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Integration of MED-RO and MSF-RO desalination with a combined cycle power plant

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ABSTRACT

Due to the water crisis and many available combined cycle power plants in any part of Iran, freshwater production from brine water resources through a combined cycle power plant is a promising scenario. In this regard, the integration of the desalination plant with the Qom power plant is investigated. To this end, the thermodynamic, exergetic and exergoeconomic modeling and simulation of the Qom combined cycle power plant are integrated with hybrid multi-stage flash (MSF) + reverse osmosis (RO) and multi-effect desalination (MED) + RO units. To do so, computer code is developed for the thermodynamic simulation of the main components of the combined cycle power plant, as well as the individual MSF-RO and MED-RO desalination units. Furthermore, computer code is developed for the exergetic and exergoeconomic analyses of the integrated MED-RO and MSF-RO combined cycle. The results of the avoidable/unavoidable exergoeconomic analysis show that the air compressor and the heat recovery steam generator are the most potent components to be improved economically because they have the highest amounts of the avoidable investment cost rate in the system. The integration of the combined cycle power plant with the desalination units leads to the production of 262.3 kg/s; 1,800 kg/s; and 2,181.6 kg/s desalinated water at the cost of about 21.89 ($/h); 4,820.1($/h); and 7,363.4 ($/h) in RO, MED-RO and, MSF-RO units, respectively.

Keywords: Multi-stage flash desalination; Multi-effect desalination; Exergy; Exergoeconomic analysis; Combined cycle power plant

1. Introduction

Due to water crisis and potential brine water resources worldwide, the development of freshwater and power cogeneration plants through integrating combined cycles with multi-effect desalination (MED), multi-stage flash (MSF) and reverse osmosis (RO) is a promising option. Different researches have been published in this area, some of which are presented as follows.

A synchronous production system including a gas power cycle plus an MSF or RO water desalination unit was investigated by Ebrahim and Abdel-Jawad [1]. This article pointed out that these two most commonly used units were water desalination units in the world. These synchronous production units were exergoeconomic and optimized. The results showed the capacity of some existing desalination plants.

In another research by Malek et al. [2], it was noted that the best way to desalinate water was MSF and RO. Then, the costs of these processes were pointed out, showing that the costs of the RO method were less than those of the MSF process. These results compared the economics of some actual RO desalination units.

Darwish and Al-Najem [3] focused on the evaluation of the status of freshwater in Kuwait and considered constraints

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on the production of freshwater and water desalination units attached to different power plants.

The thermodynamic and economic analyses of MSF plants were also presented in relation to the steam required for desalination units [4,5].

A general overview of all water desalination methods was presented by Van der Bruggen and Vandecasteele [6]. The focus was on using renewable energy sources such as wind, solar energy and nuclear energy to supply energy for desalination. The economic and environmental factors of water desalination were also studied. They attempted to improve the effectiveness of desalination units by using some new materials that prevent corrosion.

Avlonitis [7] considered various RO units in terms of unit volume and input flow rate. They carried out a complete analysis of costs associated with freshwater production. The results showed a reduction in the operating cost as the labor and maintenance cost in an RO desalination unit.

Hafez and El-Manharawy [8] investigated a small RO dilution unit in terms of economic issues. In this paper, they attempted to calculate the costs of producing freshwater using the RO unit. The actual cost of desalination using the RO unit was reported to be more than the usual global cost. Moreover, some fixed operating costs of various RO plants were discussed in this work.

Furthermore, Jaber and Ahmed [9] studied a small RO unit in terms of unit volume and inlet flow rate. They carried out a complete analysis of the costs associated with freshwater production. Moreover, with some optimizations, they were able to reduce labor costs and maintenance costs associated with this process.

Vlachos and Kaldellis [10] connected a thermal water desalination unit to a gas turbine cycle and analyzed the cycle. The goal was to meet the needs of residents in the region under study using the cycle. Thermodynamic and thermoeconomic analyses were performed on the cycle, and the results indicated that the cycle could eliminate the region's water scarcity [10].

A small RO unit was connected to a mixed air steam turbine by Poullikkas [11]. The system was investigated in terms of power and freshwater production and optimized with the help of a computer program. After optimization, the cost of investment and fuel used in the cycle declined.

The basics for building a solar power plant together with a water desalination unit were investigated by Alrobaei [12]. The desalination unit was also integrated with steam and gas power plants. Economic calculations and potential were also considered. The results showed that the emissions release could be reduced by using the solar collector.

Trieb et al. [13] focused on the economics of an RO water desalination unit. The goal was to evaluate at the costs of producing freshwater through various RO units with a variety of powers. The investment costs, operating costs and other costs were considered for thermoeconomic calculations. The results showed that the water and power problems of the MENA region could be resolved.

Yet in another study by Khoshgoftar Manesh et al. [14] a site utility system was connected to a MED-RO water desalination unit, leading to the production of freshwater. To optimize the unit, an exergoeconomic analysis was carried out on the process cycle. The analysis was based on a new method based on exergoeconomic analysis and total site utility optimization. The integrated plant resulted in better exergoeconomic outcomes.

Al-Karaghouli and Kazmerski [15] suggested a different view of water desalination units. They investigated some variables including technical features, energy consumption, environmental considerations and the ability to use renewable energy for connection to water desalination units. All the variables were compared and the results showed that RO had low emission for environmental and low costs.

An RO desalination unit was connected to a gas turbine cycle by Park et al. [16]. For the desalination unit, heat wasted by the gas turbine was used. This integration resulted in a plant with a lower wasted heat and the production of freshwater with electricity.

Eveloy et al. [17] in their study investigated a gas turbine power plant with a solid oxide fuel cell along with an RO water desalination unit. They evaluated the described cycle thermodynamically and economically to help optimize and increase the production of freshwater and electricity.

In their study, Shahzad et al. [18] investigated the link between energy and water consumption and environmental protection in water desalination units. The results revealed that energy could be used in the optimum condition by using water desalination technology and that the environment could be protected by keeping constant the temperature of the outlet to the environment.

The simultaneous use of RO water desalination units and evaporation-based desalination can greatly reduce energy consumption in a power generation unit. Shahzad et al. [19] reviewed this triple unit and showed that the lowest reported energy consumption rate was reached based on the amount of the produced desalinated water. The amount of energy was 1.76 kWh/m^3 of freshwater production.

To obtain better energy consumption, sustainability, and efficiency, it is possible to use the water evaporation method developed by Shahzad et al. [20].

Using a desalination method along with a power generation unit can help increase the efficiency of the unit. Shahzad et al. [21] attempted to select a suitable water desalination capacity for an electric power unit.

Several developments have been made in desalination methods in recent years, as reported by Ng et al. [22] and Shahzad et al. [23] particularly in the combination of MED and adsorption desalination methods.

Accordingly, Ng et al. [24] showed that adsorption and evaporation were important processes in the desalination of water in thermal methods. These methods had a high temperature during the desalination process [24].

The main purpose of the present work, which distinguishes it from previous studies is the focus on the integration of hybrid MED, RO, and MSF with a real combined cycle with regard to simultaneous energy, exergy, and exergoeconomic analyses.

In this study, we investigate the integration of the Qom combined cycle power plant as a real case study with RO, hybrid RO-MED, and RO-MSF. In this regard, we perform the thermodynamic simulation as well as exergetic and exergoeconomic analyses on different integration scenarios and evaluate them.

2. Case study

A case study is a combined cycle power plant that includes a number of gas and steam turbines. In this type of power plant, by using the recovery boiler, the heat in exhaust gases from gas turbines is used to generate steam vapor in steam turbines. If the gas turbine is not a hybrid cycle, its exhaust gases, which can withstand temperatures of up to 600°C, enter directly into the air and the remaining energy is wasted. While the combined cycle power plant uses this energy, the steam boiler generates water vapor without fuel; thus, the efficiency of the cycle increases by using this method.

Combined cycle power plants are a highly efficient, flexible, reliable, cost-effective and environmentally friendly solution for power generation.

The combined cycle power plant is, in fact, a combination of a steam turbine and a gas turbine. However, the heat dissipated from the gas turbine (by combustion products) is used to produce the steam needed by the steam turbine. In this way, additional electricity is produced. By combining these two cycles, the gain in power plants increases. A power plant with a simple cycle and without using heat dissipation typically has a 25%–40% electrical efficiency, while the same power plant has a combined efficiency of about 60%.

The case study is a combined cycle power plant in Iran, which includes four gas turbines and two steam turbines. The plant produces power about 714 MW. We simulate the plant and calculate the thermodynamic properties of each point in it.

The combined cycle power plant is shown in Fig. 1.

3. Methodology

3.1. Thermodynamic modeling

The ideal cycle for gas turbines is the Brayton cycle and for steam turbines is the Rankine cycle. For calculating the thermodynamic properties of the integrated plants, we simulate them in GT Pro and use a computer code.

In this paper, the combined cycle power plant links to RO, MED-RO, and MSF-RO desalination units and thermodynamic modeling is performed for each of them.

In thermodynamic engineering analysis, we must first define a control system. After the system is defined, all the surrounding components are called system environments. Engineers and researchers are interested to find the relationship between the system and its surroundings. Moreover, in thermodynamic analysis, the system can include a specific part of the substance (the CM control mass) or a part of the material (the volume of the control volume (CV) control). In the control system, while the system is in a thermodynamic process, energy can cross the boundaries of the system. The control mass system is also called a closed system because no mass can escape its range. However, in the volume control

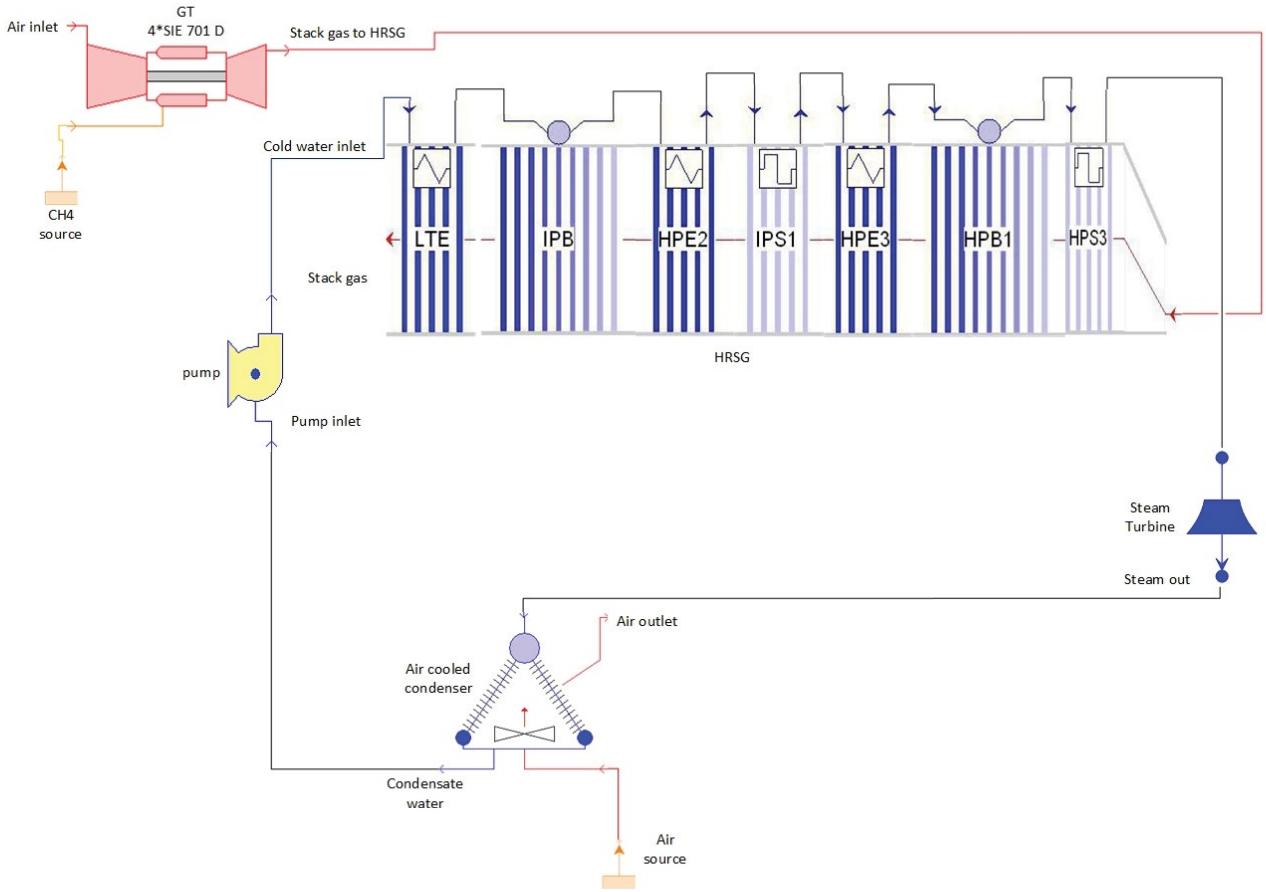

Fig. 1. Qom combined cycle power plant.

system (the open system), both the energy and the material can cross the boundaries of the system. The CV shape and size must be constant.

When the system changes, the energy change in the system is expressed by the general form of energy balance.

Energy generated in the system (reaction) + energy lost from the system – energy imported into the system = energy stored in the system [25].

3.1.1. Energy analysis of combined cycle power plant

Nowadays, considering the environmental hazards and the existing energy crisis, reducing energy consumption and producing energy by using renewable energy sources are of particular importance. In this regard, the excessive production of greenhouse gases is one of the most important problems threatening nature, especially the ozone layer. In the long run, its destructive effects on the ozone layer cause global warming which, in turn, threatens life on the planet. Moreover, construction projects are among the main sources of greenhouse gas emissions, causing many pollutants to enter the environment during the construction process. For this purpose, energy engineers attempt to minimize energy loss in construction projects using existing methods and tools and thus increase energy recovery and even sustainable energy production to the maximum. In this way, a long-term construction project not only will not be regarded as an environmental pollutant, but it will also act as a renewable energy generator.

3.1.2. RO desalination

RO is a membrane-based filtration method that eliminates a lot of large molecules and particles from the solution using pressure to the membrane-backed solution. As a result, solvents remain on the side under pressure, and the pure solvent allows the passage to the other side.

If a semi-permeable membrane is placed between two solutions with different concentrations, some of the solvent is transferred from one side of the membrane to the other. The natural direction of the solvent movement (which is from a higher chemical potential to a less chemical potential) is in such a way that the thicker solution dissolves. This difference in the surface on both sides of the membrane is called “osmotic pressure”. In the RO process, by applying more mechanical pressure than osmotic pressure to saline water, water molecules are separated from salt molecules and water moves towards the pure water section. However, there are many differences between RO and other filtration processes. The dominant mechanism of removal in membrane filtration is the application of pressure, which, in theory, results in the complete exhaust of particles, regardless of operating parameters such as pressure and concentration of wastewater. However, RO involves a diffusion mechanism whose separation efficiency depends on the solute concentration, pressure, and flow rate of water.

The efficiency of an RO water filter is affected by the pressure of water entering the system and the temperature of the water. An RO membrane is tested at a pressure of 65 psi and a temperature of 77°F. Each gradual change in either of these two variables causes a change in membrane performance. As shown in Fig. 2, the RO desalination unit has an energy recovery device.

The basis of RO supposes two dishes, one containing brine water (solution 1) and the other containing pure water (solution 2), are connected with a pipe, have an equal height of the water and are on the same surface. To balance the concentration of sodium and chloride ions from the brine

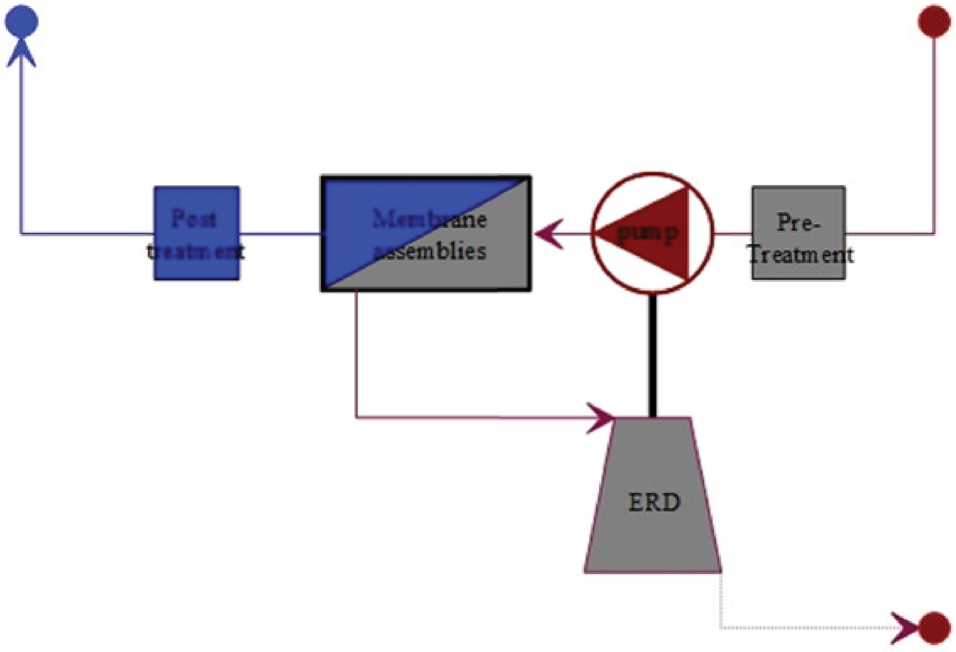

Fig. 2. Reverse osmosis desalination unit with energy recovery device (ERD).

water, salt ions are transferred to the pure water through a molecular diffusion to maintain the concentration between the two dishes. If there is a membrane between these two vessels and in the water flow path, which only allows water molecules to pass through, salt ions will not be allowed to pass. Therefore, to balance the concentration, the pure water from solution 2 is transferred to solution 1. This operation continues as long as the raised height in the saltwater creates a double pressure and allows the transfer of water from solution 2 to solution 1. This pressure is called osmotic pressure and, according to Vant Hoff's law, is the function of the salt concentration in both membrane ducts.

The Qom combined cycle power plant is linked to the RO desalination unit, as shown in Fig. 3.

3.1.3. Thermal desalination (MSF/MED)

Our country is classified as an arid region in terms of climate classification and has low rainfall. The improper management and planning in terms of water consumption have caused the country to deal with water shortage issues such as lake drying, which, in turn, has led to the damaged agriculture industry in recent years. With measures such as reducing transmission losses and saving water, one can reduce water consumption appropriately. However, given the economic and demographic growth of the country, such measures alone are not enough and the need for new water resources is felt. One of the most effective measures is water desalination. In the desalinization process, water is consumed by separating salts of soluble salts or salty water. Although desalting technologies can be used for various purposes, today, they are mostly used to produce drinking water for urban and domestic use. Similarly, desalinating waste can be used in agriculture and industry.

Different technologies are used for desalination. Common methods are divided into two general categories of thermal processes and membrane processes. From the combination of these two categories, a new category called hybrid processes is created. In this paper, all types of processes are introduced briefly.

3.1.3.1. Water desalination thermal processes

In these processes, steam energy is evaporated using the thermal energy of the saltwater, and distillation becomes virtually pure water. Since distilled water is produced in

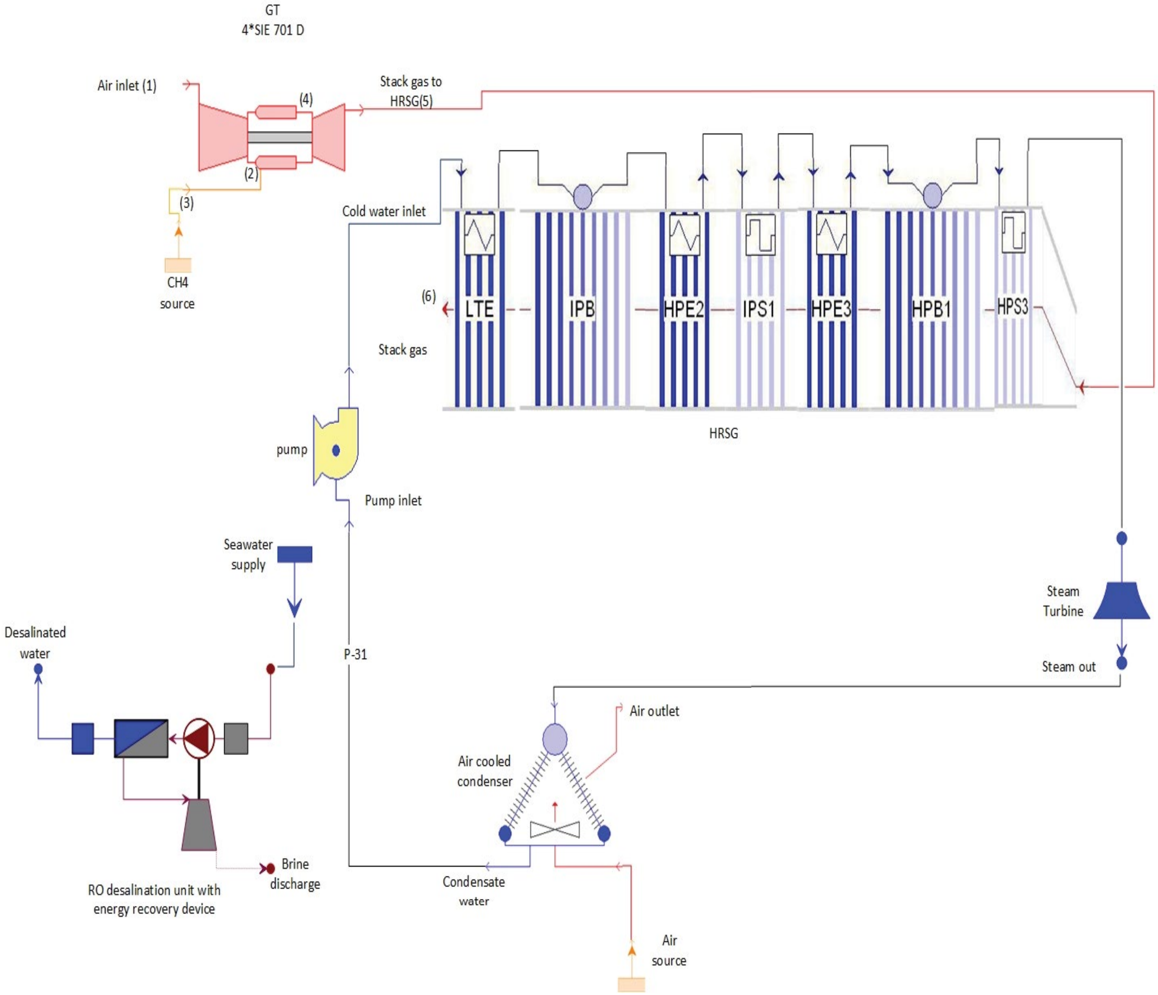

Fig. 3. Qom combined cycle power plant + RO desalination unit.

this method, if necessary, it is added to this refined water during the process of refining, to turn into drinkable water or water for use in other cases. Thermal processes require more thermal energy but consume less electricity compared to membrane processes. The source of this heat is water vapor that can be generated directly by burning fuel or using excess heat from power plants.

One of the advantages of thermal units is that with the establishment of these units along with power plants, they can be used to heat waste at power plants for water evaporation, which is expressed to be the simultaneous generation of electricity and water. In this case, due to the lack of new thermal energy, thermal efficiency will increase and desalting costs will be greatly reduced. In our country, due to the existence of numerous power plants near the southern shores, it is possible to build electricity and water generation units simultaneously.

Thermal methods for desalinating seawater are used extensively in the West Asian region. In 2013, an average of 15.9 million m^3 of water per year were produced by these processes. In the Arabian Gulf states, massive thermal desalination units have been built. For example, Al-Khabr in Saudi Arabia and Amnar in the UAE, respectively, have 811,000 and 394,000 m^3/d of freshwater production, respectively.

In this paper, we use an MSF desalination unit and an RO desalination unit simultaneously.

The diagram of the integrated plant is shown in Fig. 4.

Moreover, in this paper, we connect MED to the RO desalination unit, as shown in Fig. 5.

3.2. Exergy

Exergy is another term for 'quality of energy'. Exergy is a useful part of an energy flow, while 'anergy' refers to the non-useful part of energy flow. Energy, therefore, consists of exergy and anergy as useful and non-useful parts, respectively.

According to the first law of thermodynamics, energy balance exists in all power equipment, or according to the Energy Conservation Act, energy is not destroyed in any equipment. If one only calculates the equipment efficiency through the first law of thermodynamics, processes with the least energy loss are obtained, which have the highest returns. However, the second law of thermodynamics expresses the concept of exergy, showing that exergy cannot be balanced in any equipment since it will be destroyed in the equipment. If the efficiency of each equipment is obtained based on the second law, the highest efficiency is given to the equipment with the least exergy destruction [25].

The specific exergy of a stream can be neglected when kinetic and potential energy changes, which is given by:

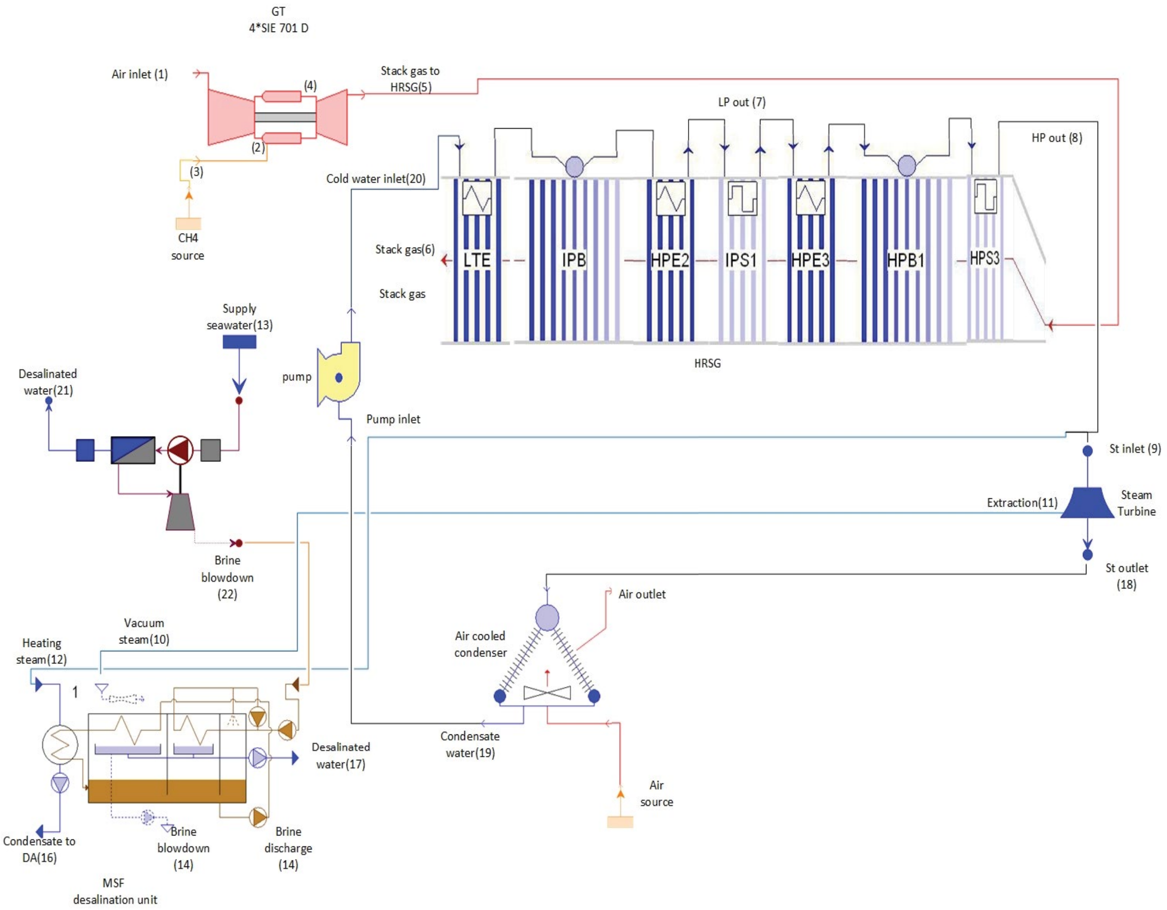

Fig. 4. Combined cycle power plant + MSF-RO desalination unit.

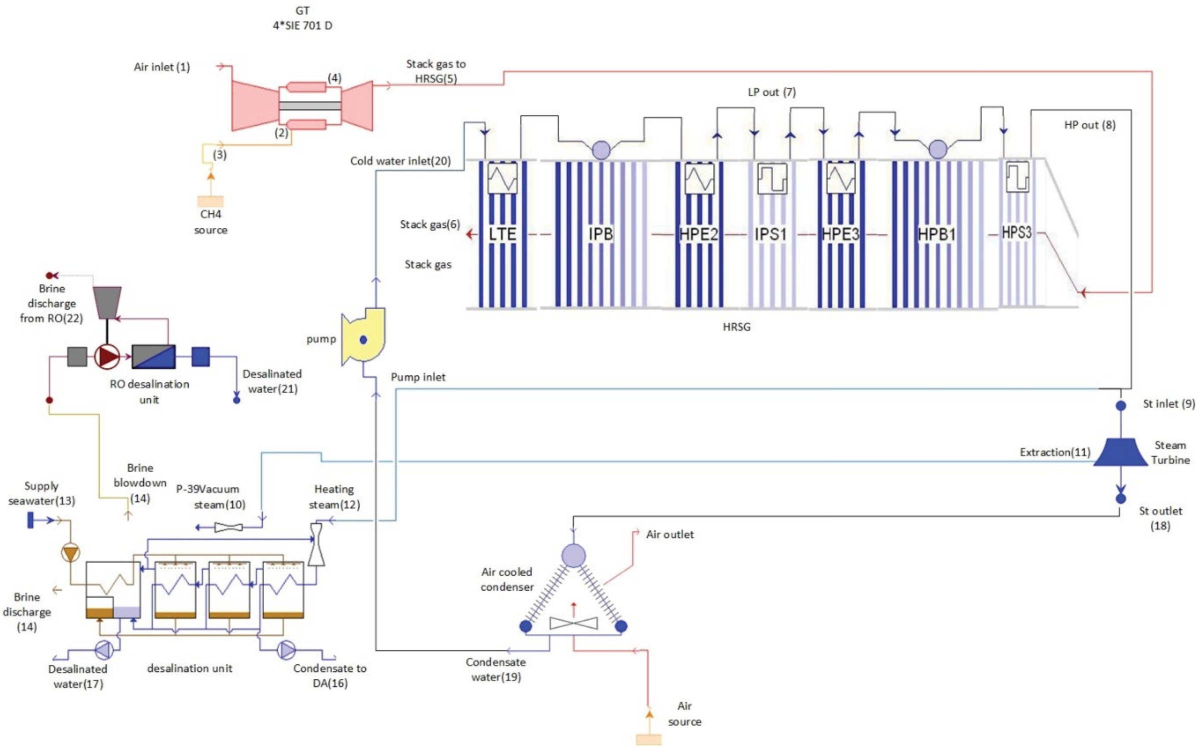

Fig. 5. Combined cycle power plant + MED-RO desalination unit.

$$e = h - h_0 - T_0\,(s - s_0) \tag{1}$$

The maximum work obtained as a stream passes from an inlet to an outlet of the system, which is given by:

$$e_2 - e_1 = h_2 - h_1 - T_0\,(s_2 - s_1) \tag{2}$$

The balanced equation of the exergy parameters can be expressed as follows:

$$\sum_j \dot{E}_{\text{qj}} \dot{W}_{\text{cv}} + \sum_i \dot{E}_i - \sum_e \dot{E}_e - \dot{E}_D = 0 \tag{3}$$

where $\dot{E}_{\text{qj}}$ denotes the exergy transfer rate associated with a thermal energy transfer rate and $\dot{W}_{\text{cv}}$ is the calculated work rate. Moreover, $\dot{E}_e$ and $\dot{E}_i$ respectively denote exergy transfer rates associated with the output and input flow through the control volume and $\dot{E}_D$ represents the exergy destruction rate associated with irreversible processes within the control volume.

3.3. Exergoeconomics

Thermoeconomics is a branch of the thermal science, which, through the combination of thermodynamic analysis (exergy) with the principles of economics, provides information to the designer or operator of an energy system, which is provided by conventional methods of thermodynamic analysis and evaluation economics is not achievable, but at the same time, it is essential for the design and operation of a system to be economically viable.

Exergy can be synonymous with energy as a concept. Exergy is the maximum power obtained from equipment in normal conditions. However, the key is economic conditions. Some streams usually have exergy or more energy, and the same amount is spent on them. Moreover, some equipment has lower energy or exergy, which results in lower costs for its flow. Using exergoeconomic analysis, we can greatly calculate the cost of different flows based on the exergy of each stream or exergy destroyed by each equipment. This analysis helps to optimize the system and identify units with the highest waste of energy and cost [26].

By calculating purchased equipment cost (PECs), as shown in Table 1, we can obtain Z_k for each component. The expected life is assumed to be 30 years [27]:

PECs of desalination units are predicted from these sources [28–32].

Finally, for each flow in a system, a parameter called the flow cost rate $\dot{C}$ ($/h) is defined, and a cost balance is written for each component as follows [33]:

$$\dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k = \sum_e \dot{C}_{e,k} + \dot{C}_{w,k} \tag{4}$$

Cost balances are generally written so that all terms are positive. According to Eq. (2):

$$\sum \left(c_e \dot{E}x_e\right)_k + c_{w,k} \dot{W}_k = c_{q,k} \dot{E}x_{q,k} + \sum \left(c_i \dot{E}x_i\right)_k + \dot{Z}_k \tag{5}$$

This section examines the cost of different input and output streams of each equipment and investment costs for purchase and maintenance of each component. A cost

Table 1
PECs equations

Component	Equations of PEC calculation
Air compressor [27]	$\mathrm{PEC}_{\mathrm{AC}} = 71.1 \times \dot{m}_{\mathrm{air}} \times \left[\frac{P_e}{P_i} \times \ln \frac{P_e}{P_i}\right]\left[\frac{1}{0.92 - \eta_{\mathrm{AC}}}\right]$
Combustion chamber [27]	$\mathrm{PEC}_{\mathrm{CC}} = 46.08 \times \dot{m}_{\mathrm{air}} \times \left[1 + e^{\left(0.018 \times T_{0,\mathrm{CC}} - 26.4\right)}\right]\left[\frac{1}{0.995 - \frac{P_e}{P_i}}\right]$
Gas turbine [27]	$\mathrm{PEC}_{\mathrm{GT}} = 479.34 \times \left[1 + e^{\left(0.036 \times T_{0,\mathrm{CC}} - 56.4\right)}\right] \times \left[\frac{\dot{m}_{\mathrm{gas}}}{0.93 - \eta_{\mathrm{GT}}}\right] \times \ln \frac{P_e}{P_i}$
HRSG [27]	$\mathrm{PEC}_{\mathrm{HRSG}} = 6,570 \times \left[\left(\frac{\dot{Q}_{\mathrm{ec}}}{\Delta T_{\mathrm{ec}}}\right)^{0.8} + \left(\frac{\dot{Q}_{\mathrm{ev}}}{\Delta T_{\mathrm{ev}}}\right)^{0.8} + \left(\frac{\dot{Q}_{\mathrm{sh}}}{\Delta T_{\mathrm{sh}}}\right)^{0.8}\right] + 21,276 \times \dot{m}_w + 1,184.4 \times \dot{m}_g^{1.2}$
Steam turbine [27]	$\mathrm{PEC}_{\mathrm{St}} = 2,210 \times \left(\dot{W}\right)^{0.7}$
Condenser [27]	$\mathrm{PEC}_{\mathrm{condenser}} = \dot{m}_w \times 1,773$
FW pump [27]	$\mathrm{PEC}_{\mathrm{pump}} = 2,100 \times \left(\frac{\dot{W}}{10}\right)^{0.26} \times \left[\frac{1 - \eta_{\mathrm{pump}}}{\eta_{\mathrm{pump}}}\right]$

equation defines the cost rate related to the product of the system (C_P); the cost rate equals the total rate of costs related to the product, namely the fuel cost rate (C_F), the cost rate related to the capital investment (Z^{CI}), and operating and maintenance costs (Z^{OM}).

The exergy cost destruction level (ECDL) and the exergy destruction level (EDL) are two new parameters defined as Eqs. (3) and (4), respectively. Using these parameters, we can develop exergy and exergoeconomic analyses.

$$\mathrm{EDL}_j = \frac{E_{D,j}}{\mathrm{TV}_j} \tag{6}$$

$$\mathrm{ECDL}_j = \frac{C_{D,j}}{\mathrm{TV}_j} \tag{7}$$

where $E_{D,j}$ and $C_{D,j}$ shows the exergy destruction and its cost in each component, respectively, and TV_j shows the amount of the target in case of exergy and economic.

Based on economic analysis, a cost model is usually defined for the overall system as follows:

$$C_{P,\mathrm{tot}} = C_{F,\mathrm{tot}} + Z_{\mathrm{tot}} \tag{8}$$

To find unknown variables, the development of equations is necessary to satisfy Eq. (4) to each component. To satisfy the number of unknown variables with the number of equations, additional equations are required.

We can obtain $\dot{C}_P$ and $\dot{C}_F$ for each component from Table 2:

3.4. Standard primary energy approach for comparing desalination processes

Considering different grades of energy as equivalent in the desalination industry can have negative economic and environmental consequences. Although this approach suffices for the comparison of the same energy input processes, omitting the grade of energy when comparing diverse technologies may lead to incorrect conclusions and, resultantly, inefficient installations. Here, a standard primary energy (SPE)-based thermodynamic framework is presented to address energy efficacy fairly and accurately. Moreover, a standard universal performance ratio (SUPR)-based evaluation method is proposed, showing that the performance of all desalination processes varies from 10%–14% of the thermodynamic limit.

The noticeable improvement of the combined cycle gas turbine (CCGT) is also observed when thermally-driven desalination processes are integrated with CCGT power plants due to better utilization of low-pressure steam in water production before dumping into the condenser. Today, combined CCGT and desalination processes are considered as the most efficient cycles for power and water production. In conventional combined CCGT power and desalination plants, the primary fuel is supplied to the gas turbine cycle, where it combusts in a combustion chamber in the presence of compressed air from the compressor. Hot and high-pressure gases are then expanded through the gas turbine to produce electricity. The gas turbine cycle consumes

Table 2
$\dot{C}_P$ & $\dot{C}_F$

Component	Auxiliary equations	Equations of product and fuel economy of each component
Air compressor	$\dot{c}_1 = 0$ $\dot{c}_{w,\mathrm{Ac}} = \dot{c}_{w,\mathrm{GT}}$	$\dot{C}_{F,\mathrm{Ac}} = \dot{C}_W$ $\dot{C}_{P,\mathrm{Ac}} = \dot{C}_2 - \dot{C}_1$
Combustion chamber	$\dot{c}$ = fuel cost	$\dot{C}_{F,\mathrm{CC}} = \dot{C}_2 + \dot{C}_3$ $\dot{C}_{P,\mathrm{CC}} = \dot{C}_4$
Gas turbine	$\dot{c}_4 = \dot{c}_5$	$\dot{C}_{F,\mathrm{GT}} = \dot{C}_4 - \dot{C}_5$ $\dot{C}_{P,\mathrm{GT}} = \dot{C}_{W,\mathrm{GT}}$
HRSG	$\dot{c}_6 = 0$ $\dot{c}_7 = \dot{c}_8$	$\dot{C}_{F,\mathrm{HRSG}} = \dot{C}_5 - \dot{C}_6$ $\dot{C}_{P,\mathrm{HRSG}} = \dot{C}_7 + \dot{C}_8 - \dot{C}_{20}$
Steam turbine	$\dot{c}_8 = \dot{c}_9$ $\dot{c}_8 = \dot{c}_{11}$ $\dot{c}_{18} = \dot{c}_8$	$\dot{C}_{F,\mathrm{ST}} = \dot{C}_9 - \dot{C}_{11} - \dot{C}_{18}$ $\dot{C}_{P,\mathrm{ST}} = \dot{C}_{W,\mathrm{ST}}$
Condenser	$\dot{c}_{w,\mathrm{fan}} = \dot{c}_{w,\mathrm{ST}}$	$\dot{C}_{F,\mathrm{cond}} = \dot{C}_{W,\mathrm{fan}}$ $\dot{C}_{P,\mathrm{cond}} = \dot{C}_{18} - \dot{C}_{19}$
FW pump	$\dot{c}_{w,\mathrm{pump}} = \dot{c}_{w,\mathrm{ST}}$	$\dot{C}_{F,\mathrm{pump}} = \dot{C}_{W,\mathrm{pump}}$ $\dot{C}_{P,\mathrm{cond}} = \dot{C}_{20} - \dot{C}_{19}$
MED or MSF desalination unit	$\dot{c}_{10} = \dot{c}_{12}$ $\dot{c}_{10} = \dot{c}_8$ $\dot{c}_{11} = \dot{c}_{12}$ $\dot{c}_{10} = \dot{c}_{16}$ $\dot{c}_{13} = \dot{c}_{14} = \dot{c}_{15} = 0$	$\dot{C}_{F,\mathrm{desalination}} = \dot{C}_{10} - \dot{C}_{12} - \dot{C}_{13}$ $\dot{C}_{P,\mathrm{desalination}} = \dot{C}_{17}$
RO desalination unit	$\dot{c}_{w,\mathrm{pump}} = \dot{c}_{w,\mathrm{ST}}$	$\dot{C}_{F,\mathrm{desalination}} = \dot{C}_{\text{seawater supply}}$ $\dot{C}_{P,\mathrm{desalination}} = \dot{C}_{\text{desalinated water}}$

the major portion of fuel exergy due to high irreversibility in the combustion chamber. The remaining exergy in hot exhaust gas is then recovered in the heat recovery steam generator (HRSG) to produce high pressure and temperature steam for the steam turbine cycle. In the combined arrangement, low-pressure steam is bled from the last stage of the low-pressure turbine to operate the seawater desalination cycle. These integrations improve the overall cycle performance because the steam bled from the last stage of the low-pressure turbine has already utilized its maximum potential but can still be useful for low-pressure desalination processes.

Conventionally, desalination processes are presented based on different kinds of energy such as electricity (kWh) and thermal (kWh) energy for comparison purposes. Even though the units are the same, this comparison is not fair as grades of energies are different. Here, we develop a detailed thermodynamic framework based on the SPE approach to resolve two main issues, namely (i) an accurate apportionment of primary fuel exergy across each process in a combined cycle arrangement based on its operational parameters and (ii) comparison of all desalination processes in a common platform called the SUPR by converting different types and grades of energy to SPE. This can be achieved by invoking the second law of thermodynamics, where primary energy can be supplied to achieve the same equivalent work of separation processes. The proposed approach circumvents the deficiency of derived energy units (kWh) used singly as these energy units omit the quality of the supplied energy. The SPE approach considers meaningful temperature ratios to complete a thermodynamic cycle from the adiabatic flame temperature to the ambient reservoir [34].

The conventional unfair performance parameter of desalination processes now can be transformed into a more accurate parameter based on the common platform of SPE. The new performance parameter is called SUPR, as shown in Eq. (9) [35].

$$\text{Standard Universal Performance Ratio}\left(\text{SUPR}\right) = \frac{\text{Equivalent heat of evaporation of distillate production}}{\text{SPE input}} \cong \frac{2{,}326\left(\dfrac{\text{kJ}}{\text{kg}}\right)}{3.6\times\left[\text{CF1}\left\{\dfrac{\text{kW.h}_{\text{elec}}}{\text{m}^3}\right\}+\text{CF2}\left\{\dfrac{\text{kW.h}_{\text{thermal}}}{\text{m}^3}\right\}+\text{CF3}\left\{\dfrac{\text{kW.h}_{\text{renewable}}}{\text{m}^3}\right\}\right]} \tag{9}$$

We can draw a flowchart for all the calculations performed in this paper as Fig. 6.

According to Fig. 6, the calculation process in this study is as follows:

In the first step, the combined cycle unit is simulated in the thermoflow software. This simulation is also performed using computer coding.

In the second step, the desalination units and the combined cycle power plant are integrated and then thermodynamic

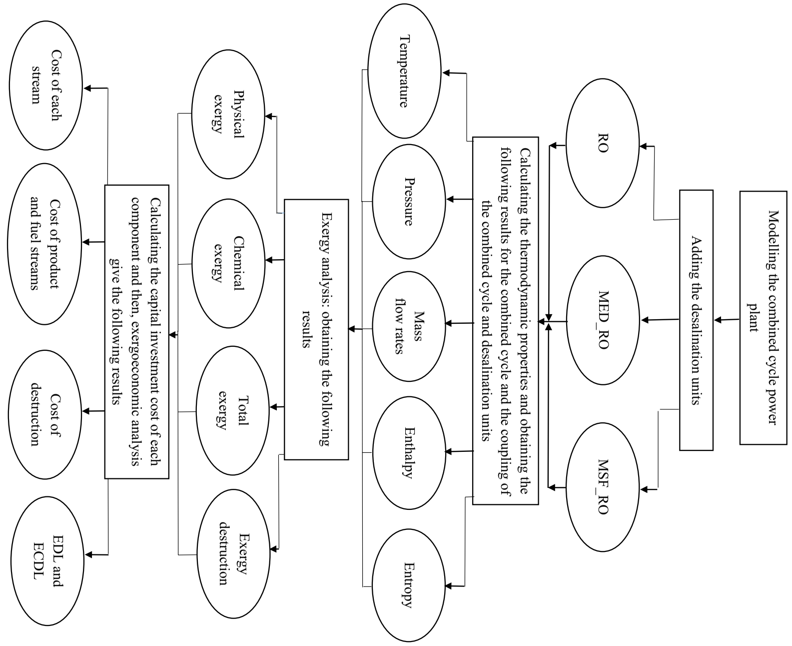

Fig. 6. Flowchart of the calculation path.

properties are calculated according to the relationships described in the thermodynamic modeling section, Appendix A and B.

In the third step, based on the previous step, the exergy analysis is carried out and the results of this analysis are calculated as the exergy value of each flow. The relationships are in the exergy section.

The fourth step is to begin the economic calculations of the cycles. To do so, it is best to calculate the investment costs associated with each equipment. The relationships in this section are presented in Table 1.

At this point, equations of economic equilibrium are written for each equipment and then the cost of each flow is obtained.

In the fifth step, first, the fuel and product exergy is calculated and then the fuel and product cost is determined for each equipment. Afterward, the cost of the exergy degradation rate is calculated. The related relationships are presented in the exergoeconomic and thermoeconomic sections.

Finally, EDL and its cost are calculated for each equipment.

4. Results and discussion

4.1. Thermodynamic results

The thermodynamic cycle of the Qom power plant is simulated using Thermoflex and computer code (EES). The results from these two are compared with the actual state in Table 3.

In addition, in this paper, we link the Qom combined cycle power plant to RO, MED-RO, and MSF-RO desalination

Table 3
Comparing thermodynamic properties between simulation and actual case

	Qom combined cycle power plant				Qom combined cycle power plant in computer code				Qom combined cycle power plant in Thermoflex			
Stream	T (c)	P (bar)	$\dot{m}$(kg/s)	H (kJ/kg)	T (c)	P (bar)	$\dot{m}$(kg/s)	H (kJ/kg)	T (c)	P (bar)	$\dot{m}$ (kg/s)	H (kJ/kg)
Inlet air to compressor	18.6	0.86	387.5	57.37	18.6	0.86	387.5	57.37	16	0.85	382.2	50.37
Air out	295	11.66	386.9	394.23	279	12.08	387.5	390.76	273	12.4	382.2	385.74
GT inlet	1,165.35	11.31	393.5	1,539.84	1,153.64	11.9	395.08	1,540.63	1,107	11.9	389.9	1,541.81
GT out	547.95	0.96	394.2	796.34	535.6	0.93	395.08	792.69	522	0.93	389.9	792.71
Stack gas	163.45	0.8975	1,643.25	377.77	158.2	0.8964	395.08	377.77	157.1	0.8964	1,559.5	377.77
ST in	462.5	78.2	180.2	3,310.5	475.3	76.9	179.6	3,335.45	482	76.9	179.3	3,358.18
ST out	68.42	0.345	233.9	2,418.65	66.35	0.2427	224.96	2,417.54	64.33	0.2427	233.8	2,416.32
Condenser out	65.31	0.287	65.98	272.56	66.35	0.6017	66.59	270.74	64.33	0.6017	66.59	269.31
Pump out	66.87	4.2	66.58	275.61	65.23	3.71	66.58	273.02	64.79	3.71	66.58	271.49
HRSG HP	301.65	85..3	184.23	2,769.35	297.8	81.18	179.6	2,760.17	296	81.18	179.3	2,758.15
HRSG LP	160.2	5.72	45.36	2,749.16	159	5.949	45.36	2,753.64	158.5	5.949	59.79	2,755.09
Fuel	69.5	23.01	7.58	55,857.58	69.5	23.01	7.58	55,857.58	78.06	23.02	7.63	55,857.58

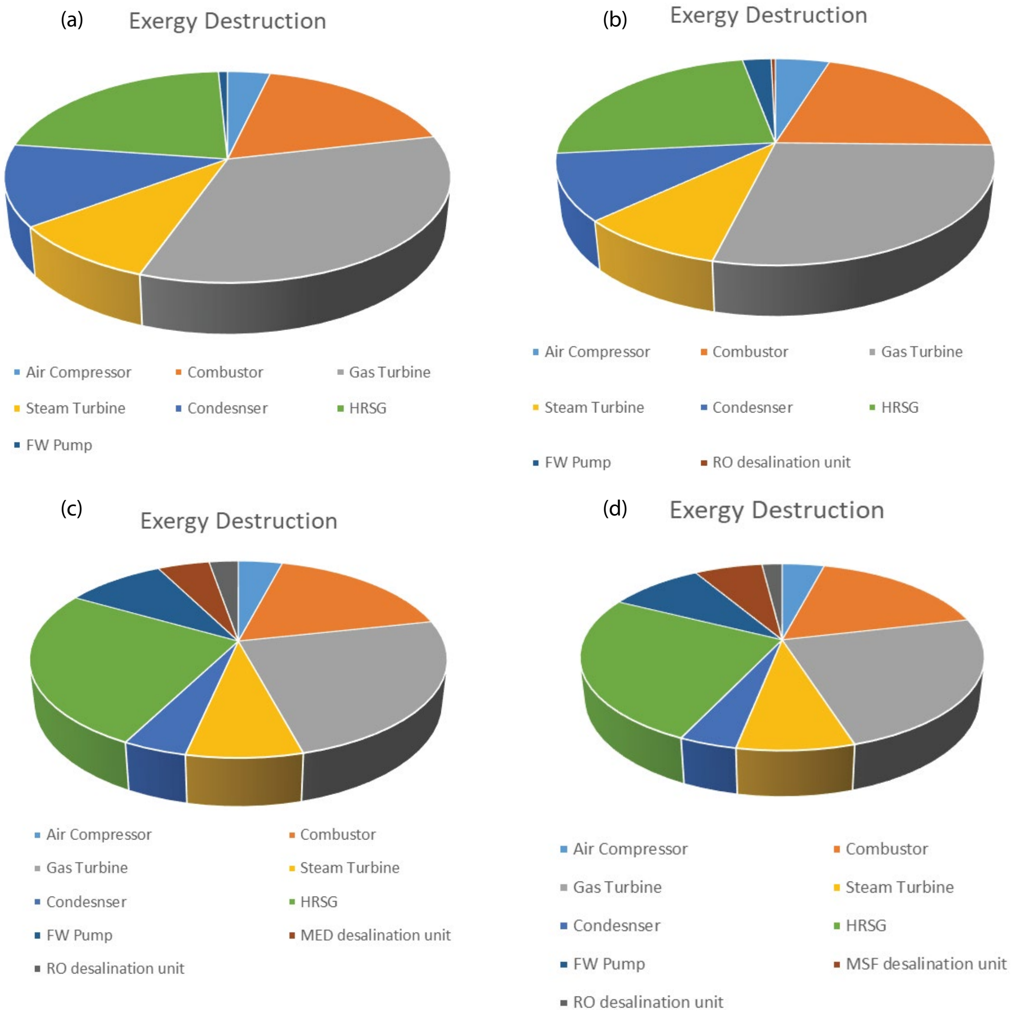

Fig. 7. Exergy destruction plot (a) combined cycle power plant, (b) combined cycle and RO desalination unit, (c) combined cycle and MED-RO desalination unit, and (d) combined cycle and MSF-RO desalination unit.

units. Thermodynamic properties of these plants are obtained as in Tables 4–6.

The water recovery ratio is assumed to be 40% in the combined cycle power plant integrated with the RO desalination unit. In the MED-RO cycle, the performance ratio introduced in Appendix B for the MED desalination unit is about 6.3 and this parameter amount increased to 8.8 in the MSF desalination unit of the MSF-RO hybrid cycle power plant.

In the RO system, the inlet water from the sea is 655.8 kg/s, some available and small, making it easier to operate. However, this flow rate will reach 14,167.6 and 13,200 kg/s in the MED-RO and MSF-RO systems, which will require the transfer of water from the river or sea to the water desalination unit.

The amounts of brine blowdown extracted from the water desalination units are compared and shown to be 393.5; 1,200; and 3,804 kg/s, in the RO, MED-RO and MSF-RO units, respectively. This indicates that the highest amount of brine blowdown is produced in the MSF-RO system.

The MED-RO system has the lowest fuel consumption at the plant, which is 7.58 kg/s of methane.

4.2. Exergy results

The calculation results of the exergy of each stream for the combined cycle, the combined cycle + RO, the combined cycle + MED-RO and the combined cycle + MSF-RO are shown in Table 7. Fig. 7 shows the exergy destruction plot (a) combined cycle power plant, (b) combined cycle and RO desalination unit, (c) combined cycle and MED-RO desalination unit, and (d) combined cycle and MSF-RO desalination unit. In addition, product and fuel cost rate (a) combined cycle power plant, (b) combined cycle and RO desalination unit, (c) combined cycle andMED-RO desalination unit, and (d) combined cycle and MSF-RO desalination unit have been shown in Fig. 8.

The total exergy entering the gas turbine is 408.71 MW, as shown in Table 7. This amount is reduced when integrating this plant with the RO, MED-RO and MSF-RO desalination units by 6.3%, 6.5%, and 6.5%, respectively. Further, the total

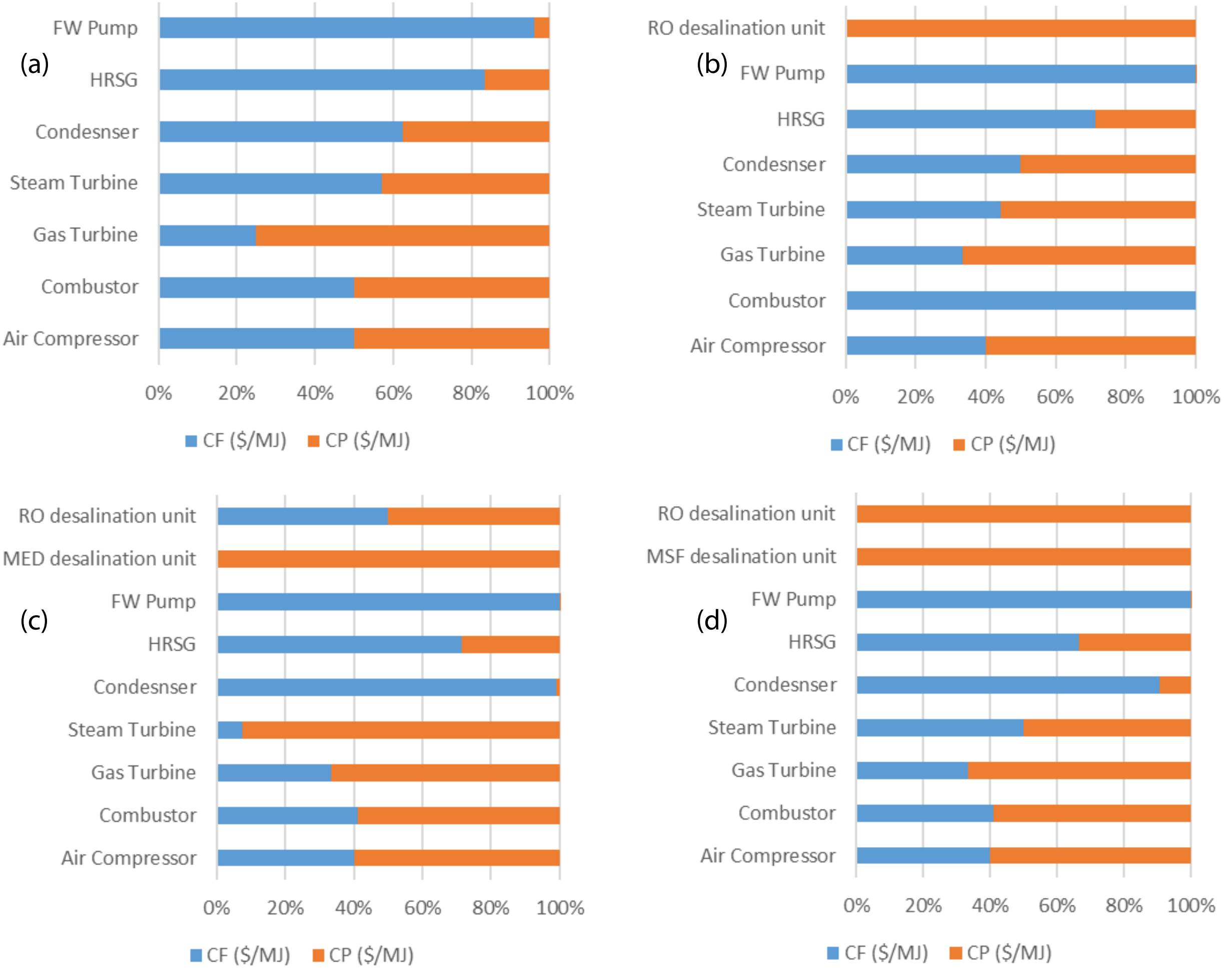

Fig. 8. Product and fuel cost rate (a) combined cycle power plant, (b) combined cycle and RO desalination unit, (c) combined cycle and MED-RO desalination unit, and (d) combined cycle and MSF-RO desalination unit.

Table 4
Thermodynamic properties of combined cycle + RO

Stream	*T* (c)	*P* (bar)	$\dot{m}$(kg/s)	*h* (kJ/kg)	*s* (kJ/c kg)
1 (Inlet air to compressor)	16	0.85	372.34	50.37	0.06
2 (Air out)	273	12.4	357.9	385.74	0.85
4 (GT inlet)	1,107	11.9	365.53	1,541.81	1.78
5 (GT out)	522	0.93	389.87	792.71	1.07
6 (Stack gas)	132.9	0.9	1,559.5	377.77	1.2E-01
7 (ST in)	482	76.9	179.3	3,358.18	6.69
8 (ST out)	64.33	0.24	233.81	2,416.32	7.12
19 (Condenser out)	64.33	0.60	233.89	269.31	0.71
11 (CW in) (Pump out)	64.79	3.71	181.1	271.49	0.89
HRSG HP	297	82.38	179.3	2,758.15	5.73
HRSG LP	159.6	6.12	59.8	2,755.09	6.7
Brine blowdown water	26.32	0.9	393.5	149.5	0.5
Desalinated water	26.24	1.01	262.3	159.7	0.5
Supply seawater	25	0.9	655.8	150	0.43
Fuel	78.06	23.02	7.63	55,857.58	–

Table 5
Thermodynamic properties of combined cycle + MED-RO

Stream	*T* (c)	*P* (bar)	$\dot{m}$ (kg/s)	*h* (kJ/kg)	*s* (kJ/c kg)
1 (Inlet air to compressor)	16.66	0.85	371.5	50.42	0.06
2 (Air out)	276.1	12.36	356.9	387.64	0.85
4 (GT inlet)	1,107.3	11.87	364.5	1,541.81	1.78
5 (GT out)	522.9	0.93	388.8	792.71	1.07
6 (Stack gas)	158.2	0.9	388.8	377.77	1.20E-01
7 (ST in)	482	76.9	88.52	3,358.18	6.69
8 (ST out)	66.47	0.27	33.53	2,398.3	7.12
19 (Condenser out)	64.33	0.6	33.53	269.28	0.71
11 (CW in) (Pump out)	140	6.1	59.58	589.28	0.89
HRSG HP	296	81.18	179.2	2,758.15	5.74
HRSG LP	158.5	5.95	55.58	2,755.09	6.7
Extraction of ST (to MED)	173.1	5.72	54.98	2,789.48	6.86
Steam inlet to MED	181.2	5.5	137.4	2,809.89	6.92
Brine blowdown water from MED to RO	38.58	1.01	2,000	150.26	0.52
Desalinated water of MED	38.12	4.1	1,000	159.94	0.55
Vacuum steam	214.1	20.68	2.747	2,764.24	6.5
Condensate to DA	38.12	3.7	137.4	159.89	0.5
Supply seawater	30	0.9	14,167.6	119.88	0.43
Seawater discharge from MED	36.05	1.01	11,168	150.26	0.43
Desalinated water from RO	40.46	1.01	800	169.44	0.43
Brine discharge from RO	42.5	0.9	1,200	123.64	0.43
Fuel	77.62	23.02	7.58	55,857.58	–

Table 6
Thermodynamic properties of combined cycle + MSF-RO

Stream	*T* (c)	*P* (bar)	$\dot{m}$ (kg/s)	*h* (kJ/kg)	*s* (kJ/c kg)
1 (Inlet air to compressor)	16.66	0.85	371.5	50.42	0.06
2 (Air out)	276.1	12.36	356.9	387.64	0.85
4 (GT inlet)	1,107.3	11.87	364.5	1,541.81	1.78
5 (GT out)	524.1	0.94	388.8	792.71	1.07
6 (Stack gas)	156.7	0.9	388.8	376.58	1.20E-01
7 (ST in)	482	76.9	88.53	3,358.18	6.69
8 (ST out)	66.47	0.27	25.88	2,398.3	7.11
19 (Condenser out)	64.33	0.6	25.88	269.28	0.71
11 (CW in) (Pump out)	140	5.89	59.97	589.28	0.89
HRSG HP	297.02	82.38	179.8	2756.39	5.74
HRSG LP	156.98	5.72	56.73	2,755.09	6.7
Extraction of ST (to MED)	161.8	5.5	86.75	2,789.48	6.86
Steam inlet to MSF	181.2	5	172.3	2,813.24	6.9
Brine blowdown water from RO to MSF	31.44	1.01	12,588.9	125.3	0.52
Desalinated water of MSF	38.37	4.137	1,521.6	160.96	0.55
Vacuum steam	214.1	20.68	3.447	2,764.24	6.5
Condensate to DA	114.2	3.70	172.3	479.49	0.5
Supply seawater to RO	30	0.9	13,200	119.88	0.4
Seawater discharge from MSF	40	1.01	7,263	128.6	0.4
Desalinated water from RO	30.56	1.01	660	128.22	0.4
Brine discharge from MSF	40.05	1.01	3,804	128.6	0.43
Fuel	77.63	23.02	7.582	55,857.58	–

Table 7
Comparing exergy between combined cycle, combined cycle + RO, combined cycle + MED-RO and combined cycle + MSF-RO

Stream	Combined cycle			Combined cycle + RO			Combined cycle + MED-RO			Combined cycle + MSF-RO		
	Physcial exergy (MW)	Chemical exergy (MW)	Total exergy (MW)	Physcial exergy (MW)	Chemical exergy (MW)	Total exergy (MW)	Physical exergy (MW)	Chemical exergy (MW)	Total exergy (MW)	Physical exergy (MW)	Chemical exergy (MW)	Total exergy (MW)
1 (Inlet air to compressor)	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00	0.00	0	0.00
2 (Air out)	107.99	0	107.99	101.12	0	101.1	101.25	0	101.25	101.25	0	101.25
4 (GT inlet)	406.42	2.29	408.71	381.02	2.15	383.1	379.98	2.14	382.12	379.98	2.14	382.12
5 (GT out)	93.77	2.29	96.06	93.76	2.29	96.05	93.82	2.28	96.10	94.41	2.28	96.69
6 (Stack gas)	23.90	9.16	33.06	11.52	9.16	20.69	6.11	2.28	8.39	5.90	2.28	8.19
7 (ST in)	245.19	0	245.19	245.19	0	245.1	121.05	0	121.0	121.06	–	121.06
8 (ST out)	69.99	0	69.99	69.99	0	69.99	9.43	0	9.43	7.28	–	7.28
19 (Condenser out)	4.12	0	4.12	14.47	0	14.47	2.07	0	2.07	1.60	–	1.60
20 (Pump out)	0.68	0	0.68	1.84	0	1.84	19.54	0	19.54	19.67	–	19.67
8(HRSG HP)	188.51	0	188.51	188.51	–	188.5	188.41	0	188.4	188.72	–	188.72
7(HRSG LP)	45.52	0	45.52	45.52	–	45.52	42.31	0	42.31	43.19	–	43.19
11 (Extraction of ST (to MED or MSF))	–	–	–	–	–	–	41.23	0	41.23	65.06	–	65.06
12 (Steam inlet to desalination)	–	–	–	–	–	–	1.42	0	1.42	1.57	0	1.57
15 (Brine blowdown water from MED or MSF)	–	–	–	–	–	–	0.00	43.98	43.98	0.29	81.95	82.24
17 (Desalinated water of MED or MSF)	–	–	–	–	–	–	0.10	0	0.10	0.12	0	0.12
10 (Vacuum steam)	–	–	–	–	–	–	9.87	0	9.87	9.60	0	9.60
16 (Condensate to DA)	–	–	–	–	–	–	0.18	3.85	4.03	0.69	4.59	5.28
13 (Supply seawater for RO)	–	–	–	0.00	15.81	15.8	0.05	302.70	302.7	0.05	282.09	282.14
14 (Seawater discharge from MED or MSF)	–	–	–	–	–	–	0.46	238.80	239.2	0.55	155.62	156.18
21 (Desalinated water from RO)	–	–	–	0.00	0	0.00	0.07	0	0.07	0.01	0	0.01
22 (Brine discharge from RO)	–	–	–	0.00	8.95	8.95	0.12	26.48	26.61	0.00	269.54	269.54
3 (Fuel)	3.68	392.06	395.74	3.68	392.05	395.7	3.66	389.59	393.2	3.66	389.59	393.25

exergy wasted in the stack of HRSG is reduced by 37%, 75% and 75% in the integrated plants.

The total exergy entering the system using the fuel is fixed approximately in the combined cycle power plant and the integrated plants.

4.3. Exergoeconomic results

According to the results obtained earlier, we can make economic, thermoeconomic and exergoeconomic calculations. The cost results for each flow are listed in Tables 8–11.

Table 8
Cost of each stream for combined cycle

		Without Z		With considering Z	
Stream	Total exergy (MW)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)
1 (Inlet air to compressor)	0.00	0	0	0	0
2 (Air out)	107.99	0.1	37,515.3	0.02	8,552.71
4 (GT inlet)	408.71	0.03	40,462.78	0.03	40,757.06
5 (GT out)	96.06	0.03	9,509.54	0.9e-2	3,250.53
6 (Stack gas)	33.06	0	0	0	0
7 (ST in)	245.19	0.03	24,714.99	0.44e-2	3,883.78
8 (ST out)	69.99	0.45e-2	1,133.8	0.44e-2	1,108.61
19 (Condenser out)	4.12	0.4	5,667.27	0.0044	65.26
20 (CW in) (Pump out)	0.68	3.8	9,252.96	0.0225	54.87
3 (Fuel)	395.74	0.21e-2	2,991.79	0.1e-2	1,567.13
$\dot{W}_{st}$	118.98	0.04	16,362.54	0.2e-2	899.51
$\dot{W}_{gt}$	202.62	0.07	53,904.49	0.5e-2	3,647.12
$\dot{W}_{fp}$	2.752	0.04	378.45	0.02	224.89
$\dot{W}_{compressor}$	119.07	0.07	31,676.31	0.5e-2	2,143.19
8 (HRSG HP)	188.51	0.03	18,323.3	0.02	15,405.15
7 (HRSG LP)	45.52	0.03	4,424.2	0.4e-2	720.99

Table 9
Cost of each stream for combined cycle + RO

		Without Z		With considering Z	
Stream	Total exergy (MW)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)
1 (Inlet air to compressor)	0.00	0	0	0	0
2 (Air out)	101.12	0.1	35,130.1	0.03	10,083.98
4 (GT inlet)	383.17	0.03	37,906.1	0.9e-2	12,966.44
5 (GT out)	96.05	0.03	9,501.9	0.9e-2	3,250.3
6 (Stack gas)	20.69	0	0	0	0
9 (ST in)	245.19	0.03	24,185.4	0.4e-2	3,883.78
18 (ST out)	69.99	0.4e-2	1,108.65	0.4e-2	1,108.66
19 (Condenser out)	14.47	0.4	19,905.67	0.02	1,172.1
20 (CW in) (Pump out)	1.84	3.79	25,167.41	0.14	913.43
3 Fuel	395.74	0.2e-2	2,991.79	0.2e-2	2,991.8
$\dot{W}_{st}$	118.98	0.04	16,491.04	0.5e-2	2,141.7
$\dot{W}_{gt}$	202.62	0.07	53,685.66	0.02	16,557.9
$\dot{W}_{fp}$	2.752	0.04	381.4	0.5e-2	49.54
$\dot{W}_{cp}$	0.32	0.04	43.7	0.5e-2	5.67
$\dot{W}_{compressor}$	119.06	0.07	31,547.7	0.02	9,730.07
8 HRSG HP	188.51	0.03	18,730.49	0.4e-2	2,986.02
7 HRSG LP	45.52	0.03	4,522.59	0.4e-2	720.99
15 (Brine blowdown water)	8.95	0	0	0	0
17 (Desalinated water)	0.1e-4	8.02	21.89	0.21	0.59
13 (Supply seawater)	15.81	0	0	0	0

Table 10
Cost of each stream for combined cycle + MED-RO

Stream	Total exergy (MW)	Without Z		With considering Z	
		$\dot{c}$ (\$/MJ)	$\dot{C}$ (\$/hr)	$\dot{c}$ (\$/MJ)	$\dot{C}$ (\$/hr)
1 (Inlet air to compressor)	0.00	0	0	0	0
2 (Air out)	101.25	0.1	35,029.4	0.03	10,352.1
4 (GT inlet)	382.12	0.03	37,967.67	0.01	13,343.71
5 (GT out)	96.10	0.03	9,548.99	0.01	3,355.98
6 (Stack gas)	8.39	0	0	0	0
9 (ST in)	121.05	0.03	11,199.45	0.4e-2	1,873.83
18 (ST out)	9.43	0.03	872.74	0.4e-2	146.02
19 (Condenser out)	2.07	0.61	4,554.2	0.02	156.01
20 (CW in) (Pump out)	19.54	0.12	8,152.9	0.17e-2	119.6
3 Fuel	393.25	0.2e-2	2,972.97	0.2e-2	2,972.97
$\dot{W}_{st}$	118.98	0.05	19,232.41	0.5e-2	2,098.86
$\dot{W}_{gt}$	202.62	0.07	49,965.6	0.02	15,099.09
$\dot{W}_{fp}$	2.752	0.05	444.8	0.5e-2	48.54
$\dot{W}_{cp}$	0.32	0.05	50.9	0.5e-2	5.56
$\dot{W}_{compressor}$	119.07	0.07	29,361.6	0.02	8,872.8
8 HRSG HP	188.41	0.03	17,499.17	0.4e-2	2,916.52
7 HRSG LP	42.31	0.03	3,929.95	0.4e-2	654.99
11 (Extraction of ST (to MED))	41.23	0.03	3,829.59	0.4e-2	638.26
12 (Steam inlet to MED)	1.42	0.03	131.75	0.4e-2	21.96
14 (Brine blowdown water from MED)	43.98	0	0	0	0
17 (Desalinated water of MED)	0.10	13.5	4,820.1	1.19	425.95
10 (Vacuum steam)	9.87	0.03	916.9	0.4e-2	152.83
16 (Condensate to DA)	4.03	0.03	374.1	0.4e-2	62.36
13 (Supply seawater)	302.75	0	0	0	0
15 (Seawater discharge from MED)	239.27	0	0	0	0
21 (Desalinated water from RO)	0.07	35.9	8,649.1	2.8	665.93
22 (Brine discharge from RO)	26.61	0	0	0	0

The cost of the GT inlet stream is shown in Table 8, which is about 40,462.78 $/h. This stream cost is reduced by 6.3%, 6.1%, and 6%, when integrating the plant with the RO, MED-RO, and MSF-RO desalination units, respectively. Moreover, the steam turbine cost decreases by 51% and 53% in the plant integrated with the MED-RO and MSF-RO units, respectively, but is fixed in the plant integrated with the RO unit.

The cost of the condenser outlet stream is 5,667.27 $/h. This stream cost is 19,905.67 $/h in the plant integrated with the RO desalination unit and is respectively 4,554.2 and 3,515.4 $/h in the plant integrated with the MED-RO and MSF-RO units.

The cost of gas turbine outlet power generation is 53,904.49 $/h in the combined cycle power plant. This cost has a value of about 53,685.66; 49,965.6; and 52,664.47 $/h in the plant integrated with the RO, MED-RO, and MSF-RO units.

Moreover, the cost of steam turbine outlet power generation is 16,362.54; 16,491.04; 19,232.41; and 15,334.53 $/h in the combined cycle power plant and the plant integrated with the RO, MED-RO, and MSF-RO units.

The cost of desalinated water stream produced in each plant integrated with the RO, MED-RO, and MSF-RO desalination units is calculated about 21.89; 4,820.1; and 7,363.4 $/h, respectively.

By comparison of Tables 8–11, we can conclude that the cost of most steam in RO reduced and is less than the combined cycle, MED-RO, and MSF-RO.

In this case, exergy and exergoeconomic rates of streams of the components are calculated. Due to these results, we develop a computer code. In addition, exergy and exergoeconomic analyses are performed for each equipment to determine the exergy destruction rate and cost, with considering capital investment cost and without this, at 100% load conditions of the combined cycle, combined cycle + RO, combined cycle + MED-RO and combined cycle + MSF, as shown in Tables 8–11.

The results from exergy analysis provide a base for an exergoeconomic analysis, that is, an exergy-aided method to determine appropriate costs. The exergy balance equation for any component can be formulated with the first and second laws of thermodynamics. A cost equation defines the cost rate related to the product of the system (C_p) and the cost rate equals the total rate of costs related to the product, namely the fuel cost rate (C_F). Now, we calculate these parameters for three thermal power plants, as shown in Tables 12–15.

Table 11
Cost of each stream for combined cycle + MSF-RO

		Without *Z*		With considering *Z*	
Stream	Total exergy (MW)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)	$\dot{c}$ ($/MJ)	$\dot{C}$ ($/hr)
1 (Inlet air to compressor)	0.00	0	0	0	0
2 (Air out)	101.25	0.1	35,029.4	0.03	9,841.77
4 (GT inlet)	382.12	0.03	37,967.7	0.01	12,793.45
5 (GT out)	96.69	0.03	9,607.27	0.01	3,237.2
6 (Stack gas)	8.19	0	0	0	0
9 (ST in)	121.06	0.03	11,200.71	0.4e-2	1,830.4
18 (ST out)	7.28	0.03	673.62	0.4e-2	110.1
19 (Condenser out)	1.60	0.61	3,515.14	0.02	119.2
20 (CW in) (Pump out)	19.67	0.12	8,206.3	0.2e-2	155.7
3 Fuel	393.25	0.2e-2	2,972.97	0.2e-2	2,972.9
$\dot{W}_{st}$	118.98	0.04	15,334.53	0.3e-2	1,499.19
$\dot{W}_{gt}$	202.62	0.07	52,664.47	0.02	15,901.4
$\dot{W}_{fp}$	2.75	0.04	354.68	0.3e-2	34.6
$\dot{W}_{cp}$	0.31	0.04	40.63	0.3e-2	3.9
$\dot{W}_{compressor}$	119.1	0.07	30,947.63	0.02	9,344.3
8 HRSG HP	188.72	0.03	17,460.43	0.4e-2	2,921.4
7 HRSG LP	43.19	0.03	3,995.72	0.4e-2	668.5
11 (Extraction of ST (to MED))	65.06	0.03	6,019.1	0.4e-2	1,007.1
Steam inlet to MSF	1.57	0.03	145.5	0.4e-2	24.3
Brine blowdown water from RO to MSF	269.54	0	0	0	0
Desalinated water of MSF	0.12	16.51	7,363.4	1.19	532.1
Vacuum steam	9.60	0.03	887.77	0.4e-2	148.5
Condensate to DA	5.28	0.03	488.39	0.4e-2	81.7
Supply seawater to RO	282.14	0	0	0	0
Seawater discharge from MSF	156.18	0	0	0	0
Desalinated water from RO	0.01	22.85	618.2	2.76	74.7
Brine discharge from MSF	82.24	0	0	0	0

Table 12
Capital investment cost, exergy destruction cost (C_D), the exergy of fuel and product, EDL and ECDL of each component for combined cycle

Component	EF (MW)	EP (MW)	*Z* ($/h)	$C_D + Z$ ($/h)	EDL (MW/MW)	ECDL ($/MW hr)
Air compressor	127.48	107.99	343.71	2,287.67	0.15	15.24
Combustor	503.73	408.7	3.23	2,598.69	0.23	6.3
Gas turbine	312.66	130.0	102.74	6,283.8	1.4	47.5
Steam turbine	175.20	124.64	52.75	853.64	0.4	6.42
Condenser	0.68	69.99	0.76	1,198.57	0.53	9.61
HRSG	62.99	245.19	88.41	6,161.76	0.48	24.7
FW pump	7.05	0.68	0.03	74.5	0.58	10.56

In these four cycles, the fuel and product (C_P, C_F) cost is approximately fixed between the combined cycle, the combined cycle + RO, the combined cycle + MED-RO and the combined cycle + MSF-RO, but is minimum in the combined cycle + RO.

The fuel and product cost of the desalination unit in the plant integrated with the RO desalination unit is about 0.16e-3 $/MJ for RO fuels and 0.5 $/MJ for RO product streams. The cost in the plant integrated with the MED-RO unit is 0.2e-3 and 0.2e-2 $/MJ for MED and RO fuel streams and also 1.31 and 0.2e-2 $/MJ for MED and RO product streams, respectively. Moreover, the cost in the plant integrated with the MSF-RO unit is about 0.2e-3 and 0.2e-2 $/MJ for MSF and RO fuel streams and 1.19 and 2.76 $/MJ for MSF and RO product streams, respectively.

Table 13
Capital investment cost, exergy destruction cost (C_D), the exergy of fuel and product, EDL and ECDL of each component for combined cycle + RO

Component	EF (MW)	EP (MW)	Z ($/h)	C_D + Z ($/h)	EDL (MW/MW)	ECDL ($/MW hr)
Air compressor	127.485	101.12	343.71	2,972.53	0.2	20.6
Combustor	496.86	383.17	3.23	3,108.9	0.3	8.1
Gas turbine	287.12	129.45	102.74	5,438.01	1.2	41.2
Steam turbine	175.20	124.63	52.75	853.63	0.4	6.42
Condenser	1.84	69.45	0.76	1,033.28	0.46	8.2
HRSG	75.36	244.64	88.41	6,858.36	0.53	27.67
FW pump	17.46	0.55	0.03	251.03	0.8	14.37
desalination unit	15.81	8.95	69.34	70.51	0.13	0.07

Table 14
Capital investment cost, exergy destruction cost (C_D), the exergy of fuel and product, EDL and ECDL of each component for combined cycle + MED-RO

Component	EF (MW)	EP (MW)	Z ($/h)	C_D + Z ($/h)	EDL (MW/MW)	ECDL ($/MW hr)
Air compressor	127.32	101.25	333.14	2,276.05	0.2	15.2
Combustor	494.50	382.12	3.07	2,915.17	0.29	7.62
Gas turbine	286.02	130.83	102.28	5,297.8	1.18	39.71
Steam turbine	111.62	63.14	32.51	765.4	0.76	11.6
Condenser	19.54	8.89	3.09	477.5	0.42	7.51
HRSG	87.71	120.50	111.6	6,158.9	1.36	50.19
FW pump	236.95	19.54	0.012	1,040.8	0.24	4.39
MED desalination unit	11.29	48.11	89.37	106.06	2.7	1.4
RO desalination unit	48.01	312.73	22.63	142.97	0.36	2.5

Table 15
Capital investment cost, exergy destruction cost (C_D), the exergy of fuel and product, EDL and ECDL of each component for combined cycle + MSF-RO

Component	EF (MW)	EP (MW)	Z ($/h)	C_D + Z ($/h)	EDL (MW/MW)	ECDL ($/MW hr)
Air compressor	127.32	101.25	333.1	2,379.29	0.2	16.07
Combustor	494.50	382.12	3.07	3,031.28	0.29	7.92
Gas turbine	285.43	130.28	102.2	5,520.05	1.19	41.58
Steam turbine	113.78	62.4	32.12	827.03	0.82	12.73
Condenser	19.67	6.74	3.09	322.47	0.40	5.11
HRSG	88.50	120.52	98.68	6,446.13	1.38	52.66
FW pump	236.95	19.67	0.012	741.84	0.24	3.13
MSF desalination unit	11.17	274.94	143.69	169.66	3.77	2.32
RO desalination unit	274.82	291.86	41.73	125.66	0.045	0.094

An exergoeconomic analysis is based on the exergy destruction of each equipment. For better production at the plant level, there are two new definitions, including EDL and ECDL. These definitions can help determine costs and energy loss in a cycle. These definitions contribute to the overall results obtained in this paper and optimize the power plant cycle. According to the previous result, we can now calculate the capital investment cost, the exergy destruction cost (C_D), the fuel and product exergy, EDL and ECDL (Tables 16–19).

Given the results of Tables 12–15, the capital investment cost of components such as the air compressor, the combustion chamber, the gas turbine and the steam turbine is reduced by using the RO desalination unit concurrent with MED or MSF. However, the capital investment cost of HRSG and the condenser increases. The capital investment cost of RO is less than that of MED and MSF. Results show that EDL in MED-RO and MSF-RO decreases in some components as the air compressor, the combustion chamber, the gas turbine and the condenser. However, the EDL of MED-RO and MSF-RO increases in HRSG and the steam turbine. Additionally, the results of ECDL are highly close to those of EDL, although the ECDL of RO is less than that of MSF-RO and MED-RO.

EDL in the gas turbine of the combined cycle power plant is 1.4 (Table 12). However, it is reduced by 14% after integrating the combined cycle with the RO desalination. Moreover, by integrating the combined cycle power plant with MED-RO and MSF-RO, this parameter is reduced by 16% and 15%, respectively.

The ECDL for HRSG in the combined cycle power plant is 24.7 $/MW h (Table 12), which increases by 11%, 51%, and 53% after integrating the system with the RO, MED-RO, and MSF-RO desalination units, respectively.

The final comparison is between the cost of each component (PEC_s) and the capital investment cost within different periods (Tables 16–19).

The investment cost of the steam turbine in the combined cycle power plant is 397,622.57 $/y, as shown in Table 16. When we combined the system with RO, the cost becomes fixed approximately. However, the cost decreases by 38% and 39% after integrating with the MED-RO and MSF-RO desalination units.

From Tables 16–19, we deduce that the combined cycle + the RO desalination unit has the minimum capital investment and component costs. However, in the comparison between MED-RO and MSF-RO, we can deduce that PEC is more in MSF-RO than in MED-RO, although using MSF-RO reduces the PEC of the condenser.

In any separator device, the governing second law equations and efficiencies represent the work and heat-driven desalination methods. The gas turbine cycle with all its components consumes 47.09% of the input fuel exergy. This is

Table 16
PEC and the capital investment cost in different period of time of each component for combined cycle

Component	Exergy destruction	PEC ($)	PW	*C* ($/yr)	*Z* ($/s)	*Z* ($/hr)
Air compressor	19.49	52,075,365	31,349,648.03	2,542,759.92	0.09	336.91
Combustion chamber	95.01	489,359.35	294,596.94	23,894.66	0.8e-3	3.16
Gas turbine	182.66	15,570,356.95	9,373,438.09	760,276.56	0.03	100.73
Steam turbine	50.56	8,143,254.36	4,902,282.6	397,622.57	0.01	52.68
Condenser	66.55	115,036.35	69,252.49	5,617.04	0.2e-3	0.74
HRSG	117.81	13,564,825.35	8,166,097.35	662,349.54	0.02	87.76
FW pump	4.14	4,065.65	2,447.54	198.51	7.3E-06	0.03

Table 17
PEC and the capital investment cost in different period of time of each component for combined cycle + RO

Component	Exergy destruction	PEC ($)	PW	*C* ($/yr)	*Z* ($/s)	*Z* ($/hr)
Air compressor	26.36	53,125,465.17	31,981,813.95	2,594,034.69	0.1	343.7
Combustion chamber	113.69	499,367.58	300,621.95	24,383.35	0.1e-2	3.23
Gas turbine	157.66	15,880,504.05	9,560,148.3	775,420.56	0.03	102.74
Steam turbine	50.56	5,532,465.34	4,908,518.01	398,128.32	0.01	52.75
Condenser	57.36	118,028.61	71,053.85	5,763.15	0.2e-3	0.76
HRSG	131.32	13,665,243.21	8,226,549.44	667,252.79	0.02	88.41
FW pump	13.94	4,135.6	2,489.65	201.93	7.43E-06	0.026
Desalination unit	2.07	10,718,415	6,452,543.11	523,363.7	0.02	69.34

Table 18
PEC and the capital investment cost in different period of time of each component for combined cycle + MED-RO

Component	Exergy destruction	PEC ($)	PW	*C* ($/yr)	*Z* ($/s)	*Z* ($/hr)
Air compressor	26.07	51,492,736.65	30,998,902.65	2,514,311.07	0.1	333.14
Combustion chamber	112.38	475,449.14	286,222.92	23,215.44	0.9e-3	3.07
Gas turbine	155.18	15,810,008.89	9,517,709.84	771,978.39	0.03	102.28
Steam turbine	48.47	5,025,443.44	3,025,343.8	245,384.66	0.01	32.51
Condenser	26.90	477,433.44	287,417.48	23,312.34	0.9e-3	3.09
HRSG	164.85	17,263,486.12	10,392,710.9	842,949.45	0.03	111.69
FW pump	59.00	1,979.51	1,191.67	96.65	3.5E-06	0.01
MED desalination unit	30.69	13,814,972	8,316,686.97	674,563.81	0.03	89.37
RO desalination unit	17.31	3,499,217	2,106,547.33	170,861.38	0.6e-2	22.63

while the remaining exergy in exhaust gases is recovered through exhaust gases operated HRSG. The steam turbine cycle extracts 47.99% of the input fuel exergy via steam produced in HRSG, and it also includes internal losses in the cycle and part of steam exergy dumped in the condenser. The bleed steam for the MED-RO cycle, including the heat input and the thermal vapor compressor, carries only 4.92% of the input fuel exergy. Moreover, the MED exergy proportion includes the share of condenser steam and unaccounted losses. For the convenience of engineers and scientists in the industry, the concept of conversion factors is proposed to convert the extracted energy input to the SPE input, as summarized in Table 20. It shows that to produce one unit of electricity, the power plant consumes 2.37 SPE units. Similarly, one SPE unit can produce 20.32 low-pressure steam units to operate MED.

Table 21 presents the SPE and SUPR calculations based on the proposed methodology. The converted SPE-based results highlight the inadequacy of conventional reporting procedures, which ignore the quality of energy supplied to cogeneration processes. It can be observed that in MED-RO processes, SPE consumption is the lowest, 9.68 kWh/m^3 SPE followed by RO and MSF-RO processes. Even though MED-RO processes have the highest efficiency, they can only achieve 8.06% of the thermodynamic limit.

If it has been intended to review the paper and present the results and compare them with the other papers presented in this field, we can say that from providing the details

Table 19
PEC and the capital investment cost in different period of time of each component for combined cycle + MSF-RO

Component	Exergy destruction	PEC ($)	PW	*C* ($/yr)	*Z* ($/s)	*Z* ($/hr)
Air compressor	26.07	51,492,736.65	30,998,902.65	2,514,311.07	0.1	333.14
Combustion chamber	112.38	475,449.14	286,222.92	23,215.44	0.9e-3	3.08
Gas turbine	155.15	15,810,008.89	9,517,709.84	771,978.39	0.03	102.29
Steam turbine	51.35	4,965,473.96	298,9241.86	242,456.45	0.9e-2	32.12
Condenser	25.35	477,433.44	287,417.48	23,312.34	0.9e-3	3.09
HRSG	166.34	15,253,694.12	9,182,805.37	744,814.40	0.03	98.68
FW pump	58.88	1,979.51	1,191.67	96.65	3.55E-06	0.01
MSF desalination unit	42.16	22,210,473	13,370,823.44	1,084,503.21	0.04	143.69
RO desalination unit	12.60	6,451,328	3,883,733.93	315,008.41	0.01	41.73

Table 20
Summary of GT, ST and desalination plants analysis and conversion factors calculation

	Exergy destruction (%)	Cumulative exergy destruction (%)
Gas turbine cycle	50.32	50.32
Steam turbine cycle	41.46	91.77
MED-RO desalination cycle	8.23	100
Conversion factors (CF) from derived energy to SPE		
For combined cycle gas turbine (CCGT) electricity (weighted factor)	2.37 (equivalent to 42.19% CCGT efficiency)	
For MED-RO	12.15	

Table 21
SPE and universal performance ratio (UPR) calculation of major desalination processes

Specific energy consumption and performance ratio	Reverse osmosis (RO)	Multi-stage flashing and reverse osmosis (MSF-RO)	Multi-effect distillation and reverse osmosis (MED-RO)
Electricity ($\text{kWh}_{\text{elec}}/\text{m}^{-3}$)	5.05	14.46	5.566
Thermal ($\text{kWh}_{\text{ther}}/\text{m}^{-3}$)	–	30.77	60.53
Equivalent standard primary energy (SPE) and standard universal performance ratio (SUPR)			
Conversion factor for electricity (weighted CF_{elec})	2.13	2.38	2.37
Conversion factor for thermal for less than 130°C operation (CF_{ther})	–	21.11	12.15
Standard primary energy (Q-SPE)	10.79	35.94	18.17
Standard universal performance ratio (SUPR)	59.88	17.98	35.56
SUPR % of thermodynamic limit	7.23%	2.17%	4.29%

of the thermodynamic analysis and the exergy and economic analysis, presented work has a new attitude to show more details of desalination in the power cycles.

In one such article, Hafdhi et al. [36] investigated a desalination unit that performs two effects and optimizes it and details specific economic properties for several specific system flows. Moreover, Gomar et al. [37] examined the capital investment costs associated with purchasing the equipment needed to add a desalination unit to a power generation system and estimated the freshwater production cost.

In another similar research, Luo et al. [38] reported that the multi effect distillation thermal vapor compression system produced 3,560 kg/s freshwater, and 2,520 kg/s in an MSF system. They realized that 768.9 and 758.5 MW thermal energy was consumed to produce this amount of freshwater. However, they observed that the high rate of freshwater production was due to high heat consumption and high power and that the net output power of the power generation cycle dropped sharply. In contrast, in the current work, more power generation leads to a lower rate of freshwater production, which will increase the efficiency of the cogeneration system.

5. Conclusion

In this paper, thermodynamic, exergetic and exergoeconomic modeling and simulation of the Qom combined cycle power plant is integrated MSF + RO and MED + RO units. Moreover, all the information was analyzed in a point-to-point manner and also the MED-RO system was compared with the MSF-RO system. In addition, analyses were performed on both systems.

In this research, the modeling and simulation of various water desalination units were addressed and also thermodynamic relations were presented in relation to the calculation of the functional efficiency of desalinating water [39]. Moreover, in this study, we examined the economic, exergy and thermodynamic properties of water desalination systems and provided comprehensive information in this regard.

Exergy analysis provides useful information for the design, analysis, assessment, and improvement of energy systems. Exergy destruction rates for each component of a system indicate possibilities for determining losses and improving efficiency. The cogeneration system exergy analysis considered here illustrated several aspects of exergy analysis, including roles of exergy destruction and exergy loss in determining thermodynamic performance. Additionally, exergy analysis often involves the determination of measures of performance including exergy destruction ratios, exergy loss ratios, and exergy efficiencies. These measures were considered in this article. Exergy destruction and exergy efficiency values provide thermodynamic measures of system inefficiencies.

For better production at the plant level, there are two new definitions, including EDL and ECDL. These definitions can help determine costs and energy loss in a cycle. These definitions contributed to the overall results obtained in this paper and optimized the power plant cycle.

Furthermore, in this paper, exergoeconomic analysis was performed to select the most feasible desalination method for the Qom combined cycle power plant.

The thermodynamic calculations showed that the freshwater production rate was more in MSF-RO than in MED-RO and RO and that the costs of MSF-RO were higher than those of MED-RO and RO. It can be concluded that it is better to use MSF-RO to have both more profit and more freshwater in the Qom combined cycle power plant. Although using MED-RO or RO is more cost-effective, the profit from MSF is higher over a given period due to the amount of fresh water produced.

Exergoeconomic analysis was performed in this study to select the most feasible desalination method for the Qom combined cycle power plant.

Symbols

AC — Air compressor
$\dot{c}$ — Cost per unit exergy rate, $/MW
$\dot{C}$ — Cost flow rate, $/hr
CC — Combustion chamber
CRF — Capital recovery factor
EDL — Exergy destruction level, MW/MW
ECDL — Exergy cost destruction level, $/hr MW
e — Exergy rate per mass, MW/kg
$\dot{E}$ — Exergy, MW
h — Specific enthalpy, kJ/kg
H — Enthalpy, kJ
i — Interest rate
$\dot{m}$ — Mass flow rate, kg/s
n — Number of years
PW — Present worth
p — Pressure, bar
s — Entropy, MW/K
T — Temperature, °C
W — Shaft work rate, MW
Z — Capital cost rate of unit, $/hr
MED — Multi-effect desalination unit
MSF — Multi-stage flash desalination unit
RO — Reverse osmosis desalination unit
LHV — Low heat value of fuel

Greek

η — Carnot factor

Subscript

00 — Without considering capital investment
0 — Ambient condition
ac — Air compressor
D — Destruction
d — Distillate
dis — Discharge
e — Exit
F — Fuel
GT — Gas turbine
i — Inlet
inv — Investment
k — kth component
L — Loss
n — Year
o — Outlet
P — Product

Q — Heat transfer
ST — Steam turbine
tot — Total
Q — Heat
$\dot{W}$ — Shaft work

Superscript

CI — Capital investment
OM — Operating and maintenance

Acronyms

FWP — Feed water pump
ST — Steam turbine

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Appendix A

For calculating some thermodynamic properties, we have some equations in each component. Some of them are as follows [25].

A1. Compressor

$$S_{\text{inlet,air}} = S_{\text{outlet,air}} \tag{A1}$$

$$\eta_{\text{isentropic,compressor}} = \frac{h_{\text{outlet,isentropic}} - h_{\text{inlet}}}{h_{\text{outlet}} - h_{\text{inlet}}} \tag{A2}$$

$$\dot{W}_{\text{compressor}} = \dot{m}_{\text{air}} \times \left[h_{\text{outlet}} - h_{\text{inlet}}\right] \tag{A3}$$

A2. Combustion chamber

$$\dot{Q}_{\text{combustion}} = \dot{m}_{\text{fuel}} \times \left[\text{LHV}\right] \tag{A4}$$

A3. Gas and steam turbine

$$S_{\text{inlet}} = S_{\text{outlet}} \tag{A5}$$

$$\eta_{\text{isentropic,turbine}} = \frac{h_{\text{inlet}} - h_{\text{outlet}}}{h_{\text{inlet}} - h_{\text{outlet,isentropic}}} \tag{A6}$$

$$\dot{W}_{\text{turbine}} = \dot{m}_{\text{gas}} \times \left[h_{\text{inlet}} - h_{\text{outlet}}\right] \tag{A7}$$

A4. Heat recovery steam generator

$$\dot{Q}_{\text{HRSG}} = \dot{m}_{\text{stack gas}} \times \left[h_{\text{inlet,stack gas}} - h_{\text{outlet,stack gas}}\right] \tag{A8}$$

A5. Pump

$$S_{\text{inlet}} = S_{\text{outlet}} \tag{A9}$$

$$\eta_{\text{isentropic,pump}} = \frac{h_{\text{outlet,isentropic}} - h_{\text{inlet}}}{h_{\text{outlet}} - h_{\text{inlet}}} \tag{A10}$$

$$\dot{W}_{\text{pump}} = \dot{m}_{\text{water}} \times \left[h_{\text{inlet}} - h_{\text{outlet}}\right] \tag{A11}$$

A6. Condenser

$$\dot{Q}_{\text{condenser}} = \dot{m}_{\text{air}} \times \left[h_{\text{outlet}} - h_{\text{inlet}}\right] \tag{A12}$$

A7. Combined cycle calculations

$$\dot{W}_{\text{net,total}} = \dot{W}_{\text{gas turbine}} + \dot{W}_{\text{steam turbine}} - \dot{W}_{\text{compressor}} - \dot{W}_{\text{pump}} \tag{A13}$$

$$\eta_{\text{combined cycle}} = \frac{\dot{W}_{\text{net,total}}}{\dot{Q}_{\text{combustion}}} \tag{A14}$$

Appendix B

The salt water's properties depend on the amount of pressure, temperature, and salinity. Accordingly, by introducing some of the parameters, we examine the relationships existing within reverse osmosis (RO) unit the first parameter is a salt mass fraction (mf_s) and the second is salt mole fraction (x_s) and mf_w show pure water mass fraction mf_s, x_s and mf_w are defined as [40]:

$$\text{mf}_s = \frac{m_s}{M_m} = x_s \frac{M_s}{M_m} \tag{B1}$$

$$\text{mf}_w = \frac{m_w}{M_m} = x_w \tag{B2}$$

M_s and M_w show the molar mass of the salt and the pure water. M_m represents the apparent molar mass of saline water that can be obtained by the following equation:

$$M_m = \frac{m_m}{N_m} = \frac{N_s M_s + N_w M_w}{N_m} = x_s M_s + x_w M_w \tag{B3}$$

According to the above relation, we can obtain a relation between the salt mass fraction and the molar salt fraction of the following [40]:

$$x_s = \frac{\text{mf}_s M_w}{M_s\left(1 - \text{mf}_s\right) + \text{mf}_s M_w} \tag{B4}$$

$$x_s + x_w = 1 \tag{B5}$$

$$\text{mf}_s + \text{mf}_w = 1 \tag{B6}$$

If the water salinity is below 5% and an ideal solution can be considered, one can ignore the effects of many factors. With this in mind, the following relationships can be proposed for obtaining special heat and enthalpy [40]:

$$\text{Cp}_{sw} = \text{mf}_w \text{Cp}_w + \text{mf}_s \text{Cp}_s \tag{B7}$$

$$h_{sw} = \text{mf}_w h_w + \text{mf}_s h_s \tag{B8}$$

Other thermodynamics equations for the RO desalination unit can obtain from this present [41].

Some of the equations are used to calculate thermodynamic properties in each stage of a multi-stage flash (MSF) or multi-effect desalination (MED) desalination unit. The thermodynamic modeling of MED and MSF is so similar. For more detailed equations, introduce the source 23 [42].

The temperature difference in each stage:

$$\Delta T = \frac{T_{\mathrm{BT}} - T_N}{N} \tag{B9}$$

T_{BT}: Temperature top brine water.
N: Number of stages.
T_N: Brine water temperature in last stage.

By the above equation we can calculate the temperature of each stage:

$$T_1 = T_{\mathrm{BT}} - \Delta T \tag{B10}$$

$$T_{i+1} = T_i - \Delta T \tag{B11}$$

The desalinated water that produces in each stage calculated from the below equation:

$$\dot{m}_{d,i} = y \times \dot{m}_r \times (1-y)^{i-1} \tag{B12}$$

where $\dot{m}_r$ is the recoverable brine water mass flow rate, and y is the ratio of specific sensible and latent heat, which is calculated by:

$$y = \frac{C_p \times \Delta T}{\lambda_{\mathrm{av}}} \tag{B13}$$

$$\lambda_{\mathrm{av}} = \left(0.00158927 \times \left(T^2\right)\right) - \left(2.36418 \times T\right) + 2{,}500.7 \tag{B14}$$

$$x_r = \frac{\left(\left(x_f - x_b\right) \times \dot{m}_f\right) + \left(x_b \times \dot{m}_r\right)}{\dot{m}_r} \tag{B15}$$

The performance of thermal desalination systems is a very important parameter. We can introduce this parameter as follow:

$$\mathrm{PR} = \frac{\dot{m}_d}{\dot{m}_s} \tag{B16}$$