Energy and Buildings 138 (2017) 118–126

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Performance assessment of an ice rink refrigeration system through advanced exergoeconomic analysis method

Gulcan Ozel Erol[a], Emin Açıkkalp[a,*], Arif Hepbasli[b]

[a] Department of Mechanical and Manufacturing Engineering, Engineering Faculty, Bilecik S.E. University, Bilecik, Turkey
[b] Department of Energy Systems Engineering, Engineering Faculty, Yasar University, Izmir, Turkey

ARTICLE INFO

Article history:
Received 24 September 2016
Received in revised form 3 December 2016
Accepted 8 December 2016
Available online 9 December 2016

Keywords:
Ice rink
Advanced exergy analysis
Exergoeconomic analysis
Buildings

ABSTRACT

Advanced exergy analysis has gained great importance as a comprehensive evaluation tool for energy conversion systems in recent years. In this regard, splitting the exergy destruction into avoidable/unavoidable parts has enabled us to identify the improvement potential of component while endogenous/exogenous parts of the exergy destruction have been detailed studied to get more information about interactions among the components. An ice rink refrigeration system was investigated using both conventional and advanced exergoeconomic analyses in this paper. The ice rink refrigeration system has a cooling load of 300 kW and ammonia was chosen as refrigerant. Exergy destruction, investment cost rates and exergy destruction cost rates based on these two analyses were calculated first. Endogenous/exogenous and avoidable/unavoidable parts of the exergy destruction, investment cost rates and exergy destruction cost rate for each system component were then presented. Finally, possible solutions to reducing inefficiencies were discussed. It was determined that 47.15% of the total exergy destruction of the system was avoidable while 22.89% of the total exergy destruction of the system was exogenous. The evaporator with 18% endogenous available investment cost rate and the condenser with 64.3% endogenous available exergy destruction cost rate were the two most important components in the ice rink refrigeration system.

1. Introduction

Ice rinks are entertainment facilities used for activities such as hockey, curling, speed skating, and ice shows. Ice rinks are operated 18 h per day, 7 days a week and depending on the skating season from 8 to 12 months in a year. A refrigeration system is used to remain the ice with a large surface area frozen [1]. In addition to this, ice rinks have heating, ventilating and air conditioning systems for the comfort of skaters and spectators. Since ice rink facilities includes all the systems referred previous sentence, energy consumption and operating cost of ice rink becomes very significant and should be improved and analyzed during the design [2].

Exergy analysis is a significant tool for optimization of complex thermodynamic systems [3]. It can help identify the location, magnitude and sources of irreversibilities and systems can be improved for operating more efficiently [4]. However, conventional exergy analysis can be inadequate about the interactions between the system components and can be misleading the real potential for improving a system component. A new method, the so- called advanced exergy analysis, was suggested to eliminate restrictions in classical (conventional) exergy analysis. This method basically consists of splitting the exergy destruction such as endogenous, exogenous, avoidable and unavoidable parts [5]. Thus, the advanced exergy analysis makes possible to inform how affect changes in a component to the all other components and the system. On the other hand, the advanced exergy analysis can be combined economic or environmental analysis like conventional exergy analysis.

In the previous studies about ice rinks, prediction of the refrigeration load or performance improvements were realized through energy and exergy analyses. Bellacheet al. [6] conducted a two dimensional numerical simulation used k-ε turbulence model for a ventilated ice rink. They considered mass transfer and calculated heat losses through the walls and ceiling as well as the latent, convective and radiative heat flux into the ice. In another study done by Ouzzaneet al. [7], their model including transient phenomena was developed and validated with the results obtained from the experimental data. Shahzad [8] discussed using the CO_2 as a secondary fluid in an ice rink refrigeration system. He optimized heat transfer and pressure drop for different pipe sizes and materials. Daoud and Galanis [9] developed a zonal model combined with

---

* Corresponding author.
E-mail addresses: eacikkalp@gmail.com (E. Açıkkalp), emin.acikkalp@bilecik.edu.tr (A. Hepbasli).

http://dx.doi.org/10.1016/j.enbuild.2016.12.025
0378-7788/

Nomenclature

$\dot{E}x$	Exergy rate (kW)
c	Unit exergy cost ($/GJ)
$\dot{C}$	Exergy cost rate ($/h)
f	Exergoeconomic factor
$\dot{m}$	Mass flow rate (kg/s)
P	Pressure (bar)
r	Relative cost difference
T	Temperature (K)
$\dot{Z}$	Capital investment cost flow rate ($/h)

Subscripts

D	Destruction
F	Fuel
k	Kth component
P	Product

Superscripts

AV	Avoidable
EN	Endogenous
EX	Exogenous
MX	Mexogenous
UN	Unavoidable

Greek letters

η	Isentropic efficiency (%)
ε	Exergetic efficiency (%)

commercial available energy simulation software. They reported that this model was more flexible and easy-to-use tool for fairly rapid evaluations of the thermal behavior of ice rinks compared CFD models. A quasi-steady model was developed by Seghouani and Galanis [10] for the refrigeration system of an indoor ice rink. The computer program could be used to simulate the ice rink refrigeration system operation, to estimate its annual energy consumption and to analyze different energy saving strategies. Seghouani et al. [11] presented a transient model that took into account heat transfer through the ground (below the ice model) towards the brine pipes under the ice of an indoor ice rink. Caliskan and Hepbasli [12] carried out energy and exergy analysis of an ice rink located in Turkey. Lowex method was utilized for the exergy analysis, which was performed for different reference temperatures. Nguyen [13] compared the performance of varied combination of ice rinks used ammonia and CO_2 as refrigeration fluids. He reported that CO_2 refrigeration system was the most efficiency in all.

The advanced exergy is a new method; therefore relatively limited studies about this method are available in the literature. Concept of splitting the exergy destruction avoidable and unavoidable parts was introduced by Tsatsaronis and Park [14]. They defended that exergy destruction had an avoidable part, which could be improved by current technologies and techniques. This method suggested concentrating on avoidable part of the exergy destruction for a correct assessment. The advanced exergy analysis was approved and developed by applying different and complex systems.This new approach took its current version in 2006 with the addition of endogenous and exogenous parts of the exergy destruction by Tsatsaronis et al. [15]. The source of the exergy destruction in a component was identified as component itself, endogenous exergy destruction, or in the structure of the system, exogenous exergy destruction. The advanced exergy analysis could be applied to various systems such as power cycle, refrigeration cycle and buildings. Acikkalp et al. [16] investigated the performance of an electricity generation facility using the advanced exergy analysis. They compared the results for conventional exergy analysis and advanced exergy analysis. They asserted that the conventional exergy analysis could lead to misinterpretations and cause incorrect improvement strategies.The environmental effects of a building heating system through the advanced exergoenvironmental analysis was assessed by Acikkalp et al. [17]. They indicated that relations between components had an important effect on environmental impact of the system and environmentally improvement potential of the system was very low. Morosuk and Tsatsaronis [18] applied the advanced exergy analysis to an absorption refrigeration machine. Total exergy destruction rate of the system was calculated as 73.6% and using the advanced exergy analysis while exergy destruction rate, which could not be improved, was obtained as 65.8% of the total exergy destruction. In addition, they suggested that generator had the maximum improving potential by the ratio of 23.9%. A water lithium bromide absorption refrigeration machine was investigated by Gong and Boulama [19]. In the study, a numerical program including the advanced exergy analysis was developed for the variable heat sink temperature, heat source temperature and evaporator existing temperature. Chen et al. [20] evaluated the performance of an ejector refrigeration system by using the advanced exergy analysis. It was reported that 35% of the overall exergy destruction was avoidable and the ejector had the highest improvement potential in the system. The advanced exergoeconomic analysis was conducted on three multi stage mixed refrigerant liquefaction processes by Mehrpooya and Ansarinasab [21]. They reported that heat exchangers were the most important component in the terms of avoidable investment cost for the liquefaction processes.

In the present study, the advanced exergy analysis and exergoeconomic analysis were considered and applied to an ice rink refrigeration system. The advanced exergoeconomic analysis is a powerful method for evaluating the system performance more detailed from the thermodynamic and economic aspects. In the open literature, there is no study on advanced exergy or advanced exergoeconomic analysis of an ice rink to the best of the authors' knowledge. Important parameters, such as advanced exergy destruction rates, advanced investment cost rates and advanced exergy cost rates, obtained from the advance exergoeconomic analysis are presented and compared for the ice rink refrigeration system.

2. System description

The considered ice rink refrigeration system is schematically illustrated in Fig. 1 where three compressors, namely water cooled condensers, expansion valves and an evaporator are included. The cooling load rate of the ice rink refrigeration system is 300 kW. Ammonia is used as the refrigerant and CO_2 is used as the secondary refrigerant, which circulates through pipes under the ice and maintains the ice surface at the needed temperature. In traditional ice rinks, ammonia or R22 is used as refrigerant and commonly calcium chloride or glycol solutions are used as a secondary refrigerant. CO_2 is a new refrigerant for the ice rink refrigerant systems and has been used in some ice rinks as a secondary refrigerant in recent years. The T-s diagram of the refrigeration system is presented in Fig. 2. It is assumed that ammonia exists in the condenser as the saturated liquid at a high pressure and enters the compressor as the saturated vapor at a low pressure. Ice rink operates under steady state conditions. Pressure drops and heat losses to the environment in the heat exchanger are neglected. The environment temperature and pressure are considered as 298.15 K and 100 kPa, respectively. Mass flow rates and thermo physical properties of the working fluids are given in Table 1. The system is operated at a full load, with4860 h in a year.

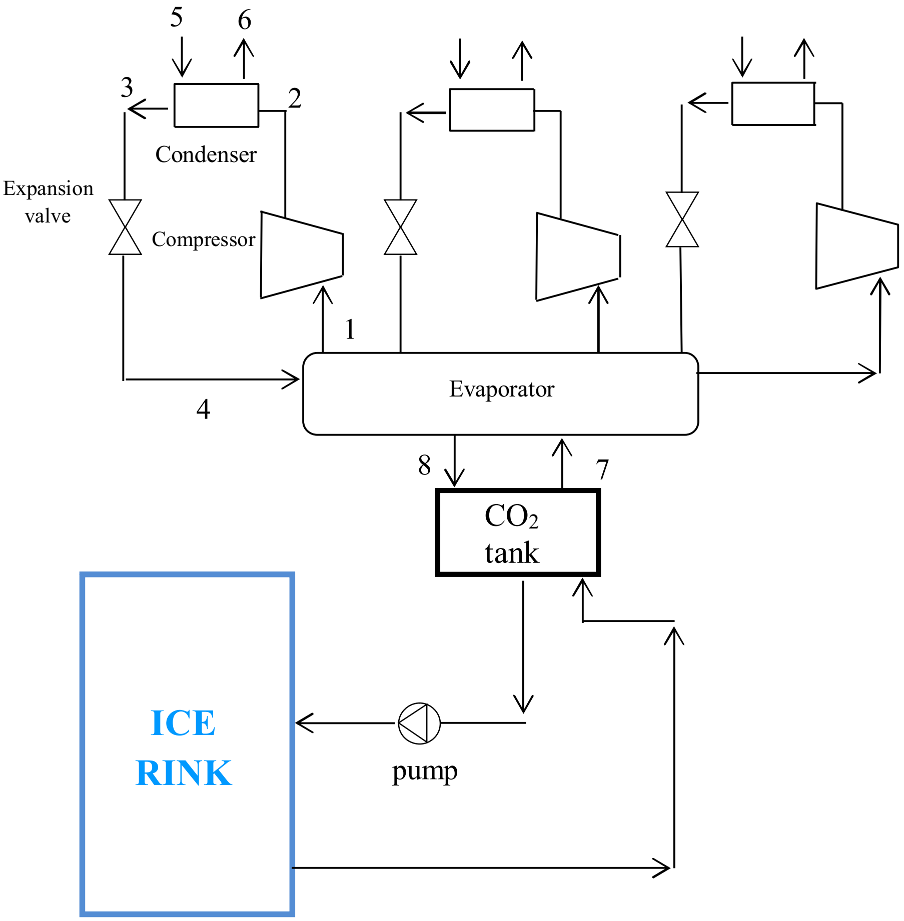

Fig. 1. A schematic of the investigated ice rink refrigeration system.

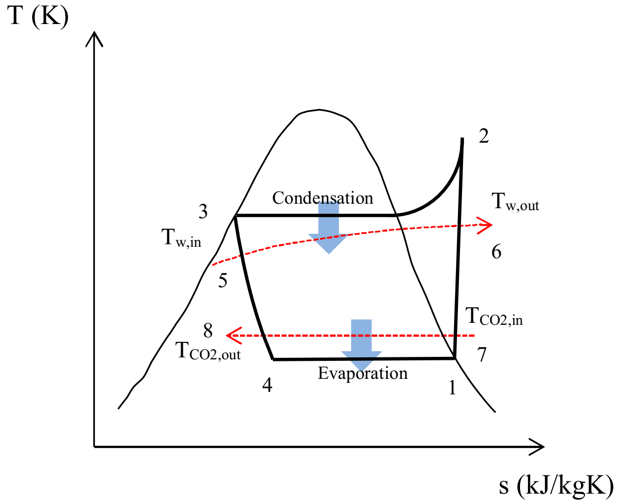

Fig. 2. T-s diagram of the ice rink refrigeration cycle.

3. Analysis

3.1. Exergy and exergoeconomic analyses

Exergy can be defined as quality of the energy, and refers to the maximum useful work obtained from a system at a given state in a reference environment [3]. Exergy analysis is used to reduce loses and design more efficient systems. The conventional exergy analysis is the first step to perform an advanced exergy analysis.

Table 1
Mass flow rates and thermophysical properties of streams.

Point	Fluid	$\dot{m}$(kg/s)	T (°C)	P (bar)	ex (kJ/kg)
1	Ammonia	0.09504	−11.37	2.75	216.90
2	Ammonia	0.09504	135.85	16	490.72
3	Ammonia	0.09504	41.03	16	390.79
4	Ammonia	0.09504	−11.37	2.75	363.13
5	Water	3	25	10	0
6	Water	3	35.33	10	0.7429
7	Carbon dioxide	1.182	−7	28.8	183.42
8	Carbon dioxide	1.182	−7	28.8	214.106

According to the (Exergetic) Fuel-(Exergetic) Product Rule, exergy destruction rate $\dot{E}x_{D,k}$ in kth component of the system is calculated by Eq. (1) [22].

$$\dot{E}x_{D,k} = \dot{E}x_{F,k} - \dot{E}x_{P,k} \tag{1}$$

where $\dot{E}x_{F,k}$ and $\dot{E}x_{P,k}$ are fuel and product exergy rates, respectively. Exergetic efficiency is defined as the ratio of the product exergy rate to the fuel exergy rate [22].

$$\varepsilon_k = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k}} \tag{2}$$

Exergoeconomic analysis is an integrated approach and help assessing the thermodynamic systems by using the cost of the streams. Applying the exergoeconomic presents the relationship between thermodynamic inefficiencies and cost of the product.

Table 2
Assumptions made for the unavoidable and ideal cycles.

Component	Real	Ideal	Unavoidable
Compressor	η_s=0.85	η_s=1	η_s=0.90
Condenser	$\Delta T_{min} = 7.73$ ΔP_R=0 ΔP_w=0	T_{min}=0 ΔP_R=0 ΔP_w=0	T_{min}=1 ΔP_R=0 ΔP_w=0
Expansion valve	$h_{in} = h_{out}$	$s_1 = s_2$	$h_{in} = h_{out}$
Evaporator	ΔT_{min}=4.37 ΔP_R=0 ΔP_w=0	T_{min}=0 ΔP_R=0 ΔP_w=0	T_{min}=1 ΔP_R=0 ΔP_w=0

The cost balance for the *k*th component of the system is given by following equations [22],

$$\dot{C}_{P,k} = \dot{C}_{F,k} + \dot{Z}_k^T \tag{3}$$

and

$$c_{P,k}\dot{E}x_{P,k} = c_{F,k}\dot{E}x_{F,k} + \dot{Z}_k^T \tag{4}$$

where $c_{P,k}$ and $c_{F,k}$ denote the cost rate per unit of exergy ($/GJ) for product and fuel streams. $\dot{Z}_k^T$ is the total cost rate($/h) associated with the capital investment, operating and maintenance costs. The exergy destruction cost rate ($/h) is calculated by [22]

$$\dot{C}_{D,k} = c_{F,k}\dot{E}x_{D,k} \tag{5}$$

The contribution of the capital cost rate $\dot{Z}_k^T$, to the total cost of *k*th component is defined as exergoeconomic factor f_k and is given as follows [23]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{6}$$

Another parameter of the exergoeconomic analysis is the relative cost difference *r* and is calculated as [23];

$$r = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} \tag{7}$$

3.2. Advanced exergetic and exergoeconomic analyses

Using the conventional exergy analysis, one can determine the location and magnitude of the exergy destruction in a system. The conventional exergy analysis has some limitation and especially can cause misleading for optimization of complex energy conversation systems. The advanced exergy analysis was developed for a detailed investigation of any system.

In the advanced exergy analysis, the exergy destruction rate is divided into parts, such as avoidable, unavoidable, endogenous and exogenous. Avoidable exergy destruction rate $\dot{E}x_{D,k}^{AV}$ within a *k*th component indicates improving potential with the design or technical possibilities. The remaining part is unavoidable exergy destruction rate $\dot{E}x_{D,k}^{UN}$ and this part cannot be reduced due to the limitations because of technology or economic issues at the present time [24]. Assumptions made for real, avoidable and ideal refrigeration cycles are given in Table 2. The exogenous exergy destruction rate $\dot{E}x_{D,k}^{EX}$ represents the effect of the remaining components to the exergy destruction rate within a *k*th component. The endogenous exergy destruction rate $\dot{E}x_{D,k}^{EN}$ is associated with the irreversibilities of the component itself [18].

Unavoidable and avoidable exergy destruction rates are calculated as follows [25]:

$$\dot{E}x_{D,k}^{UN} = \dot{E}x_{P,k}\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}}\right)^{UN} \tag{8}$$

$$\dot{E}x_{D,k}^{UN} = \dot{E}x_{D,k} - \dot{E}x_{D,k}^{AV} \tag{9}$$

The endogenous exergy destruction rate can be calculated by assuming that the considered component operates under real conditions while the others operate under theoretical conditions [26].

$$\dot{E}x_{D,k}^{EX} = \dot{E}x_{D,k} - \dot{E}x_{D,k}^{EN} \tag{10}$$

The mexogenous exergy destruction rate $\dot{E}x_{D,k}^{MX}$ is occurred by the interactions between the *k*th component and the remaining components [27].

$$\dot{E}x_{D,k}^{MX} = \dot{E}x_{D,k}^{EX} - \sum_{\substack{r=1 \\ r \neq k}}^{n} \dot{E}x_{D,k}^{EX,r} \tag{11}$$

Integrating of the two splitting approaches creates new parameters. The unavoidable endogenous exergy destruction rate $\dot{E}x_{D,k}^{UN,EN}$ and the unavoidable exogenous exergy destruction rate $\dot{E}x_{D,k}^{UN,EX}$ are defined as follows [28]:

$$\dot{E}x_{D,k}^{UN,EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}}\right)^{UN} \tag{12}$$

$$\dot{E}x_{D,k}^{UN,EX} = \dot{E}x_{D,k}^{UN} - \dot{E}x_{D,k}^{UN,EN} \tag{13}$$

The avoidable endogenous exergy destruction rate $\dot{E}x_{D,k}^{AV,EN}$ and the unavoidable exogenous exergy destruction rate $\dot{E}x_{D,k}^{AV,EX}$ are given below [28]:

$$\dot{E}x_{D,k}^{AV,EN} = \dot{E}x_{D,k}^{EN} - \dot{E}x_{D,k}^{UN,EN} \tag{14}$$

$$\dot{E}x_{D,k}^{AV,EX} = \dot{E}x_{D,k}^{AV} - \dot{E}x_{D,k}^{AV,EN} \tag{15}$$

Similar to the advanced exergy analysis, exergy destruction costs and investment costs are divided into endogenous/exogenous and avoidable/unavoidable parts in the advanced exergoeconomic analysis. To design and optimize a thermodynamic system cost effectively, the advanced exergoeconomic analysis is considered a useful tool. Endogenous and exogenous exergy destruction cost rates can be calculated as follows [29]:

$$\dot{C}_{D,k}^{EN} = c_{F,k}\dot{E}_{D,k}^{EN} \tag{16}$$

$$\dot{C}_{D,k}^{EX} = c_{F,k}\dot{E}x_{D,k}^{EX} \tag{17}$$

The endogenous and exogenous investment cost flow rates are given in Eqs. (18) and (19):

$$\dot{Z}_k^{EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}x_P}\right)_k \tag{18}$$

$$\dot{Z}_k^{EX} = \dot{Z}_k - \dot{Z}_k^{EN} \tag{19}$$

The unavoidable and avoidable exergy destruction cost rates are given below [30]:

$$\dot{C}_{D,k}^{UN} = c_{F,k}\dot{E}x_{D,k}^{UN} \tag{20}$$

$$\dot{C}_{D,k}^{AV} = c_{F,k}\dot{E}x_{D,k}^{AV} \tag{21}$$

For the investment cost, the avoidable and unavoidable parts are calculated by evaluating the minimum values of $(\dot{Z}_k/\dot{E}x_{P,k})^{UN}$ [27,30].

$$\dot{Z}_k^{UN} = \dot{E}x_{P,k}\left(\frac{\dot{Z}_K}{\dot{E}_{P,K}}\right)^{UN} \tag{22}$$

$$\dot{Z}_k^{AV} = \dot{Z}_k - \dot{Z}_k^{UN} \tag{23}$$

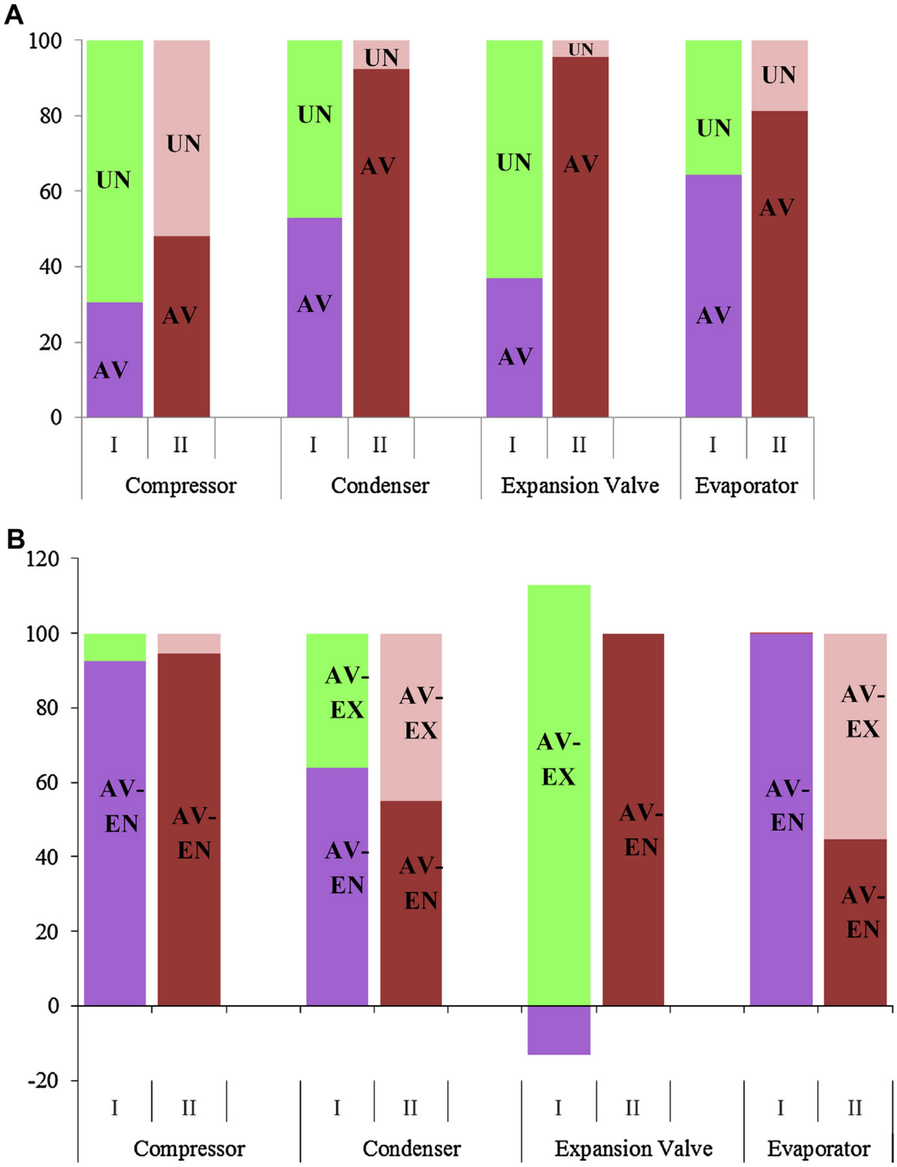

Fig. 3. (a) Comparative results for advanced exergy analysis (I: Present study, II: Reference [27]). (b) Comparative results for advanced exergy analysis (I: Present study, II: Reference [27]).

The endogenous and exogenous parts within the unavoidable and avoidable exergy destruction cost rates are defined as follows [5]:

$$\dot{C}_{D,k}^{UN,EN} = c_{F,k}\dot{E}x_{D,k}^{UN,EN} \tag{24}$$

$$\dot{C}_{D,k}^{AV,EN} = c_{F,k}\dot{E}x_{D,k}^{AV,EN} \tag{25}$$

$$\dot{C}_{D,k}^{UN,EX} = c_{F,k}\dot{E}x_{D,k}^{UN,EX} \tag{26}$$

$$\dot{C}_{D,k}^{AV,EX} = c_{F,k}\dot{E}x_{D,k}^{AV,EX} \tag{27}$$

Combining the two splitting ones, the investment cost can be rewritten as four parts; avoidable endogenous, unavoidable endogenous, avoidable exogenous and unavoidable exogenous [23].

$$\dot{Z}_k^{UN,EN} = \dot{E}x_{P,k}^{EN}\left(\frac{\dot{Z}}{\dot{E}_P}\right)_k^{UN} \tag{28}$$

$$\dot{Z}_k^{UN,EX} = \dot{Z}_k^{UN} - \dot{Z}_k^{UN,EN} \tag{29}$$

$$\dot{Z}_k^{AV,EN} = \dot{Z}_K^{EN} - \dot{Z}_k^{UN,EN} \tag{30}$$

$$\dot{Z}_k^{AV,EX} = \dot{Z}_K^{EX} - \dot{Z}_k^{UN,EX} \tag{31}$$

Mexogeneus exergy destruction and investment cost rates are calculated as follows [5]:

$$\dot{C}_k^{MX} = \dot{C}_{D,k}^{EX} - \sum_{\substack{r=1\\ r\neq k}}^{n} \dot{C}_{D,k}^{EX,r} \tag{32}$$

$$\dot{Z}_k^{MX} = \dot{Z}_k^{EX} - \sum_{\substack{r=1\\ r\neq k}}^{n} \dot{Z}_k^{EX,r} \tag{33}$$

Table 3
Exergy and exergoeconomic parameters for the system components.

Component	$\dot{E}x_F$(kW)	$\dot{E}x_P$(kW)	$\dot{E}x_D$(kW)	ε_k	$c_F(\$/GJ)$	$c_P(\$/GJ)$	f	r	$\dot{Z}_k(\$/h)$
Compressor	87.88	78.07	9.81	0.89	72.47	103.64	0.893	0.430	21.49
Condenser	28.50	6.68	21.82	0.23	113.28	634.92	0.290	4.604	3.64
Expansion Valve	111.41	103.54	7.87	0.92	113.25	125.41	0.295	0.107	1.34
Evaporator	41.69	34.98	6.71	0.84	125.46	207.50	0.706	0.654	7.30

Table 4
Advanced exergy destruction rates for the system components.

Component	$\dot{E}x_{D,k}$(kW)	$\dot{E}x_{D,k}^{EN}$(kW)	$\dot{E}x_{D,k}^{EX}$(kW)	$\dot{E}x_{D,k}^{AV}$(kW)	$\dot{E}x_{D,k}^{UN}$(kW)	$\dot{E}x_{D,k}^{AV,EN}$(kW)	$\dot{E}x_{D,k}^{AV,EX}$(kW)	$\dot{E}x_{D,k}^{UN,EN}$(kW)	$\dot{E}x_{D,k}^{UN,EX}$(kW)
Compressors	9.81	7.54	2.27	2.98	6.83	2.76	0.22	4.78	2.05
Condensers	21.82	16.87	4.9431	11.59	10.23	7.41	4.18	9.47	0.76
Expansion Valves	7.87	4.51	3.36	2.90	4.97	−0.38	3.28	4.89	0.08
Evaporator	6.70	6.7	0.00	4.32	2.38	4.31	0.00	2.39	0

Table 5
Advanced exergy destruction cost rates for the system components.

Component	$\dot{C}_{D,k}(\$/h)$	$\dot{C}_{D,k}^{EN}(\$/h)$	$\dot{C}_{D,k}^{EX}(\$/h)$	$\dot{C}_{D,k}^{AV}(\$/h)$	$\dot{C}_{D,k}^{UN}(\$/h)$	$\dot{C}_{D,k}^{AV,EN}(\$/h)$	$\dot{C}_{D,k}^{AV,EX}(\$/h)$	$\dot{C}_{D,k}^{UN,EN}(\$/h)$	$\dot{C}_{D,k}^{UN,EX}(\$/h)$
Compressors	2.561	1.968	0.592	2.373	0.188	0.721	1.652	1.248	−1.060
Condensers	8.898	6.882	2.016	8.470	0.429	3.021	5.448	3.861	−3.433
Expansion Valves	3.209	1.840	1.369	2.399	0.811	−0.154	2.553	1.995	−1.184
Evaporator	3.030	3.027	0.003	2.868	0.162	1.948	0.920	1.078	−0.917

Table 6
Mexogenous exergy destruction rates of the system components.

Exogenous exergy destruction cost rate of system components ($/h)	Effect of other components on the exogenous exergy destruction cost rate ($/h)	
Compressor 0.592	Condenser	4.403
	Expansion Valve	72.399
	Evaporator	3.839
	MEXO	−80.049
Condenser 2.016	Compressor	3.077
	Expansion Valve	1.841
	Evaporator	2.732
	MEXO	−5.634
Expansion valve 1.369	Compressor	−1.676
	Condenser	6.880
	Evaporator	2.732
	MEXO	−6.567
Evaporator 0.003	Compressor	3.408
	Condenser	7.622
	Expansion Valve	2.039
	MEXO	−13.069

4. Results and discussion

Conventional exergy and exergoeconomic analysis should be performed as the first step for the advanced exergy and exergoeconomic analysis. Results of the conventional exergy and exergoeconomic analysis are presented in Table 3. The maximum exergy destruction rate occurs in the condenser while the minimum value belongs to the evaporator. Also, the condenser has the lowest exergetic efficiency that is equal to 23%. This clearly indicates that improvements should be started from the condenser for a more efficient system based on the conventional exergy analysis. According to the exergoeconomic analysis, the highest unit exergy fuel cost rate is at the evaporator as 125.46 $/GJ and the highest unit exergy product cost rate is due to the condenser as 634.92$/GJ. Another important exergoeconomic parameter is the exergoeconomic factor. It shows the effect of the investment cost rates on the total cost rate in a component. If a component has a large exergoeconomic factor, investment costs should be decreased if the exergoeconomic factor is small, one should focus on the operating conditions. The compressor and evaporator have higher exergoeconomic factors while the condenser and expansion valve have lower ones. Large investment cost rates $\dot{Z}_k$ of the compressor and evaporator 21.49 $/h and 7.30$/h confirm these results.

For a detailed discussion about the system inefficiencies, the advanced exergy destruction rates are given in Table 4. The endogenous exergy destruction rate resulted from irreversibilities in the component itself is higher than the corresponding exogenous exergy destruction rate for all components. This clearly indicates that interactions among the components are weak for the ice rink refrigeration system. Exergy destruction in the evaporator is fully endogenous, but it affects other components in the system [28]. The important part of exergy destruction rates at the compressor and expansion valve consists of the unavoidable exergy destruction. The condenser has maximum improvement potential in terms of the avoidable endogenous exergy destruction rate as 7.41 kW. The evaporator is the second important component with 4.31 kW avoidable endogenous exergy destruction rate. At the expansion valve, inefficiencies can be reduced with improving other components because the available exogenous exergy destruction rate is higher than available endogenous exergy destruction rate. The obtained results are compared with a study, which investigated a heat pump with similar components [31]. Here, I and II denote the present study and Ref. [31], respectively. It is clear to see that the percentage of unavoidable and avoidable exergy destruction is agreeable excepting for the expansion valve (Fig. 3a, b). Because in the present study the expansion valve was considered as an isentropic turbine for the ideal cycle while in Ref. [31] the isentropic efficiency of the expansion valve was assumed as 97% for ideal cycle. Depending on the refrigeration cycle, the evaporator has 100% endogenous exergy destruction.

Results of the advanced exergoeconomic analysis are presented in Table 5. The endogenous exergy destruction cost rates constitute a significant amount of the total exergy destruction cost rates compared with the exogenous exergy destruction cost rates. Moreover, the evaporator has a less effect compared to other system compo-

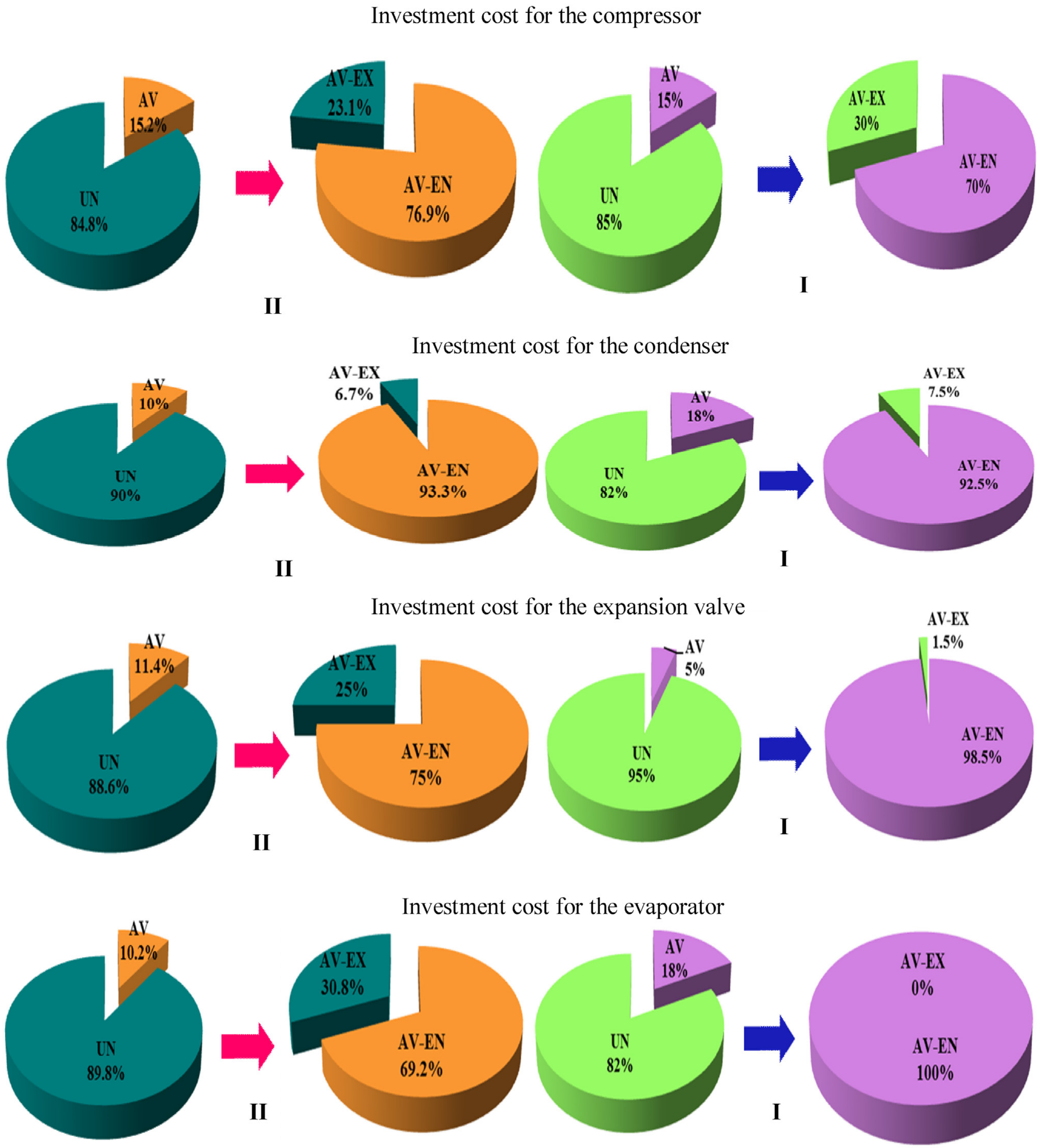

Fig. 4. Comparative results for investment cost rates (I: Present study, II: Reference [25]).

Table 7
Advanced investment cost rates for the system components.

Component	$\dot{Z}_{D,k}(\$/h)$	$\dot{Z}^{EN}_{D,k}(\$/h)$	$\dot{Z}^{EX}_{D,k}(\$/h)$	$\dot{Z}^{AV}_{D,k}(\$/h)$	$\dot{Z}^{UN}_{D,k}(\$/h)$	$\dot{Z}^{AV,EN}_{D,k}(\$/h)$	$\dot{Z}^{AV,EX}_{D,k}(\$/h)$	$\dot{Z}^{UN,EN}_{D,k}(\$/h)$	$\dot{Z}^{UN,EX}_{D,k}(\$/h)$
Compressor	21.487	15.036	6.451	3.223	18.264	2.255	0.968	12.781	5.483
Condenser	3.643	3.372	0.271	0.656	2.987	0.607	0.049	2.765	0.222
Expansion valve	1.346	1.326	0.021	0.067	1.279	0.066	0.001	1.259	0.020
Evaporator	7.300	7.300	0.000	1.314	5.986	1.314	0.000	5.986	0.000

nents. The avoidable exergy destruction costs, which represent the improving potential of the components, have greater values for all components. The condenser has a large avoidable exergy destruction cost rate of 8.470 \$/h, but a significant part of this (5.448 \$/h) associated with the remaining components. The highest percentage of avoidable endogenous exergy destruction cost rate belongs

Table 8
Mexogenous investment cost rates of the system components.

Exogenous investment cost rate of system components ($/h)	Effect of other components on the exogenous investment cost rate ($/h)	
Compressor 0.592	Condenser	1.703
	Expansion valve	36.639
	Evaporator	9.627
	MEXO	−41.519
Condenser 2.016	Compressor	29.768
	Expansion valve	2.459
	Evaporator	19.060
	MEXO	−7.977
Expansion valve 1.369	Compressor	−0.710
	Condenser	−0.080
	Evaporator	−2.918
	MEXO	−2.267
Evaporator 0.003	Compressor	11.400
	Condenser	1.291
	Expansion valve	21.270
	MEXO	−33.963

to the evaporator. Thus, one can focus on the evaporator to reduce the exergy destruction cost rate. The negative exogenous exergy destruction cost rates indicate that the exergy destruction costs within these components can be decreased by increasing the exergy destruction costs within other components.

Effect of the components on the exogenous exergy destruction cost rate is given in Table 6. All mexogenous exergy destruction cost rates are negative, which indicate that the investment cost rates of the system must be increased to reduce the investment cost rates of the system. The expansion valve has a dramatic effect on the exogenous exergy destruction of the compressor. A major part of the exogenous exergy destruction cost rate at the condenser is associated with the compressor.

Investment cost parameters are calculated and the results are summarized in Table 7. Investment cost rates for all components are mostly unavoidable and they have low improving potential. Lower exogenous investment costs for all components remark weak interactions among the components. The source of the avoidable investment costs is endogenous and especially, the compressor should be considered for improvements. Percentages of investment cost rate for the system components are compared with Ref. [29] and the results are presented in Fig. 4.

The mexogenous investment cost rates are shown in Table 8. According to the results, the expansion valve has a significant effect on the exogenous investment cost rates of the compressor and evaporator. The exogenous investment cost rate of the condenser can be decreased by improving the compressor.

5. Conclusions

In this study, the performance of an ice rink refrigeration system was comprehensively evaluated from the economic aspect through the advanced exergoeconomic analysis. The parameters associated with the investment cost and exergy destruction cost were calculated for all components and compared with the similar studies in the literature.

Some main conclusions obtained from the results of the present study arelisted as follows:

a) Total exergy destruction rate of the ice rink system is 46.21 kW and the condenser has the maximum exergy destruction rate of21.82 kW in all components. Total investment and exergy destruction cost rates are 33.77 $/h and 17.7 $/h, respectively. Maximum investment and exergy destruction cost rates belong to the compressor and condenser.
b) More than half of the system's total exergy destruction (52.84%) is unavoidable, meaning that this part of the total exergy destruction should not be improved by using current technological opportunities.
c) Endogenous available exergy destruction of the condenser was calculated as 34%. So, it should be considered as a priority.
d) According to the advanced exergoeconomic analysis, the compressor and evaporator have larger endogenous available investment cost rates as 10.5% and 18%, respectively.
e) The condenser is the most important components in the system with a high percentage of endogenous available exergy destruction cost rate (64.3%).

For a future study, it is recommended toevaluate the ice rink refrigeration system by using a combination of an environmental analysis method and advanced exergy analysis.

Acknowledgement

The authors would like to thank the reviewers for their valuable and constructive comments, which have been utilized in improving the quality of the paper.

References

[1] G. Teyssedou, R. Zmeureanu, D. Giguère, Thermal response of the concrete slab of an indoor ice rink, HVAC R Res. 15 (3) (2009) 509–523.
[2] ASHRAE Ice rinks, ASHRAE Handbook-Fundamentals, American Society of Heating, Refrigerating, and Air-Conditioning Engineers Inc., Atlanta, 2006 (Chapter 35).
[3] Y.A. Cengel, M.A. Boles, Thermodynamics: An Engineering Approach, 5th edition, McGraw-Hill Science, New York, 2005.
[4] G. Azzarelli, Advanced ExergyAnalysis: A New Approach Applied to the Gas Turbine Based Cogeneration Systems, VDM Verlag Dr Müller, Germany, 2009.
[5] E. Açıkkalp, H. Aras, A. Hepbasli, Advanced exergoenvironmental assessment of a natural gas-fired electricity generating facility, Energy Convers. Manage. 81 (2014) 112–119.
[6] O. Bellache, M. Ouzzane, N. Galanis, Numerical prediction of ventilation patterns and thermal processes in ice rinks, Build. Environ. 40 (2005) 417–426.
[7] M. Ouzzane, R. Zmeureanu, J. Scott, R. Sunyé, D. Giguère, O. Bellache, Cooling load and environmental measurements in a Canadian indoor ice rink, ASHRAE Trans. 112 (2006) 538–545.
[8] K. Shahzad, An Ice Rink Refrigeration System Based on CO_2 as Secondary Fluid in Copper Tubes, Master of Science Thesis, Master Program of Sustainable Energy Engineering, Royal Institute of Technology, Stockholm, Sweden, 2006.
[9] A. Daoud, N. Galanis, Calculation of the thermal loads of an ice rink using a zonal model and building energy simulation software, ASHRAE Trans. 112 (2006) 526–537.
[10] L. Seghouani, N. Galanis, Quasi-steady state model of an ice rink refrigeration system, Build. Simul. 2 (2) (2009) 119–132.
[11] L. Seghouani, A. Daoud, N. Galanis, Prediction of yearly energy requirements of indoor ice rinks, Energy Build. 41 (2009) 500–511.
[12] H. Caliskan, A. Hepbasli, Energy and exergy analyses of ice rink buildings at varying reference temperatures, Energy Build. 42 (2010) 418–425.
[13] T. Nguyen, Carbon Dioxide in Ice Rink Refrigeration, Master of Science Thesis, KTH School of Industrial Engineering and Management, Stockholm, Sweden, 2012.
[14] G. Tsatsaronis, M.H. Park, On avoidable and unavoidable exergy destructions and investment costs in thermal systems, Energy Convers. Manage. 43 (2002) 1259–1270.
[15] G. Tsatsaronis, S. Kelly, T. Morosuk, Endogenous and exogenous exergy destruction in thermal systems, in: Proceedings of the ASME International Mechanical Engineering Congress and Exposition, November 5–10 Chicago, USA, 2006.
[16] E. Açıkkalp, H. Aras, A. Hepbasli, Advanced exergy analysis of an electricity-generating facilityusing natural gas, Energy Convers. Manage. 82 (2014) 146–153.
[17] E. Açıkkalp, A. Hepbasli, C.T. Yucer, H.T.H. Karakoc, Advanced exergoenvironmental assessment of a building from the primary energy transformation to the environment, Energy Build. 82 (2015) 1–8.
[18] T. Morosuk, G. Tsatsaronis, A new approach to the exergy analysis of absorption refrigeration machines, Energy 33 (2008) 890–907.
[19] S. Gong, K.G. Boulama, Parametric study of an absorption refrigeration machine using advanced exergy analysis, Energy 76 (2014) 453–467.

[20] J. Chen, H. Havtun, B. Palm, Conventional and advanced exergy analysis of an ejector refrigeration system, Appl. Energy 144 (2015) 139–151.
[21] M. Mehrpooya, H. Ansarinasab, Advanced exergoeconomic analysis of the multistage mixed refrigerant systems, Energy Convers. Manage. 103 (2015) 705–716.
[22] A. Bejan, G. Tsatsaronis, M. Moran, Thermal Design and Optimization, Wiley, New York, USA, 1996.
[23] F. Petrakopoulou, Comparative Evaluation of Power Plants with CO_2 Capture: Thermodynamic, Economic and Environmental Performance, Ph.D Thesis, Berlin Technical University, Berlin, 2011.
[24] S. Kelly, Energy Systems Improvement Based on Endogenous and Exogenous Exergy Destruction, Ph.D Thesis, Berlin Technical University, Berlin, 2008.
[25] M. Callak, F. Balkan, A. Hepbasli, Avoidable and unavoidable exergy destructions of a fluidized bed coal combustor and a heat recovery steam generator, Energy Convers. Manage. 98 (2015) 54–58.
[26] S. Kelly, G. Tsatsaronis, T. Morosuk, Advanced exergetic analysis: approaches for splitting the exergy destruction into endogenous and exogenous parts, Energy 34 (2009) 384–391.
[27] E. Açıkkalp, H. Aras, A. Hepbasli, Advanced exergoeconomic analysis of a trigeneration system using a diesel-gas engine, Appl. Therm. Eng. 67 (2014) 388–395.
[28] T. Morosuk, G. Tsatsaronis, Advanced exergetic evaluation of refrigeration machines using different working fluids, Energy 34 (2009) 2248–2258.
[29] A. Gungor, G. Tsatsaronis, H. Gunerhan, A. Hepbasli, Advanced exergoeconomic analysis of a gas engine heat pump (GEHP) for food drying processes, Energy Convers. Manage. 91 (2015) 132–139.
[30] G. Tsatsaronisa, M.H. Parka, On avoidable and unavoidable exergy destructions and investment costs in thermal systems, Energy Convers. Manage. 43 (9–12) (2002) 1259–1270.
[31] Z. Erbay, A. Hepbasli, Application of conventional and advanced exergy analyses to evaluate the performance of a ground-source heat pump (GSHP) dryer used in food drying, Energy Convers. Manage. 78 (2014) 499–507.