Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

Multi Objective Exergy Based Optimization of a Solar Micro CHP System Based on Organic Rankine Cycle

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ARTICLE INFO

Received: 2 May 2017
Received in revised form: 22 May 2017
Accepted: 1 June 2017

Keywords:
Exergoeconomic, Combined Heating and Power, Solar Energy, Genetic Algorithm

A B S T R A C T

A novel micro solar combined heating and power (CHP) cycle integrated with organic Rankine cycle (ORC) is proposed in this study. The thermal storage tank is installed to correct the mismatch between the supply of the solar energy and the demand of thermal source consumed by the CHP subsystem, thus the desired system could continuously and stably operate. The cycle is investigated and optimized from the viewpoint of thermodynamics and thermoeconomics. In base case design, the thermal efficiency, exergy efficiency and product cost rate are found to be 48.45%, 13.76% and 5688.1$/year. The thermal efficiency, exergy efficiency and product cost rate are selected as three objective functions and multi-objective optimization is carried out through Genetic Algorithm.

1. Introduction

The continual uses of fossil fuels to meet our ever-increasing energy demands have led to environmental pollution to air, water and land. Renewable energy sources are alternatives to the depleting fossil fuels and offer the improved security of our future energy supply [1]. Among them, solar energy is clean and free with no gas emissions. Combined Heating and Power (CHP) is an integrated system which provide more than one product.

Several studies have been conducted on thermodynamic and thermoeconomic analysis of CHP systems [2-10]. Tempesti et al.[3] proposed two different layouts for a CHP system with two sources: solar energy and geothermal. The result of energy and exergy analysis of these two systems has been compared and evaluated. The same authors [2], applied thermoeconomic analysis for the same systems and results showed that when there is a balance between ambient temperature and the solar radiation are in balance, the lowest cost is achievable for the CHP system. Ahmadi et al. [9] evaluated a CHP system from the viewpoint of thermodynamics and thermoeconomic and found the optimum design of the system. Ahmadi et al. [10] proposed a CHP system for a paper mill and applied thermodynamic analysis and multiobjective optimization for it. In this study, thermodynamic and thermoeceonomic analysis of a CHP system driven by solar energy is carried out. Multi objective optimization of the system is conducted using GA in which, thermal efficiency, exergy efficiency, and total product cost rate are considered as objective functions.

2. Materials and Methods

Figure 1 shows the schematic of proposed CHP system. The extracted flow of the turbine goes to the heater to supply the heat to the heating user. Turbine exhaust enters the condenser to reject the heat to the cooling water, and then these two streams (outlet of heater and condenser) are mixed in a mixer and pumped into economizer, evaporator and super heater to absorb heat from the heat source. Evacuated tube solar collectors are utilized to collect the solar radiation because of its low costs. A thermal storage system and an auxiliary boiler are used to provide continuous cooling, heating and power output when solar radiation is insufficient. Auxiliary boiler utilizes natural gas. In thermodynamic modeling, some inputs have been assumed as shown in Table 1.

2.1. Exergoenomic Analysis

Exergoeconomics is a branch of engineering that combines exergy analysis and economic principles to provide the system designer or operator with the information not available through conventional energy analysis and economic evaluations, but crucial to the design and operation of a cost-effective system. We can consider exergoeconomics as exergy-aided cost minimization [11]. In SPECO method which is applied in this study, firstly exergy of all streams should be calculated. Second fuel and product for each component should be defined [11].

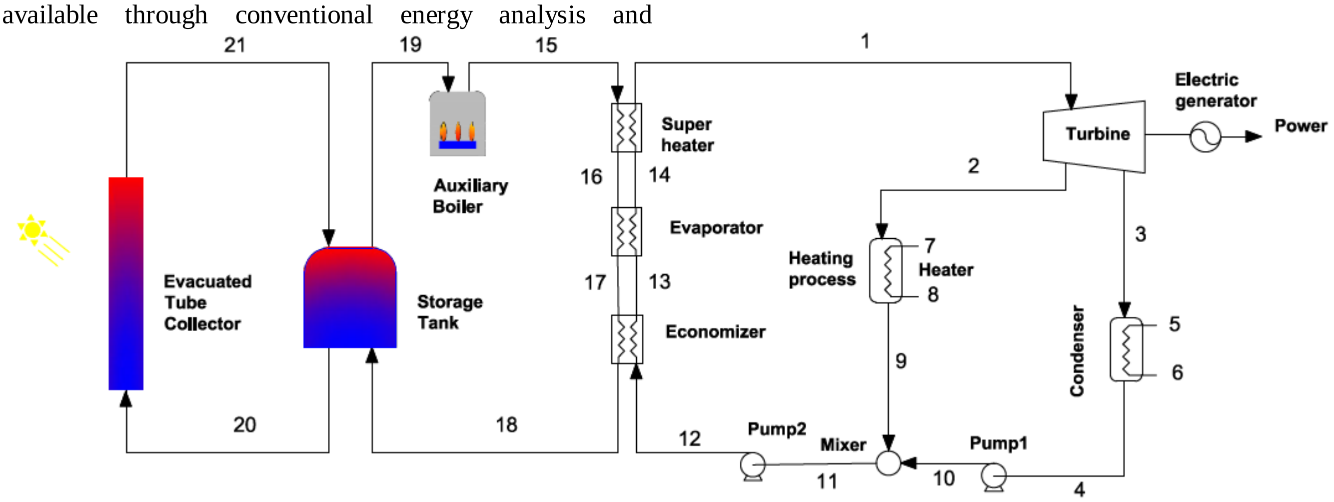

Figure1. Schematic of the proposed CHP system

Third, a cost balance applied to the kth system component shows that the sum of cost rates associated with all exiting exergy streams equals the sum of cost rates of all entering exergy streams plus the appropriate charges due to the capital investment $\dot{Z}_k^{CI}$ and operating and maintenance expenses $\dot{Z}_k^{OM}$. The sum of the last two terms is denoted by $\dot{Z}_k$. Accordingly, for a component receiving a heat transfer and generating power, we have:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{W,k} = \dot{C}_{Q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \tag{1}$$

$$\dot{C}_i = c_i \dot{X}_i \tag{2}$$

Cost rate balances, auxiliary equations and the corresponding equations for Z_k^{CI} for the CHP system are listed in Table 2 and equations 3-8 respectively.

Heat exchangers [12]:

$$Z_{HE}^{CI} = 130\left(\frac{A_{HE}}{0.093}\right)^{0.78} \tag{3}$$

Condenser [12]:

$$Z_{Cond}^{CI} = 1773\dot{m}_5 \tag{4}$$

Pump [12]:

$$Z_{pump}^{CI} = 3540\dot{W}_{pump}^{0.71} \tag{5}$$

Table 1. Input data for the system

Parameter	value
Dead state temperature	15 °C
Dead state pressure	100 kPa
Turbine inlet pressure	1000 kPa
Turbine inlet temperature	130 °C
Turbine back pressure	300 kPa
Turbine mass flow extraction ratio	0.5
Turbine isentropic efficiency	0.85
Pump isentropic efficiency	0.7
Cooling water inlet pressure	300 kPa
Cooling water inlet temperature	15 °C
Cooling water mass flow rate	0.4 kg/s
Condenser temperature difference	10 °C
Heater temperature difference	20 °C
Heater outlet temperature	80 °C
Super heater temperature difference	30 °C
Approach temperature difference	15 °C
Heating load	11 kW
Power	2.7 kW
Electrical generator efficiency	0.95
Auxiliary boiler efficiency	0.9
Low Heat Value of fuel	50654 kJ/kg
Surface area of solar collector	15.7 m^2
Monthly average insolation, H	7.99 MJ/m^2 day (December)
Monthly averaged insolation clearness index, K_T	0.52 (December)
Tilt angle	37.4°
Optical efficiency η_0	0.656
Coefficient a_1	1.4 W/m^2 K
Coefficient a_2	0.007 W/m^2 K^2

Storage Tank [13]:

$$Z_{ST}^{CI} = 4042 V_{ST}^{0.506} \quad (6)$$

Turbine [14]:

$$\log_{10}(Z_{turb}^{CI}) = 2.6259 + 1.4398 \log_{10}(\dot{W}_{turb}) - 0.1776\left[\log_{10}(\dot{W}_{turb})\right]^2 \quad (7)$$

Electric generator [15]:

$$Z_{Elec}^{CI} = 60 \dot{W}_{Elec}^{0.95} \quad (8)$$

Also, capital investments of the solar collector and auxiliary boiler in the reference year (2013) are 567 \$/m^2 and 28 \$/kW [16]. It should be noted that capital investments of ejector, mixers, and valves can usually be neglected since their contribution to the system cost is rather small [17, 18]. Capital investment of a component is converted to the cost rate by multiplying it by 1/t, the Capital Recovery Factor (CRF) and maintenance factor (φ). Here, t is the number of hours per year that the unit operates and the CRF is an economic parameter that depends on the interest rate (i) and the estimated component lifetime (N). The CRF is determined as Eq. (9) [19]:

$$CRF = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (9)$$

In the mentioned components in Table 2, investment cost rate is calculated by Eq. (10) [12]:

$$\dot{Z}_k = Z_k^{CI} \times CRF \times \varphi / t \quad (10)$$

The parameters in Eqs. (9) and (10) are assumed to be: N=20 year, i=10%, φ =1.06, t=7446h.

All cost data used in an economic analysis must be brought to the reference year (in this study 2013) by the following relation and using an appropriate cost index [11]:

Cost at the reference year = original cost (cost index for reference year/ cost index for the year when the original cost was obtained)

In this study, Chemical Engineering Plant Cost Index (CEPCI) index [20] is applied for updating all costs to the year 2013.

3. Results and Discussion

The thermodynamic and thermoeconomic analyses and optimization of a solar domestic CHP cycle with 2.7 kW electric output and 11kW heating output are conducted. The daily radiation is taken as 2.21 kWh/m^2[21]. Thermodynamic and thermoeconomic modeling of the system has been conducted based on simulation code in EES software [22]. The system thermal and exergy efficiency is determined to be 48.45% and 13.76%.

Effect of turbine inlet pressure

The effect of turbine inlet pressure on investment cost rate and product cost rate for fixed values of [T_1=130°C, P_2=300kPa, T_{29}=80°C] is shown in Figure 2. Figure 2 illustrates that investment cost rate decreases 1% as turbine inlet pressure varies, therefore, product cost rate decreases 3%. This means that if turbine works at higher pressures, it would be cost effective.

Effect of turbine inlet temperature

The influence of turbine inlet temperature on investment cost rate and product cost rate is illustrated in Figure 3 for fixed values of [P_1=1000kPa, P_2=300kPa, T_{29}=80°C]. It is

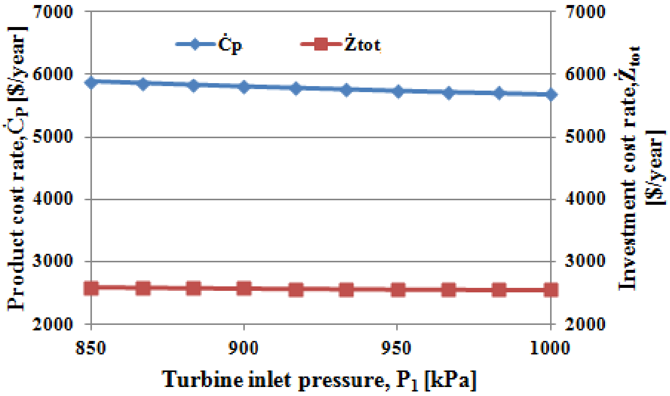

Figure 2. Variation of product cost rate and investment cost rate versus turbine inlet pressure.

indicated that by increasing turbine inlet temperature, investment cost rate decreases slightly because of slight increment in exergy efficiency and as a result, product cost rate decreases only 5%.

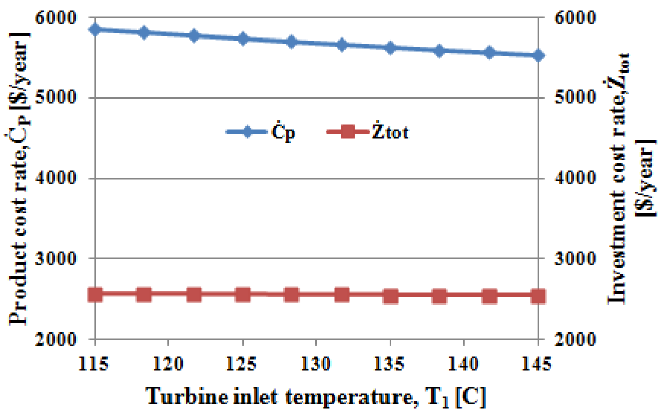

Figure 3. Variation of product cost rate and investment cost rate versus turbine inlet temperature.

Effect of turbine back pressure

Figure 4 represents the effect of turbine back pressure on the investment cost rate and product cost rate for fixed values of [P_1=1000kPa, T_1=130°C, T_{29}=80°C]. Figure 4 indicates that, with a variation of about 200kPa in turbine back pressure, investment cost rate increases 3% and consequently product coat rate increases 6%.

Effect of heater outlet temperature

Figure 5 represents the effect of heater outlet temperature on investment cost rate and product cost rate [P_1=1000kPa, T_1=130°C, P_2=300kPa] Figure 5 illustrates that investment cost rate decreases 2% due to increment in exergy efficiency and as a result, product cost rate decreases 1%.

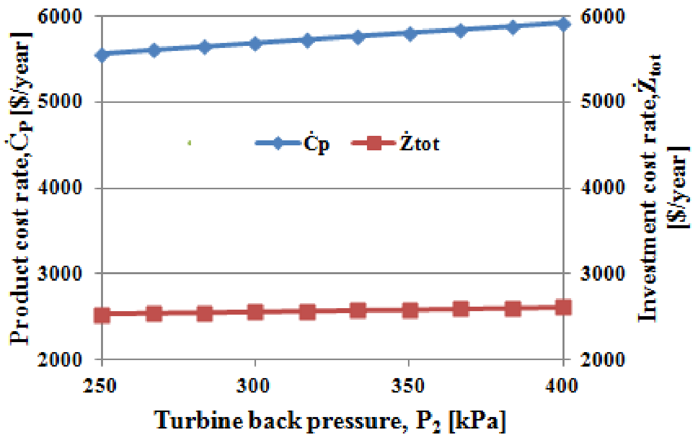

Figure 4. Variation of product cost rate and investment cost rate versus turbine back pressure.

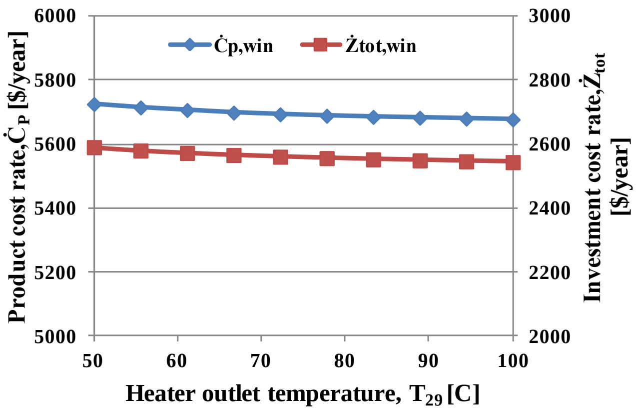

Figure 5. Variation of product cost rate and investment cost rate versus turbine back pressure.

4. Optimization

In this section, multi objective optimization is simultaneously carried out through optimizing thermal efficiency (η_{tot}), exergy efficiency of (ε_{tot}) and CHP product cost rate ($\dot{C}_{p,tot}$). Multi-objective optimization problems, generally, show a possibly uncountable set of solutions whose evaluated vectors represent the best possible trade-offs in the objective function space [23]. In this work, the genetic meta-heuristic algorithm (GA) through EES software is used for optimization of CHP plant. The selected decision variables in this work are turbine inlet temperature (T_1), turbine inlet pressure (P_1), turbine back pressure (P_2) and heater outlet temperature (T_{28}).One of the approaches to multi objective optimization problems is weighted cost functions. In this approach, we weight each function and add them together to obtain a single objective function which can be maximized or minimized using GA [24]. In fact, the different optimal solutions on the Pareto front can then be obtained by varying the weight coefficients [23, 24] and each optimal solution is selected using engineering experience and importance of each objective. For the CHP considered in this paper, the combined objective can be constructed by summing the three before mentioned objectives with some appropriate weights, as Eqs. (11) to (13):

Objective 1:

$$\eta_{CCHP,win} = \frac{\dot{W}_{elec} + \dot{Q}_H}{A_{coll} \cdot G_t + \dot{m}_{NG} \cdot LHV_{NG}} \tag{11}$$

Objective 2:

$$\varepsilon_{CCHP,win} = \frac{\dot{W}_{elec} + \dot{X}_H}{\dot{X}_{sun} + \dot{X}_{NG}} \tag{12}$$

Objective 3:

$$\dot{C}_{P,tot} = \dot{C}_{F,tot} + \dot{Z}_{tot} \tag{13}$$

$$MAX(F(P_1, T_1, P_2, T_{29}) =$$
$$w_1 \times \eta_{tot} + w_2 \times \varepsilon_{tot} + w_3 \times (1 - \dot{C}_p))$$
$$0 \le w_1, w_2, w_3 \le 1$$
$$w_1 + w_2 + w_3 = 1$$

Table 2. Cost rate balances and auxiliary equations for components

Components	Cost rate balance	Auxiliary Equation
Turbine	$\dot{C}_1 + \dot{Z}_{turb} = \dot{C}_2 + \dot{C}_3 + \dot{C}_{W_{turb}}$	$\frac{\dot{C}_1}{\dot{X}_1} = \frac{\dot{C}_2}{\dot{X}_2} = \frac{\dot{C}_3}{\dot{X}_3}$
Mixer	$\dot{C}_{17} + \dot{C}_{18} + \dot{Z}_M = \dot{C}_{11}$	_
Electric generator	$\dot{C}_{W_{net}} + \dot{Z}_{gen} = \dot{C}_{W_{elec}}$	
Evaporator	$\dot{C}_{13} + \dot{C}_{20} + \dot{Z}_{eva} = \dot{C}_{14} + \dot{C}_{21}$	$\frac{\dot{C}_{20}}{\dot{X}_{20}} = \frac{\dot{C}_{21}}{\dot{X}_{21}}$
Pump1	$\dot{C}_{10} + \dot{C}_{W_{pump1}} + \dot{Z}_{pump1} = \dot{C}_{17}$	_
Pump2	$\dot{C}_{11} + \dot{C}_{W_{pump2}} + \dot{Z}_{pump2} = \dot{C}_{12}$	_

Heater	$\dot{C}_2 + \dot{C}_{28} + \dot{Z}_H = \dot{C}_{18} + \dot{C}_{29}$	$\frac{\dot{C}_2}{\dot{X}_2} = \frac{\dot{C}_{18}}{\dot{X}_{18}}$
Economizer	$\dot{C}_{12} + \dot{C}_{21} + \dot{Z}_{eco} = \dot{C}_{13} + \dot{C}_{22}$	$\frac{\dot{C}_{21}}{\dot{X}_{21}} = \frac{\dot{C}_{22}}{\dot{X}_{22}}$
Super Heater	$\dot{C}_{14} + \dot{C}_{19} + \dot{Z}_{SH} = \dot{C}_1 + \dot{C}_{20}$	$\frac{\dot{C}_{19}}{\dot{X}_{19}} = \frac{\dot{C}_{20}}{\dot{X}_{20}}$
Condenser	$\dot{C}_5 + \dot{C}_{15} + \dot{Z}_{cond} = \dot{C}_6 + \dot{C}_{16}$	$\frac{\dot{C}_5}{\dot{X}_5} = \frac{\dot{C}_6}{\dot{X}_6}$
Auxiliary boiler	$\dot{C}_{23} + \dot{C}_{NG} + \dot{Z}_{AB} = \dot{C}_{19}$	c_{NG}=6.5×10^{-6} \$/kJ [25]
Storage tank	$\dot{C}_{22} + \dot{C}_{25} + \dot{Z}_{ST} = \dot{C}_{23} + \dot{C}_{24} + \dot{C}_{L,ST}$	$\frac{\dot{C}_{23}}{\dot{X}_{23}} = \frac{\dot{C}_{24}}{\dot{X}_{24}}$ $\frac{\dot{C}_{L,ST}}{\dot{X}_{L,ST}} = 0$
Solar collector	$\dot{C}_{24} + \dot{C}_{sun} + \dot{Z}_{coll} = \dot{C}_{25}$	$\frac{\dot{C}_{sun}}{\dot{X}_{sun}} = 0$

w_1, w_2 and w_3 are weighting factors for energetic, exergetic and thermoeconomic objectives, respectively. Selecting different values of weighting factors enable the decision maker to choose any set of optimal solutions.
Table 3 shows the decision variables and feasibility values for multi objective optimization.

Table 3. Decision variables and feasibility values

Decision variables	value
Turbine inlet pressure	$850 \le P_1(kPa) \le 1000$
Turbine inlet temperature	$115 \le T_1(°C) \le 145$
Turbine back pressure	$250 \le P_2(kPa) \le 400$
Heater outlet temperature	$50 \le T_{28}(°C) \le 100$

In this study, three of the coefficients are considered 1/3 and the results are indicated in Table 4.

Table 4. Base case and optimal case values of the decision variables and objective functions

Parameters	Base case	Optimal case
Turbine inlet pressure (kPa)	1000.00	974.30
Turbine inlet temperature (^oC)	130.00	144.90
Turbine back pressure (kPa)	200.00	258.60
Heater outlet temperature (^oC)	80.00	100
Thermal efficiency (%)	48.45	50.41
Exergy efficiency (%)	13.76	15.55
Product cost rate ($/year)	5688.1	5454.9

Table 4 shows that in the optimal case, thermal and exergy efficiencies improve 4% and 13% respectively while product cost rate decreases 4%.

5. Conclusion

The present work provides an application of well-known SPECO methodology of thermoeconomic analysis to evaluate a solar micro-CHP integrated with ORC.
By formulating exergy balance, cost balance and auxiliary equations for each component and solving them through EES software, thermal efficiency, exergy efficiency and product cost rate were calculated to be 48.45%, 13.76% and 5688.1$/year. Then the parametric analysis is done by assessing the effect of thermodynamic variables on the system investment cost rate and product cost rate. The results show that lower CHP product cost rate is obtained at higher turbine inlet pressure and temperature and heater outlet temperature but lower turbine back pressure. In the last section, multi objective optimizations are carried out through GA and results indicate that thermal efficiency, exergy efficiency, and product cost rate in optimum case improves 4%, 13% and 18%, respectively.

Nomenclature

A	Surface area (m^2)
c	Cost per exergy unit ($/GJ)
$\dot{C}$	Cost rate ($/year)
i	Interest rate (%)
$\dot{m}$	Mass flow rate (kg/s)
t	System operating hours (hour)
V	Volume
$\dot{W}$	Power (kW)
$\dot{X}$	Exergy (kW)
Z	Investment cost ($)
$\dot{Z}$	Investment cost rate ($/year)

Subscripts

AB	Auxiliary Boiler
Coll	Solar collector
Cond	Condenser
e	Outlet
Eco	Economizer
elec	Electrical
Eva	Evaporator
gen	Electric generator
H	Heater
HE	Heat Exchanger
i	Inlet
M	Mixer
NG	Natural Gas
pump	Pump
Q	Heat
SH	Super Heater
ST	Storage Tank
turb	Turbine
w	Power

Super scripts

CI	Capital Investment
N	Component lifetime (year)
OM	Operating and Maintenance

Greek symbols

ε	Exergy efficiency
η	Thermal efficiency
φ	Maintenance factor

Abbreviation

CHP	Combined Heating and Power
CEPCI	Chemical Engineering Plant Cost Index
CRF	Capital Recovery Factor
EES	Engineering Equation Solver
ORC	Organic Rankine Cycle
SPECO	Specific Exergy Costing

References

[1] G. Qiu, Y. Shao, J. Li, H. Liu, S.B. Riffat. Experimental investigation of a biomass-fired ORC-based micro-CHP for domestic applications. Fuel. 96 (2012) 374-82.

[2] D. Tempesti, D. Fiaschi. Thermo-economic assessment of a micro CHP system fuelled by geothermal and solar energy. Energy. 58 (2013) 45-51.

[3] D. Tempesti, G. Manfrida, D. Fiaschi. Thermodynamic analysis of two micro CHP systems operating with geothermal and solar energy. Applied Energy. 97 (2012) 609-17.

[4] H. Liu, Y. Shao, J. Li. A biomass-fired micro-scale CHP system with organic Rankine cycle (ORC)–Thermodynamic modeling studies. Biomass and Bioenergy. 35 (2011) 3985-94.

[5] A.M. Pantaleo, P. Ciliberti, S. Camporeale, N. Shah. Thermo-economic assessment of small scale biomass CHP: steam turbines vs ORC in different energy demand segments. (2015).

[6] R. Soltani, I. Dincer, M.A. Rosen. Thermodynamic analysis of a novel multigeneration energy system based on heat recovery from a biomass CHP cycle. Applied Thermal Engineering. 89 (2015) 90-100.

[7] D. Mikielewicz, J. Mikielewicz. A thermodynamic criterion for selection of working fluid for subcritical and supercritical domestic micro CHP. Applied Thermal Engineering. 30 (2010) 2357-62.

[8] Á. Campos-Celador, E. Pérez-Iribarren, J.M. Sala, L.A. del Portillo-Valdés. Thermoeconomic analysis of a micro-CHP installation in a tertiary sector building through dynamic simulation. Energy. 45 (2012) 228-36.

[9] P. Ahmadi, I. Dincer. Exergoenvironmental analysis and optimization of a cogeneration plant system using Multimodal Genetic Algorithm (MGA). Energy. 35 (2010) 5161-72.

[10] P. Ahmadi, A. Almasi, M. Shahriyari, I. Dincer. Multi-objective optimization of a combined heat and power (CHP) system for heating purpose in a paper mill using evolutionary algorithm. International Journal of Energy Research. 36 (2012) 46-63.

[11] A. Bejan, G. Tsatsaronis, M.J. Moran. Thermal design and optimization. John Wiley & Sons Inc., New York, 1996.

[12] F. Mohammadkhani, N. Shokati, S.M.S. Mahmoudi, M. Yari, M.A. Rosen. Exergoeconomic assessment and parametric study of a Gas Turbine-Modular Helium Reactor combined with two Organic Rankine Cycles. Energy. 65 (2014) 533-43.

[13] S. Martínez-Lera, J. Ballester, J. Martínez-Lera. Analysis and sizing of thermal energy storage in combined heating, cooling and power plants for buildings. Applied Energy. 106 (2013) 127-42.

[14] R.S. El-Emam, I. Dincer. Exergy and exergoeconomic analyses and optimization of geothermal organic Rankine cycle. Applied Thermal Engineering. 59 (2013) 435-44.

[15] L. Pierobon, T.-V. Nguyen, U. Larsen, F. Haglind, B. Elmegaard. Multi-objective optimization of organic Rankine cycles for waste heat recovery: Application in an offshore platform. Energy. 58 (2013) 538-49.

[16] http://www.apricus.com.au/downloads/. product specification sheet.

[17] L.G. Farshi, S. Mahmoudi, M. Rosen. Exergoeconomic comparison of double effect and combined ejector-double effect absorption refrigeration systems. Applied Energy. 103 (2013) 700-11.

[18] B.H. Gebreslassie, G. Guillén-Gosálbez, L. Jiménez, D. Boer. Design of environmentally conscious absorption cooling systems via multi-objective optimization and life cycle assessment. Applied Energy. 86 (2009) 1712-22.

[19] L. Garousi Farshi, S. Mahmoudi, M. Rosen. Exergoeconomic comparison of double effect and combined ejector-double effect absorption refrigeration systems. Applied Energy. 103 (2013) 700-11.

[20] CEPCI. Chemical Engineering Plant Cost Index. Chem Eng. (2010) 76.

[21] J. Paul W. Stackhouse, Ph.D. NASA Surface meteorology and Solar Energy. 2013.

[22] S.A. Klein. engineering equation solver (EES). 2013.

[23] H. Sayyaadi, A. Saffari, A. Mahmoodian. Various approaches in optimization of multi effects distillation desalination systems using a hybrid meta-heuristic optimization tool. Desalination. 254 (2010) 138-48.

[24] R.L. Haupt, S.E. Haupt. Practical genetic algorithms. John Wiley & Sons2004.

[25] http://www.alibaba.com/showroom/steam-ejector.html. 2015.