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# Exergoeconomic modeling and evaluation of a combined-cycle plant with MSF and MED desalination

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## ABSTRACT

In the coming years, numerous regions are expected to suffer from water scarcity. One of the technologies of great interest in facing this challenge has been the generation of freshwater through water desalination, a process that reduces the amount of salt and minerals to a standard level, making the water suitable for drinking or agricultural/industrial use. The efficiency of each desalination process depends on the concentration of salts in the raw water and the end-use of the produced water. The present study presents the exergetic and exergoeconomic analyses of the coupling of a power plant with desalination units for the simultaneous generation of energy and water in Iran. The plant is integrated, first, with a multi-stage flash (MSF) unit and, then, with a multi-effect desalination (MED) unit. We find that the cost of exergy destruction of the MED and MSF integrated plants is lower when compared to the standalone power plant by about 0.1% and 9.2%, respectively. Lastly, the freshwater production in the plant using MED is significantly higher than that in the plant with MSF (1,000 versus 1,521 kg/s).

**Key words** | combined-cycle power plant, exergoeconomic analysis, exergy, multi-effect desalination, multi-stage flash desalination

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## NOMENCLATURE

### Abbreviations

| | |
|---|---|
| AC | air compressor |
| c | cost per unit exergy rate ($/MW) |
| C | cost flow rate ($/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) |
| 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) |

### Greek symbol

$\eta$ Carnot factor



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### 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
W shaft work

### Superscript

CI capital investment
OM operating and maintenance

### Acronyms

FWP feed water pump
ST steam turbine

## INTRODUCTION

Life, health, and sustainable development require freshwater. Humans need water resources such as rivers, lakes, and aquifers to meet the needs of drinking, agriculture, and industry. There are two main problems with the use of these freshwater sources: river and lake pollution from domestic and industrial waste and wastewater, and non-uniform distribution of water in the different parts of the world. The oceans are the largest reservoirs of water but with about 3.5% by weight of different salts, direct use of this water is not possible (Miller 2003; Mathioulakis *et al.* 2007; Karagiannis & Soldatos 2008; Charcosset 2009; Eltawil *et al.* 2009; Lee *et al.* 2011; Porada *et al.* 2013).

Large numbers of published papers in the literature have studied the combined-cycle power plants (Kehlhofer *et al.* 2009; Godoy *et al.* 2010; Ahmadi *et al.* 2011; Ibrahim & Mohammed 2015; Almutairi *et al.* 2016; AlRafea *et al.* 2016; Sabouhi *et al.* 2016; Sahin *et al.* 2016; Blumberg *et al.* 2017; Mohammed *et al.* 2017; Ng *et al.* 2017; Ameri & Mohammadzadeh 2018; Calise *et al.* 2018; Ibrahim *et al.* 2018; Khan & Tlili 2018; Kotowicz *et al.* 2018; Martín-Gamboa *et al.* 2018; Shahzad *et al.* 2018; Xiang *et al.* 2018). An energy cost evaluation between the integration of multi-stage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO) with a simple cycle oil-fired power plant (OFPP) and a combined-cycle power plant was realized. They achieved maximum production of power and water using a mathematical model and showed that thermal desalination can improve the overall efficiency of the plant (Ihm *et al.* 2016). Salimi & Amidpour (2017) proposed the developed graphical methodology called R-curve to integrate desalination plants with cogeneration systems. The R-curve tool based on cogeneration efficiency was extended for the coupling of MED and RO desalination systems with cogeneration units to efficiently reduce the operating cost. Coupling a gas turbine with MED and RO for the region of Bashagard in southern Iran, and the generation of power and freshwater is presented in Rahimi *et al.* (2017). In that work, exergy and exergoeconomic analyses were applied and the final total cost of the produced freshwater was decreased from 2.8 to 2.3 $\$/m^3$. Hosseini *et al.* (2012) focused on the optimum integration of a combined-cycle power plant with an MSF water desalination unit from economic, exergetic, environmental, and reliability points of view.

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.* (2017) reviewed this triple unit and showed that the lowest energy consumption rate was 1.76 kWh per cubic meter of freshwater produced. They found that the product and environmental cost decreased by 13.4% and 53.4%, respectively, whereas the total exergy efficiency increased by 14.8%, relative to the base case study.

The present study evaluates the combination of a combined-cycle power plant with MED and MSF desalination systems using an exergoeconomic analysis. The computational steps followed are shown in Figure 1. First, the combined-cycle power cycle is simulated using a computer code and then it is compared with real plant data simulated using the software GT Pro. The two water desalination units are simulated with the commercial software and added to the reference power plant cycle to create two alternatives. In the second step, we obtain the thermodynamic properties of the cycles and calculate the exergy of each material stream and the exergy destruction of each component. The investment costs are calculated and the cost balances for all of the plant components are defined. All of the above allows the calculation of the exergy and cost of the fuel, product, and exergy destruction for each plant component.

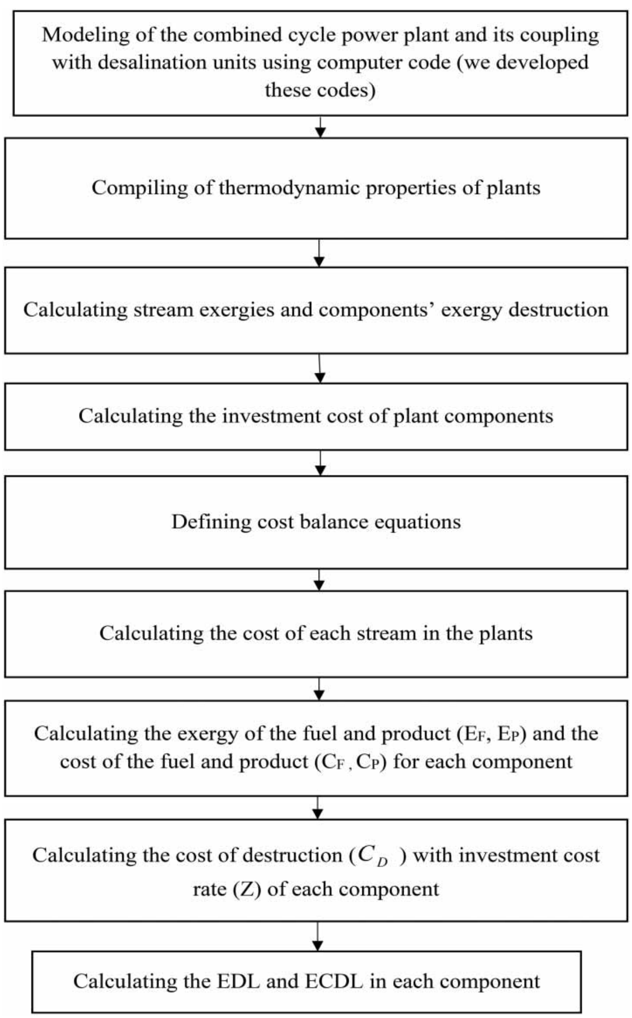


**Figure 1** | Flowchart of the computation process.

## CASE STUDY

One of the most common methods of water desalination is heat distillation. In this process, the water is first boiled using heat and then evaporated. Next, pure water can be obtained by cooling and condensing the water. The process can be done in two ways: first, by heating the hot water to a boiling temperature, and second, by using thermal energy of the steam in the Rankine cycle. In most cases, distillation is more efficient than other membrane processes and the quality of water produced by this method is higher.

One of the most important challenges of using thermal methods is the amount of thermal energy consumed. It is thus an advantageous method when thermal energy is available and is more widely used in countries where it is possible to build a water desalination station next to a thermal power plant. In this paper, the MED and MSF desalination units are connected to a combined-cycle block. Schematics of these cycles are presented in Figures 2 and 3.

## METHODOLOGY

The energy and exergy equations used are presented in the Appendix of the paper (Manesh *et al.* 2020).

### Exergoeconomic analysis

An exergoeconomic analysis combines an economic analysis with the results of the exergy analysis. With

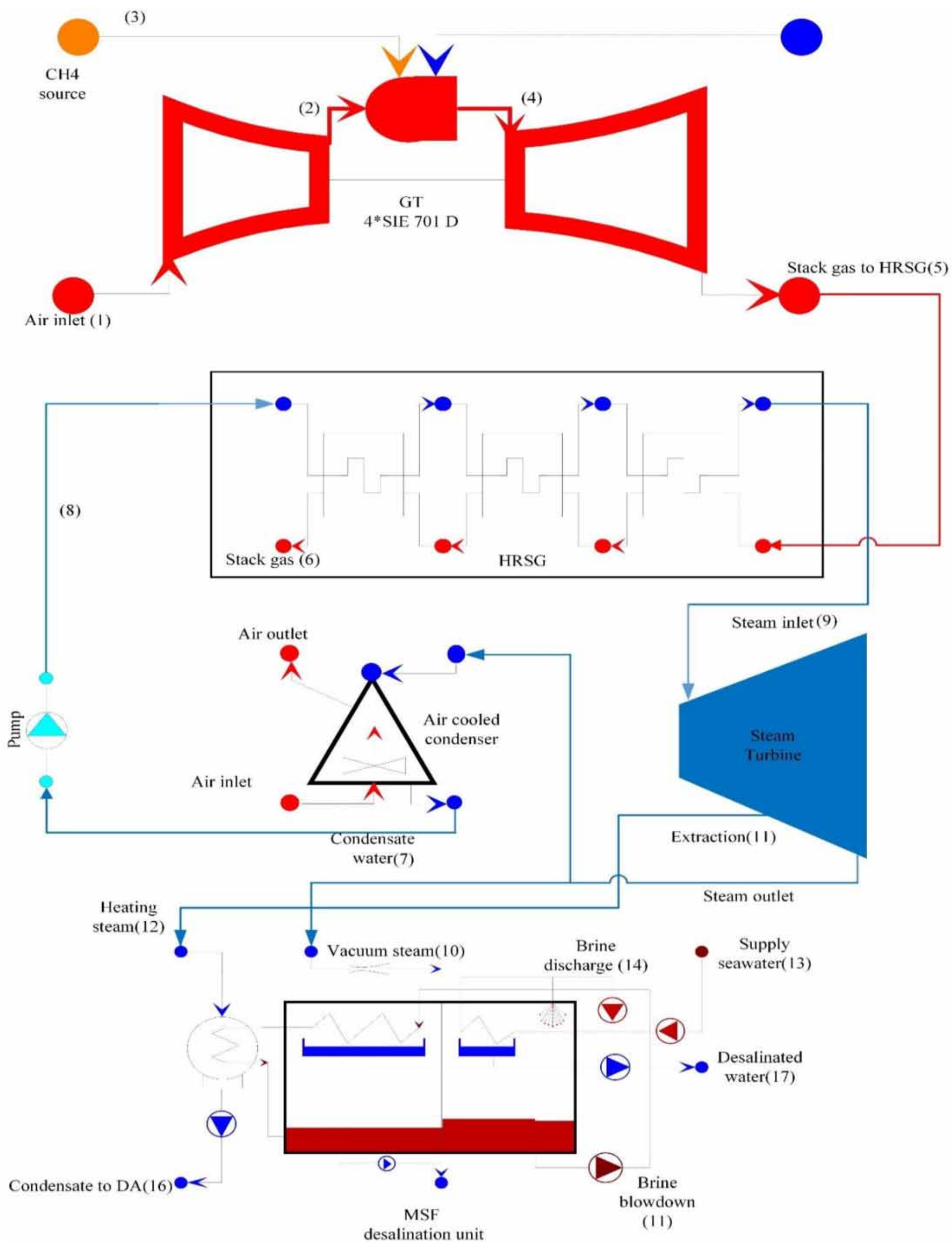


**Figure 2** | The Qom combined-cycle power plant coupled with a MSF desalination unit.

exergoeconomic analysis, we can, among others, calculate the cost of different material streams in a process and the cost of exergy destroyed within plant components. This analysis helps us to find trade-offs between thermodynamic inefficiencies and costs, identify the plant components with the highest costs and improvement potential, and optimize the overall system (Kwak *et al.* 2003).

The present worth (PW) of a plant's equipment is calculated as:

$$PW = C_i - S_n PWF(i, n) \tag{1}$$

$$C\left(\frac{\$}{year}\right) = PW \times CRF(i, n) \tag{2}$$

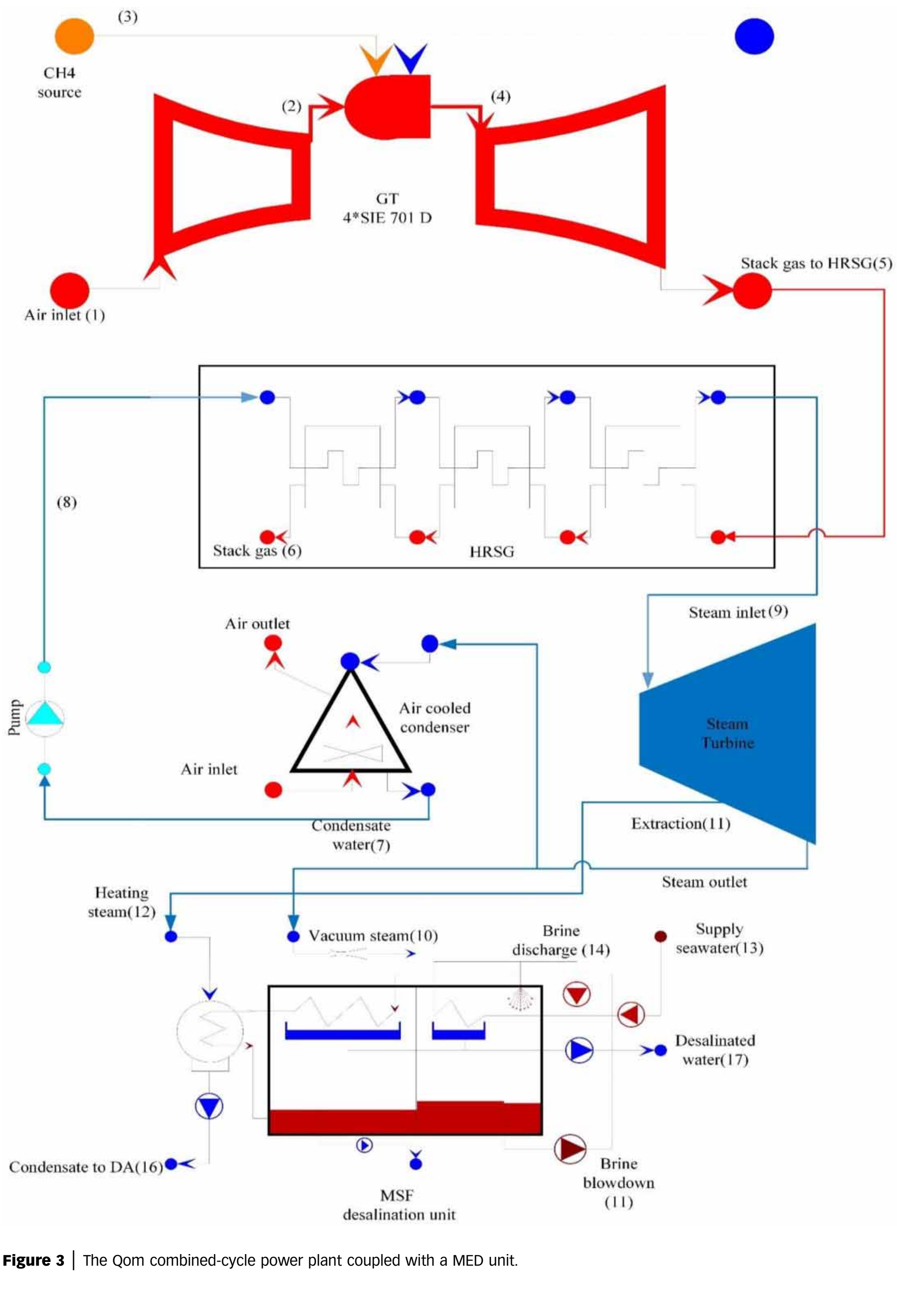


**Figure 3** | The Qom combined-cycle power plant coupled with a MED unit.

with $C_i$ the cost of each stream, $S_n$ the salvage value, *PWF* the present worth factor for each piece of equipment, and *CRF* the capital recovery factor. The PW is converted to annualized costs using the CRF. By calculating the purchase equipment costs (PECs), we can obtain the investment cost rate $\dot{Z}_k$ for each component (Table 1) (Cavalcanti 2017). The PECs of the desalination unit are estimated by the following studies (El-Sayed 2001; Nafey *et al.* 2006; Mabrouk *et al.* 2007; Mabrouk & Fath 2015; Pinto & Marques 2017). Dividing the levelized cost by 8,000 annual operating hours, we

**Table 1** | Equations used in the calculation of purchase equipment costs (PECs)

| Component | Equations of PEC calculation |
|---|---|
| Air compressor | $PEC_{AC} = 71.1 \times \dot{m}_{air} \times \left[\frac{P_e}{P_i} \times Ln \frac{P_e}{P_i}\right]\left[\frac{1}{0.92 - \eta_{AC}}\right]$ |
| Combustion chamber | $PEC_{CC} = 46.08 \times \dot{m}_{air} \times [1 + e^{(0.018 \times T_{o,CC} - 26.4)}]\left[\frac{1}{0.995 - \frac{P_e}{P_i}}\right]$ |
| Gas turbine | $PEC_{GT} = 479.34 \times [1 + e^{(0.036 \times T_{o,CC} - 56.4)}] \times \left[\frac{\dot{m}_{gas}}{0.93 - \eta_{GT}}\right] \times Ln \frac{P_e}{P_i}$ |
| HRSG | $PEC_{HRSG} = 6,570 \times \left[\left(\frac{\dot{Q}_{ec}}{\Delta T_{ec}}\right)^{0.8} + \left(\frac{\dot{Q}_{ev}}{\Delta T_{ev}}\right)^{0.8} + \left(\frac{\dot{Q}_{sh}}{\Delta T_{sh}}\right)^{0.8}\right] + 21,276 \times \dot{m}_w + 1,184.4 \times \dot{m}_g^{1.2}$ |
| Steam turbine | $PEC_{St} = 2,210 \times (\dot{W})^{0.7}$ |
| Condenser | $PEC_{condenser} = \dot{m}_w \times 1,773$ |
| FW pump | $PEC_{Pump} = 2100 \times \left(\frac{\dot{W}}{10}\right)^{0.26} \times \left[\frac{1 - \eta_{Pump}}{\eta_{Pump}}\right]$ |

find the cost rate for each component $k$ as follows (Kwak et al. 2003):

$$\dot{Z}_k = \varphi_k \dot{C}_k / (3,600 \times 8,000) \tag{3}$$

The cost rate $\dot{Z}_k$ includes the cost rate of capital investment ($Z^{CI}$) and the cost rate of operating and maintenance costs ($Z^{OM}$) (Bejan et al. 1996). The maintenance cost has been defined through the factor $\varphi_k = 1.06$ for each component of the plant, for which the expected economic life has been assumed to be 30 years (Kwak et al. 2003). A cost balance is written for each plant component as (Ahmadi et al. 2011):

$$\dot{C}_{F,k} = \dot{C}_{P,k} + \dot{C}_{D,k} + \dot{Z}_k \tag{4}$$

The defined equations and auxiliary equations for each component are shown in Table 2.

Lastly, the exergy destruction level (EDL) and the exergy cost destruction level (ECDL) are also used to better understand the cost of destruction and overall plant

**Table 2** | Definitions of the cost of fuel and product for each plant component

| Component | Auxiliary equations | Equations of product and fuel economic of each component |
|---|---|---|
| Air compressor | $\dot{c}_1 = 0$; $\dot{c}_{W,Ac} = \dot{c}_{W,GT}$ | $\dot{C}_{F,Ac} = \dot{C}_W$; $\dot{C}_{P,Ac} = \dot{C}_2 - \dot{C}_1$ |
| Combustion chamber | $\dot{c}_3 =$ fuel cost | $\dot{C}_{F,cc} = \dot{C}_2 + \dot{C}_3$; $\dot{C}_{P,cc} = \dot{C}_4$ |
| Gas turbine | $\dot{c}_4 = \dot{c}_5$ | $\dot{C}_{F,GT} = \dot{C}_4 - \dot{C}_5$; $\dot{C}_{P,GT} = \dot{C}_{W,GT}$ |
| HRSG | $\dot{c}_6 = 0$; $\dot{c}_7 = \dot{c}_8$ | $\dot{C}_{F,HRSG} = \dot{C}_5 - \dot{C}_6$; $\dot{C}_{P,HRSG} = \dot{C}_7 + \dot{C}_8 - \dot{C}_{20}$ |
| Steam turbine | $\dot{c}_8 = \dot{c}_9$; $\dot{c}_8 = \dot{c}_{11}$; $\dot{c}_{18} = \dot{c}_8$ | $\dot{C}_{F,ST} = \dot{C}_9 - \dot{C}_{11} - \dot{C}_{18}$; $\dot{C}_{P,ST} = \dot{C}_{W,ST}$ |
| Condenser | $\dot{c}_{w,fan} = \dot{c}_{w,ST}$ | $\dot{C}_{F,cond} = \dot{C}_{W,fan}$; $\dot{C}_{P,cond} = \dot{C}_{18} - \dot{C}_{19}$ |
| FW pump | $\dot{c}_{w,pump} = \dot{c}_{w,ST}$ | $\dot{C}_{F,pump} = \dot{C}_{W,pump}$;$\dot{C}_{P,cond} = \dot{C}_{20} - \dot{C}_{19}$; |
| Desalination unit | $\dot{c}_{10} = \dot{c}_{12}$; $\dot{c}_{10} = \dot{c}_8$; $\dot{c}_{11} = \dot{c}_{12}$; $\dot{c}_{10} = \dot{c}_{16}$; $\dot{c}_{13} = \dot{c}_{14} = \dot{c}_{15} = 0$ | $\dot{C}_{F,desalination} = \dot{C}_{10} - \dot{C}_{12} - \dot{C}_{13}$; $\dot{C}_{P,desalination} = \dot{C}_{17}$ |

Table 3 | Thermodynamic properties of the plants with the MED and MSF units

| Stream | Combined cycle + MED | | | | | Combined cycle + MSF | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $T(^{\circ}C)$ | $P(bar)$ | $\dot{m}\left(\frac{kg}{s}\right)$ | $h\left(\frac{kj}{kg}\right)$ | $s\left(\frac{kj}{kg.^{\circ}C}\right)$ | $T(^{\circ}C)$ | $P(bar)$ | $\dot{m}\left(\frac{kg}{s}\right)$ | $h\left(\frac{kj}{kg}\right)$ | $s\left(\frac{kj}{kg.^{\circ}C}\right)$ |
| 1 (Inlet air to compressor) | 16 | 0.85 | 382.2 | 50.37 | 0.06 | 16 | 0.85 | 382.2 | 50.37 | 0.03 |
| 2 (Air out) | 273 | 12.4 | 382.2 | 385.74 | 0.8 | 273 | 12.4 | 382.2 | 385.74 | 0.62 |
| 4 (GT inlet) | 1,107 | 11.9 | 389.9 | 1,541.81 | 1.783 | 1,107 | 11.9 | 389.9 | 1,541.87 | 1.76 |
| 5 (GT out) | 522 | 0.93 | 389.9 | 792.71 | 1.072 | 523.6 | 0.93 | 389.9 | 794.18 | 1.09 |
| 6 (Stack gas) | 157.1 | 0.89 | 1,559.5 | 377.77 | 0.12 | 157 | 0.89 | 1,559.5 | 376.01 | 0.39 |
| 9 (ST in) | 482 | 76.9 | 176.9 | 3,358.18 | 6.69 | 482 | 76.9 | 176.9 | 3,358.18 | 6.69 |
| 18 (ST out) | 64.33 | 0.24 | 66.57 | 2,416.32 | 7.11 | 64 | 0.24 | 51.84 | 2,371.59 | 7.11 |
| 19 (Condenser out) | 64.33 | 0.6 | 66.59 | 269.31 | 0.7105 | 64.33 | 0.60 | 66.59 | 269.31 | 0.52 |
| 8 (HRSG HP) | 296 | 81.18 | 179.3 | 2,758.15 | 5.7393 | 64.79 | 3.71 | 66.58 | 271.49 | 0.89 |
| 7 (HRSG LP) | 158.5 | 5.94 | 55.58 | 2,755.09 | 6.702 | 297 | 82.38 | 179.8 | 2,756.39 | 5.73 |
| 11 (Extraction of ST (to MED)) | 173.1 | 5.72 | 110.3 | 2,789.35 | 6.8554 | 157 | 5.72 | 56.73 | 2,753.4 | 6.77 |
| 12 (Steam inlet to desalination) | 181.2 | 5.5 | 137.8 | 2,809.82 | 6.916 | 161.9 | 5.5 | 125 | 2,764.24 | 6.81 |
| 15 (Brine blowdown water) | 38.52 | 0.89 | 1,999.9 | 150 | 0.52 | 181.2 | 5 | 172.3 | 2,813.24 | 6.96 |
| 17 (Desalinated water) | 38.06 | 4.137 | 1,000 | 159.7 | 0.546 | 40.05 | 0.89 | 3,804 | 156.9 | 0.54 |
| 10 (Vacuum steam) | 240.2 | 20.68 | 2.7 | 2,872.95 | 6.474 | 38.38 | 4.14 | 1,521.6 | 161.1 | 0.55 |
| 16 (Condensate to DA) | 38.05 | 3.708 | 137.8 | 159.6 | 0.543 | 240.2 | 20.68 | 3.45 | 2,872.95 | 6.47 |
| 13 (Supply seawater) | 30 | 0.89 | 14,365 | 119.9 | 0.434 | 114.2 | 3.708 | 172.3 | 479.5 | 1.8 |
| 14 (Seawater discharge) | 36 | 0.89 | 11,365 | 143.7 | 0.434 | 30 | 0.89 | 10,849 | 119.9 | 0.4 |
| 3 (Fuel) | 78.06 | 23.02 | 7.63 | 55,857.58 | | 39.99 | 0.89 | 5,524 | 159.8 | 0.4 |

Table 4 | Stream results of the exergoeconomic analysis for the combined-cycle power plant

| Stream | Total exergy (MW) | c ($/MJ) | $\dot{C}$ ($/hr) | c($/MJ) | $\dot{C}$ ($/hr) |
|---|---|---|---|---|---|
| 1 (Inlet air to compressor) | 0.00 | 0 | | | |
| 2 (Air out) | 107.99 | 0.1 | 37,515.29 | 0 | 0 |
| 4 (GT inlet) | 408.71 | 0.03 | 40,462.78 | 0.03 | 40,757.05 |
| 5 (GT out) | 96.06 | 0.03 | 9,509.5 | $0.94\times10^{-2}$ | 3,250.53 |
| 6 (Stack gas) | 33.06 | 0 | 0 | $0.94\times10^{-2}$ | 1,118.8 |
| 7 (ST In) | 245.19 | 0.03 | 24,714.99 | 0 | 0 |
| 8 (ST Out) | 69.99 | $0.5\times10^{-2}$ | 1,133.80 | $0.44\times10^{-2}$ | 1,108.60 |
| 19 (Condenser out) | 4.12 | 0.38 | 5,667.27 | $0.44\times10^{-2}$ | 65.26 |
| 20 (CW in)(Pump out) | 0.68 | 3.79 | 9,252.95 | 0.02 | 54.87 |
| 3 (Fuel) | 395.74 | $0.21\times10^{-2}$ | 2,991.79 | $0.11\times10^{-2}$ | 1,567.12 |
| Wst | 118.98 | 0.04 | 16,362.54 | $0.21\times10^{-2}$ | 899.51 |
| Wgt | 202.61 | 0.08 | 53,904.49 | $0.5\times10^{-2}$ | 3,647.12 |
| Wfp | 2.75 | 0.04 | 378.45 | 0.02 | 224.89 |
| Wcompressor | 119.06 | 0.08 | 31,676.3 | $0.5\times10^{-2}$ | 2,143.18 |
| 8 (HRSG HP) | 188.51 | 0.03 | 18,323.3 | 0.02 | 15,405.14 |
| 7 (HRSG LP) | 45.52 | 0.03 | 4,424.2 | $0.44\times10^{-2}$ | 720.99 |

performance.

$$EDL_j = \frac{E_{D,j}}{TV_j} \tag{5}$$

$$ECDL_j = \frac{C_{D,j}}{TV_j} \tag{6}$$

## RESULTS AND DISCUSSION

### Energy and exergy evaluation

The thermodynamic properties of the combined cycle coupled with the MED and MSF units are shown in Table 3. It is important to have similar results for all simulations to accurately evaluate the performance of the plant in standalone and integrated modes. Due to the use of steam from the power plant to generate freshwater in the desalination systems, the power production of the integrated systems is decreased relative to standalone operation. This reduction is found to be 9.7% (69.36 MW) in the simulation with the MED system and 8.5% (60.64 MW) in the simulation with the MSF.

The calculation of the exergy of each material stream was realized with computer code. The stream exergies of the combined-cycle plant and the coupled simulations (combined cycle with MED and combined cycle with MSF) are shown in Tables 4–6.

### Exergoeconomic evaluation

When looking at the economic performance of the plants, we find that despite the relatively high capital cost of the

**Table 5** | Stream results of the exergoeconomic analysis for the combined cycle coupled with the MED unit

| Stream | Total exergy (MW) | c ($/MJ) | $\dot{C}$ ($/hr) | c ($/MJ) | $\dot{C}$ ($/hr) |
|---|---|---|---|---|---|
| 1 (Inlet air to compressor) | 0 | 0 | 0 | 0 | 0 |
| 2 (Air out) | 107.99 | 0.1 | 37,515.2 | 0.03 | 10,768.6 |
| 4 (GT inlet) | 408.71 | 0.03 | 40,462.78 | 0.01 | 13,830.91 |
| 5 (GT out) | 96.05 | 0.03 | 9,509.53 | 0.01 | 3,250.53 |
| 6 (Stack gas) | 33.06 | 0 | 0 | 0 | 0 |
| 7 (ST in) | 241.9 | 0.03 | 23,513.3 | $0.44\times10^{-2}$ | 3,831.79 |
| 8 (ST out) | 19.92 | $0.44\times10^{-2}$ | 315.65 | $0.44\times10^{-2}$ | 315.65 |
| 19 (Condenser out) | 4.11 | 0.38 | 5,667.2 | 0.02 | 333.71 |
| 20 (CW in)(Pump out) | 0.67 | 3.79 | 9,252.9 | 0.14 | 335.82 |
| 3 (Fuel) | 395.73 | $0.21\times10^{-2}$ | 2,991.7 | $0.21\times10^{-2}$ | 2,991.79 |
| Wst | 118.98 | 0.04 | 16,362.5 | $0.5\times10^{-2}$ | 2,141.69 |
| Wgt | 202.61 | 0.07 | 53,904.49 | 0.02 | 16,557.94 |
| Wfp | 2.7 | 0.04 | 378.4 | $0.5\times10^{-2}$ | 49.5 |
| Wcompressor | 119.1 | 0.07 | 31,676.3 | 0.02 | 9,730.07 |
| 8 (HRSG HP) | 188.51 | 0.03 | 18,323.3 | $0.44\times10^{-2}$ | 2,986.02 |
| 7 (HRSG LP) | 42.31 | 0.03 | 4,112.7 | $0.44\times10^{-2}$ | 670.22 |
| 11 (Extraction of ST (to MED)) | 82.7 | 0.03 | 8,038.8 | 0.0044 | 1,310.03 |
| 12 (Steam inlet to desalination) | 1.42 | 0.03 | 138.06 | $0.44\times10^{-2}$ | 22.49 |
| 15 (Brine blowdown water) | 43.98 | 0 | 0 | 0 | 0 |
| 17 (Desalinated water) | 0.1 | 11.8 | 4,178.1 | 0.5 | 170.99 |
| 10 (Vacuum steam) | 9.92 | 0.03 | 964.62 | $0.44\times10^{-2}$ | 157.19 |
| 16 (Condensate to DA) | 4.04 | 0.03 | 392.32 | $0.44\times10^{-2}$ | 63.93 |
| 13 (Supply seawater) | 306.96 | 0 | 0 | 0 | 0 |
| 14 (Seawater discharge) | 243.47 | 0 | 0 | 0 | 0 |

**Table 6** | Stream results of the exergoeconomic analysis for the combined cycle coupled with the MSF unit

| Stream | Total exergy (MW) | c ($/MJ) | $\dot{C}$ ($/hr) | c ($/MJ) | $\dot{C}$ ($/hr) |
|---|---|---|---|---|---|
| 1 (Inlet air to compressor) | 0 | 0 | 0 | 0 | 0 |
| 2 (Air out) | 107.9 | 0.1 | 37,787.42 | 0.03 | 10,846.39 |
| 4 (GT inlet) | 408.7 | 0.03 | 40,757.05 | 0.01 | 13,830.91 |
| 5 (GT out) | 96.81 | 0.03 | 9,654.61 | 0.01 | 3,276.29 |
| 6 (Stack gas) | 33.01 | 0 | 0 | 0 | 0 |
| 9 (ST in) | 241.9 | 0.03 | 22,816.61 | $0.43\times10^{-2}$ | 3,744.71 |
| 18 (ST out) | 13.2 | 0.03 | 1,244.97 | $0.43\times10^{-2}$ | 204.32 |
| 19 (Condenser out) | 7.84 | 0.17 | 4,949.28 | 0.01 | 220.21 |
| 20 (CW in)(Pump out) | 0.67 | 3.5 | 8,531.06 | 0.9 | 2,202.27 |
| 3 (Fuel) | 395.74 | $0.21\times10^{-2}$ | 2,991.79 | $0.21\times10^{-2}$ | 2,991.79 |
| Wst | 102.76 | 0.04 | 13,799.28 | 0.05 | 1,812.77 |
| Wgt | 202.6 | 0.08 | 54,342.14 | 0.02 | 16,703.82 |
| Wfp | 2.7 | 0.04 | 372.61 | $0.49\times10^{-2}$ | 48.94 |
| Wcp | 0.32 | 0.04 | 42.36 | $0.49\times10^{-2}$ | 5.56 |
| Wcompressor | 119.06 | 0.08 | 31,933.50 | 0.02 | 9,815.80 |
| 8 (HRSG HP) | 189.14 | 0.03 | 17,840.07 | $0.43\times10^{-2}$ | 2,927.95 |
| 7 (HRSG LP) | 41.88 | 0.03 | 3,950.3 | $0.43\times10^{-2}$ | 648.34 |
| 11 (Extraction of ST (to MED) | 92.21 | 0.03 | 8,697.46 | $0.43\times10^{-2}$ | 1,427.44 |
| 12 (Steam inlet to desalination) | 1.57 | 0.03 | 148.36 | $0.43\times10^{-2}$ | 24.34 |
| 15 (Brine blowdown water) | 82.4 | 0 | 0 | 0 | 0 |
| 17 (Desalinated water) | 0.12 | 9.4 | 4,214.37 | 0.5 | 237.82 |
| 10 (Vacuum steam) | 9.65 | 0.03 | 910.4 | $0.43\times10^{-2}$ | 149.4 |
| 16 (Condensate to DA) | 5.27 | 0.03 | 497.89 | $0.43\times10^{-2}$ | 81.71 |
| 13 (Supply seawater) | 232.1 | 0 | 0 | 0 | 0 |
| 14 (Seawater discharge) | 119.01 | 0 | 0 | 0 | 0 |

**Table 7** | Cost of product and fuel of each component of the Qom plant

| Component | Exergy destruction | $C_{F0}$ | $C_{P0}$ | $C_{F0}/C_{FT}$ | $C_{DL0}$ | $C_F$ ($/MJ) | $C_P$ ($/MJ) |
|---|---|---|---|---|---|---|---|
| Air compressor | 19.49 | 0 | 0 | 0 | 0 | 0.03 | 0.03 |
| Combustor | 95.01 | 0.03 | 0.03 | 5.8 | 10,718.4 | 0.01 | 0.01 |
| Gas turbine | 182.66 | 0.03 | 0.07 | 5.69 | 20,205.1 | 0.01 | 0.03 |
| Steam turbine | 50.56 | 0.03 | 0.04 | 5.0 | 4,946.5 | $0.4\times10^{-2}$ | $3.5\times10^{-3}$ |
| Condenser | 66.55 | 3.8 | 4.74 | 702.59 | 908,902.9 | 0.01 | $0.3\times10^{-3}$ |
| HRSG | 117.81 | 0.01 | $3.2\times10^{-3}$ | 2.3 | 5,351.14 | 0.01 | $0.2\times10^{-2}$ |
| FW pump | 4.14 | $3.8\times10^{-4}$ | 1.65 | 0.07 | 5.69 | 0.01 | $0.2\times10^{-3}$ |

integrated cycles, they are viable with a payback period of below 3 years. This is possible through the sale of the electricity and the freshwater generated in the plants. The price of freshwater is calculated at about 1 USD per cubic meter. The exergoeconomic results for each material stream of the three scenarios are shown in Tables 4–6. The

**Table 8** | Cost of product and fuel of each component for the combined cycle with MED

| Component | Exergy destruction | $C_{F0}$ | $C_{P0}$ | $C_{F0}/C_{FT}$ | $C_{DL0}$ | $C_F$ ($/MJ) | $C_P$ ($/MJ) |
|---|---|---|---|---|---|---|---|
| Air compressor | 19.49 | 0.04 | 0.04 | 7.07 | 2,680.84 | 0.02 | 0.02 |
| Combustor | 95.01 | 0.02 | 0.03 | 4.13 | 7,640.45 | 0.01 | 0.01 |
| Gas turbine | 182.65 | 0.03 | 0.07 | 5.69 | 20,205.1 | 0.01 | 0.02 |
| Steam turbine | 97.33 | 0.02 | 0.04 | 3.97 | 7,516.2 | $0.4\times10^{-2}$ | $0.5\times10^{-2}$ |
| Condenser | 16.48 | 3.79 | 4.74 | 702.59 | 225,160.9 | $0.5\times10^{-2}$ | $0.3\times10^{-3}$ |
| HRSG | 121.01 | 0.04 | 0.011 | 7.76 | 18,268.5 | 0.01 | $0.4\times10^{-2}$ |
| FW pump | 3.59 | 0.04 | 205.59 | 7.1 | 494.23 | $0.5\times10^{-2}$ | $0.3\times10^{-3}$ |
| Desalination unit | 30.75 | $0.1\times10^{-2}$ | $0.2\times10^{-3}$ | 0.21 | 124.31 | $0.15\times10^{-3}$ | 0.48 |

**Table 9** | Cost of product and fuel of each component for the combined cycle with MSF

| Component | Exergy destruction | $C_{F0}$ | $C_{P0}$ | $C_{F0}/C_{FT}$ | $C_{DL0}$ | $C_F$ ($/MJ) | $C_P$ ($/MJ) |
|---|---|---|---|---|---|---|---|
| Air compressor | 19.4 | 0.03 | 0.04 | 6.90 | 2,617.95 | 0.02 | 0.03 |
| Combustor | 95.01 | 0.02 | 0.02 | 4.16 | 7,691.78 | 0.01 | 0.01 |
| Gas turbine | 182.43 | 0.03 | 0.07 | 5.2 | 20,309.34 | 0.01 | 0.02 |
| Steam turbine | 13.52 | 0.02 | 0.04 | 3.7 | 976.6 | $0.4\times10^{-2}$ | $0.3\times10^{-4}$ |
| Condenser | 6.03 | 3.4 | 4.4 | 647.7 | 75,989.43 | $0.4\times10^{-2}$ | $0.81\times10^{-3}$ |
| HRSG | 123.91 | 0.04 | 0.01 | 7.78 | 18,748.35 | 0.01 | $0.16\times10^{-2}$ |
| FW pump | 7.31 | 0.04 | 204.9 | 6.9 | 982.45 | $0.4\times10^{-2}$ | 0.07 |
| Desalination unit | 36.52 | $0.13\times10^{-2}$ | 0 | 0.02 | 17.09 | $0.2\times10^{-3}$ | 0.53 |

**Table 10** | Results of the exergoeconomic analysis for the combined cycle

| Component | EF (MW) | EP (MW) | Z ($/h) | $C_D$ +Z ($/h) | EDL (MW/MW) | ECDL ($/MW) |
|---|---|---|---|---|---|---|
| Air compressor | 127.48 | 107.99 | 343.7 | 2,287.67 | 0.15 | 15.24 |
| Combustor | 503.73 | 408.71 | 3.23 | 2,598.69 | 0.23 | 6.35 |
| Gas turbine | 312.66 | 130.0 | 102.1 | 6,283.89 | 1.40 | 47.54 |
| Steam turbine | 175.20 | 124.63 | 52.7 | 853.64 | 0.40 | 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 | 24.77 |
| FW pump | 7.05 | 0.68 | 0.02 | 74.53 | 0.58 | 10.56 |

cost of product and fuel of each component for the standalone combined cycle and the integrated MED and MSF plants are shown in Tables 7–9, respectively. The calculated capital investment cost, cost of exergy destruction ($C_D$), and the EDL and ECDL are shown in Tables 10–12.

It is found that the cost of most steams in the integrated plant with MSF is lower than that of the combined cycle with MED. Nevertheless, the power output of the steam turbine is less in the plant with MSF than in the plant with MED. The cost of fuel and product ($C_F$, $C_P$) is very similar between the base combined-cycle plant and the combined cycle with MED. However, the cost of product in the combined cycle with MSF is found to be higher, because the capital cost of the MSF unit is higher. The $C_P$

**Table 11** | Results of the exergoeconomic analysis for the combined cycle with MED

| Component | EF (MW) | EP (MW) | Z ($/h) | $C_D + Z$ ($/h) | EDL (MW/MW) | ECDL ($/MW) |
|---|---|---|---|---|---|---|
| Air compressor | 127.48 | 107.98 | 343.70 | 2,287.6 | 0.15 | 24.82 |
| Combustor | 503.72 | 408.71 | 3.23 | 2,598.6 | 0.23 | 18.6 |
| Gas turbine | 312.65 | 130.0 | 102.74 | 6,283.8 | 1.4 | 155.42 |
| Steam turbine | 221.97 | 124.6 | 52.75 | 1,594.6 | 0.78 | 60.3 |
| Condenser | 0.67 | 19.38 | 0.76 | 297.49 | 0.13 | 1,806.5 |
| HRSG | 62.99 | 241.3 | 88.4 | 6,326.9 | 0.50 | 75.6 |
| FW pump | 7.05 | 0.54 | 0.02 | 64.71 | $0.12 \times 10^{-2}$ | 906.2 |
| Desalination unit | 11.34 | 48.11 | 69.3 | 86.7 | 2.71 | 2.58 |

**Table 12** | Results of the exergoeconomic analysis for the combined cycle with MSF

| Component | EF (MW) | EP (MW) | Z ($/h) | $C_D + Z$ ($/h) | EDL (MW/MW) | ECDL ($/MW) |
|---|---|---|---|---|---|---|
| Air compressor | 127.4 | 107.98 | 343.7 | 1,950.97 | 0.15 | 12.60 |
| Combustor | 503.7 | 408.71 | 3.23 | 2,613.40 | 0.23 | 6.38 |
| Gas turbine | 311.89 | 129.4 | 102.7 | 6,276.47 | 1.40 | 47.68 |
| Steam turbine | 228.70 | 122.9 | 52.2 | 261.66 | 0.11 | 1.70 |
| Condenser | 0.67 | 12.65 | 0.59 | 107.04 | 0.04 | 0.86 |
| HRSG | 63.8 | 241.36 | 89.19 | 6,450.34 | 0.51 | 26.35 |
| FW pump | 10.8 | 0.54 | 0.03 | 129.08 | $0.24 \times 10^{-2}$ | 0.04 |
| Desalination unit | 11.2 | 87.81 | 151.62 | 177.69 | 3.25 | 2.3 |

**Table 13** | PEC and capital investment cost of each component for the combined-cycle power plant

| 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 | 0.093 | 336.91 |
| Combustion chamber | 95.01 | 489,359.35 | 294,596.9 | 23,894.66 | $0.9 \times 10^{-3}$ | 3.16 |
| Gas turbine | 182.66 | 15,570,356.95 | 9,373,438.09 | 760,276.56 | 0.027 | 100.73 |
| Steam turbine | 50.56 | 8,143,254.36 | 4,902,282.6 | 397,622.57 | 0.014 | 52.68 |
| Condenser | 66.55 | 115,036.35 | 69,252.4 | 5,617.04 | $0.2 \times 10^{-3}$ | 0.74 |
| HRSG | 117.81 | 13,564,825.35 | 8,166,097.3 | 662,349.54 | 0.02 | 87.76 |
| FW pump | 4.14 | 4,065.65 | 2,447.54 | 198.51 | $7.3 \times 10^{-6}$ | 0.02 |

and $C_F$ of the components of the Rankine cycle are higher in the integrated cycles; higher in the plant with MED, when compared to those of the plant with MSF. The exergy destruction level is found to be higher in the integrated combined plant with the MSF desalination unit and the ECDL is higher in the combined plant with MED. The ECDL depends on the cost of steam streams that enter into the desalination unit.

The cost of exergy of the product of the steam turbine, the inlet steam to the desalination unit, and the desalinated water in the MED-integrated system is 2,149.69, 22.49, and 170.59 $\left(\frac{\$}{h}\right)$, respectively. The exergy cost of product of the

**Table 14** | PEC and capital investment cost of each component for the combined cycle coupled with MED

| Component | Exergy destruction | PEC ($) | PW | C ($/yr) | Z ($/s) | Z ($/hr) |
|---|---|---|---|---|---|---|
| Air compressor | 19.49 | 53,125,465.17 | 31,981,813.95 | 2,594,034.6 | 0.09 | 343.7 |
| Combustion chamber | 95.01 | 499,367.58 | 300,621.95 | 24,383.35 | $0.9 \times 10^{-3}$ | 3.23 |
| Gas turbine | 182.65 | 15,880,504.05 | 9,560,148.3 | 775,420.6 | 0.03 | 102.74 |
| Steam turbine | 97.3 | 8,153,612.03 | 4,908,518.01 | 398,128.32 | 0.01 | 52.75 |
| Condenser | 16.4 | 118,028.61 | 71,053.85 | 5,763.15 | $0.21 \times 10^{-3}$ | 0.76 |
| HRSG | 121.01 | 13,665,243.21 | 8,226,549.4 | 667,252.7 | 0.02 | 88.41 |
| FW pump | 3.59 | 4,135.6 | 2,489.65 | 201.93 | $7.4 \times 10^{-6}$ | 0.03 |
| Desalination unit | 30.75 | 10,718,415 | 6,452,543.1 | 523,363.7 | 0.02 | 69.3 |

steam turbine and the outlet water of the condenser are increased by 58% and 80%, relative to the base power plant. The cost of the product of exergy related to the steam turbine, inlet steam to desalination unit, and desalinated water in the MSF-integrated plant is 1,812.77, 24.34, and 237.82 $\left(\frac{\$}{h}\right)$, respectively. The exergy costs of products of the steam turbine and the outlet water condenser are reduced by 100% and 8%, when compared to those of the base power plant.

The purchased equipment cost (PEC) and the capital investment cost in time are shown in Tables 13–15. The investment cost of the Brayton cycle of the three power plants is constant. Comparing the two integrated cycles, we see that the addition of the MSF unit reduces the cost of the Rankine cycle, although the MSF unit is more expensive than the MED unit. The costs of electricity production and exergy destruction are both reduced in the integrated cycles, when compared to the combined-cycle plant, due to a decrease in the exergy destruction in these cases. Our calculations show that the cost of exergy destruction is reduced more in the case of the MSF integrated case, when compared to the integrated MED plant (reductions of 9.2 and 0.1%, respectively). In addition, the EDL and ECDL are decreased significantly in the MSF, in comparison to the MED integrated system.

Most exergy destruction in the combined-cycle plant takes place in the gas turbine. In the integrated plants with desalination units, the heat recovery steam generator (HRSG) is found to have the maximum exergy destruction after the gas turbine. The integrated plants with MSF and MED can produce 1,521 and 1,000 kg/s of freshwater, respectively. It is found, thus, that the MSF plant has a 50% higher capacity of freshwater generation than the plant with the MED unit.

The ECDL and total cost $(\dot{C} + \dot{Z})$ of the HRSG in the base power plant is 21.82 ($/MW) and 6,161.11 ($/h), respectively. Nevertheless, the condenser and the pump are associated with the most EDL. In the MED integrated

**Table 15** | PEC and capital investment cost of each component for the combined cycle coupled with MSF

| Component | Exergy destruction | PEC ($) | PW | C ($/yr) | Z ($/s) | Z ($/hr) |
|---|---|---|---|---|---|---|
| Air compressor | 19.4 | 53,125,465.17 | 31,981,813.95 | 2,594,034.7 | 0.1 | 343.70 |
| Combustion chamber | 95.01 | 499,367.5 | 300,621.95 | 24,383.35 | $0.9 \times 10^{-3}$ | 3.23 |
| Gas turbine | 182.4 | 15,880,504.05 | 9,560,148.3 | 77,420.57 | 0.03 | 102.7 |
| Steam turbine | 13.5 | 8,076,892.04 | 4,862,332.17 | 394,382.20 | 0.01 | 52.2 |
| Condenser | 6.03 | 91,912.32 | 55,331.71 | 4,487.93 | $0.16 \times 10^{-3}$ | 0.59 |
| HRSG | 123.91 | 13,786,350.02 | 8,299,456.38 | 673,166.25 | 0.02 | 89.19 |
| FW pump | 7.31 | 4,050.23 | 2,438.26 | 197.76 | $7.31 \times 10^{-6}$ | 0.03 |
| Desalination unit | 36.52 | 23,435,363.17 | 14,108,213.87 | 1,144,312.71 | 0.04 | 151.62 |

case, the highest EDL is related to the MED unit, followed by the steam turbine. On the other hand, the ECDL of the condenser is the highest. The second highest ECDL is found for the HRSG. In this case, the HRSG, the steam turbine, and the condenser have the highest costs ($\dot{C} + \dot{Z}$). In the MSF integrated cycle, the highest EDL is found for the MSF unit, followed by the HRSG and the steam turbine. Furthermore, the highest ECDL is found for the HRSG. The PR (performance ratio) of the plant with MSF is found to be 8.9, while that of the plant with the MED unit is found to be 6.4.

The capital cost of the MSF integrated plant is about three times higher than that of the plant with MED. Despite the high capital cost, the profit of this integrated plant will be double its capital cost after 7 years and its payback period is before the completion of 3 years. Finally, the cost of the water production in the plant with MSF is lower by 20%, when compared to the plant with MED. The cost of electricity in the combined cycle, the MSF integrated plant, and the MED integrated plant is 0.0739, 0.0745, and 0.739$ /MWh, respectively. In addition, the cost of water production is 1.08 $/h for the MED integrated plant and 0.88 for the MSF integrated plant.

### Comparison with published studies

In a similar work, Hanafi *et al.* (2015) compared only the investment and total cost of the combined-cycle system and integrated desalination system. In the work presented here, various parameters, including the cost of exergy destruction and the costs associated with each flow in the cycle, as well as the cost of investment and fuel and product costs of each piece of equipment are calculated.

In a study by Rezaei *et al.* (2017), the thermodynamic parameters related to the coupling of the water desalination unit to the power plant were not investigated and only the economic issues related to a water desalination model of MED were studied. In our study, economic relations related to cyclical flows and economic characteristics of all equipment are presented. Furthermore, in our work, we performed a comparison between MSF and MED desalination units in terms of performance, energy, and economics.

In the study by Hafdhi *et al.* (2018), energy, exergy, and economic analyses were carried out for a steam cycle along with an MSF water desalination unit. The results included appropriate parameters such as overall efficiency and the level of heat exchange and the design parameters of the cycle. In our study, we examined the detailed thermodynamic and exergy performance of the combined-cycle power plant, calculating the exergy of each stream and the exergy destruction associated with each piece of equipment. Lastly, the economic analysis includes new parameters, like the EDL and ECDL.

## CONCLUSION

Desalination of seawater is aimed at supplying fresh and potable water for domestic, industrial, or agricultural uses. The process requires energy that can be supplied by thermal, mechanical, or electrical energy. In this work, we evaluated the coupling of a combined-cycle power plant with desalination units: first with an MSF and, second, with an MED unit. The starting combined-cycle power plant was based on the existing Qom combined-cycle power plant. In order to select the most viable desalination method for the power plant, the system was evaluated using exergoeconomic analysis.

The investment cost of the integrated combined cycle with the MSF desalination unit is higher than that of the integrated plant with the MED unit. This leads to a somewhat more expensive product, when compared to that of the plant with MED. It is seen, thus, that the use of MSF can lead to a higher profit due to the increased production of freshwater. Coupling the plant with an MED unit, on the other hand, can provide a cheaper alternative, when it comes to investment costs.

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## SUPPLEMENTARY MATERIAL

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