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Thermoeconomic investigation of coupling MED-TVC with a combined cycle power plant

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ABSTRACT

Freshwater generation has always been one of the most important issues in human communities that coincided with population increase in different areas. Freshwater desalination technology can be one of the most effective methods in utilizing power plants heat recovery. Iran has a high potential to use this technology due to the shortage of fresh water resources on the one hand and several thermal power plants in the coastal areas of North and South on the other hand. In this study, according to the project of transferring Caspian Sea water to the central plateau of Iran and the necessity of water desalination before transferring, the studied topics are exergy destruction rate in different components of the cycle and rate of both profit and loss which results from coupling thermal desalination to Neka power plant. Results have shown that the maximum exergy destruction cost occurred in thermocompressor and then in condenser. Furthermore, if at least 2,000 cubic meters water per day, equivalent to 730,000 cubic meters in a year, was daily generated and sold with trade tariffs, power plant had acquired significant benefit of 28,732 ($/year), in addition to compensation for losses resulting from reduced electricity generation and if the maximum possible amount of 7,215 cubic meters per day equivalent to 2,633,457 cubic meters in a year of water was daily generated, the power plant had gained a significant benefit about 380,786.25 ($/year).

Keywords: Seawater desalination; Multi-effect desalination with thermal vapor compressor; Combined cycle power plant; Exergy destruction; Thermo compressor; Thermoeconomic; Boiling point elevation

1. Introduction

Life, health, and sustainable development extremely require fresh water. Mankind is in dire need of rivers, lakes, and groundwater aquifers for supplying drinking water, agricultural, and industrial needs. There are two major problems in utilizing these limited fresh water resources; first, pollution of rivers and lakes by domestic and industrial brine and sewage and second, the uneven distribution of such resources around the world. The oceans are the largest sources of water supply, but it is not possible to use them directly due to the presence of approximately 3.5% salts.

Fresh water is a kind of water in which minerals are less than 1,000 milligrams per liter of water [1]. The salinity of most volumes of water on the earth is

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higher than 10,000 ppm and the open seas salinity level commonly ranges from 35,000 to 45,000 ppm, as dissolved salts in water [2]. Our country is not exempt from this theorem. Shortage of fresh water resources in Iran on the one hand and accessing to the saline water resources of Persian Gulf in the south and the Caspian Sea in the north on the other hand have necessitated us supplying fresh water from these resources for industrial and domestic consumption.

Desalination of seas and oceans water have considered by most countries all around the world in recent years. Today, over 15,000 desalination units are operating around the world. Meanwhile, the Middle East is allocated almost 50% of the total freshwater generation in the world; Saudi Arabia is the largest producer with the capacity of approximately 26% of the world fresh water generation and the USA is located in the following rank with 17%. Multi-effect Desalination is highly used in Saudi Arabia [1,3].

The process of separating salt from salt water requires energy expenditure like any other process and energy level differs from various methods of water desalination. In a specific process, energy level for volume unit of generated fresh water depends on chemical composition, brine impurity level, and thermodynamic properties [4]. Lack of energy, high and continuous cost of supplying energy, increasing energy consumption, environment pollution due to fossil fuel consumption, and declining fossil fuel resources made researchers to consider these issues related to energy recovery in industrial and processing plants in recent years. Thus, a variety of technologies can be used to recover heat from power plant unit according to requirements, potential of power generating unit, and climatic conditions.

Since, generating fresh water has always been one of major industrial issues concurrent with increase in population in different areas, using water desalination technology can be one of the most effective and useful techniques of utilizing heat recovery in power plants. Water and power cogeneration systems include two major sections: thermal power plant and water desalination unit. In fact, thermal power plant is responsible for generating conventional power energy and supplying the necessary energy to set up water desalination unit.

Extensive researches were conducted on the economics of power and water cogeneration systems during the years. Tadros investigated coupling Multi Stage Flash (MSF) with different kinds of steam and gas turbine, and recovery steam generator due to the extensive utilization of this kind of water desalination. In this study, the economy of mentioned systems and their thermodynamic attributes were investigated and optimization studies were conducted [4]. Wade compared technically three MED-TVC, MSF, and RO Water Desalination systems in [5]. Minnich et al. compared heat transfer level with required cost to set up thermal desalination plant [6].

El-Dessouky et al. in 2000 studied the performance of Multi-effect Distillation for desalinating sea water [7]. The model was presented for two kinds of systems: parallel flow and parallel-vertical flow. Analysis was performed based on motive steam temperature, sea water concentration, and the numbers of effects, consequently, the results were shown as a function of parameters that control the water generation cost.

Cardona and Piacentino in 2004 presented a research for optimum design of water and energy cogeneration plants. They investigated Reverse Osmosis Combined with Desalination and MSF systems to improve system yield. They tried to present criteria based on exergy-economy and maximize profit to design optimally such units [8].

Toufic Mezher et.al. in 2010 technically and economically investigated water desalination units and their effects on environment. In the paper, firstly, different kinds of desalination plants including MSF, MED, RO, and hybrid system were presented, their performance was studied and then systems were analyzed in terms of energy consumption, required cost for fresh water generation by each unit, potential of each system for optimum development, and performance in future and the environmental effects [9].

In the paper published by Sayyaadi in 2010, Multi-effect Desalination with Thermal Vapor Compressor (MED-TVC) was discussed in terms of economic and technique through the second law of thermodynamics. The presented model in this paper was written based on exergy and energy conservation equations. The author introduced a simple model with simplified assumptions in the static model section and the first law of thermodynamics. In this section, all heat losses and pressure drops in system are ignored and assumed that the feedwater entered all evaporators with fixed flow. Another assumption was considering a fixed number for brine salt concentration that made the model a bit far from reality. Utilizing pre-heated feedwater before entering a number of evaporators was initiative used in this project. Economic model was presented based on the total return rate (TRR) procedure and introduced an objective function for thermodynamic and thermoeconomic analysis. Finally, water generation cost was minimized based on genetic algorithm [10].

Hosseini et al. in 2011 investigated and analyzed coupling MSF desalination plants with thermal power plant in terms of technique and economic [11]. In 2012, Shakib et al investigated economically and optimized thermal desalination plants with regard to environmental considerations [12].

As it was mentioned, Iran has high potential to use this technology due to fresh water requirement and several thermal power plants in the coastal areas of North and South. In recent years, the debates were suggested and studied about the need of water supply in the central areas of Iran for development, agricultural and industrial water supply as well as investment attraction in the center of country. The main objective of this program is supplying required water resources in some central areas that have limited access to water due to regional and climatic conditions, so they were deprived from development and acquisition new investment over the years. Moreover, water desalination projects and transferring water from Caspian Sea to the central plateau of Iran were planned and implemented to prevent uneven development in the country, provide opportunities to create wealth in central Iran, supply water for industrial factories and mines and in general, achieve development in central areas. Managing this project was begun at the summer of 2012 and the predicted credit was for it in budget bill 2013 would be operational by the end of 2015.

In this project, the water is desalinated near the sea and then the desalinated water is transferred to the central plateau of Iran through the water supply pipelines. Since vulnerability and corrosion of transmission equipment, because of disadvantages of sea water salinity for water pipelines is increasing, the operation of desalination is performed near the sea. Otherwise if this process is performed in central plateau, it leads to creating environmental issues because of brine evacuating. Therefore water is desalinated near the sea and brine is transferred to the sea after desalination and released in the appropriate depth, then the desalinated water transferred to the central plateau. Thus, exergy analysis of coupling Multi-effect Desalination with combined cycle power plant for desalination of Caspian Sea water was discussed in this study.

2. System thermodynamic modeling

The studied system included Neka Power Plant (Shahid Salimi Power Plant) Steam cycle and MED-TVC system. All components are modeled and simulated using computational codes in EES Software, governed by thermodynamic equations, each of them will be explained in the following.

2.1. Multi-effect desalination system

The considered desalination system is MED-TVC with parallel feed which includes three main sections; thermocompressor, condenser, and some evaporator called effects. In this system, firstly, the sea water with the flow rate of m_c and temperature of T_c enters condenser. Then, temperature rises to T_f due to heat transfer with hot steam inside condenser tubes and hot steam condensed by releasing its latent heat to the feedwater for preheating. Part of sea water removed from system as cooling water with the flow rate of $m_{c,rej}$ and the rest went to the effects with the flow of F.

In the first effect, feedwater is sprayed on evaporator tubes, the compressed vapor which is supplied from an external source after passing through thermocompressor and achieving the desired pressure introduced into the tube side of evaporator, condensed by releasing its latent heat into the feedwater for evaporation. The steam formed in the first effect flows inside the second effect tubes as heat source and causes evaporation of feedwater in second effect. The rest of feedwater, which did not get evaporated, collected in the bottom as brine and pumped out; this process is repeated until the last effect. In the last effect, steam enters condenser and after an increase in the inlet sea water temperature, it will be pumped out from condenser. Thermal desalination schematic was shown in Fig. 1. The following assumptions were considered in thermal desalination modeling [13]:

(1) The steam produced in each effect is free of salt.
(2) Heat losses are negligible in each effect.
(3) Pressure drop in tubes is ignored.
(4) All processes are in stable condition.
(5) Feedwater flow rate is the same for all effects.
(6) Modeling is performed in such a way that the final brine salinity is less than 70,000 ppm to address environmental considerations.
(7) Temperature difference between adjacent effects is considered the same and equals to ΔT which is:

$$\Delta T = T_1 - T_2 = T_2 - T_3 = T_3 - T_4 = \ldots = T_{n-1} - T_n = T_s - T_1 = T_n - T_f \quad (1)$$

$$T_s - T_f = (n+1)\Delta T \rightarrow \Delta T = \frac{T_s - T_f}{n+1} \quad (2)$$

where n is the number of evaporators and T is temperature based on degree of centigrade.

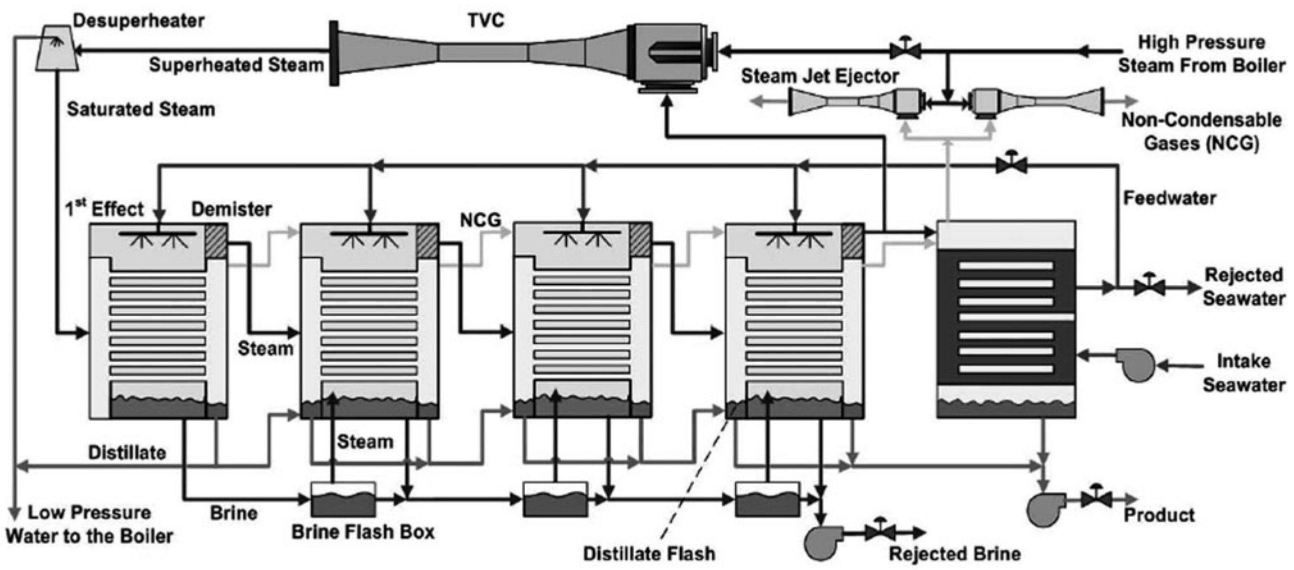

Fig. 1. Schematic of MED-TVC.

In thermal desalination systems, the temperature of generated brine in each effect is a bit higher than saturated steam temperature due to the presence of salt. To determine this temperature difference, BPE parameter called boiling point elevation is defined as follows [14]:

$$\mathrm{BPE} = T_b - T_v \tag{3}$$

Here, El-Dessouky equation is used to compute BPE [15]:

$$\mathrm{BPE} = X_b \times (B + CX_b) \times 10^{-3} \tag{4}$$

$$B = (6.71 + 6.43 \times 10^{-2}\, T_b + 9.7410^{-5}\, T_b^2) \times 10^{-3} \tag{5}$$

$$C = (22.238 + 9.59 \times 10^{-3}\, T_b + 9.4210^{-5}\, T_b^2) \times 10^{-8} \tag{6}$$

Desalinated water which would be ultimately collected and is the capacity of desalination system, is summation of distilled water from each effect [16,17].

$$D_{\mathrm{distillate}} = \sum_{i=1}^{n} D_i - \sum_{i=1}^{n-1} d_{\mathrm{flash},i} \tag{7}$$

where $d_{\mathrm{flash},n-1}$ is steam flow rate generated by brine flashing of the previous effect. Gain output Ratio (GOR) for a thermal desalination system is defined as follows:

$$\mathrm{GOR} = \frac{D_{\mathrm{distillate}}}{S} \tag{8}$$

2.2. Power generation cycle

Shahid Salimi Power Plant has two kinds of high-pressure and low-pressure steam turbines. For modeling these turbines, outlet pressure of turbines is constant and their isentropic efficiency changes based on the following relation due to the changes in inlet vapor flows [18]:

$$\frac{\eta_{\mathrm{ise,new}}}{\eta_{\mathrm{ise,first}}} = -1.0176\left(\frac{\dot m_{\mathrm{st,new}}}{\dot m_{\mathrm{st,first}}}\right)^4 + 2.4443\left(\frac{\dot m_{\mathrm{st,new}}}{\dot m_{\mathrm{st,first}}}\right)^3 - 2.1812\left(\frac{\dot m_{\mathrm{st,new}}}{\dot m_{\mathrm{st,first}}}\right)^2 + 1.0535\left(\frac{\dot m_{\mathrm{st,new}}}{\dot m_{\mathrm{st,first}}}\right) + 0.701 \tag{9}$$

The turbine power generated is equal to:

$$\dot W_{\mathrm{st}} = \sum_{\mathrm{stages}} \dot m_{\mathrm{st,in}} \left(h_{\mathrm{st,in}} - h_{\mathrm{st,out}}\right) \tag{10}$$

Isentropic efficiency can be obtained from the following equation:

$$\eta_{\mathrm{ise,st}}\left(h_{\mathrm{st,in}} - h_{\mathrm{st,out,ise}}\right) = \left(h_{\mathrm{st,in}} - h_{\mathrm{st,out}}\right) \tag{11}$$

2.2.1. Heat recovery steam generator

The HRSG has two pressure levels with two steam outlet; low-pressure steam and high-pressure steam. Fig. 2 shows the schematic of HRSG in Neka Power Plant [19].

The energy balance equations in different parts of HRSG are written as follows [19]:

High-pressure super heater

$$\dot{m}_g c_p (T_{11} - T_{12}) = \dot{m}_{s,HP} (h_{10} - h_9) \quad (12)$$

High-pressure evaporator

$$\dot{m}_g c_p (T_{12} - T_{13}) = \dot{m}_{s,HP} (h_9 - h_8) \quad (13)$$

High-pressure economizer

$$\dot{m}_g c_p (T_{13} - T_{14}) = \dot{m}_{s,HP} (h_8 - h_7) \quad (14)$$

Low-pressure super heater

$$\dot{m}_g c_p (T_{14} - T_{15}) = \dot{m}_{s,LP} (h_6 - h_5) \quad (15)$$

Low-pressure evaporator

$$\dot{m}_g c_p (T_{15} - T_{16}) = \dot{m}_{s,LP} (h_5 - h_4) \quad (16)$$

Dearator evaporator

$$\dot{m}_g c_p (T_{16} - T_{17}) = \dot{m}_{s,LP} (h_3 - h_2) \quad (17)$$

Condensate preheater

$$\dot{m}_g c_p (T_{17} - T_{18}) = \dot{m}_{s,LP} (h_2 - h_1) \quad (18)$$

c_p is also considered as a function of temperature.

3. Exergy analysis

Exergy analysis is relatively a new approach developed based on the notion of availability. Availability or exergy is defined as potential for task production or the system energy quality in contrast to its surroundings. Exergy analysis is a powerful tool for technical evaluation of complex systems. In a system with several components, system efficiency and availability losses of different components as well as the entire system can be determined by using exergy analysis in terms of the second law of thermodynamics and consequently the location and reason of thermodynamic inefficiency can be determined.

Specific exergy (Total exergy per unit mass) of system, which is shown by e, is presented as the sum of the physical, kinetic, chemical, and potential exergy in the absence of nuclear, magnetic, electrical and adhesions effects:

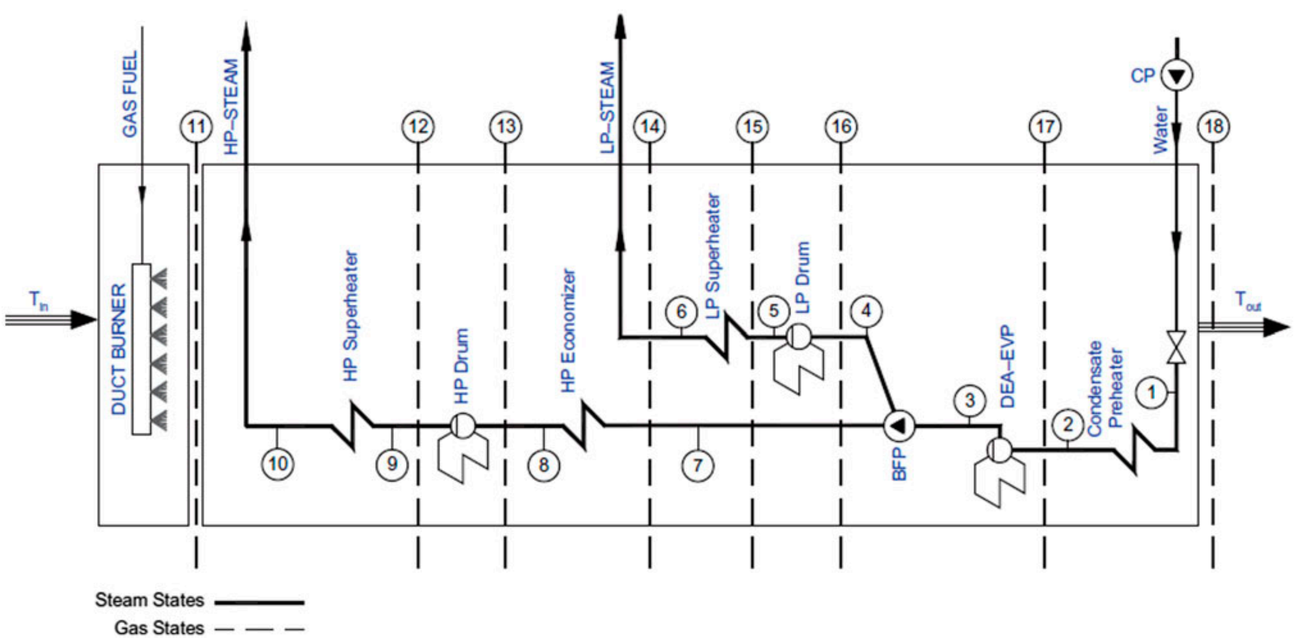

Fig. 2. Scheme of heat recovery generator in Neka power plant [19].

$$e = e^{PH} + e^{KN} + e^{PT} + e^{CH} \tag{19}$$

The physical exergy of flow is computed by following definition:

$$e^{PH} = (h - h_0) - T_0(s - s_0) \tag{20}$$

Furthermore, the chemical exergy of a multi-component mixture is expressed as follows:

$$e^{-CH} = \sum x_k \overline{e_k^{CH}} + \bar{R}T_0 x_k \ln x_k \tag{21}$$

In the above equation, x is molar ratio of k^{th} component and e_k^{-CH} is standard exergy of k^{th} component. The magnitudes of kinetic and potential exergies have been neglected. Assuming constant chemical composition of streams in the PWR power plant, the chemical exergy is canceled out in exergy balance equations applied to the PWR system. It should be noted that, in the MED-TVC system, since the salinity of seawater changes in the process, the magnitude of chemical exergy cannot be ignored. Therefore, the specific exergy at every arbitrary state of the PWR can be assumed equivalent with the physical exergy [20].

Exergy balance for a control volume is:

$$E_2 - E_1 = \int_1^2 \left(1 - \frac{T_0}{T_b}\right) \delta Q - [W - P_0(V_2 - V_1)] - E_D \tag{22}$$

To compare exergy destruction in different sections of the system, which is shown as the ratio of exergy destruction of i^{th} components to total exergy destruction, as well as to compute exergy destruction rate of system, the following equations are used:

Exergy destruction rate:

$$\dot{E}_D = T_0 \dot{S}_{gen} \tag{23}$$

Exergy destruction percentage:

$$Y_{loss,i} = \frac{\dot{E}_{D,i}}{\dot{E}_{D,tot}} \tag{24}$$

Fig. 3 shows n-effects desalination unit and inlet and outlet flows. By assuming insulated boundaries of system and the steady state flow, entropy generation in the whole system is given by the following equation:

$$\sum_{in} \dot{m}e - \sum_{out} \dot{m}e - T_0 \dot{S}_{gen} = 0 \tag{25}$$

4. Economic modeling

Although exergy analysis is a powerful tool for technical evaluation of complex systems, the thing which is important in Process Engineering is the required cost of setting up and usage of various components in a complicated system besides the cost of exergy destruction. Such information helps the energy analyzer to increase technoeconomic efficiencies of desired complex systems by decreasing thermodynamics inefficiencies and the cost for final product.

It is clear that just exergy analysis cannot entirely optimize the energy system because it does not consider economic parameters. Exergy-economic analysis is used to overcome this problem. The objective of exergy-economic analysis is considering and applying economic parameters in thermodynamic optimization.

4.1. Exergy pricing method

Exergy pricing method is one of the most complicated techniques in energy analysis systems. In this method, first, all flow lines in different components of system in terms of thermodynamic properties are determined by using physical modeling and exergy analysis, and then amount of exergy flow in every component of system is determined. At last, cost balance equation is obtained by investigating the cost of inlet exergy, investment cost, and economic value of outlet exergy per component.

By determining cost balance equations for all components and exergy flow lines; a system of equitation will be formed that by solving them, rate of exergy cost in each flow of the system will be determined. Studying exergy with this method, Determining fuel exergy flow and products of the system components are necessary. Note that using the term "fuel" for naming exergy flows does not mean that they are formed from fossil fuels such as oil. For example, in multi-effect desalination systems, fuel means driving steam flow in thermocompressor and electricity current used in pumps.

4.2. Economic functions

For determining exergy cost in different flow lines, functions that determine purchase cost of components in considered system are needed. These functions should express the cost resulting from investment on each system and equipment applied in the supposed system as functions of the variables decision. Investment cost rate function was defined as follows [21,22]:

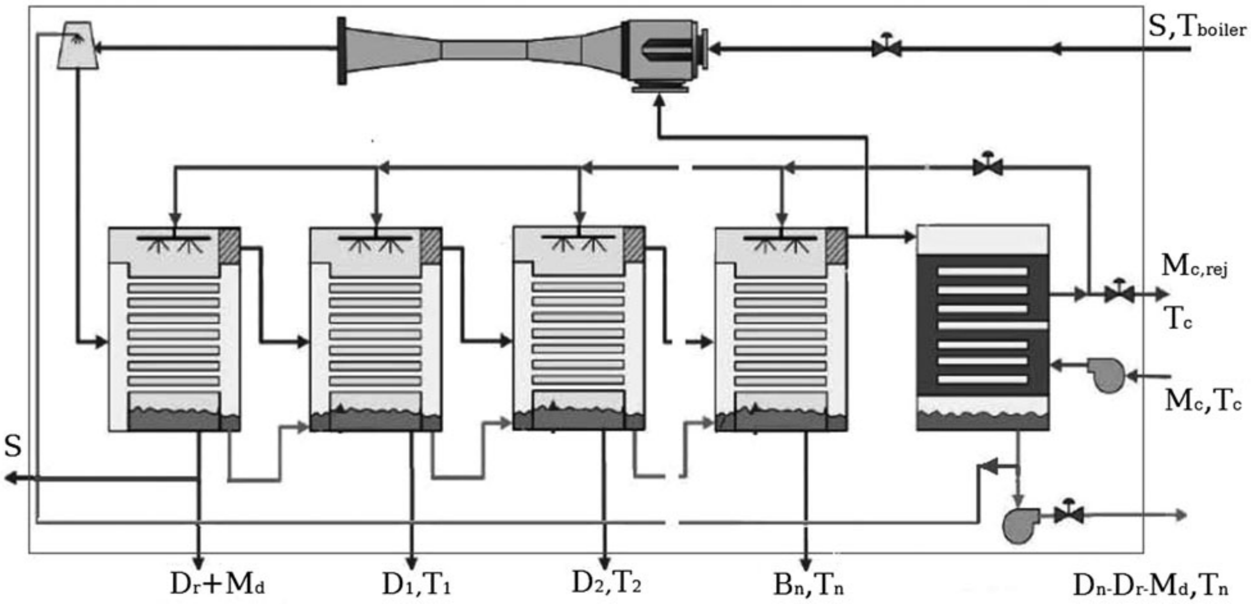

Fig. 3. n-effects desalination unit as control volume.

$$\dot{z}_i = \frac{Z_i \times \mathrm{CRF} \times \varphi}{(N \times 3600)} \quad (26)$$

$$\mathrm{CRF} = \frac{i_{\mathrm{eff}}(1 + i_{\mathrm{eff}})^{\mathrm{BL}}}{(1 + i_{\mathrm{eff}})^{\mathrm{BL}} - 1} \quad (27)$$

$$Z_i = Z_i^{\mathrm{CI}} + Z_i^{\mathrm{OMC}} \quad (28)$$

where Z_i is investment costs function of i^{th} components of the studied system and is computed by determining decision-making independent variables. Z_i^{OMC} is operating and maintenance cost function, Z_i^{CI} is investment costs function [20], CRF is capital recovery factor which is determined according to the annual profit rate of money and the time considered for annual return on investment. BL is book life of system to year and N represents the number of annual operating hours and φ is operating and maintenance cost coefficient of system and i_{eff} is the average general inflation rate. Annual return on investment ratio (CRF) is considered to be 0.182 and operating and maintenance cost of φ is considered 1.06 [21–23].

Equations related to equipment computations are determined based on designing parameters that are influential in component costs.

4.3. Auxiliary equations of cost balance

In many cases, more than one exergy flows have exited from a system component. In these cases, using exergy cost balance equation in the studied component does not suffice for determining exergy unit costs of all outlet flows due to increasing the number of unknown variables (number of outlet flows) because the number of unknown suggested variables are more than cost balance equations.

In such cases, equations should be used that are known as technoeconomic auxiliary equations.

Auxiliary equations are mainly defined based on considering the final goal of each component. In this technique, current spending costs and investments are accounted for outlet exergy flow and the unit cost of output exergy of non-objective flows (if another flow, not the target exergy, exits from the intended component) are considered constant and equivalent to inflow cost. The unknown variables balance in cost equations can be maintained using these equations.

4.4. Exergy destruction cost

The cost resulting from exergy destruction, E_{D}, is one of the major parameters in technoeconomic analysis which is known as exergy destruction rate, c_{D}. This quantity is important because it clearly provides the costs resulting from thermodynamic inefficiencies. There is not a term that clearly expresses the exergy destruction cost in the total relation of exergy cost balance. Exergy destruction costs are known as hidden costs that are imposed to different components of a system. Exergy destruction unit cost in K^{th} component, $c_{\mathrm{D,k}}$, is supposed to be equal to fuel exergy unit cost in this component, $c_{F,k}$, assuming constant product exergy and we will have:

$$c_{D,k} = c_{F,k} \quad (29)$$

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \quad (30)$$

Exergy destruction rate of *k*th component, $c_{D,k}$ in accompany with investment cost rate, operating and maintenance $\dot{Z}_k$, showed total consumed cost rate in that component. $\dot{C}_{D,k} + \dot{Z}_k$ has particular importance for each component and its highness in each component indicates the need for greater attention to design parameters of that component from exergy-economic analysis viewpoint.

4.5. Cost balance equations

The equation of product cost rate for an energy system can be written as follows [24]:

$$\dot{C}_{F,tot} + \dot{Z}^{CI}_{tot} + \dot{Z}^{OMC}_{tot} = \dot{C}_{P,tot} \quad (31)$$

where $\dot{C}_{F,tot}$ and $\dot{C}_{P,tot}$ are fuel cost rate and final product cost, respectively. $\dot{Z}^{CI}_{tot}$ and $\dot{Z}^{OMC}_{tot}$ indicate total investment and total operating and maintenance cost, respectively, obtained from solving system economic functions. This equation indicates that total cost rate for a product equals total cost rate related to fuel and initial investment cost and operating and maintenance cost.

5. Result and conclusion

In this paper, coupling Multi-effect Desalination with Neka Combined Cycle Power Plant was simulated and investigated in terms of technoeconomic analysis. To set up thermal desalination system, flow rate of LP turbine in steam cycle is used because the pressure of LP turbine feed line was located in the range of thermocompressor operation pressure [20,25], so utilizing this steam was appropriate for setting up the MED-TVC desalination unit (based on Fig. 4). The base values listed in Table 1 were used to investigate desalination system technically [26]. The values obtained for the desalination unit with a number of technically efficient processes are listed in Appendix Table A1 [26]. Caspian Sea water concentration and temperature were extracted from reference [27]. The base values applied in economic modeling are presented in Table 2 [20,21].

Fig. 5 showed exergy destruction in various components of desalination system. As could be seen, the highest rate of exergy destruction occurred in thermocompressor. This is natural due to the low efficiency of thermocompressors. After thermocompressor, condenser has the highest exergy destruction rate.

Fig. 6 shows exergy destruction rate by increasing the number of effects. Exergy destruction rate decreases by increasing the number of effects up to the 8th. After that, exergy destruction rate increases by increasing the number of effects. Fig. 7 shows exergy efficiency of desalination systems by various numbers of effects. By considering decrease in exergy destruction rate due to increasing number of effects, it is clear that the exergy efficiency of total complex increases up to 8th effect and after that it starts decreasing.

Fig. 8 shows exergy destruction rate in a series of evaporators. First effect has the highest exergy destruction rate, but it gradually decreases by increasing the number of effects. It's because of the constant temperature degree in the last effect while decreasing the temperature difference between each effect and the last constant one.

5.1. Final cost rate changes of generated fresh water in terms of number of effects

Fig. 9 shows the final unit cost of product changes for a desalination system with various numbers of effects. Based on the figure, for temperature difference of 4 and 5˚C between effects, 5 effects desalination system has technically the lowest cost of product, but due to low efficiency and high exergy destruction rate, using this number of effects is not efficient. For temperature difference of 3˚C between evaporators, seven effects desalination system has the lowest cost of product but at the same input conditions; 8 effects would technically have the highest efficiency ratio so it is optimum and because efficiency ratio difference between seven and eight effects desalination systems is very small (lower than 4%); seven effects desalination is technically and economically in optimum condition for Caspian Sea desalination, but the number of optimum effects were practically determined based on technical or economic priorities, that is, economic issues during construction and operation of the system are more important than the system efficiency and energy consumption in the system; seven effects system would be a priority if technical issues and system performance are considered more important than economic issues; 8 effects system would be chosen, but in most cases, both technical and economic sections take into consideration at the same time.

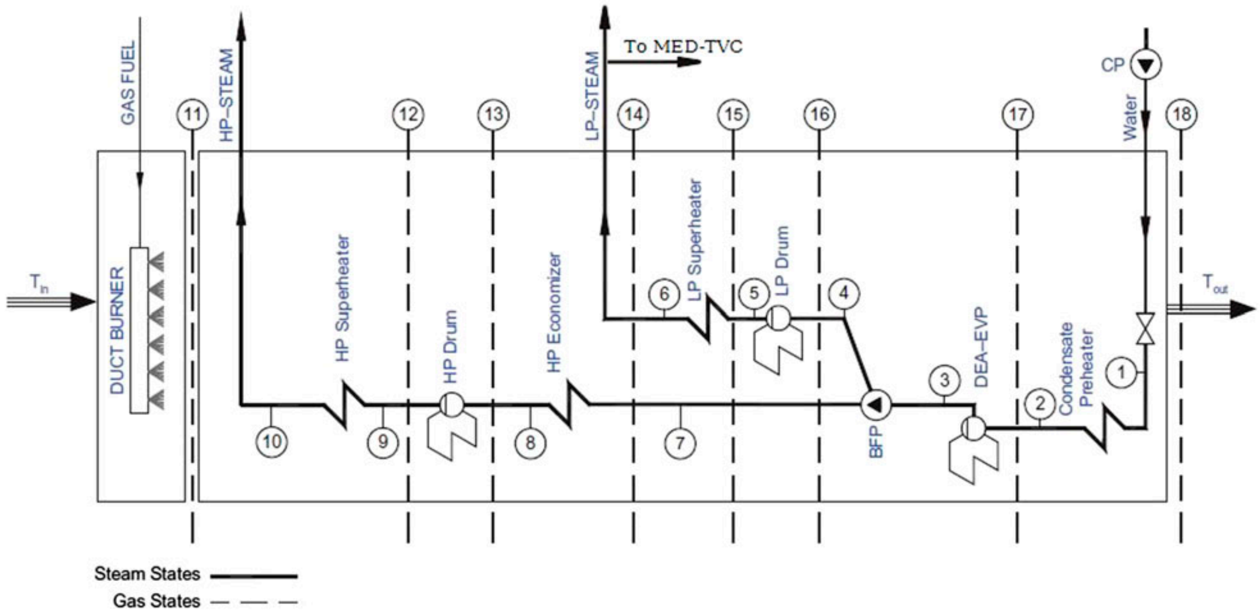

Fig. 4. Schematic location of extraction flow rate of HRSG of Neka Power plant for setting up MED-TVC.

Table 1
Reference values of desalination technical modeling [26]

Parameter	Values
Temperature difference between effects	5℃
Number of effects	8
Feedwater concentration	13,500 ppm
Maximum concentration in final brine	70,000 ppm
Feedwater temperature entering the first effect	45℃
Generator pressure (first effect pressure)	10 bars
Sea water temperature	25℃

Table 2
The base values used in solving economic models [28]

Parameter	Values
The number of annual operating hours (N)	8,700
System book life in year (BL)	30
System operating and maintenance coefficient (φ)	1.06
Annual inflation rate (i_{eff})	0.15
Annual Capital Return coefficient (CRF)	0.182

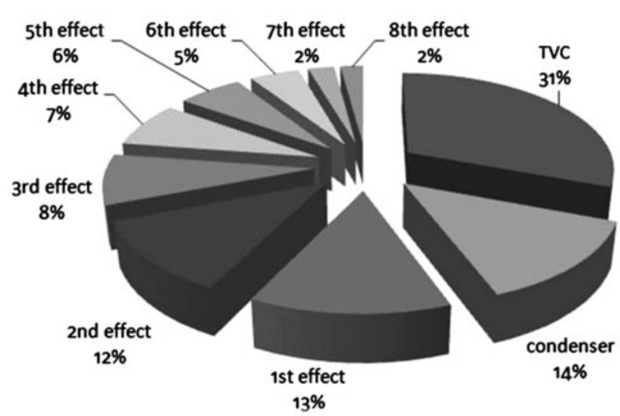

Fig. 5. Percentage of exergy destruction in different components of thermal desalination system with motive steam pressure of 10 bars.

5.2. Changes in the cost of electricity generated based on the LP turbine flow rate variations

Fig. 10 shows the increase in cost of power generated by decreasing the LP turbine flow rate. When there is no flow rate extraction from the LP turbine,

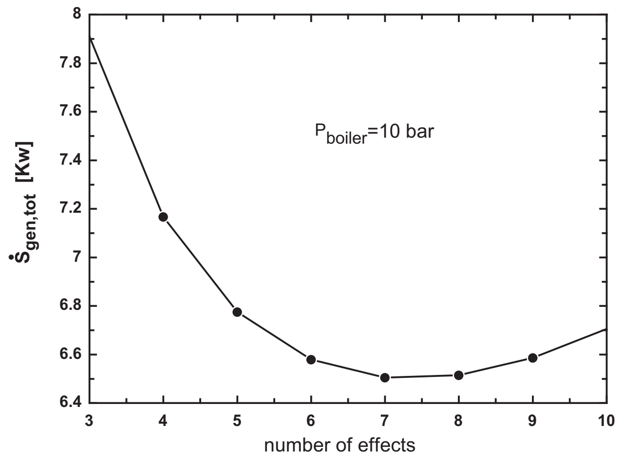

Fig. 6. Exergy destruction rate in terms of number of effects.

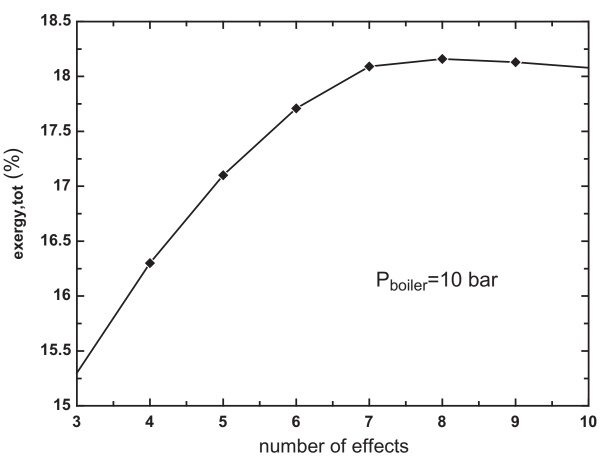

Fig. 7. Total exergy efficiency of MED-TVC in terms of number of effects.

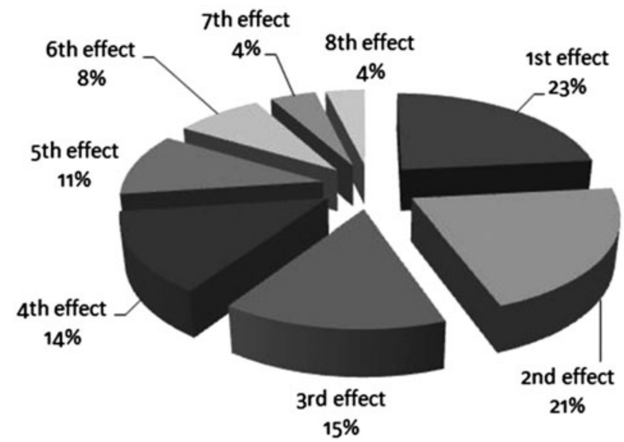

Fig. 8. Percentage of exergy destruction in a series of evaporators.

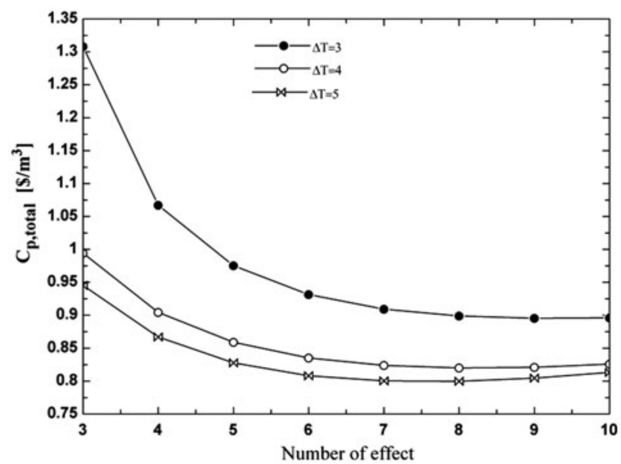

Fig. 9. The cost of product of fresh water rate based on the number of effects in optimal technical conditions.

generated power cost was $41.31 per megawatt hour, but it would increase by increasing steam extraction from LP turbine, as for the flow rate of 2.66 kg/s, which is the minimum required flow rate to prevent increasing outlet flow rate steam humidity more than 12% [23,25], generated power cost would be $41.76 per megawatt hour. That is, we encountered 1.1% increase in power generation cost by 73% decrease in the LP turbine flow rate.

5.3. Exergy destruction cost

Table 3 shows thermoeconomic parameters such as exergy destruction cost in different sections of desalination system. As it was determined, the maximum exergy destruction cost is natural which relates to thermocompressor. It would cause high energy loss, low efficiency, and high exergy destruction. Feedwater pumps have the lowest exergy destruction cost.

5.4. Comparison of annual profit before and after coupling desalination system

(1) In normal operation of Neka power plant, LP turbine flow rate equals 9.965 kg/s, the minimum inlet flow rate in LP turbine should not be less than 2.66 kg/s to prevent moisture increase in LP turbine outlet flow rate more than 12% [23,25]. Table 4 included annual gains and losses arising from coupling a

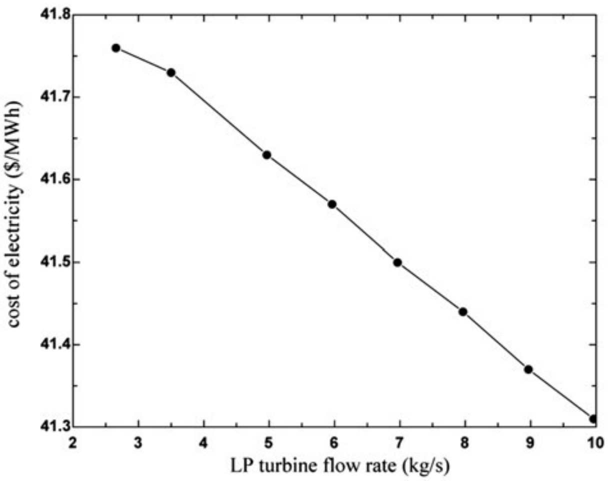

Fig. 10. Changes in cost of generated electricity by the LP turbine flow rate variations.

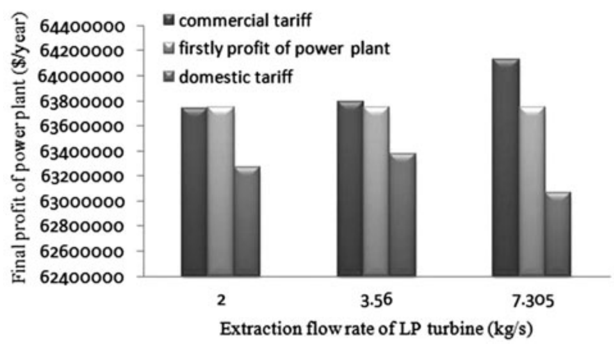

Fig. 11. Comparison of yearly profit in both produced fresh water sale with commercial and domestic tariffs compared to basic earnings before coupling to MED-TVC.

MED-TVC with Neka combined cycle power plant in three different modes of flow rate from LP turbine feed line. The following results obtained based on the table.

(2) If the maximum allowed flow, i.e. 7.305 kg/s is removed from LP line, yearly profit generated by power plants with domestic tariffs would encounter 1.9% reduction. On the other hand, 7,215 cubic meters of fresh water per day would cover 0.84% loss in profit made during its sale, caused by reduced power sales in domestic sector, finally 1.06% of the yearly profit would be deducted from the sale of electricity. If the produced fresh water and electric power sold with trade tariffs, with such an amount of fresh water production, the loss resulting from power generation reduction would not be compensated and finally the annual profit of power plant resulting from the sale of power would be reduced by 7,616.82$ per year equivalent to 0.012%.

(3) If half of the allowed flow, i.e. 3.65 kg/s is removed from LP line, yearly profit resulting from generated power sale with domestic tariff would reduce by 0.96%. On the other hand, 3,197 cubic meters of fresh water would be produced per day by this flow rate, which the amount of profit from fresh water sale with domestic tariff would compensate 0.38% loss resulting from reduced power sales in the domestic sector, but finally 0.58% of the final yearly profit would be deducted from the sale of power and if the produced water and power sold with trade tariffs, with such an amount of fresh water in addition to the compensation of loss resulting from power generation reduction, the power plant would obtain 45,927.95$ profit from the sale of fresh water.

(4) If 20% of the allowed flow, i.e. 2 kg/s is removed from LP line, yearly profit results from the sale of generated power with domestic tariff would be reduced by 0.54%. On the other hand, 1,650 cubic meters of fresh water could be generated per day by this flow rate, which the amount of profit resulting from the sale of fresh water with domestic tariff would compensate 0.18% loss resulting from reduced power sales in the domestic sector. But finally, 0.33% of the final yearly profit would be deducted from the sale of power. If the produced water and power sold with trade tariffs, with such an amount of fresh water production the loss resulting from power generation reduction would not be compensated and

Table 3
Thermoeconomic parameters of MED-TVC various components

Part	$\dot{Z}_k (\$/m^3)$	$\dot{C}_{D,k} + \dot{Z}_k (\$/m^3)$	$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} (\%)$	$\dot{C}_{D,k} (\$/m^3)$
TVC	0.08247	0.3521	23.42	0.2696
Condenser	0.03527	0.08786	40.14	0.05259
Evaporators	0.3682	0.5763	63.89	0.2081
Pumps	0.0111	0.0341	55.36	0.023

Table 4
comparison of the gain and loss from desalination system coupling to Neka combined cycle power plant

	First mood 20% allowed extraction flow rate	Second mood Half of allowed extraction flow rate	Third mood Maximum allowed extraction flow rate
Maximum fresh water production (m^3/d)	1,650	3,197	7,215
Extraction flow rate from turbine (kg/s)	2	3.65	7.305
Final cost of fresh water product ($/$m^3$)	0.9956	0.8279	0.6869
Final cost of generated power ($/Mwh)	41.44	41.7	41.76
Profit from the sale of water with domestic tariff ($/year)	12,450	233,381	526,695
Profit from the sale of water with trade tariff ($/year)	528,775.5	10,24,542.59	23,12,191.05
Profit reduction from the sale of power with domestic tariff ($/year)	330,567.36	603,099.72	1,207,128
Profit reduction from the sale of power with trade tariff ($/year)	536,392.32	978,614.64	193,1404.8
Reduction of total power of power plant (%)	0.54	0.96	1.9
Final net profit with trade tariff ($/year)	−7,616.82	+45,927.95	+380,786.25
Final net profit with domestic tariff ($/year)	−210,117.36	−369,718.72	−680,433
Final net profit with trade tariff (%)	−0.012	+0.072	+0.6
Final net profit with domestic tariff (%)	−0.33	−.058	−1.06

finally the final annual profit of power plant resulting from the sale of power would be reduced by 7,616.82$ per year equivalent to 0.012%.

(5) The above-mentioned issues are shown in Fig. 11. The figure shows that by water sale produced in power plant with domestic tariff, neither power plant obtain any profit, nor percentage of the yearly profit resulting from the sale of generated power would decrease, but by the sale of produced fresh water with trade tariff, after a certain amount of production rate, not only the loss resulting from the reduction of power sale would be reduced, but also the power plant obtained a significant profit resulting from the sale of produced water.

(6) The minimum amount of fresh water that led to annual profit for the power plant could be achieved by using Fig. 12. This figure shows the power plant annual profit results from selling electricity before coupling desalination system and yearly profit resulting from the sale of fresh water and electricity after coupling desalination system. As the figure shows, profit resulting from the sale of fresh water and electricity is firstly less than the profits from the sales of electricity, but this trend changed from A point which is the confluence of the two figures, and the profit resulting from the sale of fresh water and electricity rises from the profit resulting from the sale of power. The minimum fresh water generation determined which led to power plant profitability by finding coordinates of the A point on the horizontal axis. This amount equaled to 1,674 m^3/d. That is, with a daily production of more than 1,674 cubic meters of water, not only the loss resulting from the power sale reduction would be compensated, but also the power plant obtained a yearly profit.

(7) Note that commercial and domestic selling prices of water and power are related to September 2013.

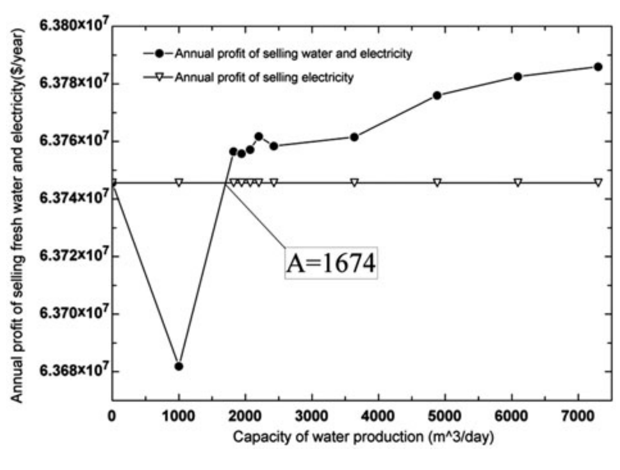

Fig. 12. Comparison of annual profit and loss after coupling desalination system.

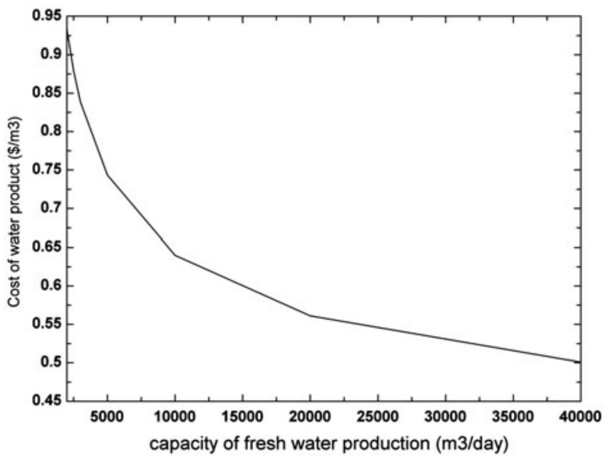

Fig. 13. The final cost of fresh water produced by various capacity of fresh water production.

(8) Final cost of water product decreased for the same input conditions and by increasing the generation capacity of fresh water. The trend of such decrease for various production capacities for the same input conditions are shown in Fig. 13.

6. Conclusion

After thermodynamic and thermoeconomic modeling of various components of water and power cogeneration system and solving the mentioned model using EES Software and investigating different parameters affecting the cycle, the following results were obtained:

(1) MED-TVC desalination system has an optimum number of evaporators in terms of economic viewpoint, energy consumption, and thermal efficiency, in a constant operating condition, it has the highest efficiency. Based on modeling and results obtained from these models, MED-TVC with seven effects and eight effects have economically and technically the optimum condition, respectively. For Caspian Sea, seven effects desalination system could be considered as the optimum system in terms of technoeconomic conditions due to the precedence of economic priorities than technical priorities in most cases and also the high closeness of efficiency ratio of seven effects and eight effects desalination.

(2) This study has showed that the highest exergy destruction rate in MED-TVC systems is related to thermocompressor and then condenser. Furthermore, exergy destruction rate of the entire system increased by increasing the number of effects. The total exergy efficiency decreased by increasing the number of system effects.

(3) Exergy destruction percentage in the first effect (first evaporator) is more than other effects which is reduced by the last effect.

(4) Finally, it is recommended that power and water cogeneration power plant is constructed in this area despite the reduced power generation capacity after coupling desalination unit and because that using MED-TVC system and extraction motive steam from LP turbine is economically explainable for the higher capacities of 2,000 cubic meters per day, and by selling fresh water production in addition to compensating the losses resulting from reduced electricity sales, the power plant obtained a considerable net profit.

(5) Furthermore, as the consumed water is supplied from three wells inside the power plant, part of the produced water could be used for the uses of power plant and the water of mentioned wells could be used in the household sector. According to NekaNews news reports, despite the closeness of Neka city and Behshahr city to the sea, these areas faced with a lack of drinking water and frequent interruptions in water, particularly in summer.

Symbols and abbreviations

B	—	brine (kg/s)
BPE	—	boiling point elevation
T_b	—	brine temperature (℃)
c_p	—	cost of water product ($/m^3)
T_s	—	desuperheater steam flow rate (℃)
d_{flash}	—	discharge flash steam from the flash tank (kg/s)
M_d	—	desuperheater flow rate (kg/s)
D_r	—	entrained vapor (kg/s)
E,e	—	exergy
h_{boiler}	—	enthalpy of saturated steam (kj/kg)
h_{ss}	—	enthalpy of super heat steam (kj/kg)
$h_{g,boiler}$	—	enthalpy of motive steam (kj/kg)
h_F	—	enthalpy of feedwater (kj/kg)
h_s	—	enthalpy of saturated steam of disuperheater (Ki/kg)
h_c	—	enthalpy of saturated liquid at sea water temperature (kj/k)
h_b	—	enthalpy of brine (kj/kg)
h_{fg}	—	enthalpy of vaporization in the evaporator temperature (kj/kg)
P_v	—	entrained vapor pressure (kPa)
$D_{distillate}$	—	fresh water flow rate (kg/s)
$\dot{S}_{gen}$	—	entropy generation

T_f	—	feedwater temperature (°C)
GOR	—	gain output ratio
T_{boiler}	—	motive steam temperature (°C)
P_{boiler}	—	motive steam pressure (kPa)
S	—	motive steam flow (kg/s)
n	—	number of effects
m_{evap}	—	steam flow of last effect brine flash (kg/s)
M_c	—	sea water flow rate (kg/s)
X	—	water concentration (ppm)

Subtitles

b	—	brine
in	—	entrance
HP	—	high pressure
LP	—	low pressure
rej	—	rejected flow
sat	—	saturate
c	—	sea
v	—	vapor

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Appendix

Table A1
The values obtained for MED-TVC with the optimum number of phases in terms of technical analysis

Parameters	Symbol	Value
Desalination capacity (m^3/d)	$D_{distillate}$	7,215
Feedwater temperature (℃)	T_f	45
Sea water concentration (ppm)	X_f	13,500
Number of phases	n	8
Sea water temperature (℃)	T_c	25
Temperature differences between phases (℃)	ΔT	3
Condenser area (m^2)	A_c	843/6
Gain ratio	GOR	12/31
Inlet flow rate of sea water (kg/s)	M_c	186/9
Outlet flow rate of sea water (kg/s)	$M_{c,rej}$	86/2
Injected water to di-super heater (kg/s)	M_d	0/3341
First level temperature (℃)	T_1	69
Last level temperature (℃)	T_n	48
Outlet steam temperature from thermocompressor (℃)	T_{ss}	108/4
Suctioned steam flow rate from the last effect (kg/s)	D_r	4/679
Inlet steam to thermocompressor (kg/s)	S	6/781
Feedwater flow rate (kg/s)	F	100/7
Brine outlet flow rate (kg/s)	B	86/518
LP turbine pressure	P_s	10/1 bar
LP turbine total flow (kg/s)	$\dot{m}_{LP}$	9/965