Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2015.1021851

57 (2016) 8161–8173
April

Taylor & Francis
Taylor & Francis Group

Thermo-economic analysis of combined power and water production in Iran by multi effect desalination method

Pedram Hanafizadeh*, Mojtaba Mirzakhani Siahkalroudi, Alireza Taklifi, Mohammad Ali Akhavan-Behabadi

School of Mechanical Engineering, College of Engineering, Center of Excellence in Design and Optimization of Energy Systems, University of Tehran, Kargar Shomali Ave., Tehran P.O. Box: 11155-4563, Iran, Tel. +98 21 88353894; Fax: +98 21 88013029; emails: hanafizadeh@ut.ac.ir (P. Hanafizadeh), m.mirzakhani@ut.ac.ir (M. Mirzakhani Siahkalroudi), alireza_taklifi@ut.ac.ir (A. Taklifi), akhavan@ut.ac.ir (M.A. Akhavan-Behabadi)

Received 2 August 2014; Accepted 16 February 2015

ABSTRACT

Current study reports thermo-economic evaluation of various configurations of combined electricity and potable water production systems. All of these systems use single pressure heat recovery steam generators and multi-effect seawater desalination systems coupled to single cycle gas turbine power plants. These combined power and water production plants are located in the south of Iran near salt water of the Persian Gulf. The aim of this work is to find the most appropriate combination of gas turbines with different capacities (4, 10, 25 MW) to produce 18,000 m^3/d fresh water. In this regard, a complete model of the system, including thermodynamics, heat transfer, and economic models as well as pressure loss calculations are developed. In this model, steady state mass and energy conservation equations are considered for each component of every configuration as a control volume. The results from this thermo-economic analysis of whole cycle are reported as the levelized cost of electricity, desalination water cost, and internal rate of return for investment. The capital, operation, and fuel costs were assumed due to available data for these specific systems and market of Iran.

Keywords: Multi-effect desalination; Thermo-economic analysis; Gas turbine configuration; TRR method

1. Introduction

There is a huge amount of water on the Earth, but only about 2.5% is potable. Many countries in the world are suffering from lack of fresh water. The world population and economic growth, increase in humans living standards, and fast development of industrial activities multiplies attention on the importance of cleanliness and fresh water production. Production of low cost fresh water in the dry, arid and dry, semiarid climate of Middle Eastern countries such as Iran is very important. One of the most obvious requirements for installation of a desalination system is the energy needed for this system to operate. The water and power stress analysis shows that Iran is in an urgent need for electricity and water. In Iran, the annual potable available water for each person is less than 1,000 m^3 for each year; however,

*Corresponding author.

1944-3994/1944-3986 © 2015 Balaban Desalination Publications. All rights reserved.

this index is more than 2,000 m^3 in most of the countries in the world [1,2].

Thermal energy constitutes most of the required energy for thermal desalination systems. Today, according to the increasing fuel costs, a variety of methods are used to reduce the cost of steam generation which is required for thermal desalination systems. These desalination plants do not require high temperature and high pressure steam as combined cycle power production needs. This source of steam can be generated by thermal boilers or heat recovery boilers. Multi-effect desalination (MED) system is suitable for being coupled with gas turbine power plants because it can utilize the waste heat of gas turbine's exhaust gases as its heat source. So, this system improves the fuel efficiency of the whole cycle; however, other thermal desalination methods such as multi-stage flushing are also available.

The country of Iran has many installed single cycle gas turbine plants located in the south of this country, near the seashore region [1]. As the fresh water shortage is also concentrated in these regions, these power plants are excellent choices for supplying fresh water besides electricity generation. In order to integrate a desalination plant with a gas turbine cycle, a selective heat recovery steam generator (HRSG) is required for producing motive steam [3]. Thermo-economics, which is a combination of thermodynamics (Second Law) and economics (the concept of cost), provides a rational procedure for analyzing a complex energy system, as well as for assessing the cost of the internal flows and final plant products [4].

Many researchers have studied desalination systems from thermodynamics and economics point of view. Ansari et al. [5] studied thermo-economic optimization of a hybrid pressurized water reactor (PWR) power plant coupled to multi-effect distillation desalination system with thermo-vapor compressor. Wu [6] studied analysis of the water production cost of a nuclear desalination with a nuclear heating reactor coupled with MED processes. Arena and Borchiellini [7] studied application of different productive structures for thermo-economic diagnosis of combined cycle power plant. Sayyaadi and Saffari [8] presented thermo-economic optimization of multi-effect distillation desalination systems. Ali El Saie et al. [9] presented techno-economic study of combined cycle power generation with desalination plants at Sharm El Sheikh. Hosseini et al. [10] studied cost optimization of a combined power and water desalination plant with exergetic, environment, and reliability considerations. Tian et al. [11] studied economic evaluation of seawater desalination for a nuclear heating reactor with multi-effect distillation. Khoshgoftarmanesh et al. [12] studied evaluation of coupling desalination with a PWR power plant with pinch, exergy and thermo-economic analysis. Mabub et al. [13] studied exergo-economic analysis of a combined water and power plant.

In all these researches, the aim was to find the cost of water for a given specific water production plant and the economics of the electricity generation part was ignored. But in this paper, for a MED desalination system with specified conditions, various layouts of gas turbines have been investigated and compared specifically for Iran. Then, the most appropriate system from the thermodynamic and economic point of view has been determined considering the Persian Gulf water specifications and site environmental conditions.

In the current study, the most appropriate combination of gas turbines with different capacities (4, 10, 25 MW) to produce 18,000 m^3/d fresh water has been investigated. A complete thermo-economic model consisting of thermodynamics, heat transfer, economic, and pressure loss concerns is developed for this evaluation.

2. Plant description

Figs. 1 and 2 show the schematic combined power and water production plant and different assumed configurations of gas turbines, possible and available for Iran's market, respectively. As it was mentioned before, the choices of gas turbines with their characteristics is done based on the available models of them in Iran. A HRSG consisting of the economizer, evaporator, director, and low temperature economizer (LTE) is considered to produce required steam for desalination system. For each component of this combined cycle, the governing energy equations are solved to analyze their thermodynamic and heat transfer performance. The considered MED plant has been assumed to have a constant capacity of 18,000 m^3/d regardless of any different gas turbine configuration being considered. This distilled water capacity is a case study, according to the desalination plant in the south of Iran and as the base problem in this research is the production of this amount of water in the country. So, the performance of each configuration to produce 18,000 m^3/d distillated water is compared at the end and the best system from thermo-economic aspects is being selected finally. This capacity is fixed to produce maximum potable water for each configuration. The schematic of MED system is shown in Fig. 3. In the MED system which is used in this paper, the seawater is heated with the steam in the first effect and a fraction of the water evaporates. In this system,

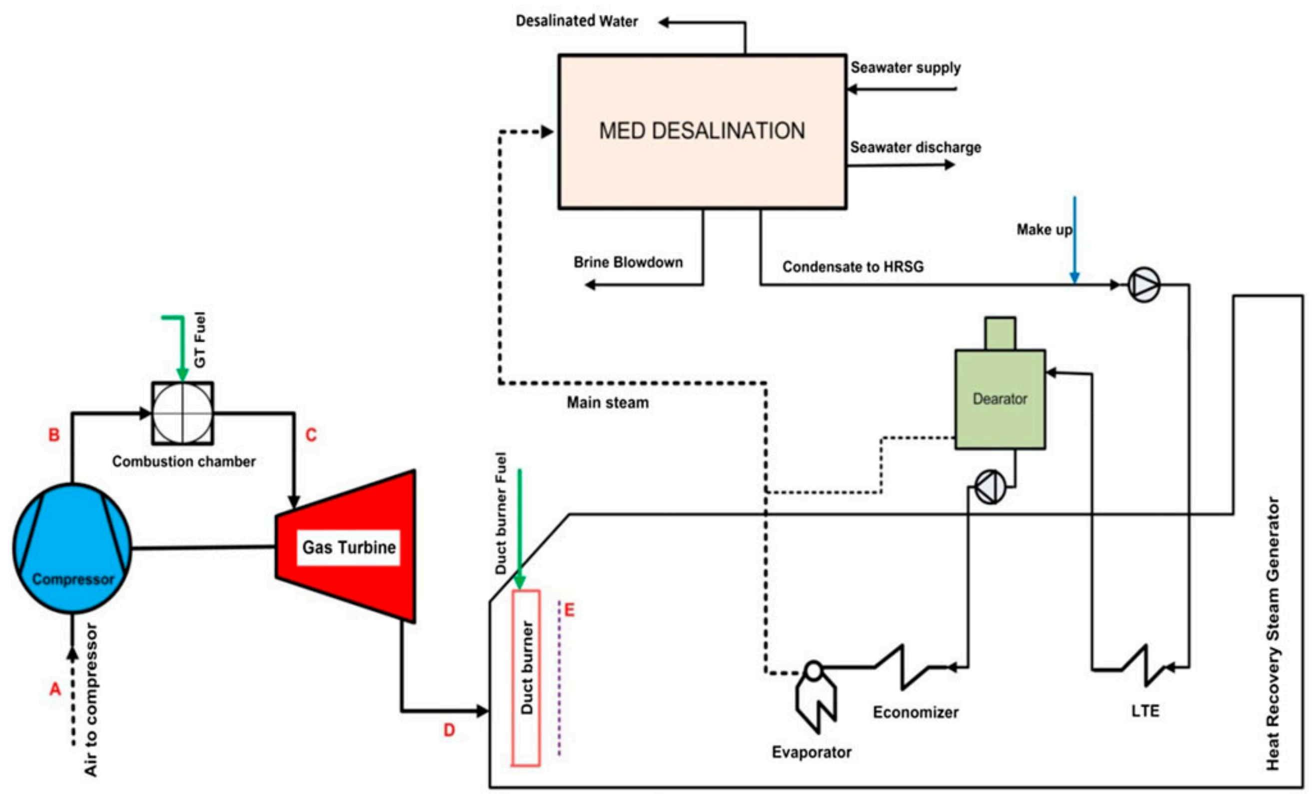

Fig. 1. Schematic of power and water production cycle.

steam flows in tubes and brine is sprayed on their external surface. The concentrated brine is sent to the next effect with lower pressure than the previous effect. The vapor produced in the first effect condenses on the tubes in the second effect. The process is repeated for another effect at sequentially lower pressures. The condensate is collected as product water. To improve efficiency of unit, heat is recovered from the condensing vapor and is used to evaporate additional brine at a lower pressure.

Various studied configurations are depicted in Fig. 2. These configurations are selected due to the other researchers' experience on possible output water by each system according to thermodynamics modeling and real working plants.

(1) Configurations A and B consist of 25 MW gas turbines (in configuration A, there are two gas turbines coupled to one HRSG and one MED system, and in configuration B there are two parallel units with one gas turbine coupled to one HRSG and one MED system).
(2) Configurations C and D consist of 10 MW gas turbines (in configuration C there are two parallel units, including three gas turbines coupled to one HRSG and one MED system and configuration D consist of three parallel units that two gas turbines coupled to one HRSG and one MED system).
(3) Finally, configurations E and F consist of 4 MW gas turbines (there are two parallel units in configuration E including eight gas turbines coupled to one HRSG and one MED system in each unit and in configuration F there are four parallel units with four gas turbines coupled to one HRSG and one MED system) with specific arrange. It is assumed that all configurations are able to produce 18,000 m^3/d potable water in Iran's south environmental conditions.

3. Energy analysis

The energy balance equations of each component are used as follows:

(1) Air compressor [14]:

The relation for non-ideal compressor between points A and B as being indicated in Fig. 1 is presented as follows:

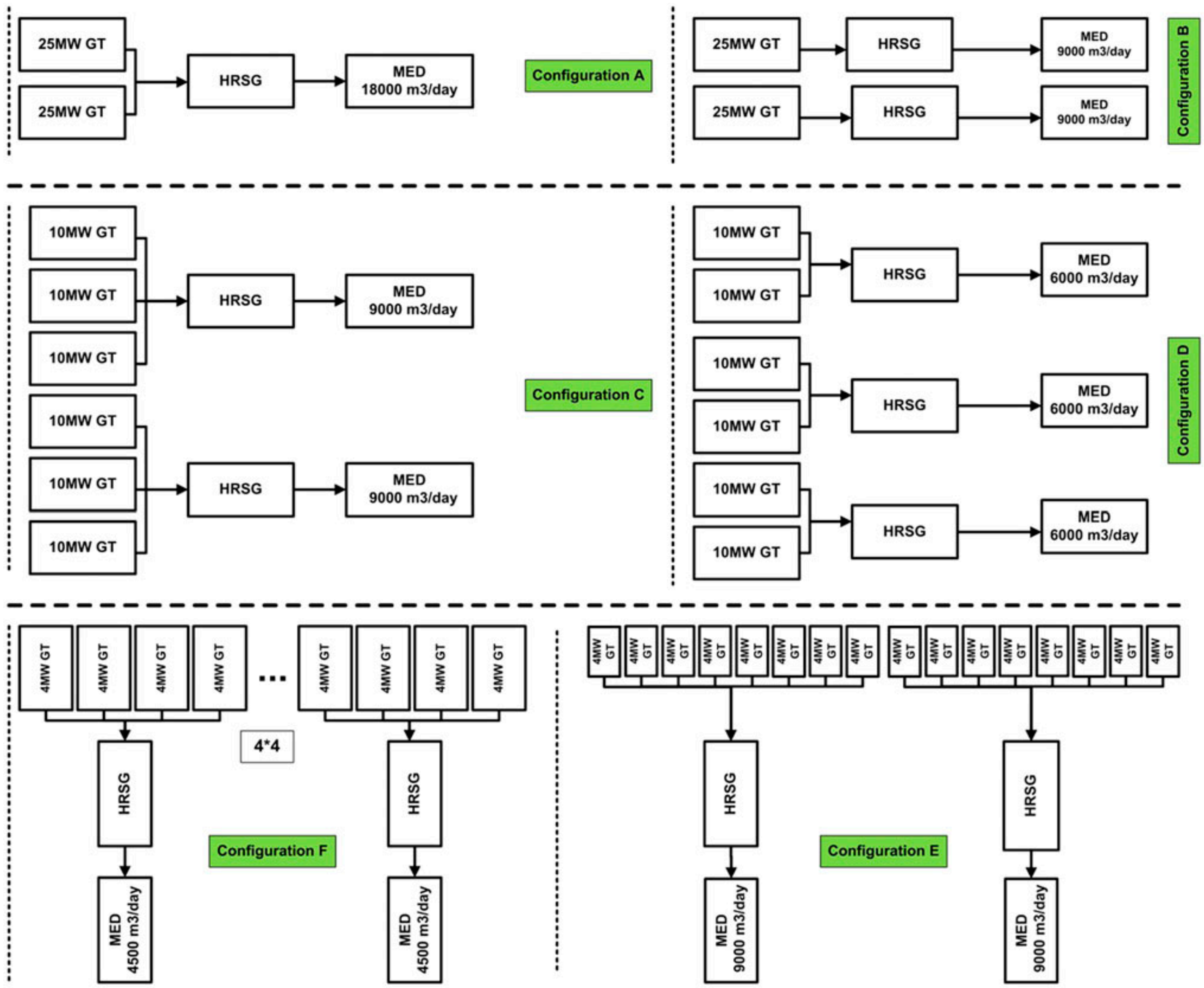

Fig. 2. Schematic of different configurations of gas turbines in cycle.

$$T_B = T_A \left\{ 1 + \frac{1}{\eta_{AC}} \left[r_c^{\frac{\gamma_a - 1}{\gamma_a}} - 1 \right] \right\} \quad (1)$$

where, η_{AC}, r_c, γ_a are air compressor isentropic efficiency, pressure ratio of the compressor, and air ratio of specific heat, respectively.

The consumed power of compressor is presented as follows:

$$\dot{W}_{AC} = \dot{m}_a c_{pa} (T_B - T_A) \quad (2)$$

where, $\dot{m}_a$ and c_{pa} are air mass flow rate and specific heat, respectively.

(2) Combustion chamber (CC) [14]:

The energy balance of CC is presented as follows:

$$\dot{m}_a h_B + \dot{m}_F \mathrm{LHV} = \dot{m}_g h_c + (1 - \eta_{cc}) \dot{m}_F \mathrm{LHV} \quad (3)$$

where, η_{cc} and LHV, and h_c are combustion chamber efficiency, lower heating value, and enthalpy of point C, respectively. The mass flow rate of flue gas is presented as follows:

$$\dot{m}_g = \dot{m}_F + \dot{m}_a \quad (4)$$

The pressure ratio between points B and C is calculated as follows:

$$\frac{P_C}{P_B} = (1 - \Delta P_{cc}) \quad (5)$$

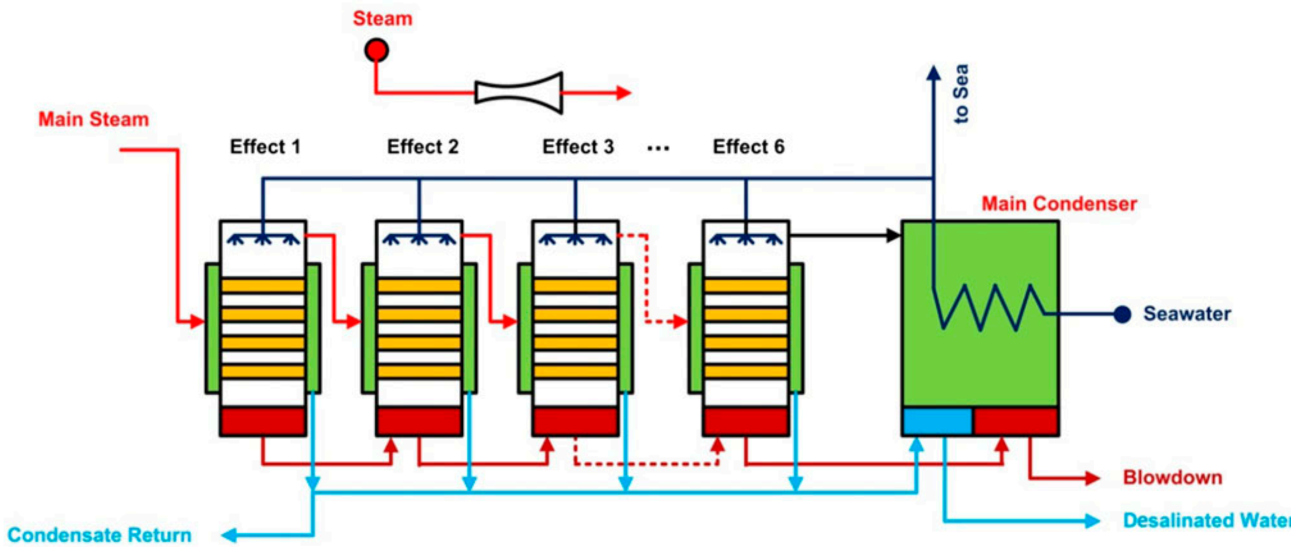

Fig. 3. Schematic of multi-effect desalinated water.

where, ΔP_{cc} is pressure loss of combustion chamber.

(3) Gas turbine:

The exhaust temperature of gas turbine is calculated as below [14]:

$$T_D = T_c\left\{1 - \eta_{GT}\left[1 - \left(\frac{P_c}{P_D}\right)^{\frac{1-\gamma_g}{\gamma_g}}\right]\right\} \tag{6}$$

where, η_{GT} and γ_g are gas turbine efficiency and ratio of specific heat of flue gas.

The gas turbine generated power and net power of cycle are presented as follows:

$$\dot{W}_{GT} = \dot{m}_g c_{pg}(T_C - T_D) \tag{7}$$

$$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{AC} \tag{8}$$

When the ambient temperature rises to 40℃ and more than it, duct burner is used to produce required motive steam of desalination. The energy balance for duct burner will be expressed as:

$$\dot{m}_g h_D = (\dot{m}_g + \dot{m}_{F,db})h_E - \eta_{db}\dot{m}_{F,db}\mathrm{LHV} \tag{9}$$

in which, $\dot{m}_{F,db}$ and η_{db} are fuel flow rate and efficiency of duct burner, respectively. By rising temperature up to 40℃ and more, the air mass flow rate declines, resulting in reduction of HRSG available heat and steam generation. Therefore, duct burner is applied in line to generate sufficient steam. At the design and site conditions, the duct burner is not considered; but, for ambient temperatures above 40℃, duct burners are in service. The fuel of duct burner and gas turbine are assumed to be similar.

Gas turbine efficiency can be calculated as follows:

$$\eta_{GT} = \frac{\dot{W}_{GT} - \dot{W}_{AC}}{\dot{Q}_{F,CC}} \tag{10}$$

where, $\dot{Q}_{F,CC}$ is heat rate in the combustion chamber.

(4) HRSG:

The boiler efficiency is an important variable that is impacted by the type of fuel, its composition, the GT exhaust gas temperature, amount of excess air, and ambient conditions. Unlike in a conventional steam generator, the ratio of gas to steam flow in an HRSG varies significantly with steam generation. This, in return, affects the gas and steam temperature profiles in the HRSG [15].

The energy balance of gas and water in each component of HRSG is presented by following equations:

Evaporator:

$$\dot{m}_g c_{pg}(T_{g,in} - T_{g,out})_{eva} = \dot{m}_{s,eva}(h_{out} - h_{in})_{eva} \tag{11}$$

Economizer:

$$\dot{m}_g c_{pg}(T_{g,in} - T_{g,out})_{eco} = \dot{m}_{w,eco}(h_{out} - h_{in})_{eco} \tag{12}$$

LTE:

$$\dot{m}_g c_p(T_{g,in} - T_{g,out})_{LTE} = \dot{m}_{w,LTE}(h_{out} - h_{in})_{LTE} \tag{13}$$

HRSG efficiency:

$$\eta_{HRSG} = \frac{\text{Heat content of output steam}}{\text{Flue gas heat energy}} \tag{14}$$

(5) MED Modeling:

The following assumptions are made to develop the MED simplified model [16]:

(1) Constant specific heat, C_p, for the seawater at different temperature and concentration.
(2) Constant thermodynamic losses in all effects.
(3) Constant heat transfer area in all effects.
(4) No vapor flashing takes place inside the effects.
(5) Feed seawater is at the saturation temperature of the first effect.
(6) Equal thermal loads in all effects
(7) The formed vapors are salt free.
(8) The driving force for heat transfer in the effect is equal to the difference of the condensation and evaporation temperatures.
(9) Energy losses to the surroundings are negligible.

Heat recovery steam generation supplied the required steam of first effect. The energy balance of that is written as:

$$D_{first} = \frac{1}{h_{first}} \times \left[m_s h_s - F c_p(T_{first} - T_f)\right] \tag{15}$$

$$T_f = T_N - \Delta T_{cond} \tag{16}$$

where, D, F, m_s, h_s are distillated mass flow rate, feed mass flow rate of each effect, mass flow rate of heating steam, and enthalpy of heating steam, respectively. And the subscripts first, f, N, and cond denote first stage, feed water, number of effect, and condense.

The energy balance of the effects 2 to N can be written as [14]:

$$D_i = \frac{1}{h_i} \times \left[(D_{i-1} + D'_{i-1})h_{i-1} - F c_p(T_i - T_f) - B_{i-1} c_p \Delta T\right] \tag{17}$$

$$D'_i = D_{i-1} \times C_p \times \frac{T_{vi-1} - T'_i}{h_i} \tag{18}$$

where, D'_i, B, and T_V are the mass flow rate of vapor in the flash box, rejected mass flow rate, and vapor temperature, respectively.

Finally, total distillated mass flow rate is presented as follows:

$$M_d = \sum_{i=1}^{N} D_i \tag{19}$$

The operation parameters of diverse configurations gas turbine have been summarized in Table 1.

Table 1
Operational parameters of diverse configurations of gas turbine

Parameter	A–B	C–D	E–F
Site condition			
Temperature	30	30	30
Humidity (%)	60	60	60
GT performance parameters			
Compression ratio	10	16	10
Turbine inlet temperature (℃)	963	1,104	916
Power output-one GT (MW)	25	10	4
Turbine exhaust temperature (℃)	501.4	519.6	456.7
HRSG performance parameters			
Pinch point temperature (℃)	9.9	9.5	9.5
Approach point temperature (℃)	10.8	10.8	10.8
Produced steam pressure (kPa)	13	13	13
Desalination unit			
Capacity of MED (m^3/d)	18,000	18,000	18,000
Number of effects	6	6	6
Heating temperature steam (℃)	70	70	70
Temperature of last effect (℃)	40	40	40
Seawater temperature (℃)	30	30	30

4. Economic analysis

In this section, the economic analysis of the system which consider the amount of investment, the operating and maintenance costs, the return on investment, and etc., are performed. The cost balance of the overall system can be formulated in steady state condition as follows:

$$\dot{C}_F + \dot{Z} = \dot{C}_p \tag{20}$$

where, $\dot{C}_F$ and $\dot{C}_p$ are fuel and production costs, respectively.
where,

$$\dot{Z} = \dot{Z}^{CI} + \dot{Z}^{O\&M} \tag{21}$$

where, $\dot{Z}^{CI}$ and $\dot{Z}^{O\&M}$ are capital investment and operation and maintenance costs, respectively.

$$\dot{C}_F = c_F \times \text{LHV} \times \left(\dot{m}_{\text{F,CCplus db}}\right) \tag{22}$$

where, c_f is cost flow rate of fuel.

For evaluation of total investment and electricity price, an economic method, TRR, is applied that has been presented by Bejan et al. [17]. In this method, based on economic assumptions and calculating the purchase price and fuel price, the total investment is calculated for year to year.

The series of annual costs associated with carrying charges (CC*j*) and expenses (FC*j* and OMC*j*) for the *j*th year of plant operation is not uniform. A levelized value TRR_L for a total annual revenue requirement can be computed by applying a discounting factor and the capital recovery factor CRF [4]:

$$\text{TRR}_L = \text{CRF} \sum_{1}^{n} \frac{\text{TRR}_j}{(1 + i_{\text{eff}})^j} \tag{23}$$

where i_{eff} and n are the average annual effective discount rate and the plant life, respectively.

CRF is calculated as follows:

$$\text{CRF} = \frac{i_{\text{eff}}(1 + i_{\text{eff}})^n}{(1 + i_{\text{eff}})^n - 1} \tag{24}$$

The levelized carrying charges are obtained from [3]:

$$\text{CC}_L = \text{TRR}_L - \text{FC}_L - \text{OMC}_L \tag{25}$$

where, FC and OMC are fuel cost and operation and maintenance cost, respectively.

The levelised cost of electricity generation (LCOE) is defined as the ratio of the net present value of total capital and operating costs of a generic plant to the net present value of the net electricity generated by that plant over its operating life [18].

LCOE calculated as follows:

$$\text{LCOE} = \frac{\text{Total costs}}{\text{Total life time energy production}} \tag{26}$$

Table 2
Economics constant and assumptions of various configurations [1,19]

Parameters	A–B	C–D	E–F
Project life in years	20	20	20
Depreciation term in years	7	7	7
Interest rate (%)	6	6	6
Unit electricity price (USD/kWh)	0.06	0.06	0.06
Water price ($/m^3)	0.96	0.96	0.96
Fuel LHV price ($/GJ)	2.63	2.63	2.63
Fixed O & M costs (USD/kWh)	32	36	38
Variable O & M costs (USD/kWh)	0.003	0.006	0.008
Reserved gas turbine cost (M$)	12.5	5.6	2.5

Return on investment (ROI) is the concept of an investment of some resource yielding a benefit to the investor.

ROI calculated as follows:

$$\text{ROI} = \frac{\text{Gainfrom investment } - \text{Cost ofinvestment}}{\text{Cost of investment}} \times 100 \tag{27}$$

In Table 2, the economics constants and assumptions of various configurations are shown. Also, costs of reserved gas turbine for each configuration are presented (redundancy). To calculate total investment the land price, contractor and labor costs are added.

5. Results and discussion

Figs. 4–9 indicate the mass and energy balance for each block of each configuration at site conditions. The energy balance generally shows the basic structure of cycle and energy balance calculations show the net power output used for electricity generation in site condition after considering all of the internal dissipations of turbine and connection to HRSG with dissipations due to pressure drop and heat losses of the HRSG. It should be noted that at these site conditions, the net power output of gas turbine is well below the nominal rate due to higher ambient temperature and lower density of inlet air. In more details, the compressor of a gas turbine motor is designed to work with a constant volume of air. When the ambient temperature increases, the specific mass is declined. In order to ensure the same air volumetric flow (conservation of continuity), the mass flow is reduced; as a result, it causes decrease in power output of the gas turbine. This high temperature affects the efficiency, but in a lighter manner. The results of thermo-economic

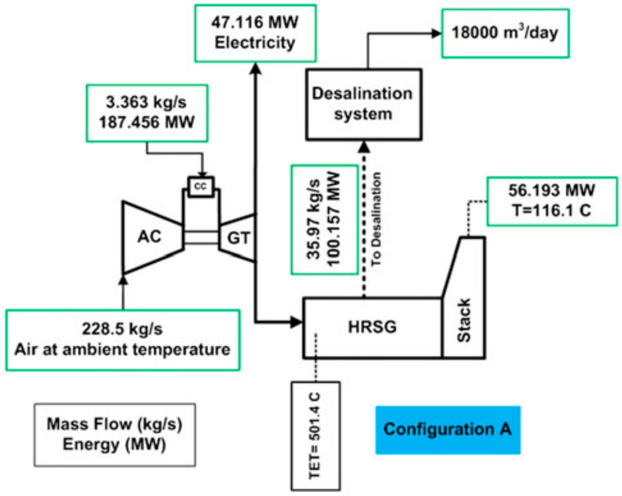

Fig. 4. Mass and energy balance of configuration A.

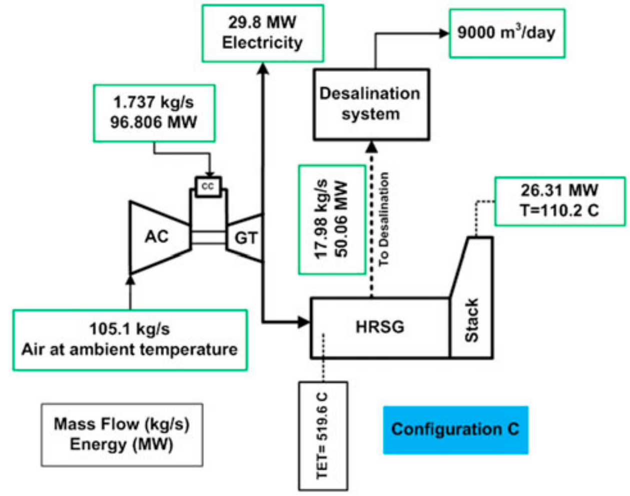

Fig. 6. Mass and energy balance of configuration C.

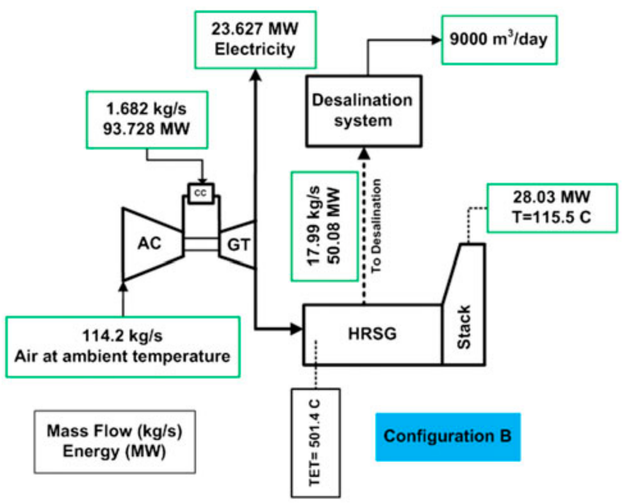

Fig. 5. Mass and energy balance of one unit of configuration B.

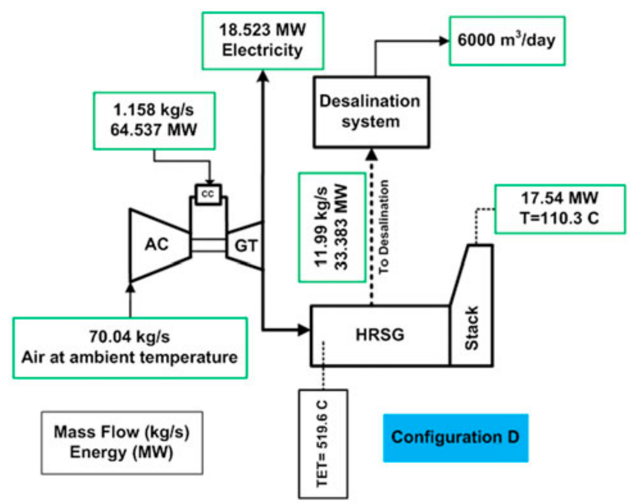

Fig. 7. Mass and energy balance of one unit of configuration D.

analysis are presented by Figs. 10–16. In Fig. 10, the variations of GT efficiency according to ambient temperature changes are presented. Fig. 10 also indicates that the 10 MW gas turbine configuration has the highest efficiency compared to the others at assumed site conditions. Changing a single cycle gas turbine power plant to a combined heat and power for the ambient conditions with higher average temperature than ISO conditions has a great advantage. One of the most important advantages is that because of the increased exhaust temperature, the efficiency of the steam process (HRSG section) increases, which helps the combined cycle to compensate the reduced efficiency of the gas turbine unit for high temperatures. The HRSG efficiency of various configurations has been presented in Fig. 11. Results show that the HRSG efficiency increases as the ambient temperature rises. Again, the 10 MW configuration shows maximum HRSG efficiency at same condition of the system. The effect of ambient temperature on overall electrical efficiency is presented in Fig. 12. In this figure, it could be seen that the overall electrical efficiency (consist of GT+HRSG according to the first law of thermodynamics) decreases for higher ambient temperatures. This overall electrical efficiency is defined as below:

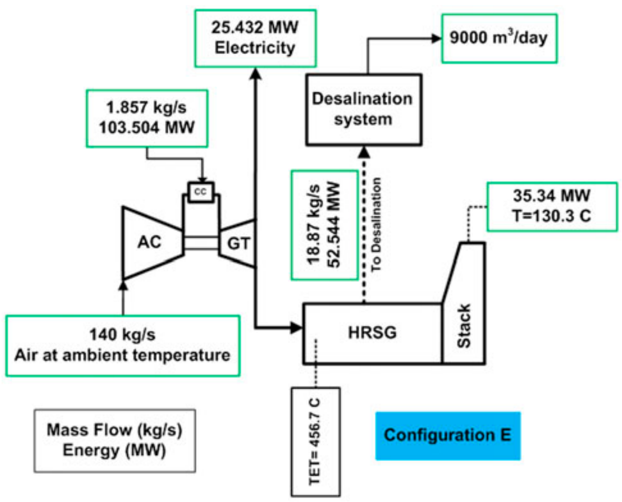

Fig. 8. Mass and energy balance of one unit of configuration E.

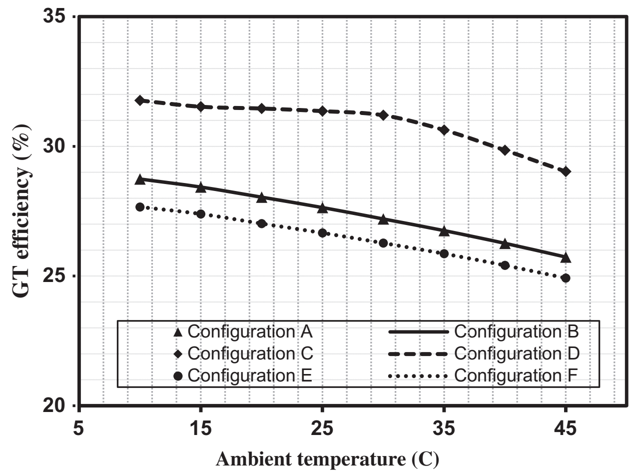

Fig. 10. Effect of ambient temperature on GT efficiency.

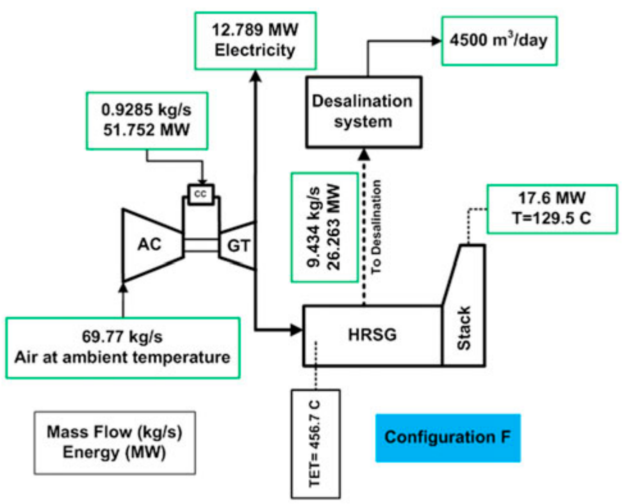

Fig. 9. Mass and energy balance of one unit of configuration F.

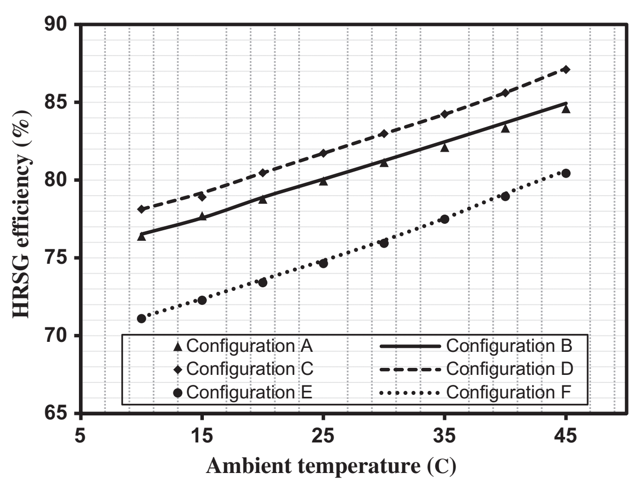

Fig. 11. Effect of ambient temperature on HRSG efficiency.

$$\text{Over all Electrical Efficiency} = \eta_O = \frac{W_{net}(\text{Network of the cycle by considering the effect of HRSG back pressure})}{Q_{in}} \tag{28}$$

It is because of the significant decrease in the efficiency of gas turbine by an ambient temperature augmentation in the presence of the HRSG. This efficiency shows the effect of HRSG's backpressure on GT's working efficiency [20]. Also, with increasing losses of the main stack due to increase in exit temperature, the cycle efficiency declines. Finally, according to the results, it is inferred that for a certain MED

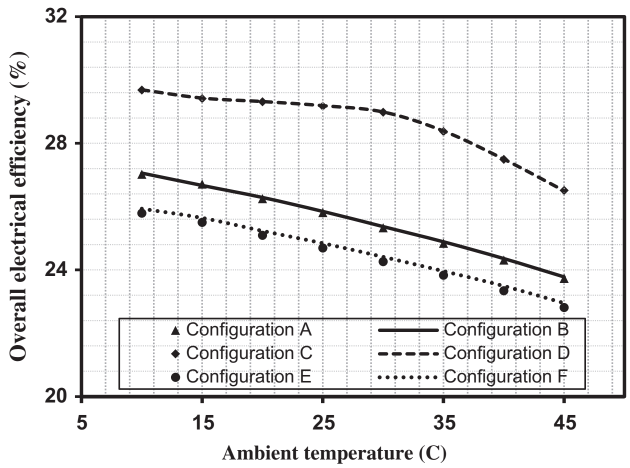

Fig. 12. Effect of ambient temperature on overall electrical efficiency.

desalination system (which is defined in plant description section) from the thermodynamic point of view, using various configurations of 10 MW gas turbine is technically better than 25 and 4 MW gas turbine, and has the highest efficiency at the same conditions (when the efficiency is the main element of making a decision but to choose the best configuration the result of thermo-economic analysis must be considered as follows).

The economic analysis of the system has been performed. The results of economic evaluation of the combined system (GT + HRSG + MED) have been indicated in Figs. 13–16. Fig. 13 shows that the levelized cost of electricity will increase as the system configuration changes from a single 25 MW to multiple 4 MW gas turbines. Also, in each configuration, when there are more gas turbines used such as configuration B, D, and F, the LCOE increases reasonably. Decision and judgments in the most appropriate manner of investment in order to maximize shareholder's wealth is one of the most important issues in the field of financial management. To achieve this objective, improving the income from investments and minimizing the total investment are considered in the appropriate solution. Accordingly, knowing about the total investment has always been an important issue for economic decisions. Access to appropriate cost to determine the optimum combination of financial structure is very important. The capital costs and operational costs for the systems being studied here are assumed based on data available from the manufacturers, suppliers, and constructors in Iran and these values may be different in other countries. In Fig. 14, the total investment required for the combined power and water production system is presented. These results are obtained from economic analysis section considering the data from Table 2. In these systems, in order to be ensured of system reliability, one reserve gas turbine has been considered. This extra gas turbine definitely has obvious effect on total investment and levelized cost of electricity and water, respectively. For the 4 MW gas turbine arrangement, more than one GT could be considered for secure redundancy (because of the delicacy of technology and maintenance). Comparison of different

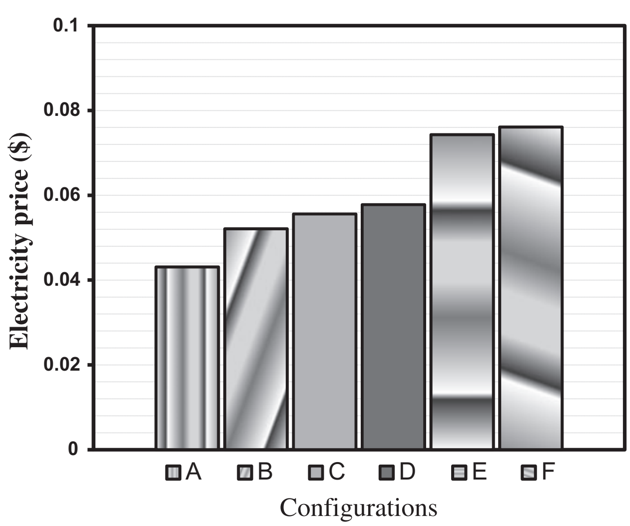

Fig. 13. Levelized cost of electricity price of various configurations of GT (configurations A to F are as shown in Fig. 2).

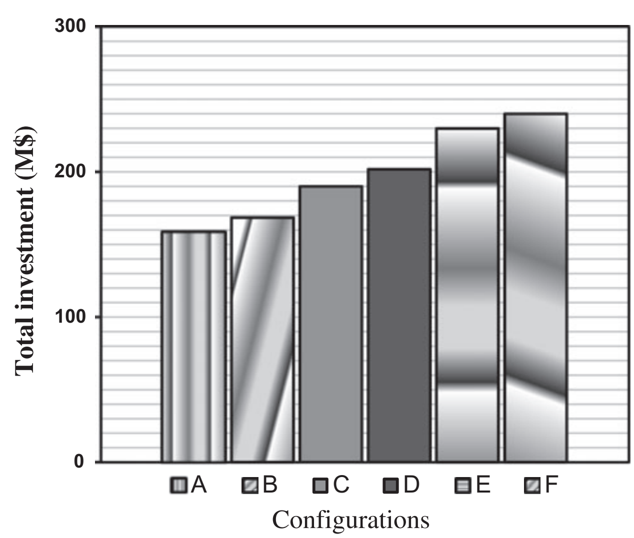

Fig. 14. Total investment of various configurations of GT (configurations A to F are as shown in Fig. 2).

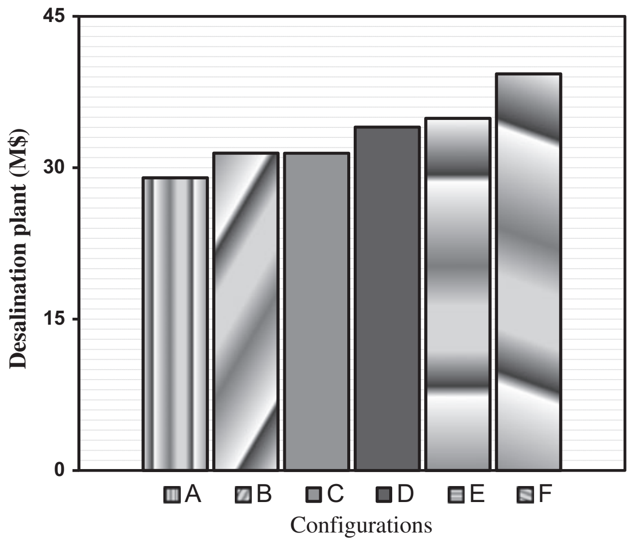

Fig. 15. Desalination plant cost of various configurations of GT (configurations A to F are as shown in Fig. 2).

configurations from an economic point of view indicates that configuration F needs the largest amount of total investment and configuration A needs the least. Fig. 15 shows the comparison of various configurations required for investment in desalination part of the system. The result shows the configuration A has a minimum desalination cost. Also, Fig. 16 shows the comparison of various configurations ROI. The result shows that ROI decreases with decrease in gas turbine capacity and the configuration A has the maximum amount of ROI and is the most appropriate one in an economical point of view. It is notable that in this research the constraint being imposed is to provide the certain amount of water demand out of the desalination system for all of the configurations. So, for different conditions, a certain amount of water must be produced which is 18,000 m^3/d. As it can be concluded from the results, the configuration A has the most favorable situation regarding the investment costs. Thus, the best choice of configuration depends on the cycle conceptual design philosophy (the highest efficiency or minimum cost). From the technical part of the study, it can be found that the C and D configurations are the best ones thermodynamically; so, it could be concluded that, although, the A configuration could be the best fit for combined water and power production economically, but using a 25 MW gas turbine would provide better efficiency and this contrast would need a trade-off for plant investors. It could be clearly found that this evaluation completely shows the nonconformity of fuel prices and electricity and water prices in Iran, which imposes a lot of penalties for Iran's power and water market's economy.

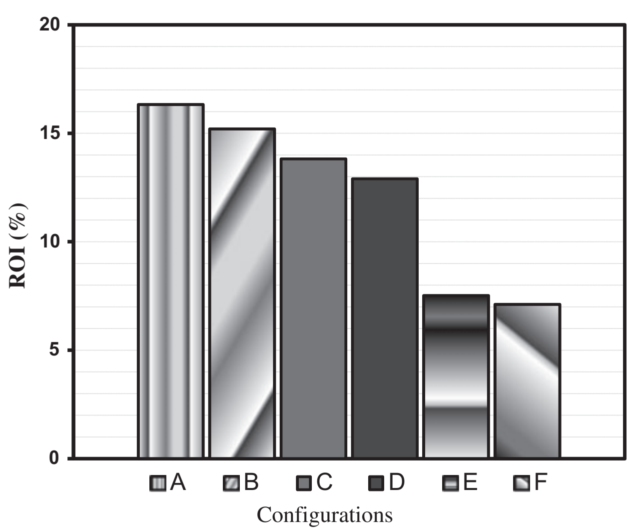

Fig. 16. Internal Rate of Return Investment of various configurations of gas turbine (configurations A to F are as shown in Fig. 2).

6. Conclusion

In this paper, different configurations of combined power and water production system consisting of MED and single pressure HRSG coupled to gas turbines were investigated. This analysis was performed according to certain needs for electricity and water in Iran's market and therefore available gas turbines in Iran with specific capacity to produce 18000 m^3/d in a site located in the south of Iran have been considered. All changes in the structure of the different systems were done in order to reach the target which was providing 18,000 m^3/d demand of potable water. Energy equations for all parts of the cycle were developed. An economic model is used to evaluate the cost of electricity and water for various configurations. The effect of ambient air temperature changes on the cycle was studied. It was found that the ambient temperature strongly influences the overall electrical efficiency of the cycle for different gas turbine configurations and these effects were quantified technically and economically. The gas turbine's exhaust gas temperature also has a remarkable influence on the performance of the cycle. When the gas turbine exhaust temperature is decreased, the HRSG efficiency also decreases. Results showed that the configurations C and D are better than others when only thermodynamic concerns are important.

The parallel economic analysis has been performed rather than thermodynamic analysis. The results showed that the difference between the levelized cost of electricity generation for the configurations A, B, and C are not so much. However, when it is about cogeneration, it is obvious that the A configuration is the most economic configuration for water and power generation. Finally, it can be concluded that, from thermo-economic point of view, use of configuration A would be best despite higher thermodynamic efficiency of the 10 MW gas turbine for Iran's market as the price of fuel is insignificant in Iran and so efficiency would not play a great role in this market now. If the worldwide market fuel prices are being considered, the calculations may show other results; however, in combined power and water generation systems, the utilization factor would be above 80%.

Nomenclature

B	—	rejected mass flow rate [kg/s]
C_{f}	—	cost of fuel [$/MJ]
C_{p}	—	specific heat at constant pressure [kJ/kg K]
C_{p}	—	cost of product [$/MJ]
C_{F}	—	cost flow rate of fuel [$/sec]
C_{p}	—	cost flow rate of product [$/sec]
F	—	feed mass flow rate of each effect [kg/s]
h	—	enthalpy [kJ/kg]
i_{eff}	—	effective discount rate
LCOE	—	levelized cost of electricity [$]
LHV	—	lower heating value [kJ/kg]
M	—	mass flow rate [kg/s]
$\dot{m}$	—	mass flow rate [kg/s]
N	—	number of effect
TRR	—	total revenue requirement
$\dot{Z}$	—	Capital cost rate [$/sec]

Greek

η	—	efficiency
ΔP	—	pressure loss [bar]
ΔT	—	temperature difference [°C]
Γ	—	ratio of specific heat

Subscripts

a	—	air
c	—	compressor
cc	—	combustion chamber
db	—	duct burner
eco	—	economizer
eva	—	evaporator
f	—	feed water
F	—	fuel
g	—	flue gas
GT	—	gas turbine
i	—	inlet, effect number
L	—	levelized
P	—	products
s	—	steam
v	—	vapor

Superscripts

CI	—	capital investment
O&M	—	operation and maintenance

References

[1] Website of The World Bank, Data archive, Available from: http://siteresources.worldbank.org/INTMENA/Resources/App-all-Scarcity.pdf.

[2] GWI DesalData: Desalination Markets 2010. Available from: http://desaldata.com/marketprofile/desalination-market-2010.

[3] S.E. Shakib, M. Amidpour, C. Aghanajafi, Simulation and optimization of multi effect desalination coupled to a gas turbine plant with HRSG condiseration, Desalination 285 (2012) 366–376.

[4] T. Rensonnet, J. Uche, L. Serra, Simulation and thermoeconomic analysis of different configurations of gas turbine, Energy 32 (2007) 1012–1023.

[5] K. Ansari, H. Sayyaadi, M. Amidpour, Thermoeconomic optimization of a hybrid pressurized water reactor, Energy 35 (2010) 1981–1996.

[6] S. Wu, Anaysis of water production costs of a nuclear desalination plant with a nuclear heating reactor coupled with MED processes, Desalination 190 (2006) 287–294.

[7] A.P. Arena, R. Borchiellini, Application of different productive structures for thermoeconomic diagnosis of a combined cycle power plant, Int. J. Therm. Sci. 38 (1999) 601–612.

[8] H. Sayyaadi, A. Saffari, Thermoeconomic optimization of multi effect distillation desalination systems, Appl. Energy 87 (2010) 1122–1133.

[9] M.H. Ali El Saie, Y.M.H. Ali El Saie, H. El Gabry, Techno-economic study for combined cycle power generation with desalination plants at Sharm El Sheikh, Desalination 153 (2003) 191–198.

[10] S.R. Hosseini, M. Amidpour, S.E. Shakib, Cost optimization of a combined power and water desalination plant with exergetic, environment and reliability consideration, Desalination 285 (2012) 123–130.

[11] L. Tian, Y. Tang, Y. Wang, Economic evaluation of seawater desalination for a nuclear heating reactor with multi-effect distillation, Desalination 180 (2005) 53–61.

[12] M.H. Khoshgoftarmanesh, M. Amidpour, A. Farhadi, G.R. Salehi, Evaluation of coupling desalination with PWR nuclear power plant with pinch, exergy and thermoeconomic analysis, Proceedings of Sixteenth International Conference on Nuclear Energy, ASME, Orlando, FL, 2008, pp. 157–170.

[13] F. Mabub, M.N.A. Hawlader, A.S. Mujumdar, Exergoeconomic analyses of a combined water and power, Proceedings of Third International Conference on Energy Sustainable, ASME, San Francisco, CA, 2009, pp. 1017–1024.

[14] P. Ahmadi, I. Dincer, Thermodynamic analysis and thermoeconomic optimization of dual pressure combined cycle power plant ith a supplementary firing unit, Energy Convers. Manage. 52 (2011) 2296–2308.

[15] V. Ganapathy, R.L. Vandagriff, Industrial Boilers and Heat Recovery Steam Generators, Marcel Dekker, New York, NY, 2003.
[16] H.T. EL-Dessouky, H.M. Ettouney, Fundamentals of Salt Water Desalination, Elsevier, Amsterdam, 2002.
[17] A. Bejan, G. Tstsaronis, M. Moron, Thermal Design and Optimization of Dual Pressure Combined, New York, NY, Wiley, 1996.
[18] Elecricity Generations Costs 2013, Annual Report Being Published by UK Department of Energy and Climate Change (DECC), July, London, UK Department of Energy and Climate Change (DECC), 2013. Available from: https://www.gov.uk/government/collections/energy-generation-cost-projections.
[19] Energy Reports At Website of Iranian Energy Efficiency Organization, Available from: http://www.saba.org.ir/en/home.
[20] R. Kehlhofer, B. Rukes, F. Hannemann, F. Stirnimann, Combined-cycle Gas and Steam Turbine Power Plants, third ed., PennWell, Tulsa, OK, 1996.