluded that the energy and exergy efficiencies respectively increased by 23% and 15% when the pressure was increased, and by 17% and 14% while increasing the anode stoichiometry. Unlike pressure and anode stoichiometry, increasing the temperature has not affected the efficiency level. Exergy analyses were conducted on 10 kW [13] and 1.2 kW [14] PEM fuel cells, respectively, to observe the effect of the operating temperature, cell voltage, air stoichiometry and pressure on the efficiency. The studies concluded that the air stoichiometry should be less than 4, otherwise the membrane will dry out at a high temperature and the relative humidity level in the product air will not be maintained.

The economics of producing electricity from a PEM fuel cell was examined under various conditions [15], investigating the possibility of using a fuel cell vehicle to generate power while parking outside houses or offices. The study found that, for California, USA, net savings could be reached if the fuel cell costs are about \$6000 for a 5 kW home system (\$1200/kW) with favourable natural gas costs of \$6/GJ at residences.

Cogeneration using PEM and other potential fuel cell types was investigated, using both exergy and energy analyses [16]. The research found that exergy analysis is more rational and meaningful as it considers the equivalent work potentials of the thermal and electrical energy products. The study added that energy analyses often present misleadingly optimistic views of performance. The feasibility of fuel cells in cogeneration applications was studied concentrating on both engineering and economic viewpoints [17], using an optimisation approach through a numerical study. The investigation concluded that, in terms of plant capacity, economics, and energy savings, fuel cell cogeneration is better than conventional gas engine cogeneration.

In this work, a MATLAB model was developed to provide an exergoeconomic analysis of a 1.2 kW Nexa™ PEM fuel cell module at variable operating mass flow rates, pressure, temperature, cell voltage and air stoichiometry. The model calculates the fuel and product exergy and the cost rates associated with these energies. Further details are given in the following sections.

2. Exergy and exergoeconomic analysis of the PEM fuel cell

The exergy efficiency of the PEM fuel cell, defined as the ratio between the fuel cell power output and maximum possible work output [18], is carried out by applying the second law of thermodynamics to the control volume shown by Fig. 1. By adding the cost, capital investment, operations, and maintenance cost, the exergoeconomic analysis is also performed. The exergoeconomic analysis is defined by the ratio of the difference between the exergetic cost rate (cost per unit time) of the streams entering and exiting the PEM fuel cell plus the capital investment, operation and maintenance cost of the PEM fuel cell to the electrical power output. The analyses consider all inlet hydrogen is consumed in the reaction, therefore the excess H₂ is zero.

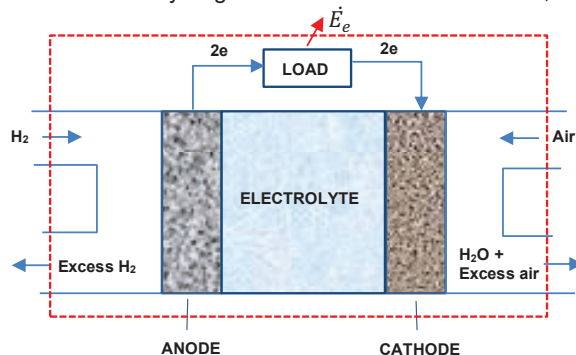


Figure 1. PEM fuel cell schematics.

2.1. Exergy analysis

The fuel cell efficiency (η) is calculated by the ratio of the electrical power output (\dot{E}_e) and the differences between the reactant and the product exergies [13]:

$$\eta = \frac{\text{Electrical output}}{(\text{Total exergy})_R - (\text{Total exergy})_P} = \frac{\dot{E}_e}{(\dot{E}x_{air,R} + \dot{E}x_{H_2,R}) - (\dot{E}x_{air,P} + \dot{E}x_{H_2O,P})} \quad (1)$$

Where R , P and $\dot{E}x$ are reactants, products, and the total exergy, respectively. Kinetic and potential energy effects are neglected in the cell reactions.

The electrical power output is the sum of the auxiliary load (\dot{E}_{aux}) and the external load from reactant consumption (\dot{E}_{ext}), calculated by:

$$\dot{E}_e = \dot{E}_{aux} + \dot{E}_{ext} = I_{fc} \cdot V_{fc} \quad (2)$$

where I_{fc} and V_{fc} are the fuel cell stack current and voltage, respectively.

The external load (\dot{E}_{ext}) is the product of the measured current (I_m) and voltage (V_m):

$$\dot{E}_{ext} = I_m \cdot V_m \quad (3)$$

The auxiliary load is determined by the difference between the electrical power output and the external load.

The fuel cell current is calculated by:

$$I_{fc} = \frac{n_{H_2} \cdot F \cdot \dot{m}_{H_2}}{N} \quad (4)$$

where n_{H_2} is the number of moles of hydrogen consumed per mol of oxidant in the reaction, taken as 2, F is Faraday's constant (96,485 C/mol), \dot{m}_{H_2} is hydrogen mass flow rate, and N is the number of cells in the stack. The total exergy transfer per unit mass (ex) of products and reactants includes both chemical (ex_{CH}) and physical exergies (ex_{PH}) [13]:

$$ex = ex_{CH} + ex_{PH} \quad (5)$$

The physical exergy combines the pressure and temperature of both reactants and products. It can be distinguished as the maximum beneficial work attained by passing the unit of mass of an element from the generic state (T, P) to the environmental state (T_0, P_0). The general expression of the physical exergy is [13]:

$$ex_{PH} = (h - h_0) - T_0(s - s_0) \quad (6)$$

Where h and s are the specific enthalpy and entropy at the actual temperature and pressure condition (T, p), and h_0 and s_0 are the specific enthalpy and entropy at the standard condition of $T_0 = 298$ K and $p_0 = 1$ atm. The physical exergy of an ideal gas with constant specific heat c_p and specific heat ratio k is written as [13]:

$$ex_{PH} = c_p T_0 \left[\frac{T}{T_0} - 1 - \ln \left(\frac{T}{T_0} \right) + \ln \left(\frac{p}{p_0} \right)^{\frac{k-1}{k}} \right] \quad (7)$$

The chemical exergy is the attainment of a maximum quantity of valuable work by assigning a system in equilibrium with the environment using T_0 and P_0 , calculated by [13]:

$$ex_{CH} = \sum x_n ex_{CH,n} + RT_0 \sum x_n \ln x_n \quad (8)$$

where $x_n, ex_{CH,n}^n$ are the respective mole fraction and chemical exergy of each component (n).

The total exergy $\dot{E}x$ of products (P) and reactants (R) are calculated by the following equations [13]:

$$\dot{E}x_{H_2,R} = \dot{m}_{H_2,R} ex_{H_2,R} = \dot{m}_{H_2,R} (ex_{CH} + ex_{PH})_{H_2,R} \quad (9)$$

$$\dot{E}x_{air,R} = \dot{m}_{air,R} ex_{air,R} = \dot{m}_{air,R} (ex_{CH} + ex_{PH})_{air,R} \quad (10)$$

$$\dot{E}x_{H_2O,P} = \dot{m}_{H_2O,P} ex_{H_2O,P} = \dot{m}_{H_2O,P} (ex_{CH} + ex_{PH})_{H_2O,P} \quad (11)$$

$$\dot{E}x_{air,P} = \dot{m}_{air,P} ex_{air,P} = \dot{m}_{air,P} (ex_{CH} + ex_{PH})_{air,P} \quad (12)$$

The chemical and physical exergies, efficiency and mass flow rates are calculated at temperature (T/T_0) and pressure (p/p_0) ratios from 0.94 to 1.2 and 7.40 to 4.88, respectively, which are performing temperature and pressure varieties distinctive for PEM fuel cells [13]. The voltage used in the calculations varies are 0.001 V and 0.79 V at air stoichiometry (λ) between 12.0 and 2.0 to examine its effect on efficiency.

2.2. Exergoeconomic analysis

The exergoeconomic analysis considers the exergy cost (c) of all reactants and products of the electrochemical process at several operating conditions, such as cell voltage, inlet air stoichiometry, temperature and pressure. The cost balance of the PEM fuel cell is given by [18]:

$$c_{H_2O} \dot{X}_{H_2O,P} + c_{air} \dot{X}_{air,P} + c_E \dot{E}_e = c_{air} \dot{X}_{air,R} + c_{H_2} \dot{X}_{H_2,R} + c_{FC,I} \quad (13)$$

Rearranging Eq. (13) for the exergetic power cost (c_E) to find the exergy cost [18]:

$$c_E = \frac{c_{air} \dot{X}_{air,R} + c_{H_2} \dot{X}_{H_2,R} - c_{H_2O} \dot{X}_{H_2O,P} - c_{air} \dot{X}_{air,P} + c_{FC,I}}{\dot{E}_e} \quad (14)$$

The total fuel cell investment cost ($c_{FC,I}$) is given by summation of the fuel cell stack capital cost ($c_{FC,C}$) and the cost rate of operation and maintenance (c_{OM}) [18]:

$$c_{FC,I} = c_{FC,C} + c_{OM} \quad (15)$$

The fuel cell investment cost can be calculated in terms of the power output (\dot{E}_e), capacity factor (CF), i.e., the projected functioning rate, and the annual capital cost (ACC) [18]:

$$c_{FC,I} = \frac{ACC \cdot \dot{E}_e}{CF \cdot 8760(h/year) \cdot 3600(s/h)} \quad (16)$$

Taking the projected functioning rate CF as 90%, the annual capital cost, ACC , can be calculated in terms of the fuel cell stack capital cost and the capital recovery factor (CRF), which can be considered based on the equivalent annual cost over the number of years (n_y) of a specified venture at an annual interest rate (i_r) [18]:

$$ACC = c_{FC,C} \cdot CRF \quad (17)$$

The capital recovery factor can be calculated through the following equation [18]:

$$CRF = \frac{i_r(1 + i_r)^{n_y}}{(1 + i_r)^{n_y} - 1} \quad (18)$$

Where (i_r) has been chosen to be 10% and (n_y) is five years [18]. CRF is calculated as 0.264/year. The fuel cell capital cost, $c_{FC,C}$, is calculated based on the annual average cost for mass production as 2500 \$/kW of power output [19]. The PEM fuel cell parameters and the related costs are shown by Table 1 [15,18,20-22]. Considering the annual operation and maintenance cost (c_{OM}) of 300 \$/kW [15], the cost rate of operation and maintenance, c_{OM} , can be calculated as follow [18]:

$$c_{OM} = \frac{c_{OM} \cdot \dot{E}_e}{8760(h/year) \cdot 3600(s/h)} \quad (19)$$

Table 1. Baseline properties of PEM fuel cell for exergoeconomic evaluation.

PARAMETER	VALUE
Standard conditions	298 K, 1 atm
Electrical energy output	1.2 kW
Air stoichiometry	3
Hydrogen cost	10 \$/kg
Water cost	1 \$/m ³
Air cost (O ₂)	0.011 \$/kg
Fuel cell cost (capital cost)	2500 \$/kW
The capacity factor of the fuel cell	0.9
Fuel cell lifetime	5 years
Average annual interest rate	10%
Annual operation and maintenance cost	300 \$/kW yr

3. Experimental setup

Both the exergy and exergoeconomic analyses use data from experiments performed in a Ballard Nexa model fuel cell stack system consisting of 47 cells capable of generating 1.2 kW DC power output with 48% efficiency at 65°C. Each cell produces 1.0 V and 0.6 V at open-circuit and maximum current output, respectively. The stack voltage is 43 V and 26 V at no load and full load, respectively. The fuel is 99.99% hydrogen, maintained by the control system at 0.3 bar. The reactant oxygen comes from the ambient air, which pressure is maintained at 0.1 bar and humidified by a built-in humidifier. The area of the cells is 120 cm². The fuel cell stack specifications are shown by Tab. 2.

Table 2. Fuel cell stack specifications.

DOMAIN	PARAMETER	VALUE
Performance	Rated power	1.2kW
	Dissipated heat at rated power	1.6kW
	Idle/full voltage at rated power	43 V / 26 V DC
	Operating voltage rate	22 V to 50 V
	Input voltage allowable	18 V to 30 V
	Current at rated power	46 A DC
	Number of cells	47
	Lifetime	1,500 hours
Reactant	Hydrogen (dry)	99.99%,
	Pressure range of hydrogen	0.7 to 17 bar
	Hydrogen consumption	<18.5 L/min
	Process Air	≤ 90 L/min
Operating environment	Air pressure	atm
	Ambient temperature	(3°C to 40°C)
	Maximum stack temperature	65°C
Product	Humidity	5% to 95%
	Pure water (vapour and liquid)	0.870 L/h
Physical	L x W x H	56 x 25 x 33 cm
	System mass	13 kg

4. Results and discussion

The results presented in this section were obtained considering fuel cell operation along 5 years (Tab. 1) without the need of replacement, corresponding to 39,420 h of operation according to Eq. (16). This is based on a previous report that the polymer membrane of a PEM fuel cell can exceed 40,000 h of operation at harsh conditions [22]. Thus, the manufacturer's declaration of 1,500 h lifetime (Tab. 2) and the need of capital reinvestment each time this limit was reached along the evaluation period have not been part of the calculation.

4.1. Exergy analysis

Figure 2 illustrates the energy and exergy efficiencies of the system. While the exergy efficiency was calculated using Eq. (1), the energy efficiency was determined by the ratio of the fuel cell electrical power output and the inlet hydrogen energy content given by the product of hydrogen high heating value and its mass flow rate. It can be observed that both the energy and exergy of the fuel cell system decrease as the current density increases. The energy efficiency varies between 37 to 56% and the exergy efficiency ranges from 26 to 39% as the current density is changed from 0.02 to 0.37 A/cm². This behaviour is due to the increase of reactant air and decrease of hydrogen pressure with increasing current density (Fig. 3). The maximum energy efficiency here found is 9% lower compared with the fuel cell manufacturer datasheet, while the exergy efficiency is 3% lower compared to values reported by other authors [23]. The ambient air conditions may have been determinant to the discrepancies.

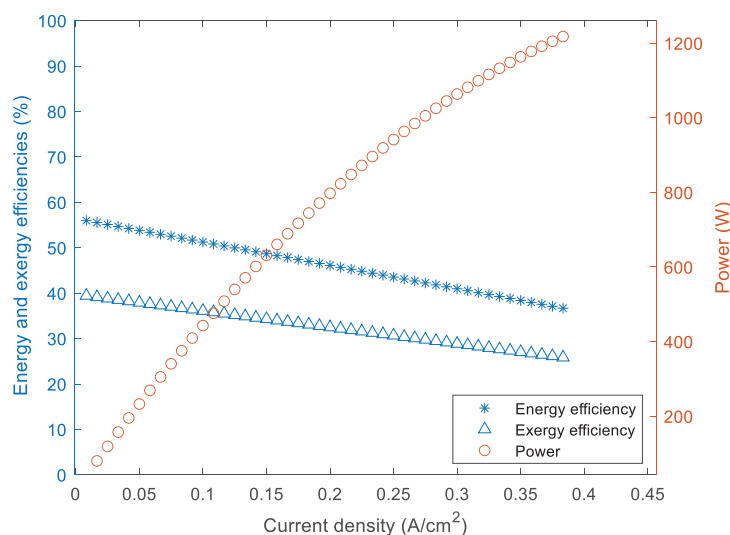


Figure 2. Variation of fuel cell output power, energy and exergy efficiencies with current density.

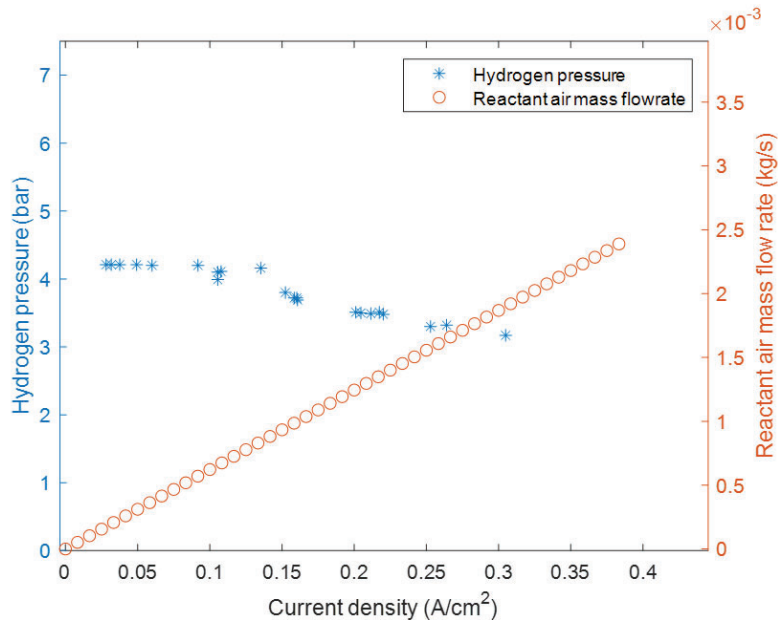


Figure 3. Variation of fuel cell hydrogen pressure and inlet air mass flow rate with current density.

Figures 4 and 5 show that the physical exergy of the flow stream through the fuel cell increase with both temperature and pressure ratios, though with different patterns. Higher temperature ratios intensify the growth of the physical exergy (Fig. 4), while, with increasing pressure ratio, the growth of physical exergy tends to be less intense (Fig. 5). Higher temperatures increase the diffusivity of the reactants and improve ionic conduction of the membrane, but they also lead to greater evaporation of water and, therefore, drying of the membrane and reduced conductivity [24]. The fuel cell system here considered has a humidity exchanger, therefore water vapour in the reactant gases balances the drying effect of temperature. On the other hand, increasing pressure benefits performance as this increases the diffusivity of the reactant gases, facilitating mass transport to the electrodes. The fuel cell humidity exchanger minimises the diffusion of product water into the membrane by the pressure gradient towards the anode, as the product water is used to humidify the inlet air.

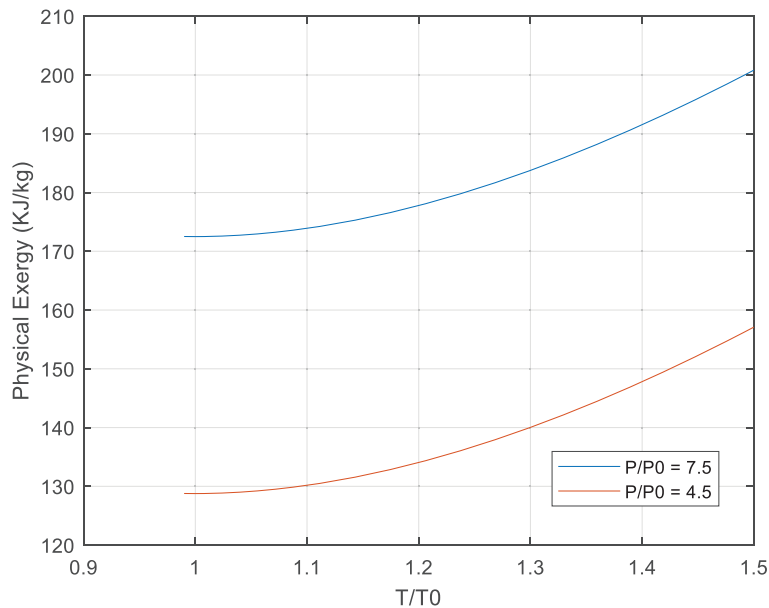


Figure 4. Variation of fuel cell physical exergy with temperature ratio.

The physical exergy of product water is shown by Figs. 6 and 7, as it varies with temperature ratio and pressure ratio, respectively. The increase of product water helps the reactant air to attain an ideal temperature without the need to operate at low pressure as it is heated when flowing through the compressor, thus evaporating the water to be used by the humidifier. The absence of an internal humidifier could lead to nonattractive options such as lowering the temperature, which increases losses, lowering air flowrate and hence the air stoichiometry, which would reduce the cathode performance, or increasing pressure, which would increase the auxiliary power to run the compressor [25]. Furthermore, the humidification of reactants favours the conduction of hydrogen ions in the membrane. Water content dramatically influences the membrane conductivity, and it is vital to transport the reactants and the reaction kinetics in the electrode. If water diffusion between the cathode and membrane is insufficient to keep the membrane hydrated, the ohmic losses in the membrane at high current density can cause a significant fraction of the cell voltage loss. Consequently, to minimise ohmic losses, the hydrogen flow must also be humidified [26].

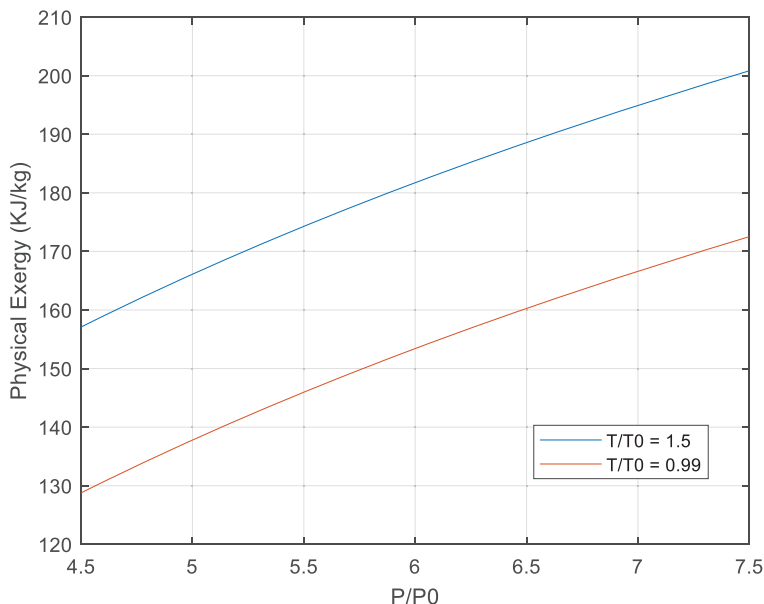


Figure 5. Variation of fuel cell physical exergy with pressure ratio.

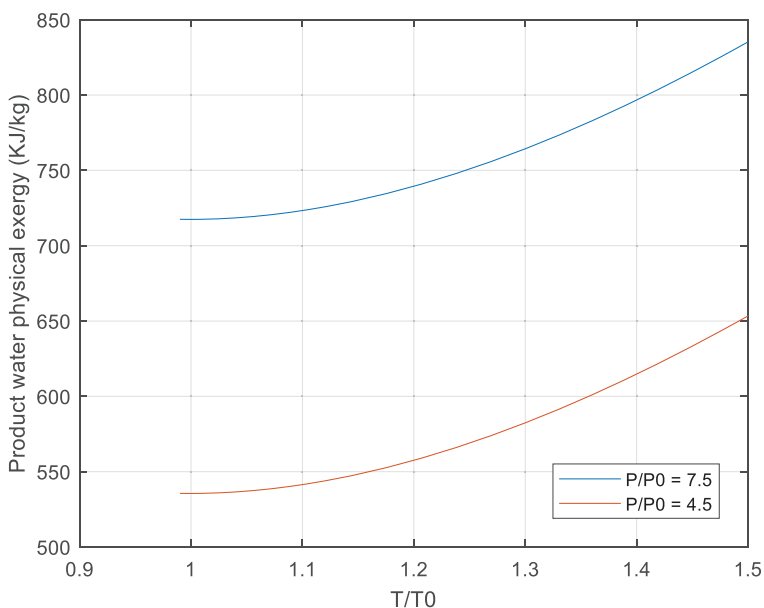


Figure 6. Variation of product water physical exergy with temperature ratio.

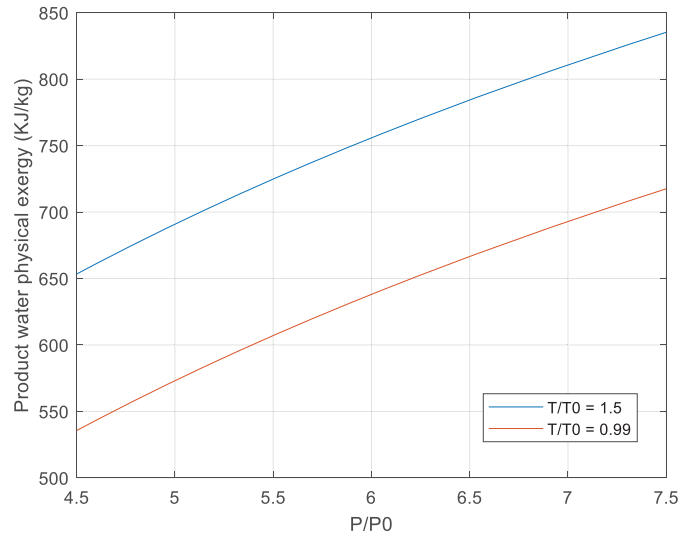


Figure 7. Variation of product water physical exergy with pressure ratio.

4.2. Exergoeconomic analysis

The exergoeconomic analysis considers the exergy cost of all reactants and products for the electrochemical process in the system at various operating conditions, such as temperature, pressure, cell voltage and inlet air stoichiometry (λ). The analysis was performed for cell operation from 0.55 V to 0.85 V, air stoichiometry ranging between 2 and 4, pressure ratio from 4.5 to 7.5, and temperature ratio ranging from 0.99 and 1.5. The capital recovery factor CRF was calculated by Eq. (18) as 0.244 per year. The fuel cell cost could range from as high as 9000 \$/kW to as low as 300 \$/kW for mass production, from which an average value of 2500 \$/kW of power output was used in this analysis. The exergy cost of the fuel cell system is not significantly affected by temperature and pressure variation, as shown by Fig. 8, staying in the range of 115.46 ± 0.01 \$/GJ.

Since hydrogen costs are expected to decrease dramatically over the next decade due to production, distribution, equipment and component manufacturing scale up, the estimated hydrogen price in 2030 was assumed to be 1.9 \$/kg to build the results of Fig. 9, representing a drop of 71.6% to the current hydrogen price of 6.7 \$/kg used in the exergy cost analysis of Fig. 8 [27]. The predicted hydrogen price will reduce the exergy cost by about 14.3 \$/GJ, corresponding to a relative decrease of 12.4% compared with today's price. These results reveal a long way to go to decrease hydrogen price in order to obtain a significant improvement on the fuel cell exergy cost. Anticipated lowering of capital cost due to production of electrodes, membranes and catalyst layers at a mass scale may further reduce the fuel cell exergy cost [28,29].

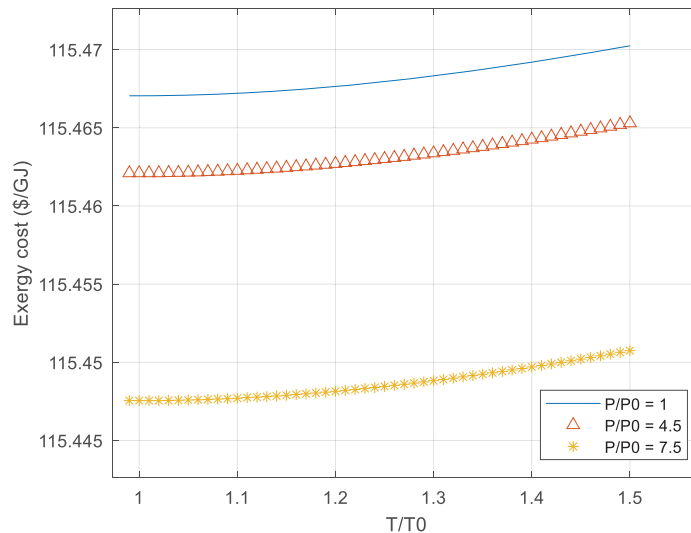


Figure 8. Variation of fuel cell exergy cost with temperature and pressure ratios, at current hydrogen cost.

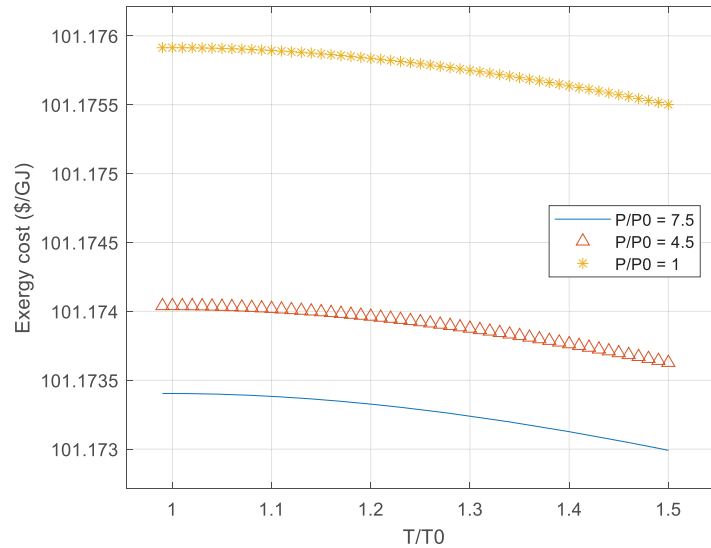


Figure 9. Variation of fuel cell exergy cost with temperature and pressure ratios, at estimated 2030 hydrogen cost.

An improvement of 35 \$/GJ can be achieved by operating at a higher stoichiometric ratio ($\lambda = 4$) rather than using the recommended ratio of $\lambda = 3$, as shown by Fig. 10. In opposition, a similar increase of exergy cost will occur if operating at the lower stoichiometric ratio of $\lambda = 2$. However, one should be extremely careful in setting up the air stoichiometry higher than the recommended range because, at high fuel cell operating temperature and air stoichiometry, the relative humidity of the product air will be lowered. Hence, a higher risk of the cells dehydrating could occur, causing a sharp decrease in the system's efficiency [25,30].

The fuel cell system voltage can also play a key role in its exergy cost, as Fig. 11 shows. The cost can be lowered from 115.5 \$/GJ to 108.40 \$/GJ if the cell voltage is increased from 0.56 V to 0.6 V. The lower the cell voltage, the higher will be the mass flow rates required for reactants and the products to operate the system to produce the desired power output thus leading to lower exergetic efficiency and higher exergy cost. Changes in the exergy cost of the fuel cell system from various operating temperatures are negligible (see Fig. 8), as opposed to the effect of various cell voltages. However, it should be noted that PEM fuel cells are regarded as a low-temperature systems (up to 65°C) in comparison with other fuel cell types such as solid oxide fuel cells or molten carbonate fuel cells. For these fuel cells, the operating temperatures should play a more significant role to exergy efficiency and costs [25].

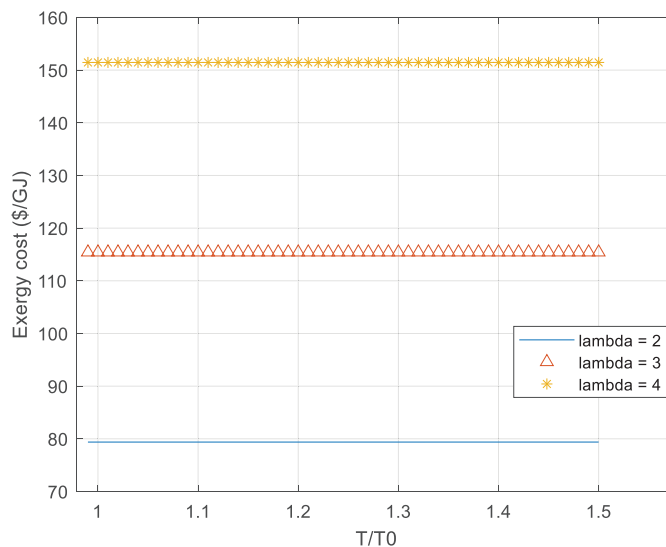


Figure 10. Variation of exergy cost with temperature and air/fuel stoichiometric ratios ($V = 0.56$ V, $P/P_0 = 1$).

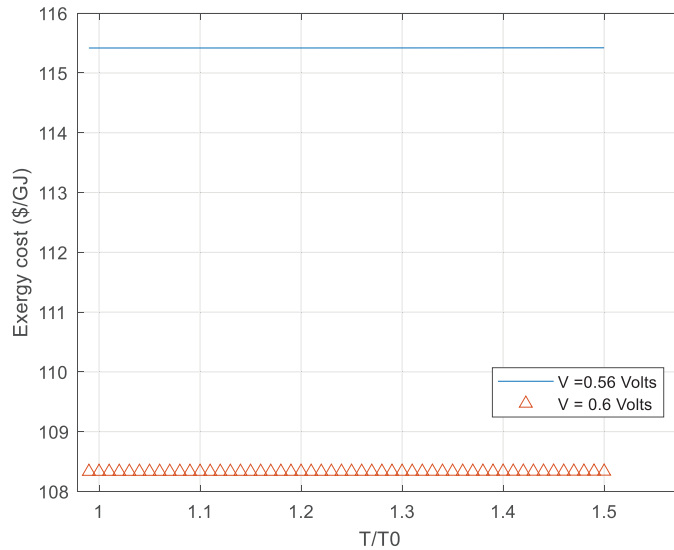


Figure 11. Variation of exergy cost with temperature ratio and voltage ($\lambda = 3$, and $P/P_0 = 1$).

5. Conclusion

This work revealed that the PEM fuel cell and product water physical exergies can be improved with increased operating temperature and pressure. However, operation at high temperatures is limited by excessive water evaporation with consequent drying of the membrane and, thus, reduced conductivity, while operation at increased pressure will require higher power demand by the compressor. High product water exergy benefits membrane conductivity and cathode performance as water evaporated during the air compression process can be used to humidify the membrane and enhance its conductivity. The operating temperature and pressure had negligible effect on the exergy cost, but it can significantly be affected by hydrogen price, air/fuel stoichiometry and operating voltage. An estimated reduction of just over 70% on the hydrogen price by 2030 will produce a decrease of the exergy cost by about 12%. Increasing the air stoichiometry by a third of its recommended value can reduce the exergy cost by 30%, but there are imposed limitations on this strategy by the risk of cell dehydration causing loss of efficiency. Operating voltage increase by 7% can produce a reduction of exergy cost by a similar rate. As overall recommendation, the fuel cell exergy cost can noticeably be improved by adopting a combination of higher inlet air stoichiometry and cell voltage, while more emphatic enhancement will be achieved by lowering the capital cost, annual operation and maintenance cost and hydrogen price.

Nomenclature

ACC	annual capital cost, US\$
c	cost, US\$
CF	capacity factor, dimensionless
CRF	capital recovery factor, dimensionless
\dot{E}_{aux}	auxiliary load, kW
\dot{E}_e	electrical power output, kW
\dot{E}_{ext}	external load from reactant consumption, kW
ex	total exergy transfer per unit mass, kW/kg
ex_{CH}	chemical exergy per unit mass, kW/kg
ex_{PH}	physical exergy per unit mass, kW/kg
$\dot{E}x$	exergy, kW
F	Faraday's constant (96,485 C/mol)
h	specific enthalpy, kJ/kg
i_r	annual interest rate, dimensionless
I_{fc}	fuel cell stack current, A
I_m	measured current, A
\dot{m}_{H_2}	hydrogen mass flow rate, kg/s
n_{H_2}	number of moles of hydrogen consumed per mol of oxidant in the reaction, mol
n_y	number of years, dimensionless
N	number of cells in the stack, dimensionless

P	pressure, kPa
s	specific entropy, kJ/kg.K
T	temperature, K
V_{fc}	fuel cell stack voltage, V
V_m	measured voltage, V
x_n	mole fraction of component n, dimensionless

Greek symbols

η	fuel cell efficiency, %
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Subscripts and superscripts

0	standard condition (1atm, 298 K)
<i>air</i>	air
C	capital
E	exergy
FC	fuel cell
H_2	hydrogen
H_2O	water
I	investment
n	component in the reaction
OM	operation and maintenance
P	products
R	reactants

References

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