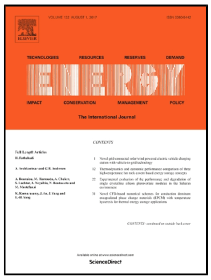
Accepted Manuscript



Energy, exergy and environmental analysis of a novel combined system producing power, water and Hydrogen

Kiyan Parham, Hamed Alimoradiyan, Mohsen Assadi

PII:	S0360-5442(17)31008-3
DOI:	10.1016/j.energy.2017.06.016
Reference:	EGY 11020
To appear in:	*Energy*
Received Date:	30 January 2017
Revised Date:	16 May 2017
Accepted Date:	04 June 2017

Please cite this article as: Kiyan Parham, Hamed Alimoradiyan, Mohsen Assadi, Energy, exergy and environmental analysis of a novel combined system producing power, water and Hydrogen, *Energy* (2017), doi: 10.1016/j.energy.2017.06.016

Energy, exergy and environmental analysis of a novel combined system producing power, water and Hydrogen

Kiyan Parham [1, *], Hamed Alimoradiyan [2], Mohsen Assadi [1]

[1] Department of Petroleum Engineering, Faculty of Science and Technology, University of Stavanger, 4036 Stavanger, Norway
[2] Department of Mechanical Engineering, Eastern Mediterranean University, G. Magosa, TRNC, Mersin 10, Turkey

* E-mail: kiyan.parham@uis.no
Fax: +47 51831750
Tel: +47 51833606

Abstract

During last years, absorption heat transformers have been used widely for boosting low-grade heat sources. In this paper, a novel multi-generation system including an open absorption heat transformer (OAHT), an organic Rankine cycle with Internal Heat Exchanger (ORC-IHE) and an electrolyzer for hydrogen production is proposed and analyzed from both first and second laws of thermodynamics and exergoenvironmental analysis points of view. To assess the cycle's performance, thermodynamic models were developed and a parametric study was carried out. The results indicate that the net power output and the hydrogen production rate will increase by boosting the inlet temperature of the waste heat using OAHT. By the growth of evaporator temperature, exergoenvironmental impact index, exergetic stability factor and exergetic sustainability index is increasing which is advantageous for the environment.

Keywords: Open absorption heat transformer, organic Rankine cycle with Internal Heat Exchanger, electrolyzer, energy, exergy, exergoenvironmental analysis.

Nomenclature

AHT	absorption heat transformer
COP	coefficient of performance
CV	Control volume
DAHT	double stage absorption heat transformer
EES	Engineering Equation Solver
f	flow ratio
GTL	Gross temperature lift
h	enthalpy (kJ/kg)
IHE	internal heat exchanger

$\dot{m}$	mass flow rate (kg/s)
OAHT	Open absorption heat transfer
P	pressure
PR	performance ratio
Q	heat capacity (kW)
SAHT	single stage absorption heat transformer
SFEE	Steady-flow energy equation
S-ORC	Simple organic Rankine Cycle
THAT	triple stage absorption heat transformer
turb	turbine
X	concentration
ΔX	concentration difference

Subscript

0	ambient property
abs	absorber
con	condenser
eva	evaporator
gen	generator
s	strong
w	weak

I. Introduction

During recent past, great interest has been focused on employing mid/low-level temperature heat sources from industries, solar radiation and geothermal heat source [1]. In fact, these heat sources represent a considerable amount of energy by the capability of being recycled in secondary heat recovery technologies such as organic Rankine cycles (ORCs) [2] Kalina cycle [3], absorption refrigeration systems [4-6], and heating implements [7]. The second type refrigeration cycles, also called absorption heat transformers (AHTs), stand as the superlative relevant applicants of getting benefit of mid/low-level heat sources [8]. Operating as reversed absorption heat pumps (AHPs), AHTs have the capability of boosting the low-grade heat to higher temperature levels and thereby improving their usefulness by a negligible input of electric power [9].

The first category of AHTs, known as single stage absorption heat transformers (SAHT), capable of recovering about half of the input waste heat can supply the demanded energy of the succeeding industrial processes [10]. The quantities of absorption effects has a main role on the temperature level of out-coming heat from AHTs [11]. For single, double and triple AHTs, COPs (coefficient of performances) and GTLs (gross temperature lifts) of about (0.5, 0.35 and 0.2) and (50, 80 and 140 °C) are accessible [9, 11, 12].

Solutions of $LiBr–H_2O$ and NH_3-H_2O are the most commonly utilized pairs in absorption cycles [13]. Neglecting the crystallization problem of $LiBr–H_2O$ systems, they have better performance in comparison to NH_3-H_2O solutions [14]. Waste heat from different industrial plants, standing in mid-low level temperature range has the potential to be employed as an appropriate heat source for AHTs [15]. Higher temperatures of waste heat to be utilized in auxiliary processes can be gained easily by these systems [8]. This outstanding characteristic of AHT sorts them a worthy candidate to be used in desalination applications [16]. Within last decade a huge attention has been paid to integrating absorption cycles into desalination set-ups [12, 15]. For instance, open absorption heat transformer (OAHT) were coupled to single and multiple desalination systems [17, 18] and demonstrated the aptitude of having higher COPs than those of common AHTs. The higher COP, the higher quantity of distilled water [18, 19].

OAHTs can also be connected to organic Rankine cycles. Owning the outstanding characteristics such as structure simplicity and satisfactory economic besides thermodynamic aspects, ORCs can be integrated with OAHTs as the secondary cycle. The integrated system has the capability of generating power by means of low-temperature heat input [20]. Recently, Zare [21] applied thermodynamic and economic analyses of three different configurations of organic Rankine cycles. It was demonstrated that the ORC utilizing Internal Heat Exchanger (ORC-IHE) had the best performance concerning the first and second laws of thermodynamic. A similar trend has also been reported by Yari [20] through thermodynamic analysis of different set ups of ORCs. Hydrogen production system can be a proper candidate as the subsequent arrangement of ORC-IHE due to the organic Rankine cycle turbine power. Environmentally friendly characteristics besides the feature of being a potential fuel for next generation vehicles dedicates Hydrogen production a great importance. Conducted several studies have proved that the role of Hydrogen on upcoming sustainable progress is going to be highlighted [22-24]. In the current research, a cogeneration cycle comprising of an OAHT, an ORC-IHE and an electrolyzer for supplying power, distilled water, and hydrogen is studied both from first and second laws of thermodynamics. For the aim of investigating the effects of imperative variables such as waste water inlet temperature, turbine inlet temperatures and pressure, gross temperature lift and generation temperature on the cycle performance and Hydrogen production a code has been developed in Engineering Equation Solver (EES) [25] and a comprehensive parametric study has been carried out. Additionally, an inclusive exergoenvironmental analyses has also be done.

II. System description

The combined cycle demonstrated in Fig. 1 is made up of an open absorption heat transformer, an organic Rankine cycle, and an electrolyzer. The consisting elements of a basic AHT are a condenser, a generator, an absorber, an evaporator, an expansion valve, a pair of pumps and a solution heat exchanger. Mid-low level temperature heat is transferred to the working pair (LiBr/H_2O) through generator and is rejected from condenser and absorber. In the generator, a portion of the solution water is evaporated and set off to condenser. This will lead to increased solution concentration. The outcoming strong solution of LiBr+H_2O from generator passes through economizer and then absorbs the water vapor coming from the evaporator. Since the absorption process is exothermic, the absorber temperature will rise. The boosted heat from absorber has the potential to provide the demanded heat for desalination set up. Following the absorber that partially evaporates water, separator vessel divides the obtained two phase flow into vapor and liquid phases. The latent heat of the water vapor is employed for evaporating the liquid part which goes back to the absorber. Now the outcomig fluid from evaporator has the capability to drive organic Rankine cycle (point 12). The obtained weak solution of the absorber is heated by economizer and then enters generator. The main advantage of OAHT in comparison to common AHTs is that the condensed water from the condenser is extracted as distilled water instead of flowing to the evaporator (stream 23, Fig. 1). Considering the fact that some contaminations and impurities are to be accumulated within the evaporator, a portion of the outgoing flow from the evaporator (1/20 of the waste feed water of the system) is considered as "discharged wastewater" denoted by stream 13. Next to open absorption heat transformer, ORC-IHE utilizes the heat of absorber as the secondary cycle. A typical organic Rankine cycle (TORC) comprises a pump, a condenser, an evaporator and a turbine. The evaporator has the role of heat source for ORC where the passing working flow is heated. At the subsequent stage by fluid expansion through the turbine, power is produced which is followed by a cooling process in the condenser and then flowing back to the evaporator assisted by the pump.

It is worth mentioning that in contrary to common steam plants, the exiting fluid from the turbine for most of the ORC fluids is in vapor phase rather than that of two-phase flow. By employing an Internal Heat Exchanger (IHE) and recovering a portion of the available heat at the turbine outlet, the performance of the

ORC can be improved. The mid part of Fig. 1 demonstrates this set up which is denoted as organic Rankine cycle with Internal Heat Exchanger. As common power cycles, there's an additional aspect of this cycle stating that the properties of the working fluid have a great impact on its performance [21]. At the current study, Isobutane was selected as the working fluid considering the temperature of the heat source and the fluid properties. Half of the power produced by ORC-IHE is transferred to the electrolyzer where water is converted to hydrogen and oxygen. The produced hydrogen can be stored later use as per consumer need, and the oxygen can be used e.g. for performance improvement of digestion based biogas generator.

Fig. 1. Schematic illustration of the proposed cycle.

III. Thermodynamic model

A code is developed in Engineering Equation Solver (EES) for thermodynamic simulation of the latter mentioned proposed cycle. Any element of the system has been considered as a control volume and first and second laws of thermodynamic besides mass conservation principle have been employed on them.

III.1. First law analyses

The mass balance can be expressed as:

$$\Sigma\dot{m}_{in} - \Sigma\dot{m}_{out} = 0 \quad (1)$$

Where $\dot{m}$ stands for the fluid mass flow rate. Any element is treated as a steady state system as follows:

$$\Sigma(\dot{m}\, h)_{in} - \Sigma(\dot{m}\, h)_{out} + \dot{Q}_{cv} - \dot{W}_{cv} = 0 \quad (2)$$

Here $\dot{Q}_{cv}$ and $\dot{W}_{cv}$ are the heat and power interactions of the CV with the surroundings.

Based on the thermal energy input to the integrated cycle, the thermal or first law efficiency may be expressed as follows:

$$\eta_I = \frac{\dot{W}_{net}}{Q_{gen}} \quad (3)$$

where

$$\dot{W}_{net} = \dot{W}_{turb} - \dot{W}_{pump} \quad (4)$$

The in depth mass and energy analysis which are very simple mathematical calculations are taken from those of Zhang et al. [17]. Due to not repeating them once more, they are not brought up here.

III.2. Second law

For evaluation of the systems' performance, use of the second law of thermodynamic has been emphasized due to its suitability for assessment of the selected system.

By neglecting kinetic, potential and chemical exergies the exergy of the fluid stream can be stated as:

$$\dot{E} = \dot{m}[(h - h_o) - T_o(s - s_o)] \qquad (5)$$

The exergy transferred by waste heat to the OAHT generator is assumed as input exergy and thus the second law efficiency of the propsed cycle is defined as:

$$\eta_{II} = \frac{\dot{W}_{net}}{E_{in}} \qquad (6)$$

For any element, the exergy destruction rate is calculated by the following equation:

$$\dot{E}_{D,k} = \Sigma \dot{E}_{in,\,k} - \Sigma \dot{E}_{out,\,k} \qquad (7)$$

III.3. Performance evaluation

In absorption cycles, COP is considered as the indicator of boosting the provided heat at given temperature of the evaporator and generator to the level of absorber temperature. For closed AHTs it is defined as follows:

$$COP = \frac{\dot{Q}_{abs}}{\dot{Q}_{gen} + \dot{Q}_{eva}} \qquad (8)$$

Where $\dot{Q}$ stands for heat transfer rate (kW).

It is worth mentioning that in OAHTs, the demanded heat for evaporator ($\dot{Q}_{eva}$) is provided by absorber and hence no external heat source is needed which leads definition of the COP as:

$$COP = \frac{\dot{Q}_{abs}}{\dot{Q}_{gen}} \qquad (9)$$

One of the most imperative parameters in designing and optimizing absorption heat transformers, is the flowing ratio:

$$f = \frac{\dot{m}_s}{\dot{m}_r} \quad (10)$$

in which $\dot{m}_s$ and $\dot{m}_r$ stand for strong solution and weak refrigerant mass flow rates (kg/s) respectively.

Similarly, in desalination systems, the quantity of distilled water over spent motive steam by generator is called performance ratio (PR) and from the view point of design and optimization is of great importance:

$$PR = \frac{\text{the amount of distilled water}}{\text{the amount of motive stream}} = \frac{\mathrm{D}}{\dot{\mathrm{Q}}_{\mathrm{gen}} / \mathrm{r}_{\mathrm{gen}}} \quad (11)$$

(D and r_{gen} are the quantity of produced water and latent heat of water at generator temperature).

Gross temperature lift is the ability of AHT to increase the temperature of the available heat source to more useful level. The temperature lift for OAHT is defined as [18]:

$$\Delta T = T_{abs} - T_{gen} \quad (12)$$

III. 4. Exergoenvironmental aspects

Nowadays, environmental analysis is of great interest in different aspects of science. Studying combined cycles only from the view point of energy and exergy does not seem to be satisfactory. Recently, exergy-based environmental analyses and sustainability examines have been employed in Hydrogen production cycles [24]. The effects of exergy efficiency and destruction on environmental subjects are the base of exergoenvironmental analyses.

According to [26, 27] the chief exergoenvironmental parameters are as follows:

A. **Exergoenvironmental impact factor (f_{ei}),** which clarifies the optimistic impact of the system on the environment for the aim of decreasing environmental harms through reduction of irreversibilities which is defined as:

$$f_{ei} = \frac{\dot{E}x_{dest,tot}}{\sum \dot{E}x_{in}} \quad (13)$$

Where $\dot{E}x_{des,tot}$ and $\dot{E}x_{in}$ stand for total exergy destruction and provided exergy to the system respectively.

B. **Exergoenvironmental impact index (θ_{ei}),** which determines if the system damages environment or not. The less exergoenvironmental impact index, the desired environmental performance.

$$\theta_{ei} = f_{ei} * C_{ei} \quad (14)$$

While

$$C_{ei} = \frac{1}{\frac{\eta_{ex}}{100}} \quad (15)$$

where C_{ei} and η_{ex} characterize exergoenvironmental impact coefficient and exergetic efficiency, correspondingly.

C. **Exergoenvironmental impact improvement (θ_{eii}),** which aims to discover the environmental relevance of the system. In contrary to the exergoenvironmental impact index, it would be as high as possible which revenues the fact that it is more beneficial to the environment.

$$\theta_{eii} = \frac{1}{\theta_{ei}} \quad (16)$$

D. **Exergetic stability factor (f_{es})** is defined as:

$$f_{es} = \frac{\dot{E}x_{tot,out}}{\dot{E}x_{tot,out} + \dot{E}x_{des,tot} + \dot{E}x_{uu}} \quad (17)$$

Where exergy $\dot{E}x_{uu}$ stands carried exergy by unused fuel (if any fuel is consumed in the system). Approaching to “one”, is the desired quantity for this parameter.

E. **Exergetic sustainability index (θ_{est}),** that is calculated as:

$$\theta_{est} = f_{es} * \theta_{eii} \qquad (18)$$

It is evident that acquiring highest quantity of exergetic sustainability index is preferred.

III. 5. Validation of the results

The results of Rivera et al. [28] for a single stage absorption heat transformer, have been used for verifying the achieved outcomes of the current study. By assuming the same input data (T_{gen} = T_{eva} = 74.1 °C and Tcon= 20 °C) and conditions in terms of negligible pressure and heat drops in pipes, isenthalpic expansion valve and 70% efficiency for economizer, our results correspond to those of their outcomes. Fig. 2 demonstrates the comparison of absorber temperature versus flow ratio by a negligible relative, which is completely reasonable.

Fig. 2. Comparison of the simulation results with those of Rivera et al [28].

Tables 1 and 2 demonstrate the input assumptions and operational properties for any point.

Table. 1. The Initial Design and Operation Parameters of the System.

Table. 2. Thermodynamic properties of the System at each state point.

IV. Results and discussion

The effect of T_{gen} on the COP of OAHT and the performance ratio have been plotted in Fig. 3. The COP decreases exponentially as T_{gen} increases. This is in contrast to the results obtained for a closed AHT in Ref. [8] wherein by increasing T_{gen} ,COP enhanced. This is completely reasonable according to equation 9 which is basically different from definition of COP for common AHTs. In OAHT, $\dot{Q}_{abs}$ correspondingly covers $\dot{Q}_{eva}$ and so $\dot{Q}_{eva}$ is not considered in the calculation of COP which leads to a different trend and is totally acceptable. Unlike the common closed AHTs, in which the COP is approximately 0.5, the COP values of OAHT can reach higher values, which is assumed as an advantage for OAHTs. One of the major compensations of OAHTs is their higher COPs in comparison with ordinary AHTs. As it is evident from Fig. 3, for the considered OAHT COP is more than those of common absorption heat transformers which stand approximately in the range of 0.2-0.5 [29]. A similar trend has also been reported by Zhang et al [15]. This is due to the fact that the latent/sensible heat of the steam in the evaporator is recycled and then used in absorber which eradicates the demand for external heat supply. As mentioned in [12], by increasing T_{gen}, X_s and consequently the flow ratio are boosted, which leads to the reduction of absorber heat capacity and correspondingly performance ratio which is evident on Fig. 3.

Fig. 3. Effects of T_{gen} on COP and PR of the system.

The effect of increased inlet temperature of the heat supply on the net power produced and the hydrogen production rate is displayed in Figure 4. The net power and the mass flow rate of produced hydrogen rises from 76.6 kW to 85.4 kW and 0.067 gr/s to 0.076 gr/s respectively by boosting the temperature T_7 from 100 °C to 130 °C. This is due to the fact that increasing the inlet temperature of the waste heat increases the temperature of the absorber, which leads to the elevation of the evaporator's temperature [18]. Enhancing T_{eva} as the heat source of ORC-IHE boosts the net power produced by the organic Rankine cycle [21]. A portion of the turbine power is consumed for Hydrogen generation through electrolyzer. This means that by increasing the amount of power generation by turbine, the power feed to the electrolyzer will enhance which will lead to higher rate of hydrogen production [30].

Fig. 4. Variations of net power generation and rate of hydrogen production by waste water inlet temperature.

Figure 5 displays the thermal and exergy efficiencies of the integrated system as a function of waste heat inlet temperature. It is observed that as T_7 increases, both thermal and exergy efficiency increases. Referring to Figure 4, it is apparent that $\dot{W}_{net}$ increases by boosting T_7 which has a direct impact on thermal and exergy efficiency according to equations 3 and 6. Considering the fact that the only power generation element in the integrated cycle is the turbine of ORC-IHE, it is reasonable to have an operational effect on both the efficiencies. A similar trend is reported by El-Emam and Dincer [31].

Fig. 5. Variations of energy and exergy efficiencies by waste water inlet temperature.

Figure 6 examines the first and second law efficiency trends against generation temperature, within a temperature range of 65- 90 °C. As is seen, both the efficiencies decrease by increasing generation temperature. This is because of the fact that while T_{gen} growths, the concentration of the strong solution will increase by enhancement of flow ratio-which will lead in lower absorption heat capacity which in turn results in lower thermal and exergy efficiency.

Fig. 6. Influence of T_{gen} on energy and exergy efficiencies.

Net power and Hydrogen productions as the functions of turbine inlet temperature have been plotted in Fig. 7. It shows that net power generated increases with turbine inlet temperature. This is because of increased enthalpy at point 17 as consequence of higher turbine inlet temperature and according to equation $\dot{W}_{tur} = \dot{m}_{17}(h_{17} - h_{18})$, the generated power by the turbine and consequently the net power produced enhances. Increased net power output will also boost the rate of hydrogen production and once more the explanations of Figure 4 can be employed herein.

Fig. 7. Effect of turbine inlet temperature on net power generation and rate of hydrogen production.

The effect of gross temperature lift ($\Delta T = T_{abs} - T_{gen}$) on the net power produced and the rate of hydrogen production are investigated in Fig. 8. It is clear that as ΔT is increased from 0 °C to 40 °C, net power generation and rate of hydrogen production decrease by 10.8% and 12.1%. [8, 32, 33] it is clear that as T_{abs} increases, the absorber heat capacity decrease. This is due to the fact that as T_{abs} increases, X_w and consequently flow ratio (f) increase, resulting in a decrease in the absorber heat capacity. By decreasing absorber heat capacity which is considered as the heat input reduction to ORC, the net power production and correspondingly hydrogen production will decrease.

Fig. 8. Effect of gross temperature lift on net power generation and rate of hydrogen production.

The influence of entering water mass flow rate to the electrolyser on exergoenvironmental impact factor of the system is demonstrated in Fig. 9. It is revealed that by increasing the inlet water, total exergy destruction of the system is decreasing which leads to the reduction of exergoenvironmental impact factor which can be presumed as the better performance of the cycle. A similar trend is observed by increasing the environment temperature changing from 25 ^oC to 35 ^oC.

Fig. 9. Effect of water mass flow rate on exergoenvironmental impact factor.

Fig. 10 presents the reduction of exergoenvironmental impact index by the growth of evaporator temperature. The reason is that, by boosting evaporator temperature, exergetic efficiency and internal exergy rate increase which causes a slight decline in the exergoenvironmental impact index. Once more by increasing environmental temperature, exergoenvironmental impact index decreases. By recalling the fact that the desired condition is the minimum quantity of exergoenvironmental impact index, both the latter mentioned variations, are beneficial.

Fig. 10. Effect of evaporator temperature on the exergoenvironmental impact index.

The effect of evaporator temperature on the exergoenvironmental impact improvement has been plotted on Fig. 11. It is obvious that by raising the evaporator temperature, the exergoenvironmental impact index of the system is increasing. As mentioned earlier, the higher amount of exergoenvironmental impact index, the better environmental influence. Thus, from this point of view, increasing evaporator temperature has an advantageous trend. The same tendency is observed while environment temperature is boosted.

Fig. 11. Effect of evaporator temperature on the exergoenvironmental impact improvement.

The effect of evaporator temperature on the exergetic stability factor, has been plotted on Fig. 12. According to the definition of exergetic stability factor, the optimum operation is while its quantity is close to one which is completely acceptable according to its definition. As is obvious from Fig.12, there is an increasing approaching trend to “one” for the exergetic stability factor by increasing the evaporator temperature. This clarifies the fact that by increasing evaporator temperature, less exergy destruction rate is achieved. It would be noted that herein, no fuel is consumed. The trend of environment temperature is similar to exergoenvironmental impact index demonstrated in previous diagram.

Figure. 12. Effect of evaporator temperature on the exergetic stability factor.

Fig. 13 illustrates the relation between evaporator temperature and exergetic sustainability index. By the growth of evaporator temperature from 115 ^{o}C to 120 ^{o}C, exergetic sustainability index is increasing which is considered as an advantage for the system. Once more by enhancing environment temperature, cycle performs better and higher amount of exergetic sustainability index is attained.

Figure. 13. Effect of evaporator temperature on the exergetic sustainability index.

V. Conclusion

An analysis of a novel multi-generation system including an open absorption heat transformer (OAHT), an organic Rankine cycle with Internal Heat Exchanger and an electrolyzer was studied. Based on energy, exergy and exergoenvironmental analyses through the code developed in Engineering Equation Solver and results presented in the paper, following conclusions are made:

- By increasing T_{gen}, COP of the OAHT decreases, which is in contradiction to the results obtained in ordinary AHTs incorporated with a desalination system.
- The net power output and the hydrogen production rate increase by boosting the inlet temperature of the waste heat.
- Both thermal and exergy efficiency of the integrated system will increase when the inlet temperature of the waste heat increases.
- Generation temperature has an opposite impact on the thermal and exergy efficiency.
- Increasing the inlet water mass flow rate to the electrolyzer, the exergoenvironmental impact factor reduces which can be presumed as the better performance of the cycle.
- By the growth of evaporator temperature, exergoenvironmental impact index, exergoenvironmental impact index, exergetic stability factor and exergetic sustainability index is increasing which is advantageous for the environment.

VI. Future work

Considering the importance of exergoeconomic analysis, as the second stage of the current work, authors will investigate the exergoeconomic model of the current research in terms of cost-optimal design point of view.

References

[1] Ma Z, Bao H, Roskilly AP. Performance analysis of ultralow grade waste heat upgrade using absorption heat transformer. Applied Thermal Engineering.

[2] Vélez F, Segovia JJ, Martín MC, Antolín G, Chejne F, Quijano A. A technical, economical and market review of organic Rankine cycles for the conversion of low-grade heat for power generation. Renewable and Sustainable Energy Reviews. 2012;16(6):4175-89.

[3] Zhang X, He M, Zhang Y. A review of research on the Kalina cycle. Renewable and Sustainable Energy Reviews. 2012;16(7):5309-18.

[4] Zhai XQ, Qu M, Li Y, Wang RZ. A review for research and new design options of solar absorption cooling systems. Renewable and Sustainable Energy Reviews. 2011;15(9):4416-23.

[5] Li T, Yu H, Li Y-Y, Liu Q, Chen C, Guo L, et al. Study on washwater effluent quality discharged by ship exhaust gas DeSO x system with magnesium and seawater desulphurisation method. International Journal of Environment and Pollution. 2014;56(1-4):1-10.

[6] Khamooshi M, Parham K, Atikol U. Overview of ionic liquids used as working fluids in absorption cycles. Advances in Mechanical Engineering. 2013;2013.

[7] Fang H, Xia J, Zhu K, Su Y, Jiang Y. Industrial waste heat utilization for low temperature district heating. Energy policy. 2013;62:236-46.

[8] Parham K, Yari M, Atikol U. Alternative absorption heat transformer configurations integrated with water desalination system. Desalination. 2013;328:74-82.

[9] Parham K, Khamooshi M, Tematio DBK, Yari M, Atikol U. Absorption heat transformers - A comprehensive review. Renewable and Sustainable Energy Reviews. 2014;34:430-52.

[10] Donnellan P, Cronin K, Byrne E. Recycling waste heat energy using vapour absorption heat transformers: A review. Renewable and Sustainable Energy Reviews. 2015;42:1290-304.

[11] Khamooshi M, Parham K, Egelioglu F, Yari M, Salati H. Simulation and optimization of novel configurations of triple absorption heat transformers integrated to a water desalination system. Desalination. 2014;348:39-48.

[12] Khamooshi M, Parham K, Roozbeh I, Ensafisoroor H. Applications of innovative configurations of double absorption heat transformers in water purification technology. Desalination and Water Treatment. 2016;57(18):8204-16.

[13] Parham K, Atikol U, Yari M, Agboola OP. Evaluation and optimization of single stage absorption chiller using (LiCl + H2O) as the working pair. Advances in Mechanical Engineering. 2013;2013.

[14] Rivera W, Romero R, Cardoso M, Aguillón J, Best R. Theoretical and experimental comparison of the performance of a single‐stage heat transformer operating with water/lithium bromide and water/Carrol™. International journal of energy research. 2002;26(8):747-62.

[15] Horuz I, Kurt B. Absorption heat transformers and an industrial application. Renewable Energy. 2010;35(10):2175-81.

[16] Ensafisoroor H, Khamooshi M, Egelioglu F, Parham K. An experimental comparative study on different configurations of basin solar still. Desalination and Water Treatment. 2016;57(5):1901-16.

[17] Zhang X, Hu D, Li Z. Performance analysis on a new multi-effect distillation combined with an open absorption heat transformer driven by waste heat. Applied Thermal Engineering. 2014;62(1):239-44.

[18] Hamidi A, Parham K, Atikol U, Shahbaz AH. A parametric performance analysis of single and multi-effect distillation systems integrated with open-cycle absorption heat transformers. Desalination. 2015;371:37-45.

[19] Khamooshi M, Parham K, Yari M, Egelioglu F, Salati H, Babadi S. Thermodynamic analysis and optimization of a high temperature triple absorption heat transformer. Scientific World Journal. 2014;2014.

[20] Quoilin S, Van Den Broek M, Declaye S, Dewallef P, Lemort V. Techno-economic survey of Organic Rankine Cycle (ORC) systems. Renewable and Sustainable Energy Reviews. 2013;22:168-86.

[21] Zare V. A comparative exergoeconomic analysis of different ORC configurations for binary geothermal power plants. Energy Conversion and Management. 2015;105:127-38.

[22] Hamada Y, Takeda K, Goto R, Kubota H. Hybrid utilization of renewable energy and fuel cells for residential energy systems. Energy and Buildings. 2011;43(12):3680-4.

[23] Asghari S, Mokmeli A, Samavati M. Study of PEM fuel cell performance by electrochemical impedance spectroscopy. International Journal of Hydrogen Energy. 2010;35(17):9283-90.

[24] Midilli A, Dincer I. Development of some exergetic parameters for PEM fuel cells for measuring environmental impact and sustainability. International Journal of Hydrogen Energy. 2009;34(9):3858-72.

[25] Klein SA, F A. Engineering Equation Solver, F-Chart Software. Middelton. 2012.

[26] Ratlamwala TAH, Dincer I, Reddy BV. Exergetic and environmentalimpact assessment of an integrated system for utilization of excess power from thermal power plant. Causes, Impacts and Solutions to Global Warming2013. p. 803-24.
[27] Ratlamwala TAH, Dincer I, Gadalla MA. Comparative environmental impact and sustainability assessments of hydrogen and cooling production systems. Causes, Impacts and Solutions to Global Warming2013. p. 389-408.
[28] Rivera W, Cerezo J, Rivero R, Cervantes J, Best R. Single stage and double absorption heat transformers used to recover energy in a distillation column of butane and pentane. International Journal of Energy Research. 2003;27(14):1279-92.
[29] Parham K, Khamooshi M, Daneshvar S, Assadi M, Yari M. Comparative assessment of different categories of absorption heat transformers in water desalination process. Desalination. 2016;396:17-29.
[30] Ratlamwala TAH, Dincer I. Development of a geothermal based integrated system for building multigenerational needs. Energy and Buildings. 2013;62:496-506.
[31] El-Emam RS, Dincer I. Exergy and exergoeconomic analyses and optimization of geothermal organic Rankine cycle. Applied Thermal Engineering. 2013;59(1):435-44.
[32] Gomri R. Thermal seawater desalination: Possibilities of using single effect and double effect absorption heat transformer systems. Desalination. 2010;253(1–3):112-8.
[33] Romero RJ, Rodríguez-Martínez A. Optimal water purification using low grade waste heat in an absorption heat transformer. Desalination. 2008;220(1):506-13.

Figures:

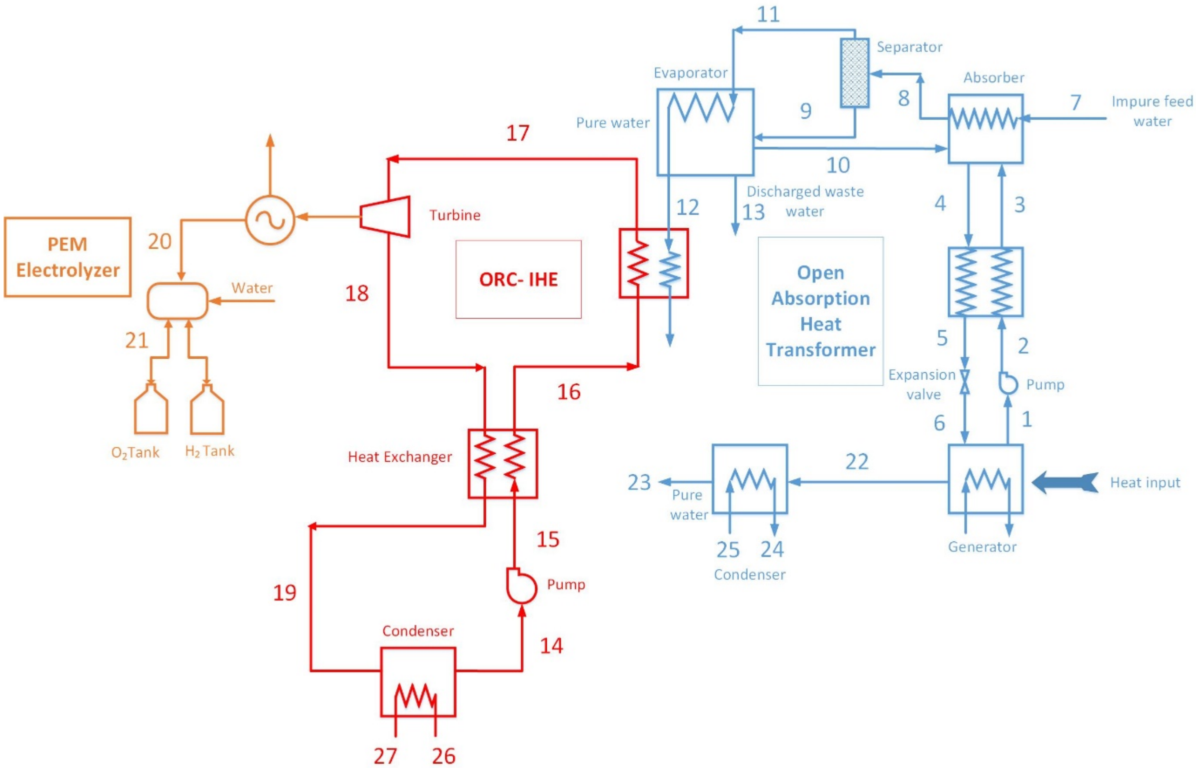


Fig. 1. Schematic illustration of the proposed cycle.

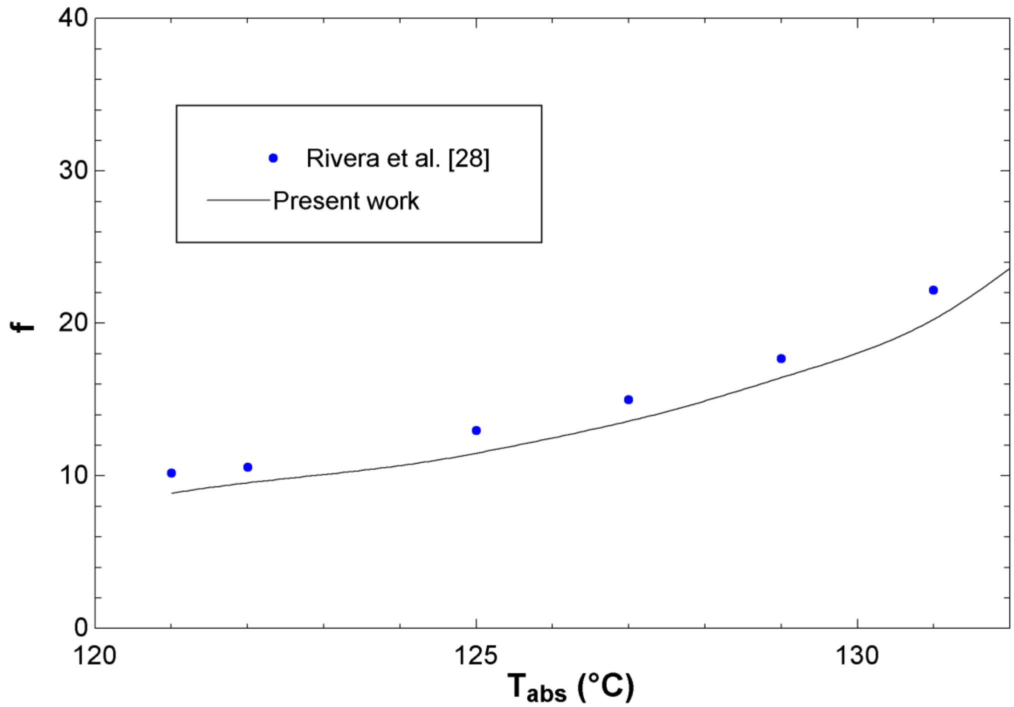


Fig. 2. Comparison of the simulation results with those of Rivera et al [28].

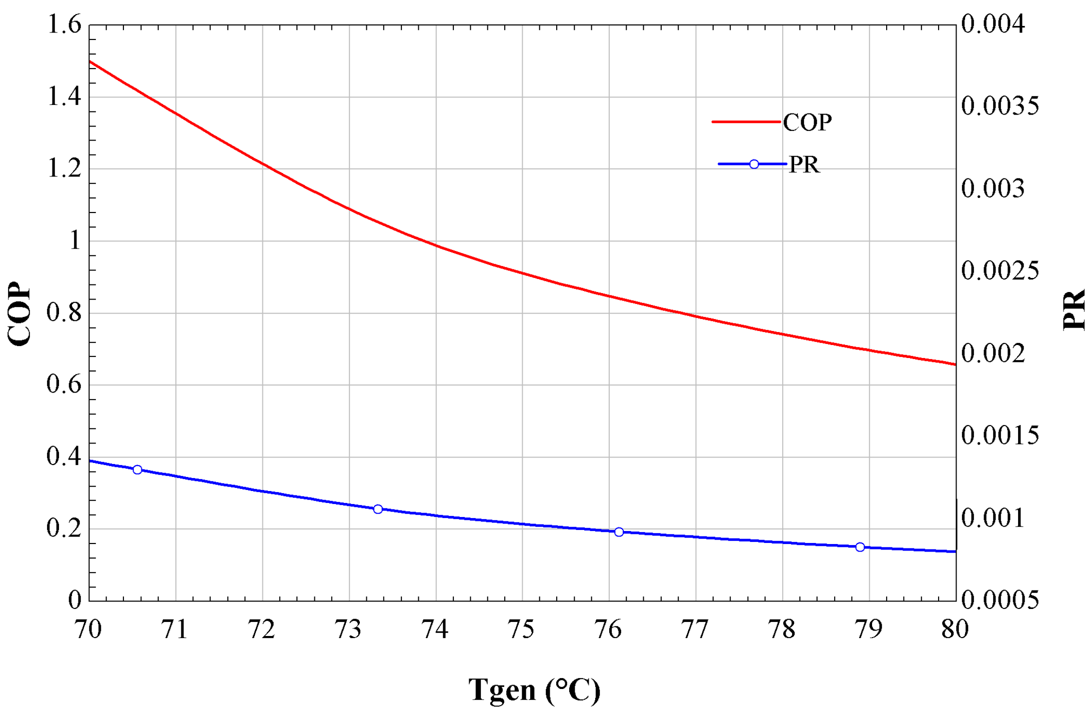


Fig. 3. Effects of T_{gen} on COP and PR of the system.

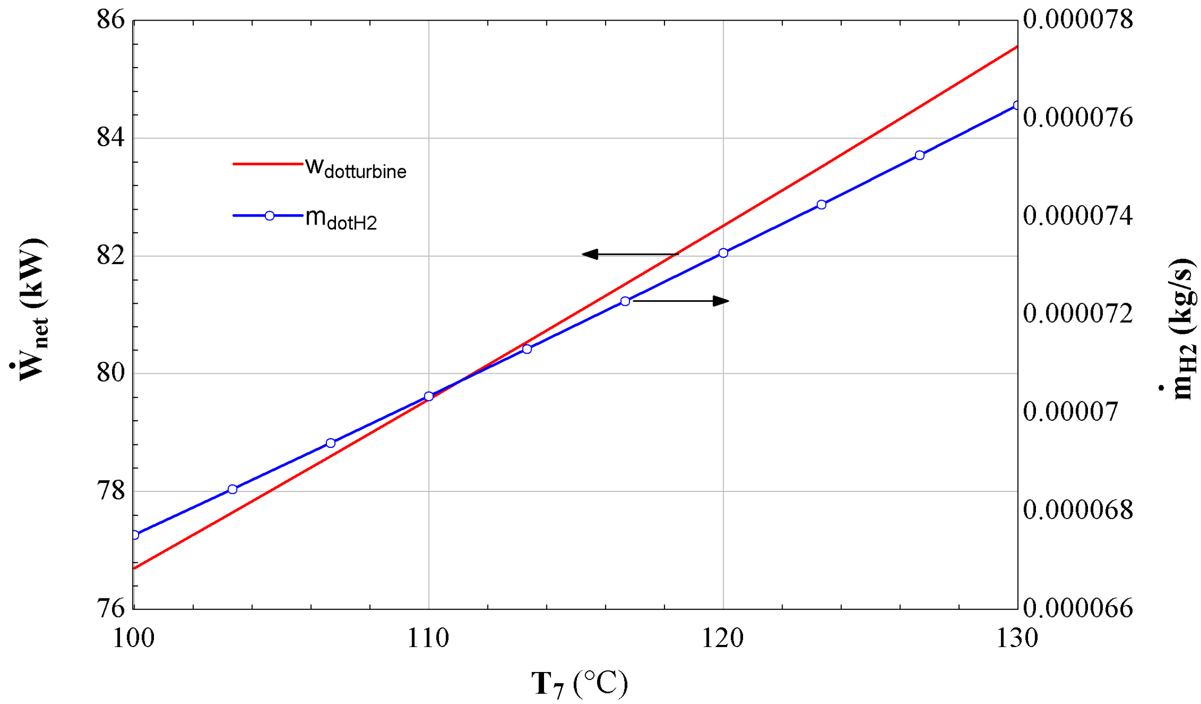
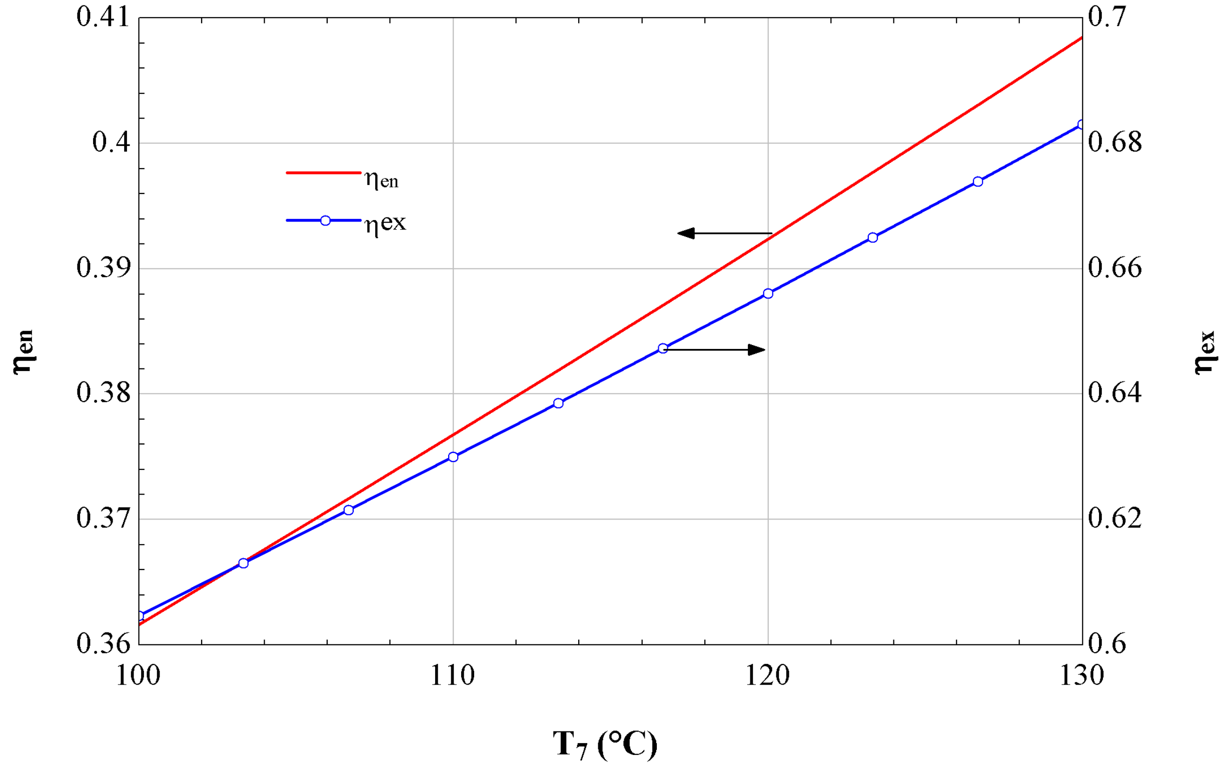


Fig. 4. Variations of net power generation and rate of hydrogen production by wastewater inlet temperature.



486

487 Fig. 5. Variations of energy and exergy efficiencies by waste water inlet temperature.

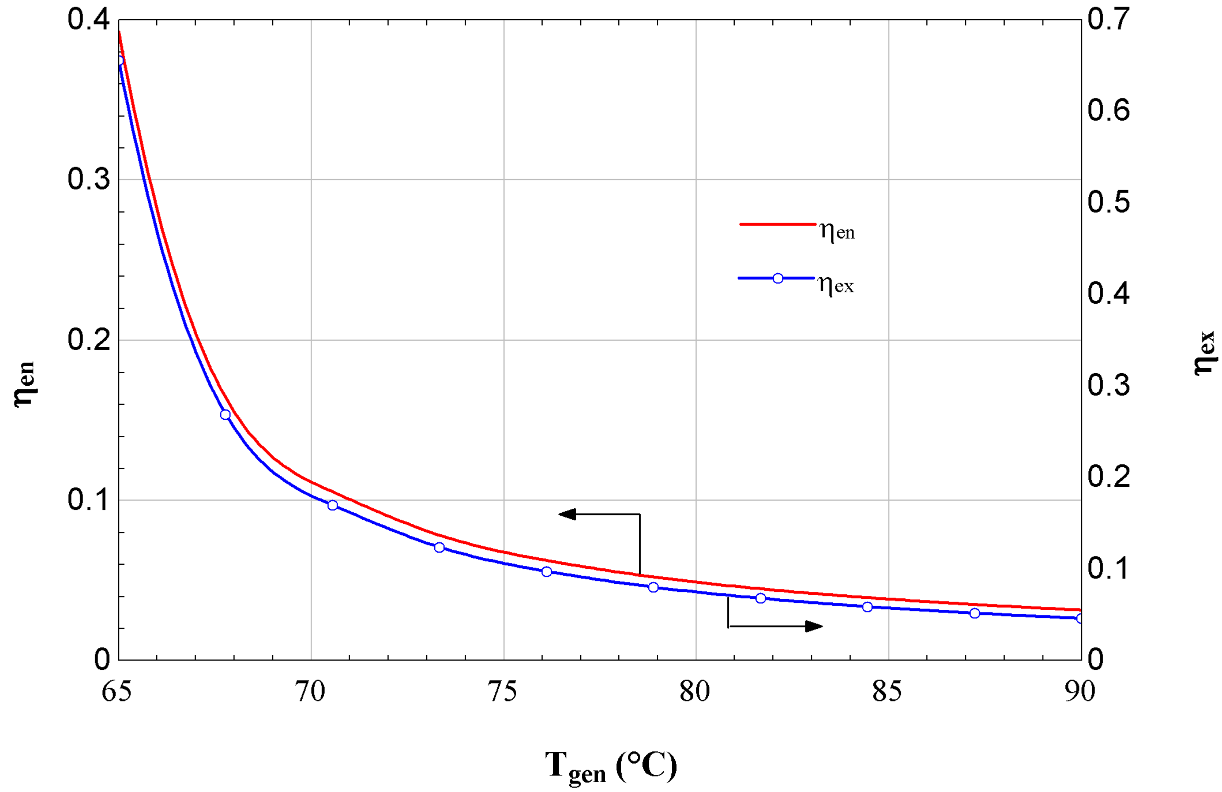


Fig. 6. Influence of T_{gen} on energy and exergy efficiencies.

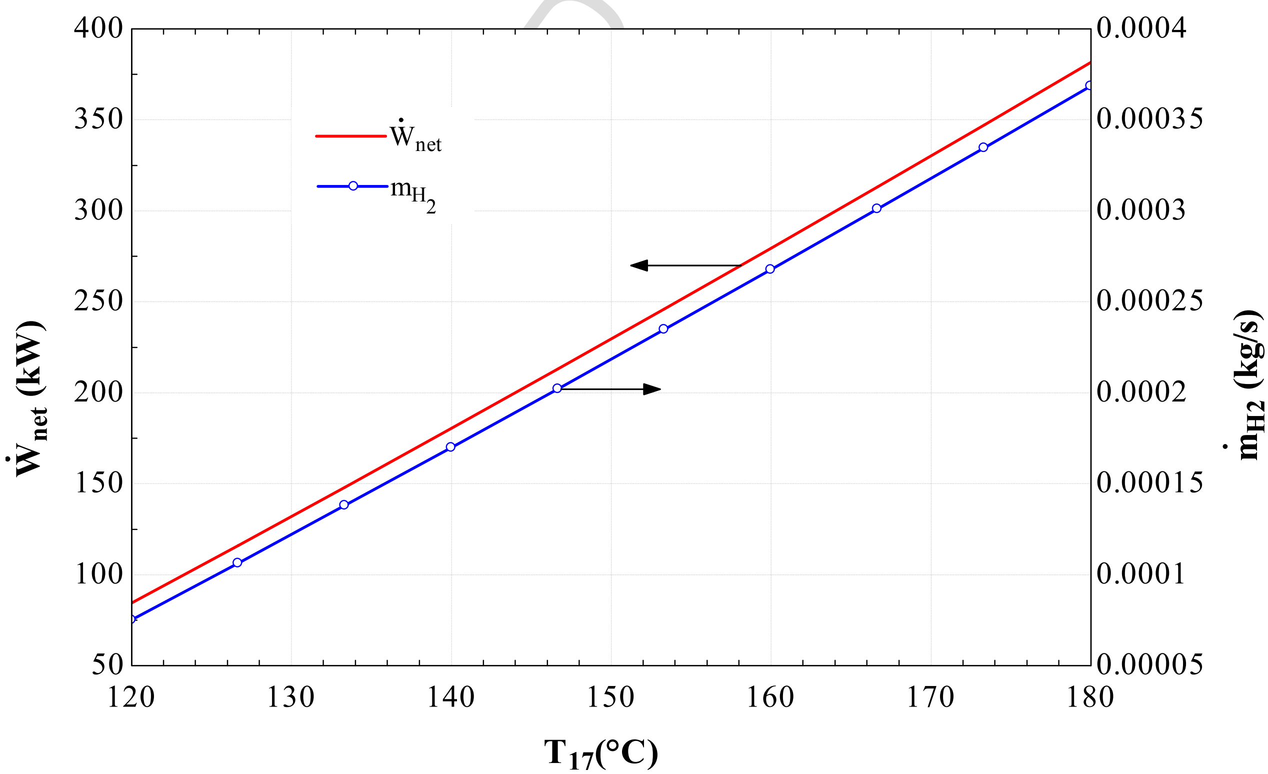


Fig. 7. Effect of turbine inlet temperature on net power generation and rate of hydrogen production.

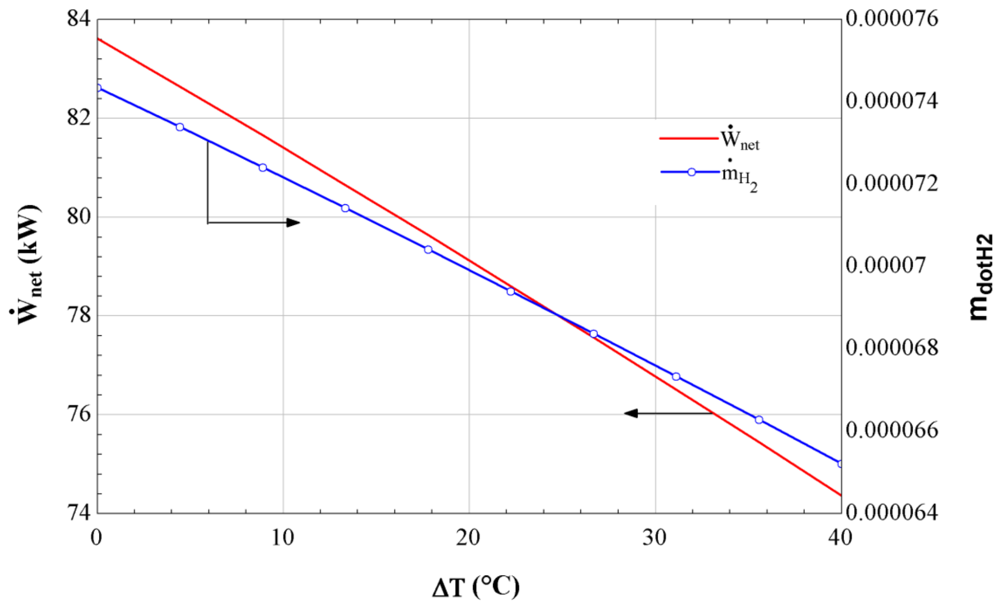
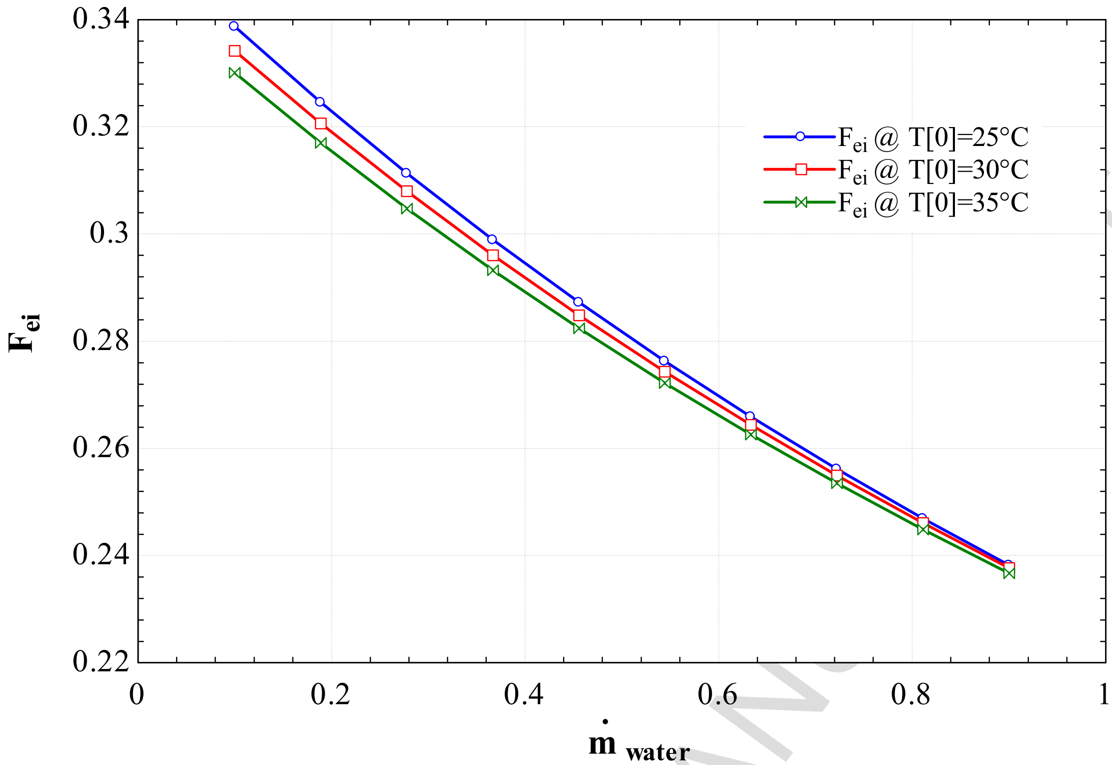


Fig. 8. Effect of gross temperature lift on net power generation and rate of hydrogen production.



498

499 Fig. 9. Effect of water mass flow rate on exergoenvironmental impact factor.

500

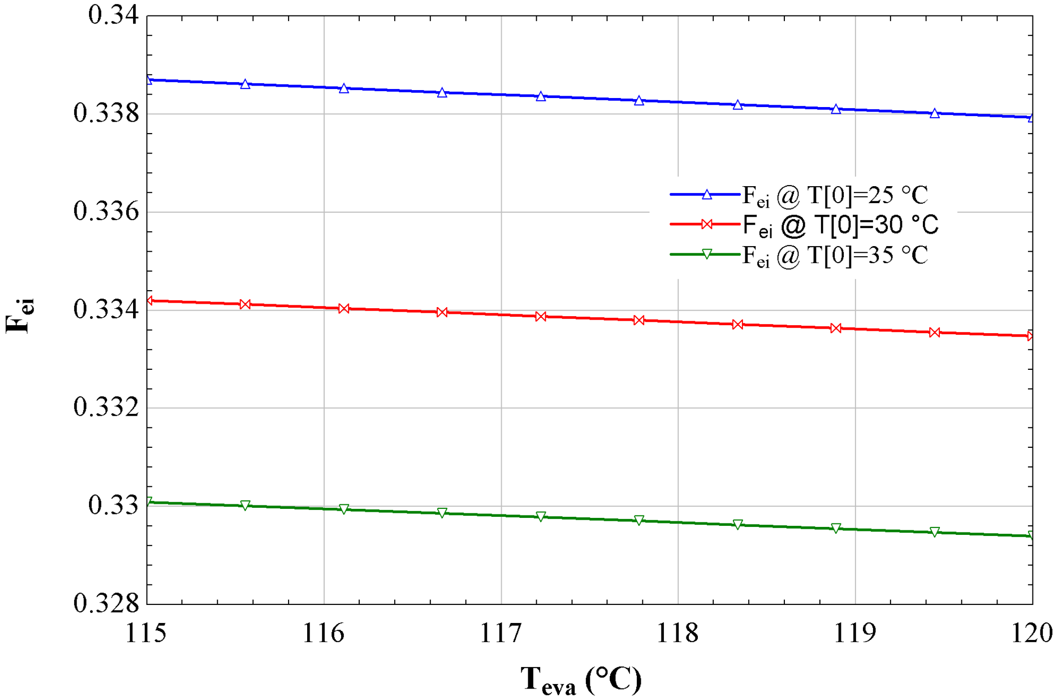


Fig. 10. Effect of evaporator temperature on the exergoenvironmental impact index.

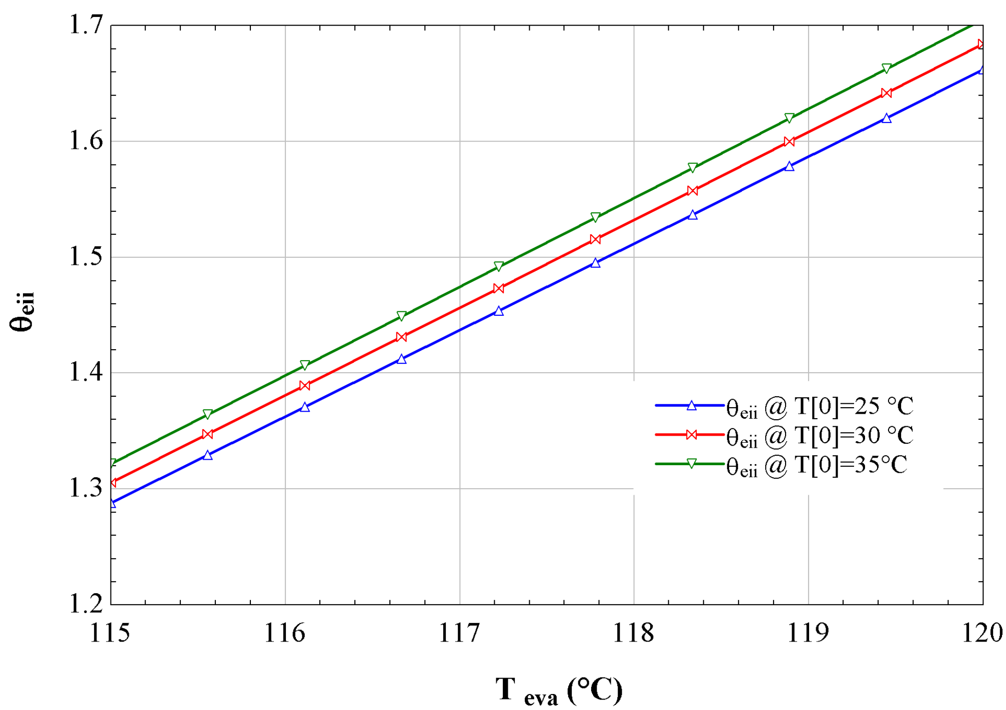
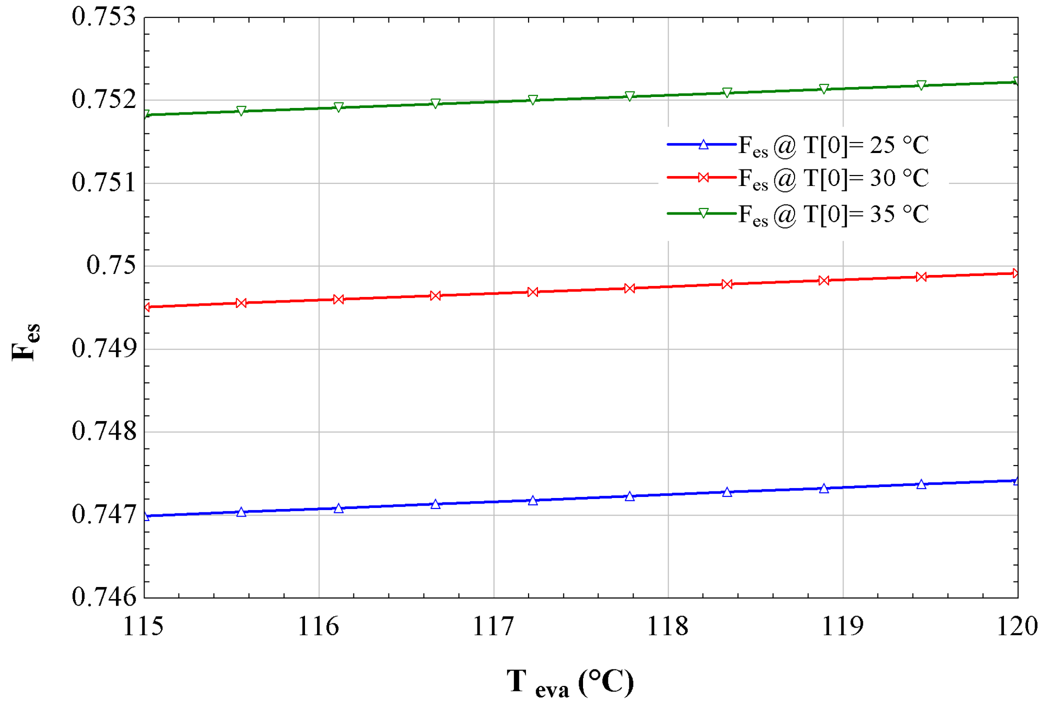
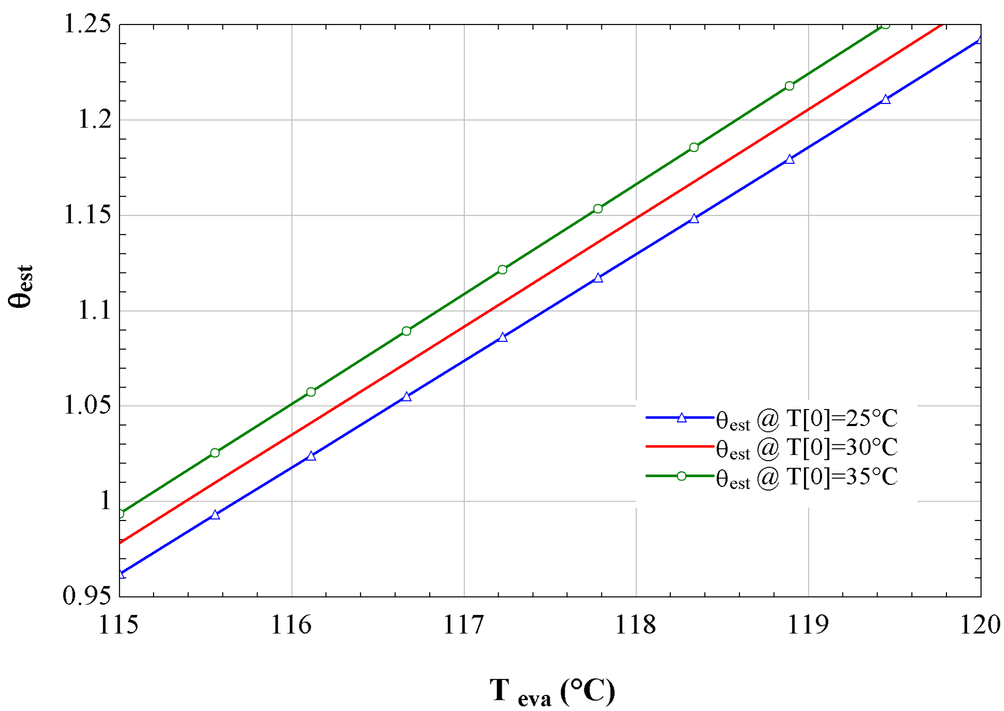


Fig. 21. Effect of evaporator temperature on the exergoenvironmental impact improvement.



505

506 Figure. 12. Effect of evaporator temperature on the exergetic stability factor.



507

508 Figure. 13. Effect of evaporator temperature on the exergetic sustainability index.

Tables:

$T_0 = 30$ (°C)	Ambient Temperature
$\omega = 40\%$	Specific Humidity of the Ambient Air
$P_0 = 101$ (kPa)	Ambient Pressure
$\eta_{elec} = 56\%$	Electrolyzer Efficiency
$T_{water,in} = 25$ (°C)	Temperature of the Water Injected to Electrolyzer
$\dot{m}_{water,in} = 1$ (kg/s)	Mass Flow Rate of the Water Injected to Electrolyzer

Table. 1. The Initial Design and Operation Parameters of the System.

State Points	Temperature (°C)	Specific enthalpy (kJ/kg)	Pressure (kPa)	Mass flow rate (kg/s)	Specific entropy (kJ/kg K)
0	35	129.4	101	-	5.764
1	65	138.2	7.381	3	0.4522
2	65	138.2	198.5	3	0.4522
3	98	212.4	198.5	3	0.6604
4	125	281.6	101	3.265	0.8834
5	125	281.6	101	3.265	0.8834
6	56.57	281.6	7.381	3.265	0.4398
7	120	503.8	198.5	0.1	1.528
8	120	1504	101.5	0.1	7.459
9	120	503.8	198.5	0.05459	1.528
10	120	2706	198.5	0.04959	7.13
11	120	2706	198.5	0.04541	7.13
12	120	503.8	198.5	0.04541	1.528
13	120	503.8	198.5	0.005	1.528

14	85	542.3	250	2	1.827
15	85	538.1	400	2	1.749
16	120	606.6	400	2	1.931
17	124.6	615.9	400	2	1.954
18	100	570.7	250	2	1.904
19	70	514.6	250	2	1.748
20	-	-	-	-	-
21	25	0	101	$\dot{M}_{H2}$	64.78
22	65	2621	7.381	0.2648	8.401
23	40	167.5	7.381	0.2648	0.5723

Table. 2. Thermodynamic properties of the System at each state point.

1. A novel cycle has been proposed for producing water, power and Hydrogen.
2. To assess the cycle's performance a model has been developed in EES.
3. First and second laws of thermodynamics besides exergoenvironmental analysis have been investigated.
4. Imperative system parameters are studied.