



## Thermo-environmental performance analysis of irreversible solid oxide fuel cell – Stirling heat engine

Emin Açıkkalp

To cite this article: Emin Açıkkalp (2018) Thermo-environmental performance analysis of irreversible solid oxide fuel cell – Stirling heat engine, International Journal of Ambient Energy, 39:7, 751-758, DOI: [10.1080/01430750.2017.1345011](https://doi.org/10.1080/01430750.2017.1345011)

To link to this article: <https://doi.org/10.1080/01430750.2017.1345011>



Published online: 04 Jul 2017.



Submit your article to this journal [↗](#)



Article views: 190



View related articles [↗](#)



View Crossmark data [↗](#)



Citing articles: 1 View citing articles [↗](#)



# Thermo-environmental performance analysis of irreversible solid oxide fuel cell – Stirling heat engine

Emin Açıkkalp

Department of Mechanical Engineering, Engineering Faculty, Bilecik S.E. University, Bilecik, Turkey

## ABSTRACT

A hybrid, irreversible solid oxide fuel cell – Stirling heat engine system is taken into account. Thermo-environmental criterion approach, which enables to evaluate environmental impact of any thermal cycle, is applied to the considered system for the first time. Power density, exergy density, thermo-environmental function density, energy and exergy efficiencies are considered. Results are presented and discussed to determine optimum operating conditions. Some important results for the hybrid system are ordered: maximum power density is 7489.92 ( $A\ m^{-2}$ ), maximum energy and exergy efficiencies are 0.800 and 0.887, respectively, and finally, thermo-environmental function density is 0.0276 ( $W\ mpts^{-1}\ m^{-2}$ ).

## ARTICLE HISTORY

Received 26 April 2017  
Accepted 18 June 2017

## KEYWORDS

Solid oxide fuel cell; Stirling cycle; thermo-environmental function; irreversibility; finite-time thermodynamics

## 1. Introduction

There is a growing demand for energy in the world, and fossil fuels are the main energy sources that cause environmental pollutions. Fuel cells and heat engine hybrid cycles may be an alternative for sustainable energy technology. They are already used in automotive and power generation industry. Solid oxide fuel cell (SOFC) is appropriate for using in hybrid cycles because of the high temperature obtained from them.

In the last decades, studies on modeling irreversible fuel cells (Zhao, Ou, and Chen 2008; Zhang, Guo, and Chen 2010; Zhang, Lin, and Chen 2011a; Zhang, Lin, and Chen 2012; Zhang et al., “Performance Analysis of a Direct Carbon” 2014) and fuel cell–heat engine hybrid systems (Haseli, Dincer, and Naterer 2008a, 2008b; Zhao and Chen 2009; Zhang and Chen 2010; Chen et al. 2011, 2014; Zhang et al. 2011; Zhang, Lin, and Chen 2011b; Zhang et al. 2012; Zhang, Guo, and Chen 2012; Chen, Gao, and Zhang 2013; Zhang et al., “A Unified Model” 2014; Yang and Zhang 2015; Zhang et al. 2015; Zhao et al. 2015; Huang et al. 2016; Açıkkalp 2017a, 2017b) increased. In previous studies, Stirling, Brayton, Braysson heat engines, absorption refrigerator and thermoelectric generator were chosen as in hybrid systems. Stirling engines are remarkable among heat engines because of their high efficiency, simple design and wide variety of energy sources. As a result, they have many engineering applications.

Finite-time thermodynamic (FTT) is a useful way to optimize and evaluate actual thermal cycles because it considers irreversibilities in the considered system. Some studies about FTT can be found in Ahmadi et al., “Optimal Design” (2013), Sadatsakkak, Ahmadi, and Ahmadi (2015), Ahmadi et al. (2014, 2017), Sadatsakkak et al. (2015), Ahmadi, Ahmadi, and Feidt (2015), Ahmadi and Ahmadi (2016), Ahmadi, Ahmadi, and Pourfayaz (2016), Ahmadi and Mehrpooya (2015), Ahmadi et al., “Thermodynamic Analysis and Evolutionary” (2016). Ahmadi et al., “Multi-objective Optimization and Exergetic” (2016), Andresen et al.

(1984), Bejan (1996), Chen, Wu, and Sun (1999), Wu, Chen, and Chen (1999), Sieniutycz (2000, 2016), Chen and Sun (2004), Chen (2005), Andresen (2011), Chen, Meng, and Sun (2016), Ge, Chen, and Sun (2016), Chen, Feng, and Xie (2016), Feng et al. (2015), Chen and Xia (2017a, 2017b) and Bi and Chen (2017). In addition, some examples of investigating Stirling engines can be found in Wu et al. (1998), Chen et al. (1998), Ahmadi et al., “Designing a Solar Powered Stirling” (2013), Ahmadi et al., “Application of the Multi-objective” (2013), Ahmadi et al., “Thermoeconomic Multi-objective” (2013), Ahmadi et al., “Multi-objective Thermodynamic-based” (2013), Ahmadi et al., “Thermodynamic Analysis and Multi Objective” (2016) and Ahmadi, Ahmadi, and Pourfayaz (2017).

In this work, irreversible SOFC – Stirling hybrid heat engine is studied. The considered system is investigated in terms of thermo-environmental criterion for the first time as well as power density, exergy destruction density, energy and exergy efficiencies. Thermo-environmental criterion provides an engineer or scientist opportunity to evaluate environment effect of any thermal cycle. Results are obtained numerically and optimum operating conditions are presented.

## 2. Thermodynamic analysis

### 2.1. Analysis for the SOFC

A hybrid SOFC – Stirling heat engine is shown in Figure 1; it includes SOFC, regenerator and Stirling engine. SOFC acts as high-temperature heat source that is required to power generating in the Stirling engine. The role of the regenerator in the hybrid system is to preheat the incoming fuel and air with the high-temperature exhaust gas of the fuel cell (Zhang and Chen 2010).  $H_2$  is the fuel; air is the oxidant; and water, electricity and heat are products. This chemical reaction is described as  $H_2 + 0.5O_2 \rightarrow H_2O + \text{heat} + \text{electricity}$ . Efficiency and power of

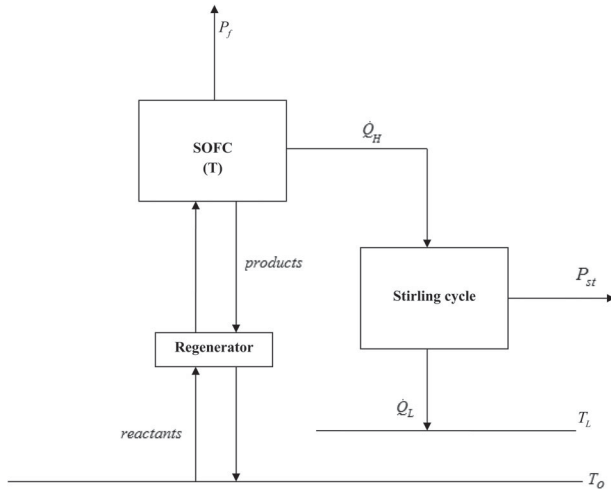


Figure 1. SOFC – Stirling hybrid heat engine.

the SOFC can be respectively described as follows (Zhao, Ou, and Chen 2008):

$$\eta_f = \frac{P_f}{-\Delta H} = \frac{1}{-\Delta h} \left( m - \frac{k}{RTd_1} m^2 \right), \quad (1)$$

$$P_f = \frac{iA}{n_e F} \left( m - \frac{k}{RTd_1} m^2 \right), \quad (2)$$

where  $i$  is the current density,  $F$  is the Faraday constant,  $n_e$  is the number of electrons,  $A$  is the polar plate area,  $R$  is the universal gas constant,  $T$  is the operating temperature of the fuel cell,  $d_1$  and  $m$  are written respectively as

$$d_1 = 2n_e \sinh^{-1} \left( \frac{i}{2i_{o,a}} \right) + 2n_e \sinh^{-1} \left( \frac{i}{2i_{o,c}} \right) - \ln \left( 1 - \frac{i}{i_{L,a}} \right) - \ln \left( 1 - \frac{i}{i_{L,c}} \right) + \frac{in_e F L_{el}}{\sigma_o R} \exp \left( \frac{E_{el}}{RT} \right), \quad (3)$$

$$m = -\Delta g(T) + RT \ln \left( \frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}} \right) - RTd_1, \quad (4)$$

where  $i_{o,a}$  and  $i_{o,c}$  are the anode and cathode exchange current densities;  $L_{el}$  is the thickness of the electrode;  $\sigma_o$  is the reference ionic conductivity;  $p_{H_2}$ ,  $p_{O_2}$  and  $p_{H_2O}$  are the partial pressures of  $H_2$ ,  $O_2$  and  $H_2O$ ;  $i_{L,a}$  and  $i_{L,c}$  are the limiting current densities of the anode and cathode;  $E_{el}$  is the activation energy of the  $O^{2-}$ ; and  $\Delta g$  is the molar Gibbs function change. Enthalpy change in the SOFC is

$$-\Delta H = -\frac{iA}{n_e F} \Delta h, \quad (5)$$

where  $\Delta h$  is the molar enthalpy change. Reversible power of the fuel cell is Zhao, Ou, and Chen (2008):

$$P_{f,rev} = -\frac{iA}{n_e F} \Delta g. \quad (6)$$

Exergy destruction rate of the fuel cell can be defined as

$$Exd_f = P_{f,rev} - P_f. \quad (7)$$

Heat transfer rate in the regenerator is defined as follows

$$\dot{Q}_r = K_r(1 - \varepsilon_r)(T - T_o), \quad (8)$$

where  $T_o$  is the ambient temperature,  $K_r$  is the heat conductance of the regenerator and  $\varepsilon_r$  is the regenerator efficiency. Using the first law of the thermodynamics, heat input to the bottom cycle can be expressed as:

$$\dot{Q}_H = -\Delta H - P_{fc} - \dot{Q}_r. \quad (9)$$

## 2.2. Analysis of the Stirling engine

After investigated the SOFC, the power output, energy and exergy efficiencies, exergy destructions of the Stirling engine must be described. Heat inputs and outputs are described in Equations (10) and (11) (Chen et al. 1998; Wu et al. 1998):

Heat inputs are:

$$Q_H = \theta(T - T_1)t_1, \quad (10a)$$

$$Q_H = nRT_1 \ln x. \quad (10b)$$

Heat outputs are:

$$Q_L = \theta(T_2 - T_L)t_2, \quad (11a)$$

$$Q_L = nRT_2 \ln x, \quad (11b)$$

where  $\theta$  is the heat conductance ( $W m^{-2} K^{-1}$ ),  $n$  is the mol number,  $x$  is the compression ratio ( $x = V_{max}/V_{min}$ ),  $T_1$  and  $T_2$  are average temperatures of the compression and expansion processes,  $t_1$  and  $t_2$  are the times spent on the two isothermal branches.  $t_1$  and  $t_2$  can be determined by using Equations (10) and (11). Using Equations (9) and (10a), one can yield  $T_1$ . Regenerative loss is Wu et al. (1998) and Chen et al. (1998):

$$\Delta Q = \alpha nC(T_2 - T_L)t_2, \quad (12)$$

where  $C$  is the heat capacity ( $J mol^{-1}$ ),  $\alpha$  is the imperfect regeneration coefficient. Time spent on regeneration time is (Chen et al. 1998):

$$t_r = b(t_2 + t_1). \quad (13)$$

Heat rate can be obtained as

$$\dot{Q}_H = \frac{\ln x + \frac{\alpha(1-y)}{(\delta-1)}}{(1+b) \left( \frac{\ln x}{\theta(T-T_1)} + \frac{y \ln x}{\theta(yT_1-T_L)} \right)}. \quad (14)$$

Using Equations (9) and (14),  $x$  can be defined. Energy efficiency of the irreversible Stirling cycle can be described as Wu et al. (1998)

$$\eta_{st} = 1 - \frac{\dot{Q}_L}{\dot{Q}_H} = \frac{(1-y)}{\left( 1 + \frac{\alpha(1-y)}{(\delta-1) \ln x} \right)}, \quad (15)$$

where  $\delta$  is the ratio of the specific heats, and heat rejection from the irreversible Stirling engine is obtained by using Equation (15):

$$\dot{Q}_L = \dot{Q}_H(1 - \eta_{st}). \quad (16)$$

Power of the irreversible Stirling, exergy destruction of the irreversible Stirling engine and reversible power of the Stirling

engine are shown respectively in Equations (17)–(19):

$$P_{st} = \dot{Q}_H - \dot{Q}_L, \quad (17)$$

$$\text{Exd}_{st} = T_o \left( \frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T} \right), \quad (18)$$

$$P_{rev,st} = \dot{Q}_H \left( \frac{T_o}{T} \right) - \dot{Q}_L \left( \frac{T_o}{T_L} \right). \quad (19)$$

**Table 1.** Parameters used in calculations (Goedkoop, Demmers, and Collignon 1995; Goedkoop and Spriensma 2000; Zhao, Ou, and Chen 2008; Zhao and Chen 2009; Zhang et al. 2011; Chen, Gao, and Zhang 2013; Zhang et al., “A Unified Model” 2014).

Parameter	Unit	Value
$p_{H_2}, p_{H_2O}$	atm	0.97, 0.03
$p_{O_2}, p_{N_2}$	atm	0.21, 0.79
$n_e$	–	2
$i_{o,a}$	$\text{A m}^{-2}$	$1.3 \times 10^3$
$i_{o,c}$	$\text{A m}^{-2}$	$5.6 \times 10^3$
$L_{el}$	$\mu\text{m}$	20
$E_{el}$	$\text{J mol}^{-1}$	$8 \times 10^4$
$\sigma_o$	$\text{S m}^{-1}$	$3.6 \times 10^7$
$k$	–	1/100
$i_{i,a}$	$\text{A m}^{-2}$	$2.99 \times 10^4$
$i_{i,c}$	$\text{A m}^{-2}$	$2.16 \times 10^4$
$F$	$\text{C mol}^{-1}$	96,485
$R$	$\text{J mol}^{-1} \text{K}^{-1}$	8.314
$\Delta g$	$\text{J mol}^{-1}$	–183,100
$\Delta h$	$\text{J mol}^{-1}$	–248,921
$T$	K	1173
$K_f$	$\text{W m}^{-2} \text{K}^{-1}$	10
$\alpha$	–	0.3
$\delta$	–	1.66
$y$	–	0.5
$\theta$	$\text{W m}^{-2} \text{K}^{-1}$	500
$b$	–	$30 \times 10^{-3}$
$T_o$	K	293.15
$T_L$	K	300
$b_1$	$\text{Mpts kg}^{-1}$	17
$b_2$	$\text{mpts MJ}^{-1}$	0.57
$M$	kg	5000

### 2.3. Parameters of the hybrid system

Power output, energy efficiency, exergy efficiency and exergy destruction of the hybrid system can be respectively defined as follows:

$$P_h = P_f + P_{st}, \quad (20)$$

$$\eta_h = \frac{P_f + P_{st}}{-\Delta H}, \quad (21)$$

$$\varphi_h = \frac{P_f + P_{st}}{P_{rev,f} + P_{rev,st}}, \quad (22)$$

$$\text{Exd}_h = \text{Exd}_f + \text{Exd}_{st}. \quad (23)$$

The last parameter called thermoenvironmental function has been proposed in Özel et al. (2015) and it is expressed for the considered system in Equation (24). Environmental effect of hydrogen is neglected in calculations, and  $b_1$  and  $b_2$  are obtained from Eco indicator 95 and Eco indicator 99 (Goedkoop, Demmers, and Collignon 1995; Goedkoop and Spriensma 2000). Aim of this criterion is to determine environmental impact of the system, which is described as power output per environmental effect as milipoints. This function aims to obtain maximum power output and to minimize the environmental effects and it is shown as follows:

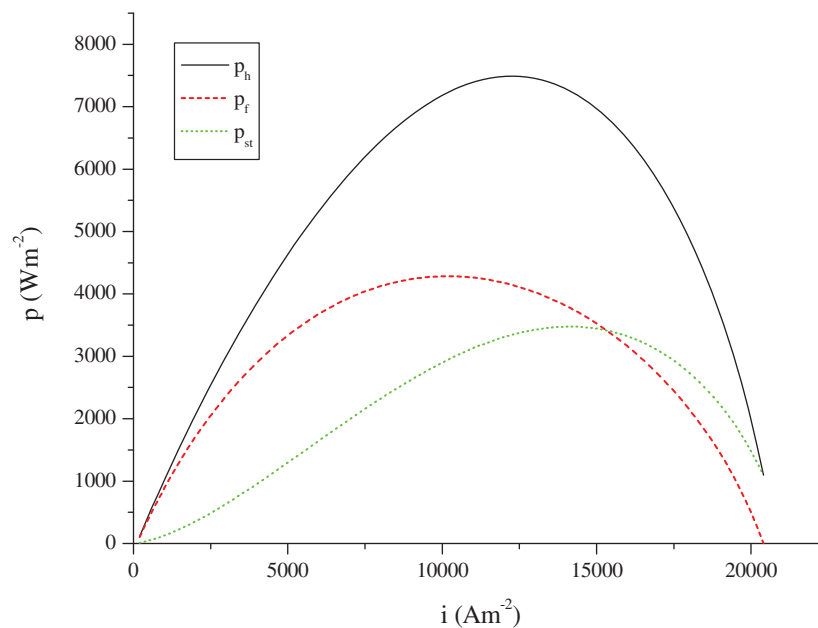
$$F = \frac{P_h}{Mb_1 + \text{Exd}_h b_2 + P_h b_3}, \quad (24)$$

$b_2$  is assumed as (Özel et al. 2015):

$$b_2 = (1 - \varphi) b_3. \quad (25)$$

### 3. Results and discussion

In this section, parametric analysis is carried out to evaluate the performance of the considered system. Power output, exergy destruction, thermoenvironmental criterion, energy and exergy



**Figure 2.** Variation of power density with  $i$ .

efficiencies are presented by using Equations (15)–(19) and they are investigated. Fixed parameters used in calculations can be seen in Table 1.

In Figures 2–6, changes of parameters according to  $i$  are shown. In Figure 2, it is seen that power densities ( $p = P/A$ ) reach their maximum (optimum) values at  $i = 12,200$  ( $A m^{-2}$ ),  $i = 10,200$  ( $A m^{-2}$ ) and  $i = 14,200$  ( $A m^{-2}$ ) for the hybrid system, fuel cell and Stirling engine, respectively. Corresponding values are  $7489.92$  ( $A m^{-2}$ ) and  $4283.67$  ( $A m^{-2}$ ) and  $3476.77$  ( $A m^{-2}$ ). As seen in Figure 3, energy efficiencies reach their maximums (optimums) at  $i = 1600$  ( $A m^{-2}$ ),  $1000$  ( $A m^{-2}$ ) and  $200$  ( $A m^{-2}$ ) for the hybrid system, fuel cell and Stirling engine respectively and their values are equal to  $0.800$ ,  $0.688$  and

$0.485$ . Optimum values for the exergy efficiencies can be shown in Figure 4, maximum exergy efficiency of hybrid system is obtained at  $i = 1000$  ( $A m^{-2}$ ) and it is equal to  $0.887$ , maximum exergy efficiencies for fuel cell and Stirling engines are provided at  $i = 1000$  ( $A m^{-2}$ ) and  $200$  ( $A m^{-2}$ ), they are equal to  $0.934$  and  $0.657$ , respectively. When exergy efficiencies are considered, it is shown that exergy efficiency value of the fuel cell is bigger than that of the hybrid system and Stirling engine. Maximum current densities at maximum power and maximum energy efficiency are described as  $i_p$  and  $i_\eta$  respectively and system are designed classically such that current density is  $i_\eta \leq i \leq i_p$ . Exergy destruction density ( $exd = Exd/A$ ) is plotted in Figure 5, they increase logarithmically steady for the hybrid system, fuel

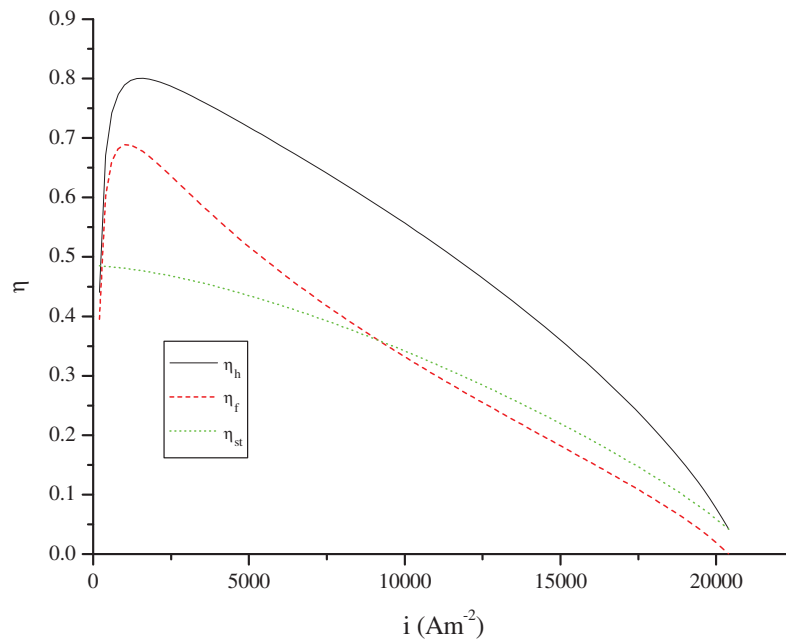


Figure 3. Variation of energy with  $i$ .

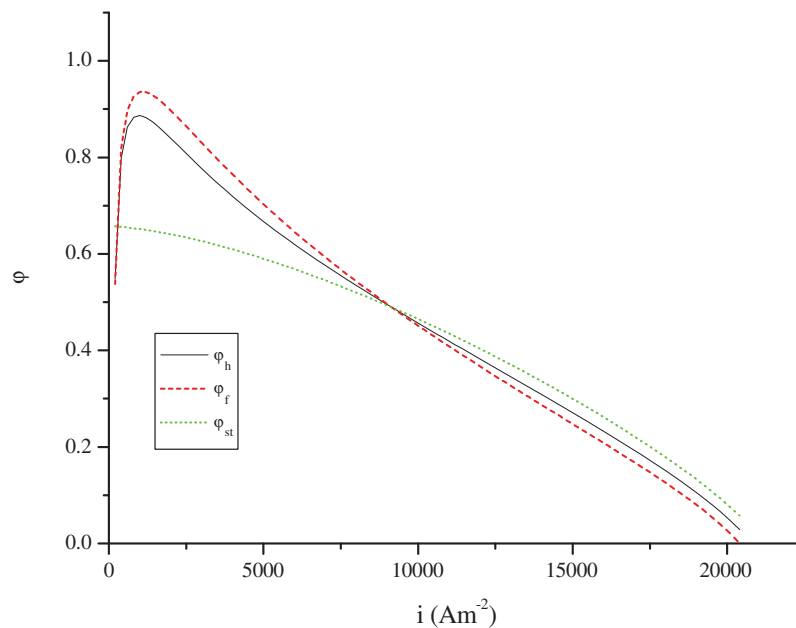


Figure 4. Variation of exergy efficiencies with  $i$ .

cell and Stirling engine. exd of the hybrid system is equal to 12,491.20 ( $\text{W m}^{-2}$ ) at maximum power density, 260.88 ( $\text{W m}^{-2}$ ) at maximum energy efficiency, 130.173 ( $\text{W m}^{-2}$ ) at maximum exergy efficiency and 7600.70 ( $\text{W m}^{-2}$ ) at maximum thermoenvironmental function. It is seen that exergy destruction density gets its minimum value at maximum exergy efficiency. According to Figure 6,  $f$ , which is called as thermoenvironmental function density ( $f = F/A$ ), reaches its maximum (optimum) point at  $i = 9400$  ( $\text{A m}^{-2}$ ) and it is 0.0276 ( $\text{W mpts}^{-1} \text{m}^{-2}$ ). At the maximum  $f$ , exd is 7600.7 ( $\text{W m}^{-2}$ ), exergy efficiency is 0.480. In Figure 7, illustration of variation of the power density with energy efficiency for the hybrid system is shown.  $p_{\max}$  represents the maximum power density,  $P_{\eta}$  represents the power

density at the maximum efficiency, similarly,  $\eta_p$  is the efficiency at the maximum power and  $\eta_{\max}$  is the maximum efficiency. Efficiency and power values should be chosen as  $\eta_p \leq \eta \leq \eta_{\max}$  and  $p_{\eta} \leq p \leq p_{\max}$ .  $p_{\eta}$  is 1651.96 ( $\text{W m}^{-2}$ ) that is corresponding to 22% of the maximum power and  $\eta_p$  is 0.476 which is equal to 59% of the maximum efficiency. In Figure 8,  $f_{\max}$  represents the maximum thermoenvironmental density,  $f_p$  is the thermoenvironmental density corresponding to maximum power density,  $f_{\eta}$  is the thermoenvironmental density corresponding to maximum efficiency,  $p_f$  is the power density at the maximum thermoenvironmental density, and  $\eta_f$  is efficiency at the maximum thermoenvironmental density.  $p_f$  values are 7003.122 ( $\text{W m}^{-2}$ ), which is corresponding nearly 94% of the maximum

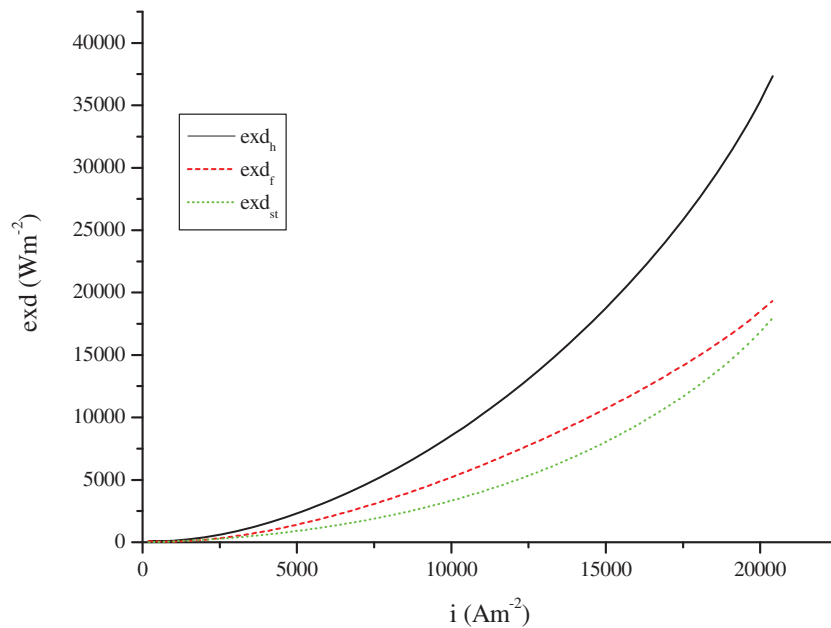


Figure 5. Variation of exergy destruction density with  $i$ .

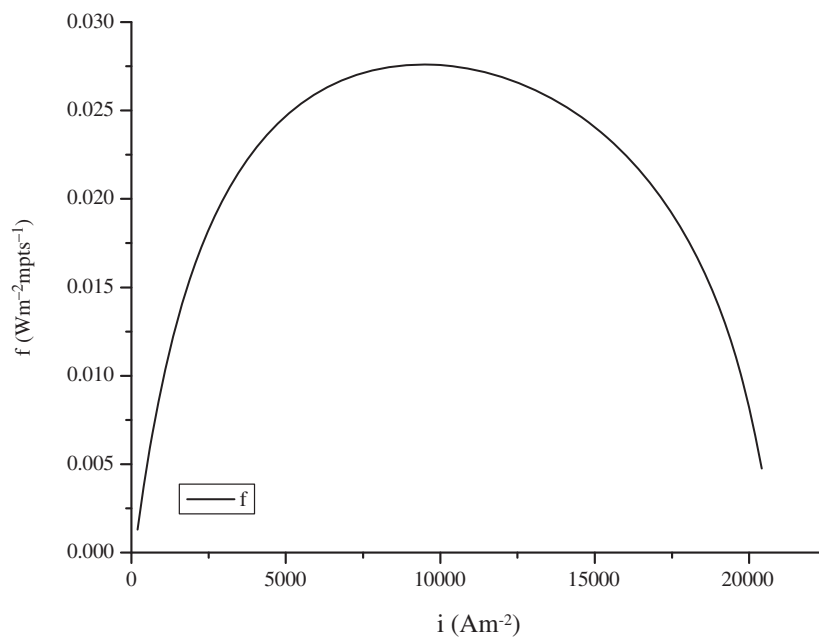


Figure 6. Variation of thermoenvironmental function density with  $i$ .

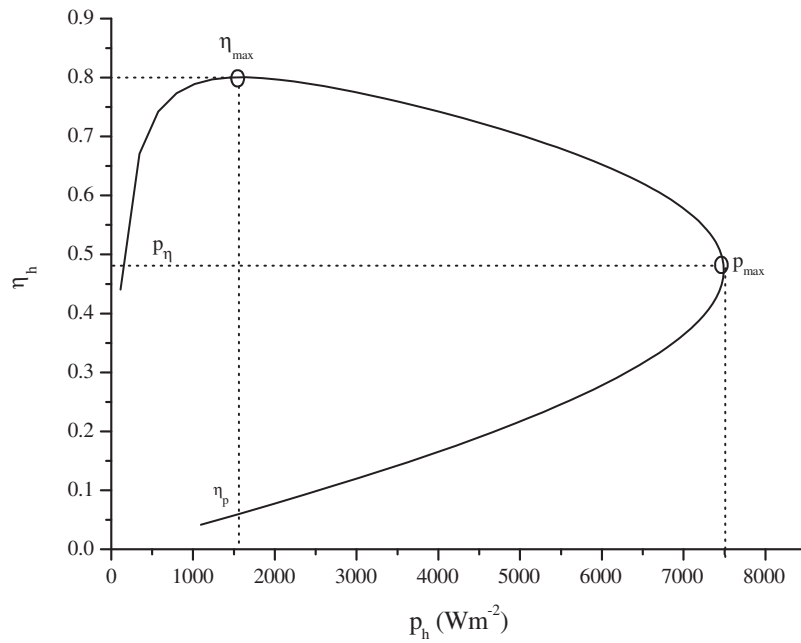


Figure 7. Variation of power density with energy efficiency.

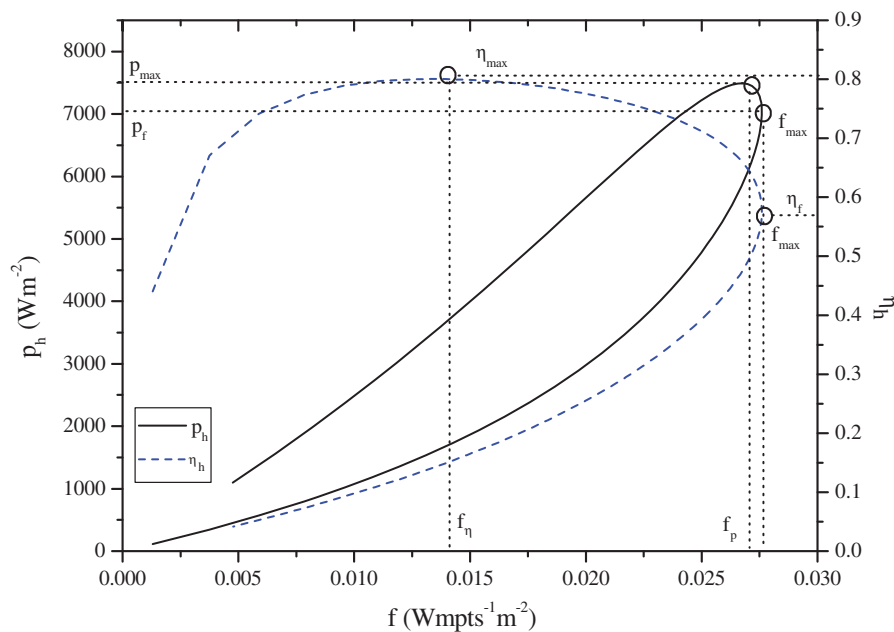


Figure 8. Variation of thermoenvironmental function with power density and energy efficiency.

power,  $f_p$  is equal to  $0.0268 \text{ (W mpts}^{-1} \text{ m}^{-2}\text{)}$  and it is 97% of the maximum thermoenvironmental function.  $\eta_f$  is the 0.578 which is 78% of the maximum efficiency and, finally,  $f_\eta$  is the 0.14 corresponding to 50% of the maximum thermoenvironmental function. Results show that the maximum power and maximum thermoenvironmental function are very close to each other in terms of current density. However, in these values energy and exergy efficiencies get small values in contrast to exergy destruction. In addition, power output values are small. Interpreting these results, one may be claim that  $f$  should be chosen as  $f_\eta \leq f \leq f_{\max}$ .

#### 4. Conclusions

An irreversible SOFC – Stirling heat engine is taken into account in this study. Thermoenvironmental criterion is considered as well as basic thermodynamic parameters, such as power density, exergy destruction density, energy and exergy efficiencies. Thermoenvironmental function is new criterion for thermal cycles, which provides us information about environmental impact of any thermal cycle. Optimum points for power density, thermoenvironmental function, energy and exergy efficiencies are Obtained. In addition, it is found that thermoenvironmental

function reaches its optimum at the current density where is close to the optimum power. According to results, optimum points for the hybrid system are determined as follows:

- maximum power density is 7489.92 ( $\text{A m}^{-2}$ )
- maximum energy and exergy efficiencies are 0.800 and 0.887, respectively
- thermoenvironmental function density is 0.0276 ( $\text{W mpts}^{-1} \text{m}^{-2}$ ).

In low  $i$  values,  $exd$  and  $p$  have small values, in contrast,  $\eta$  and  $\varphi$  have high values and vice a versa is correct for high  $i$  values. Investigating all results a new selection range is suggested for the considered system as  $f_{\eta} \leq f \leq f_{\max}$ . Finally, it is recommended that thermoenvironmental criterion should be extended to other thermal systems to provide the optimal environment-management strategies.

## Acknowledgements

The author thanks the reviewers for their valuable comments, which have been utilized in improving the quality of the paper.

## Disclosure statement

No potential conflict of interest was reported by the author.

## References

- Açikkalp, E. 2017a. "Ecologic and Sustainable Objective Thermodynamic Evaluation of Molten Carbonate Fuel Cell – Supercritical  $\text{CO}_2$  Brayton Cycle Hybrid System." *International Journal of Hydrogen Energy* 42: 6272–6280.
- Açikkalp, E. 2017b. "Performance Analysis of Irreversible Molten Carbonate Fuel Cell – Braysson Heat Engine with Ecological Objective Approach." *Energy Conversion and Management* 132: 432–437.
- Ahmadi, Mohammad H., and Mohammad Ali Ahmadi. 2016. "Thermodynamic Analysis and Optimisation of an Irreversible Radiative-type Heat Engine by Using Non-dominated Sorting Genetic Algorithm." *International Journal of Ambient Energy* 37 (4): 403–408.
- Ahmadi, Mohammad H., Mohammad-Ali Ahmadi, and Michel Feidt. 2015. "Thermodynamic Analysis and Evolutionary Algorithm Based on Multi-objective Optimization of Performance for Irreversible Four-temperature-level Refrigeration." *Mechanics & Industry* 16 (2): 207.
- Ahmadi, Mohammad H., Mohammad-Ali Ahmadi, Akbar Maleki, Fathollah Pourfayaz, Mokhtar Bidi, and Emin Açikkalp. 2017. "Exergetic Sustainability Evaluation and Multi-objective Optimization of Performance of an Irreversible Nanoscale Stirling Refrigeration Cycle Operating with Maxwell–Boltzmann Gas." *Renewable and Sustainable Energy Reviews* 78: 80–92.
- Ahmadi, Mohammad H., Mohammad-Ali Ahmadi, Mehdi Mehrpooya, Hadi Hosseinzade, and Michel Feidt. 2014. "Thermodynamic and Thermo-economic Analysis and Optimization of Performance of Irreversible Four-temperature-level Absorption Refrigeration." *Energy Conversion and Management* 88: 1051–1059.
- Ahmadi, Mohammad H., Mohammad Ali Ahmadi, Mehdi Mehrpooya, Seyed Mohsen Pourkiaei, and Maryam Khalili. 2016. "Thermodynamic Analysis and Evolutionary Algorithm Based on Multi-objective Optimisation of the Rankine Cycle Heat Engine." *International Journal of Ambient Energy* 37 (4): 363–371.
- Ahmadi, Mohammad Hossein, Mohammad Ali Ahmadi, Adel Mellit, Fathollah Pourfayaz, and Michel Feidt. 2016. "Thermodynamic Analysis and Multi Objective Optimization of Performance of Solar Dish Stirling Engine by the Centrality of Entransy and Entropy Generation." *International Journal of Electrical Power & Energy Systems* 78: 88–95.
- Ahmadi, Mohammad H., Mohammad Ali Ahmadi, and Fathollah Pourfayaz. 2016. "Thermodynamic Analysis and Evolutionary Algorithm Based on Multi-objective Optimization Performance of Actual Power Generating Thermal Cycles." *Applied Thermal Engineering* 99: 996–1005.
- Ahmadi, Mohammad H., Mohammad A. Ahmadi, and Fathollah Pourfayaz. 2017. "Thermal Models for Analysis of Performance of Stirling Engine: A Review." *Renewable and Sustainable Energy Reviews* 68 (Part 1): 168–184.
- Ahmadi, Mohammad H., Mohammad-Ali Ahmadi, Fathollah Pourfayaz, Mokhtar Bidi, and Emin Açikkalp. 2016. "Multi-objective Optimization and Exergetic-sustainability of an Irreversible Nano Scale Braysson Cycle Operating with Maxwell–Boltzmann Gas." *Alexandria Engineering Journal* 55 (2): 1785–1798.
- Ahmadi, Mohammad H., Saeed Dehghani, Amir H. Mohammadi, Michel Feidt, and Marco A. Barranco-Jimenez. 2013. "Optimal Design of a Solar Driven Heat Engine Based on Thermal and Thermo-economic Criteria." *Energy Conversion and Management* 75: 635–642.
- Ahmadi, Mohammad H., Hadi Hosseinzade, Hoseyn Sayyaadi, Amir H. Mohammadi, and Farshad Kimiaghaleh. 2013. "Application of the Multi-objective Optimization Method for Designing a Powered Stirling Heat Engine: Design with Maximized Power, Thermal Efficiency and Minimized Pressure Loss." *Renewable Energy* 60: 313–322.
- Ahmadi, Mohammad Hossein, and Mehdi Mehrpooya. 2015. "Thermo-economic Modeling and Optimization of an Irreversible Solar-driven Heat Engine." *Energy Conversion and Management* 103: 616–622.
- Ahmadi, Mohammad H., Amir H. Mohammadi, Saeed Dehghani, and Marco A. Barranco-Jimenez. 2013. "Multi-objective Thermodynamic-based Optimization of Output Power of Solar Dish-Stirling Engine by Implementing an Evolutionary Algorithm." *Energy Conversion and Management* 75: 438–445.
- Ahmadi, Mohammad Hossein, Hoseyn Sayyaadi, Saeed Dehghani, and Hadi Hosseinzade. 2013. "Designing a Solar Powered Stirling Heat Engine Based on Multiple Criteria: Maximized Thermal Efficiency and Power." *Energy Conversion and Management* 75: 282–291.
- Ahmadi, Mohammad H., Hoseyn Sayyaadi, Amir H. Mohammadi, and Marco A. Barranco-Jimenez. 2013. "Thermo-economic Multi-objective Optimization of Solar Dish-Stirling Engine by Implementing Evolutionary Algorithm." *Energy Conversion and Management* 73: 370–380.
- Andresen, B. 2011. "Current Trends in Finite-time Thermodynamics." *Angewandte Chemie International Edition* 50 (12): 2690–2704.
- Andresen, B., R. S. Berry, M. J. Ondrechen, and P. Salamon. 1984. "Thermodynamics for Processes in Finite Time." *Accounts of Chemical Research* 17 (8): 266–271.
- Bejan, A. 1996. "Entropy Generation Minimization: The New Thermodynamics of Finite-size Devices and Finite-time Processes." *Journal of Applied Physics* 79 (3): 1191–1218.
- Bi, Y. H., and L. G. Chen. 2017. *Finite Time Thermodynamic Optimization for Air Heat Pumps*. Beijing: Science Press.
- Chen, L. G. 2005. *Finite-Time Thermodynamic Analysis of Irreversible Processes and Cycles*. Beijing: Higher Education Press.
- Chen, X., L. Chen, J. Guo, and J. Chen. 2011. "An Available Method Exploiting the Waste Heat in a Proton Exchange Membrane Fuel Cell System." *International Journal of Hydrogen Energy* 36: 6099–6104.
- Chen, L. G., H. J. Feng, and Z. H. Xie. 2016. "Generalized Thermodynamic Optimization for Iron and Steel Production Processes: Theoretical Exploration and Application Cases." *Entropy* 18 (10): 353.
- Chen, L., S. Gao, and H. Zhang. 2013. "Performance Analysis and Multi-Objective Optimization of an Irreversible Solid Oxide Fuel Cell-Stirling Heat Engine Hybrid System." *International Journal of Electrochemical Science* 8: 10772–10787.
- Chen, L. G., F. K. Meng, and F. R. Sun. 2016. "Thermodynamic Analyses and Optimizations for Thermoelectric Devices: The State of the Arts." *Science China Technological Sciences* 59 (3): 442–455.
- Chen, L. G., and F. R. Sun. 2004. *Advances in Finite Time Thermodynamics: Analysis and Optimization*. New York: Nova Science.
- Chen, L. G., C. Wu, and F. R. Sun. 1999. "Finite Time Thermodynamic Optimization or Entropy Generation Minimization of Energy Systems." *J. Non-Equilib. Thermodyn.* 24 (4): 327–359.
- Chen, L. G., and S. J. Xia. 2017a. *Generalized Thermodynamic Dynamic Optimization for Irreversible Processes*. Beijing: Science Press.

- Chen, L. G., and S. J. Xia. 2017b. *Generalized Thermodynamic Dynamic Optimization for Irreversible Cycles*. Beijing: Science Press.
- Chen, J., Z. Yan, L. Chen, and B. Andresen. 1998. "Efficiency Bound of a Solar-driven Stirling Heat Engine System." *International Journal of Energy Research* 22: 805–812.
- Chen, L., H. Zhang, S. Gao, and H. Yan. 2014. "Performance Optimum Analysis of an Irreversible Molten Carbonate Fuel Cell–Stirling Heat Engine Hybrid System." *Energy* 64: 923–930.
- Feng, H. J., L. G. Chen, Z. H. Xie, and F. R. Sun. 2015. "Constructal Optimization for a Single Tubular Solid Oxide Fuel Cell." *Journal of Power Sources* 286: 406–413.
- Ge, Y. L., L. G. Chen, and F. R. Sun. 2016. "Progress in Finite Time Thermodynamic Studies for Internal Combustion Engine Cycles." *Entropy* 18 (4): 139–130.
- Goedkoop, M., M. Demmers, and M. Collignon. 1995. *The Eco-indicator 95: Manual for Designers*. <http://www.pre.nl>
- Goedkoop, M., and R. Spriensma. 2000. "The Eco-indicator 99: A Damage Oriented Method for Life Cycle Impact Assessment." Methodology Report, Amersfoort, the Netherlands. <http://www.pre.nl>
- Haseli, H., I. Dincer, and G. F. Naterer. 2008a. "Thermodynamic Analysis of a Combined Gas Turbine Power System with a Solid Oxide Fuel Cell Through Exergy." *Thermochimica Acta* 480: 1–9.
- Haseli, H., I. Dincer, and G. F. Naterer. 2008b. "Thermodynamic Modeling of a Gas Turbine Cycle Combined with a Solid Oxide Fuel Cell." *International Journal of Hydrogen Energy* 33: 5811–5822.
- Huang, C., Y. Pan, Y. Wang, G. Su, and J. Chen. 2016. "An Efficient Hybrid System Using a Thermionic Generator to Harvest Waste Heat from a Reforming Molten Carbonate Fuel Cell." *Energy Conversion and Management* 121: 186–193.
- Özel, G., E. Açıkkalp, A. H. Savaş, and H. Yamık. 2015. "Novel Thermo-environmental Evaluation Criteria and Comparing Them for an Actual Heat Engine." *Energy Conversion and Management* 106: 1118–1123.
- Sadatsakkak, Seyed Abbas, Mohammad Hossein Ahmadi, and Mohammad Ali Ahmadi. 2015. "Thermodynamic and Thermo-economic Analysis and Optimization of an Irreversible Regenerative Closed Brayton Cycle." *Energy Conversion and Management* 94: 124–129.
- Sadatsakkak, Seyed Abbas, Mohammad H. Ahmadi, Roham Bayat, Seyed Mohsen Pourkiaei, and Michel Feidt. 2015. "Optimization Density Power and Thermal Efficiency of an Endoreversible Braysson Cycle by Using Non-dominated Sorting Genetic Algorithm." *Energy Conversion and Management* 93: 31–39.
- Sieniutycz, S. 2000. "Hamilton-Jacobi-Bellman Framework for Optimal Control in Multistage Energy Systems." *Physics Reports* 326 (4): 165–258.
- Sieniutycz, S. 2016. *Thermodynamic Approaches in Engineering Systems*. Oxford: Elsevier.
- Wu, C., L. G. Chen, and J. C. Chen. 1999. *Recent Advances in Finite Time Thermodynamics*. New York: Nova Science.
- Wu, F., L. G. Chen, C. Wu, and F. Sun. 1998. "Optimum Performance of Irreversible Stirling Engine with Imperfect Regeneration." *Energy Conversion and Management* 39: 727–732.
- Yang, P., and H. Zhang. 2015. "Parametric Analysis of an Irreversible Proton Exchange Membrane Fuel Cell/Absorption Refrigerator Hybrid System." *Energy* 85: 458–467.
- Zhang, X., and J. Chen. 2010. "Performance Analysis and Parametric Optimum Criteria of a Class of Irreversible Fuel Cell/Heat Engine Hybrid Systems." *International Journal of Hydrogen Energy* 35: 284–293.
- Zhang, H., L. Chen, J. Zhang, and J. Chen. 2014. "Performance Analysis of a Direct Carbon Fuel Cell with Molten Carbonate Electrolyte." *Energy* 68: 292–300.
- Zhang, X., J. Guo, and J. Chen. 2010. "The Parametric Optimum Analysis of a Proton Exchange Membrane (PEM) Fuel Cell and its Load Matching." *Energy* 35: 5294–5299.
- Zhang, X., J. Guo, and J. Chen. 2012. "Influence of Multiple Irreversible Losses on the Performance of a Molten Carbonate Fuel Cell-gas Turbine Hybrid System." *International Journal of Hydrogen Energy* 37: 8664–8671.
- Zhang, H., G. Lin, and J. Chen. 2011a. "Performance Analysis and Multi-objective Optimization of a New Molten Carbonate Fuel Cell System." *International Journal of Hydrogen Energy* 36: 4015–4021.
- Zhang, H., G. Lin, and J. Chen. 2011b. "Performance Evaluation and Parametric Optimum Criteria of an Irreversible Molten Carbonate Fuel Cell-Heat Engine Hybrid System." *International Journal of Electrochemical Science* 6: 4714–4729.
- Zhang, H., G. Lin, and J. Chen. 2012. "Multi-objective Optimization Analysis and Load Matching of a Phosphoric Acid Fuel Cell System." *International Journal of Hydrogen Energy* 37: 3438–3446.
- Zhang, X., H. Liu, M. Ni, and J. Chen. 2015. "Performance Evaluation and Parametric Optimum Design of a Syngas Molten Carbonate Fuel Cell and Gas Turbine Hybrid System." *Renewable Energy* 80: 407–414.
- Zhang, X., S. Su, J. Chen, Y. Zhao, and N. Brandon. 2011. "A New Analytical Approach to Evaluate and Optimize the Performance of an Irreversible Solid Oxide Fuel Cell-gas Turbine Hybrid System." *International Journal of Hydrogen Energy* 36: 15304–15312.
- Zhang, H., S. Su, G. Lin, and J. Chen. 2012. "Performance Analysis and Multi-Objective Optimization of a Molten Carbonate Fuel Cell Braysson Heat Engine Hybrid System." *Int. J. Electrochem. Sci.* 7: 3420–3435.
- Zhang, X., Y. Wang, J. Guo, and T.-M. Shih, and J. Chen. 2014. "A Unified Model of High-temperature Fuel-Cell Heat Engine Hybrid Systems and Analyses of its Optimum Performances." *International Journal of Hydrogen Energy* 39: 1811–1825.
- Zhao, Y., and J. Chen. 2009. "Modeling and Optimization of a Typical Fuel Cell–Heat Engine Hybrid System and Its Parametric Design Criteria." *Journal of Power Sources* 186: 96–103.
- Zhao, Y., C. Ou, and J. Chen. 2008. "A New Analytical Approach to Model and Evaluate the Performance of a Class of Irreversible Fuel Cells." *International Journal of Hydrogen Energy* 33: 4161–4170.
- Zhao, M., H. Zhang, Z. Hu, Z. Zhang, and J. Zhang. 2015. "Performance Characteristics of a Direct Carbon Fuel Cell/Thermoelectric Generator Hybrid System." *Energy Conversion and Management* 89: 683–689.