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Parametric analysis and optimization of combined gas turbine and reverse osmosis system using refrigeration cycle

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ABSTRACT

This study proposes a systematic approach to analyzing and optimizing combined gas turbine (GT) and reverse osmosis (RO) systems. Two systems combining RO to produce freshwater and a GT power plant to generate the required power for the RO system were modeled. In the first system, the coupling between the RO and the power plant was only mechanical; while in the second system, the coupling was both mechanical and thermal, using a refrigeration cycle. The effects of seawater temperature and intake air temperature on the freshwater production of the systems were investigated and their optimal values were calculated. Economic modeling was applied in order to calculate the unit product cost of freshwater. The second system, with two RO units under optimal operation conditions, can increase freshwater production by 26% and save 21% in the production cost of 1 m^3 of freshwater as compared to the first system as a base system.

Keywords: Reverse osmosis; Gas turbine; Mathematical modeling; Economic costs; Optimization

1. Introduction

Water is available in large quantities on earth but only a small amount is suitably low enough in salinity to be fit for drinking and irrigation. Desalination of sea and brackish water is the main source of supplying freshwater in regions suffering from scarcity of natural freshwater supplies [9,10]. The two most widely used desalination techniques are reverse osmosis (RO) membrane separation and thermal desalination systems such as multi-effect distillation (MED) and multi-stage flash (MSF) [11]. Thermal desalination units are operated by moderate pressure steam as an energy source, usually extracted from a steam turbine or generated by a boiler. RO systems have minimal energy consumption compared to other desalination methods and their energy consumption is only in the form of electric power. Therefore, a gas turbine (GT) power plant can be utilized to operate RO systems [2,6].

The energy consumption of RO pumps required to drive the membrane module accounts for a major portion of the total cost of water desalination. In RO systems, as the feed water temperature increases, the membrane permeability also increases [4,5] and thereby the pump power consumption is decreased. Recently, several studies have been performed on methods of reducing power consumption in RO systems. Bouzayani et al. [10], Li [5], Kaghazchi et al. [11], Bilton et al. [4], and Ataei et al. [2] have developed mathematical models to investigate the decrease

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in power consumption and the effects of temperature on RO performance.

GT air inlet cooling is one of many available commercial methods to improve efficiency and power generation. When the intake air temperature to the GT compressor is decreased, both the efficiency and power output of the GT are increased. Different methods are used to cool the intake air of the GT compressor. These include evaporative coolers, spray inlet coolers or fogging systems, and mechanical vapor compression or absorption chillers [3,6]. Recently, several studies have been carried out on the effect of ambient temperature on the power generation and efficiency of GT power plants. Darwish et al. [6], Farzaneh-Gord and Deymi-Dashtebayaz [3], and Al-Ibrahim and Varnham [1] have investigated air cooling methods in GT power plants using mathematical models. Based on the literature, it is concluded that ambient temperature has the most significant effect on GT power plant performance.

This paper contributes to a new structure of coupling between an RO and a GT power plant based on the Brayton cycle. The intake air temperature of the GT compressor is decreased using the evaporator of the refrigeration cycle and the waste heat of the refrigeration condenser is recovered to increase the RO intake seawater temperature. A parametric optimization was performed to obtain the optimal preheated RO intake seawater temperature and precooled intake air temperature in order to maximize freshwater production. The objectives of this paper are summarized in two sections. The first section is a parametric analysis using a mathematical model to investigate the effect of the intake air temperature and intake seawater temperature on the freshwater production and obtain the best operation condition with maximum freshwater production. The third calculates the unit product cost (UPC) of freshwater using an economic model.

2. Material and methods

2.1. Systems configuration

The two systems under consideration are shown in Figs. 1 and 2. The system presented in Fig. 1 comprises an RO system coupled to a GT power plant, which is introduced as the base system. The coupling between the RO and power plant is only mechanical. The air at ambient temperature is compressed using a compressor and then sent to a combustion chamber where the fuel is injected. The hot gas is expanded through the GT and generates shaft work to operate the RO system.

In the system presented in Fig. 2, the RO system is coupled to the GT power plant mechanically by the shaft and thermally using a refrigeration system which is introduced as the new system. In this system, the ambient air is cooled by the evaporator of the refrigeration system and compressed by the compressor of the GT. The compressed air with injected fuel is sent to the combustion chamber. The hot gas is expanded in the GT and the generated shaft work is applied to operate the RO pump and refrigeration system's compressor. The waste heat in the condenser of the refrigeration system is recovered to increase the RO intake seawater temperature. Preheated seawater is then driven through the RO membrane as unit 1 by a high pressure provided by pump 1. The power generated in the GT can exceed the demand in pump 1. Therefore, the additional power generated in GT can

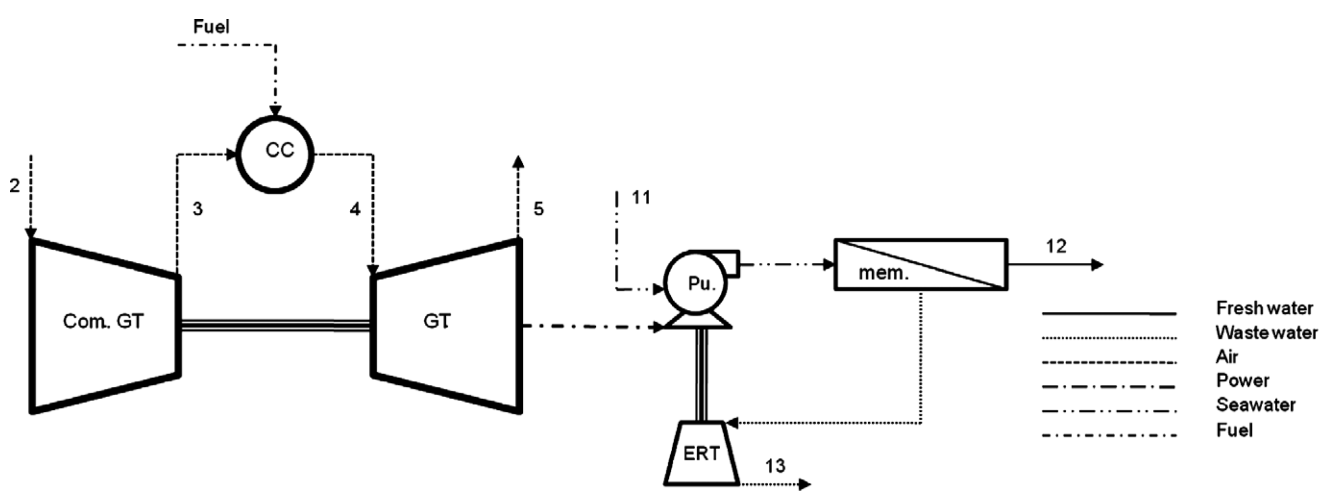

Fig. 1. Schematic of basic coupling of an RO system and a GT power plant (base system).

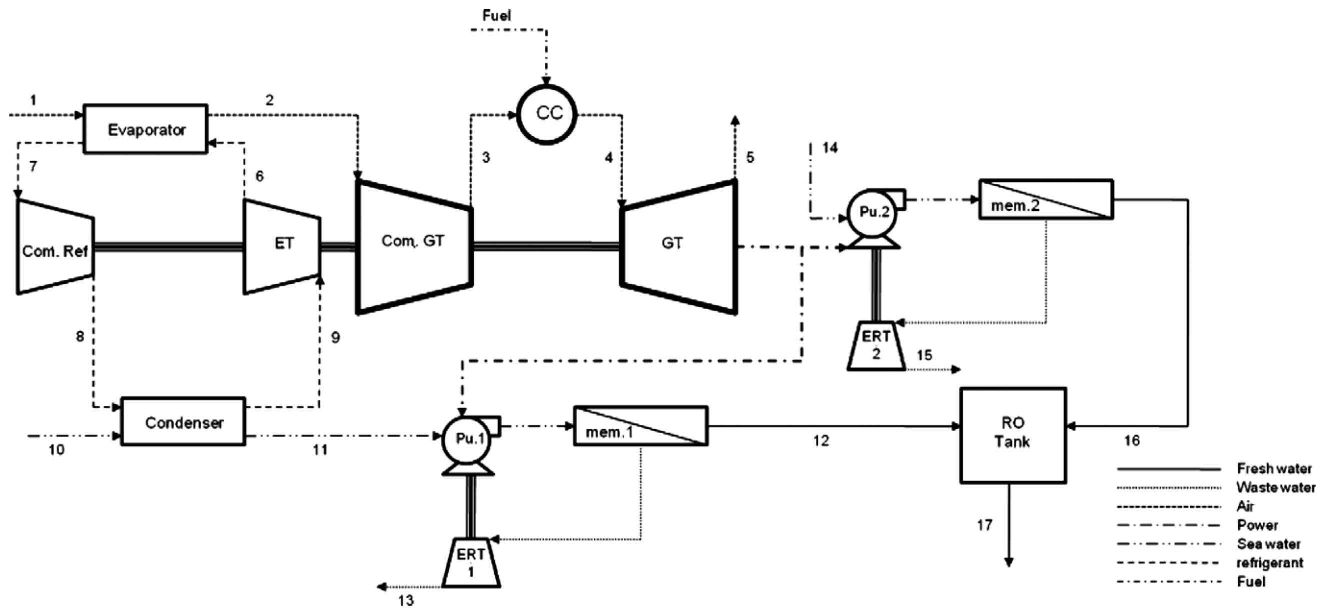

Fig. 2. Coupling of an RO system and a GT power plant to a refrigeration system (new system).

be used in RO unit 2. The high-pressure brine streams of RO units pass through a turbine to recover their energy and then are rejected back to the sea.

2.2. *Theoretical modeling of the systems*

The systems have been modeled mathematically and economically. The models developed by Vince et al. [8], Lu et al. [9], Helal et al. [7], Bilton et al. [4], and Kaghazchi et al. [11] have been applied in the current study.

Several simplifying assumptions listed below [10,11] were used in the development of the mathematical models in this study:

- The plant is operated at steady-state condition.
- There is no chemical reaction.
- Membrane is non-porous and the transport mechanism of the solute and solvent is solution-diffusion.
- Seawater temperature increasing by pumps is negligible.

The operating parameters and thermodynamic parameters' initial circumstances are presented in Table 1. The Persian Gulf seawater properties were considered as the feed water properties which are presented in Table 1. Membrane element is modeled by Eqs. (1)–(12) presented in Table 2. The influence of temperature on membrane permeability is expressed by the temperature correction factor TFC given by Eq. (13), where e is estimated for membrane at 25,000 when $T \leqslant 298\,\text{K}$ and at 22,000 when $T > 298\,\text{K}$. The influence of membrane fouling on membrane permeability is expressed by the fouling factor (FF) which varies between 100% for new membrane and 80% for 4-year-old membranes [8]. Since the membrane is assumed to be new, the FF is considered to be equal 1. Membrane module constructed by Filmtec with trade name SW30HR-380 is used in the current study. The characteristics of membrane module are presented in Table 3. GT power plant and refrigeration system are modeled by energy and mass balance equations presented in Table 4. To satisfy the economic aspect of heat exchangers, the minimum

Table 1
Operating and thermodynamic parameters as the initial circumstances

Parameter	Value	Parameter	Value
T_{seawater}	25°C	P_8	1,500 kpa
T_{ambient}	35°C	X_f	36,000 ppm
T_4	900°C	$\dot{m}_{\text{fuel}}$	0.1 kg/s
Refrigerant type	R-22	$\eta_{\text{rotatory equipment}}$	0.85

Table 2
Governing equations in the reverse osmosis system

Equation	Describe	
$\dot{m}_p = (J_w + J_s) \cdot S$	Membrane permeate mass flow rate	(1)
$\dot{m}_f = \dot{m}_p + \dot{m}_c$	Water mass balance across the membrane	(2)
$\dot{m}_f X_f = \dot{m}_p X_p + \dot{m}_c X_c$	Salts mass balance across the membrane	(3)
$r = \dot{m}_p / \dot{m}_f$	Water recovery rate	(4)
$Rs = 1 - (X_p / X_f)$	Membrane salt rejection rate	(5)
$J_w = A \cdot (\Delta P - \Delta\pi)$	Permeate mass flux through the membrane	(6)
$J_s = B \cdot (X_w - X_p)$	Salt mass flux through the membrane	(7)
$X_w - X_p = \left(\frac{X_f + X_c}{2} - X_p\right) \cdot e^{k \cdot r}$	Concentration polarization factor	(8)
$\Delta P = P_f - P_p - \frac{\Delta P_{drop}}{2}$	Transmembrane pressure	(9)
$\Delta P_{drop} = 9.5 \times 10^8 \cdot \left(\frac{\dot{m}_f + \dot{m}_c}{2 \cdot \rho}\right)^{1.7}$	Pressure drop along the membrane channel	(10)
$\Delta\pi = \frac{2 \cdot Ru \cdot T \cdot \rho}{0.0585} \cdot (X_w - X_p)$	Transmembrane osmosis pressure	(11)
$A = A_{ref} \cdot FF \cdot \mathrm{TFC}$	Membrane water permeability	(12)
$\mathrm{TCF} = e^{\frac{e}{Ru}\left(\frac{1}{298} - \frac{1}{T}\right)}$	Temperature correction factor	(13)
$P_{pump} = 27.78 \frac{P_f \cdot Q_f}{\eta_{pump}}$	Power consumption of reverse osmosis pump	(14)
$P_{ERT} = 27.78 \cdot P \cdot_c Q_c \cdot \eta_{ERT}$	Power recovered by energy recovery turbine	(15)

different temperature between streams is considered at least 10°C.

The economic model equations used to calculate the TAC and UPC of freshwater are shown in Table 5 [8,7,4]. TAC is calculated by Eq. (54), where AOC is annual operating cost and ACC is annual capital cost. The amortization factor is given by Eq. (47), in which the interest rate (i) and plant life cycle (n) have been assumed to be equal to 15% and 20 years, respectively. The cost of energy is assigned based on the price of fuel being 0.11 ($/kg). The plant load factor (*f*) is considered to be 0.9.

3. Result and discussion

The objective of this investigation was to parametrically optimize, analyze, and compare the fresh water production of two consideration systems. Two operating parameters were varied during this study in order to evaluate their effect on the freshwater production of the two systems under consideration. They are the intake air temperature of the GT compressor (T_2) and

Table 3
Characteristics of SW30HR-380 reverse osmosis membrane element

Membrane specific parameters	Unit	Value
Active surface area	m^2	35.3
Reference pure water permeability	$kg/m^2\,s\,pa$	2.7×10^{-9}
Salt permeability constant	$kg/m^2\,s$	2.3×10^{-5}
Maximum operating pressure	Bar	82
Maximum feed flux	m^3/h	16.2
Minimum consternate flux	m^3/h	2.27
Maximum recovery rate	%	30
Stabilized salt rejection	%	99.7

intake seawater temperature of the RO system (T_{11}). Since the ambient air temperature is considered to be 35°C, the studied range of T_2 is from 15 to 35°C. Due to the membrane can be used to desalinate seawater with a maximum temperature of 45°C, the studied range of T_{11} is from 25 to 45°C.

3.1. The base system

In this system, there is no thermal coupling between the GT power plant and the RO system. Therefore, RO system desalinates seawater without preheating. Fig. 3 shows the effects of seawater temperature (T_{11}) and intake air temperature (T_2) on freshwater production. It is obvious that freshwater production increases as T_2 decreases and T_{11} increases. The maximum value of freshwater production can be achieved as T_2 has the minimum value and T_{11} has maximum value in their investigated ranges. Fig. 3 clearly shows that the freshwater

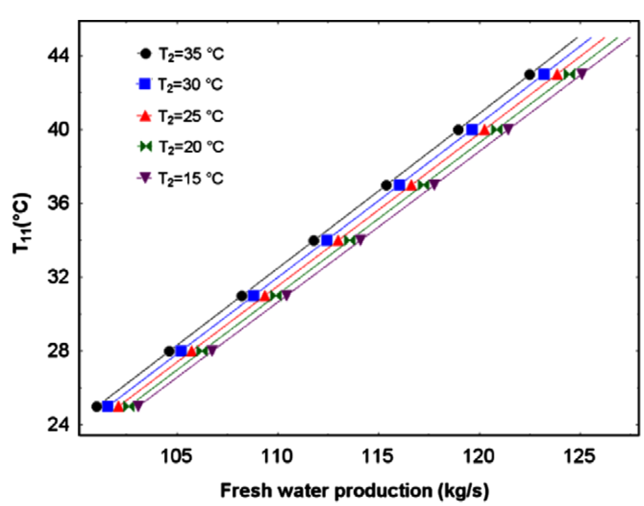

Fig. 3. Effects of T_{11} and T_2 on the freshwater production for the base system.

Table 4
Mathematical equations of the GT power plant and refrigeration cycle

Equation	Describe	
$\frac{T_{3i}}{T_2} = (\frac{P_3}{P_1})^{(\gamma-1)/\gamma}$	Compression process in compressor of GT power plant	(16)
$\dot{W}_{com.GT} = \dot{m}_{air} \cdot C_p \cdot (T_{3i} - T_2)/\eta_{com.GT}$	GT compressor power consumption	(17)
$\frac{T_{5i}}{T_4} = (\frac{P_5}{P_4})^{(\gamma-1)/\gamma}$	Expansion process in GT	(18)
$\dot{W}_{GT} = \dot{m}_4 \cdot C_p \cdot (T_4 - T_{5i}) \cdot \eta_{GT}$	Gas turbine power generation	(19)
$\dot{m}_{fuel} \cdot LHV + \dot{m}_{fuel} h_{fuel} = C_p(\dot{m}_4 T_4 - \dot{m}_{air} T_3)$	Combustion chamber energy balance	(20)
$\dot{m}_{air} + \dot{m}_{fuel} = \dot{m}_4$	Combustion chamber mass balance	(21)
$\dot{W}_{com.refrigeration} = \dot{m}_{Ref.}(h_{8i} - h_7)/\eta_{com.refrigeration}$	Power consumption of refrigeration compressor	(22)
$\dot{W}_{E.T.} = \dot{m}_{ref} \cdot (h_9 - h_6) \cdot \eta_{E.T.}$	Power generation of refrigeration expander turbine	(23)
$\dot{W}_{net} = \dot{W}_{GT} - \dot{W}_{com.GT} - \dot{W}_{com.refrigeration}$	Net power generation of GT power plant	(24)
$\dot{m}_{seawater}(h_{11} - h_{10}) = \dot{m}_{Ref.}(h_8 - h_9)$	Energy balance in condenser	(25)
$\dot{m}_{air} \cdot C_p \cdot (T_1 - T_2) = \dot{m}_{Ref.}(h_7 - h_6)$	Energy balance in evaporator	(26)

production increases sharply as T_{11} increases, consequently it can be said that the effect of T_{11} is more significant than T_2. It can be obvious from Fig. 3 that the maximum freshwater production is 101 kg/s as the system operates based on conditions specified in Table 1. Using economic model presented in Table 4, UPC of freshwater is calculated by 1.67 $\$/m^3$.

3.2. The new system

In this system, there is a thermal coupling between the GT power plant and the RO system indirectly, using refrigeration system. During the cooling process of intake air of GT compressor, the seawater temperature increases. With variations of T_2 and T_{11} in their studied ranges, value of preheated seawater ($\dot{m}_{11}$) and net power generation of power plant ($\dot{W}_{net}$) are changed. The power consumption of RO system to desalinate the preheated seawater is not always equal to the net power generation. Fig. 4 shows variations of preheated seawater and required preheated seawater to use net power generation with variations of T_2 and T_{11}. The continued lines represent the preheated seawater values by waste heat recovery of condenser, and interrupted lines indicate the required preheated seawater values to use net power generation of GT power plant. Therefore, wherever there is not contact between continued and interrupted lines, the values of preheated seawater and required preheated seawater are not equal, and where the continued and interrupted lines have contact, the values of preheated seawater and required preheated seawater are equal. Based on preheated seawater values by waste heat recovery and required preheated seawater values to use net power generation, the new system is studied in three regions: region I, preheated seawater values are less than the required preheated seawater values (there is not any contact between continued and interrupted lines); region II, preheated seawater values are equal to the required preheated seawater values (the continued and interrupted lines have contact together); region III, preheated seawater values are greater than the required preheated seawater values

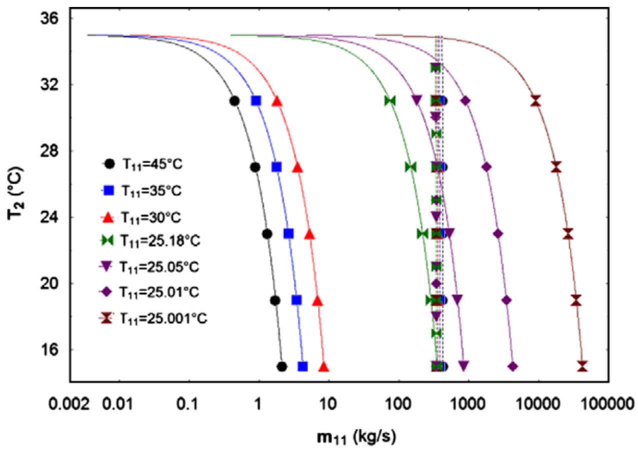

Fig. 4. Effects of T_{11} and T_2 on preheated seawater values for the new system.

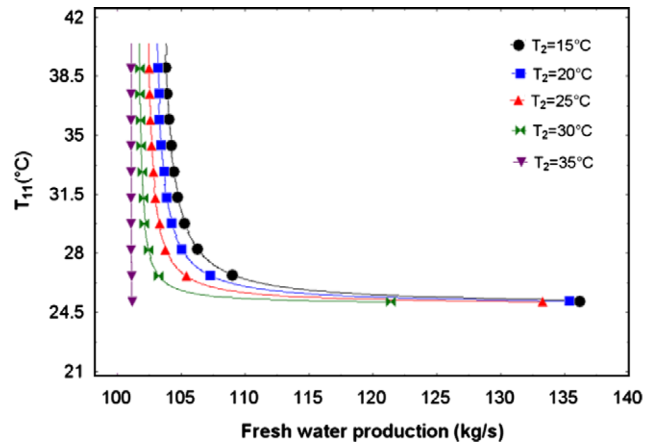

Fig. 5. Effects of T_{11} and T_2 on freshwater production for the new system (region I).

(there is not any contact between continued and interrupted lines).

3.3. Region I

This region includes the whole of preheated seawater temperature curves of $25.18°C < T_{11} \leqslant 45°C$ and part of preheated temperature curves of $25°C \leqslant T_{11} \leqslant 25.18°C$. As shown in Fig. 4 in this region, the preheated seawater values are less than the required preheated seawater values to use the net power generation of GT power plant. It means that the net power generation is greater than the required power of RO system to desalinate the preheated seawater. Additional power generation is used to operate the RO system unit 2. Therefore, two RO units are used to produce freshwater. Since the total waste heat of condenser is recovered to preheat the intake seawater of RO system unit 1, the feed water in RO unit 2 is not preheated. It is apparent from Fig. 4 that the intake air compressor can be cooled until 15°C when the seawater preheated temperature range is $25.18°C \leqslant T_{11} \leqslant 45°C$. Fig. 5 shows variations of fresh water production with variations of T_2 and T_{11} when the system operates in region I. It can be obvious that the maximum freshwater production is 136.2 kg/s as the seawater is preheated until 25.19°C and the intake air temperature is cooled until 15°C. Using economic equations presented in Table 4, UPC of freshwater was calculated by 1.32 $/m^3 when the system operates with maximum freshwater production.

3.4. Region II

As shown in Fig. 4, this region includes the intersection points of preheated seawater temperature curves (continued lines) and required preheated seawater temperature curves (interrupted curves) in the temperature range of $25°C \leqslant T_{11} \leqslant 25.18°C$. In intersection points, preheated seawater values are equal to the required preheated seawater values. It means that when the system operates in region (II), the net power generation is equal to the required power of RO system to desalinate the preheated seawater. Therefore, one RO unit is used to desalinate the preheated seawater and applied net power generation of GT power plant. Fig. 6 shows variation of freshwater production with variation of T_{11} when the system operates in region II. It can be obvious that the maximum freshwater production is 106 kg/s as the seawater temperature increases to 25.18°C and the intake air temperature decreases to 15°C. Using economic equations presented in Table 4, UPC of freshwater was calculated by 1.61 $/m^3 with maximum freshwater production.

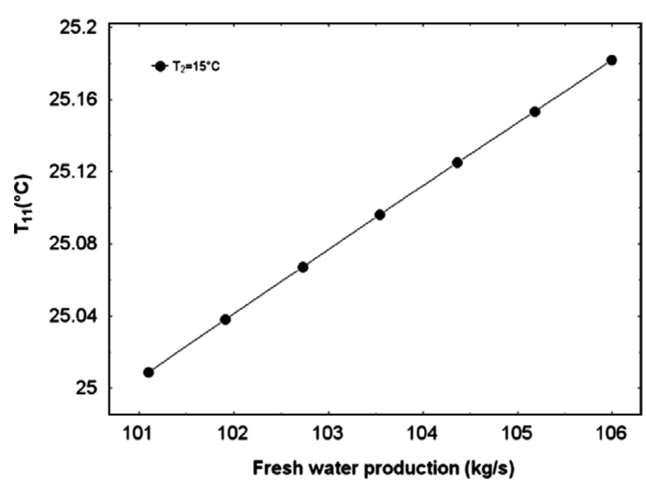

Fig. 6. Effects of T_{11} and T_2 on freshwater production for the new system (region II).

Table 5
Equations for economic modeling of the RO

Equation	Describe	
$\mathrm{CC_{swip}} = 996 \cdot Q_f^{0.8}$	Seawater intake and pretreatment capital cost	(27)
$\mathrm{CC_{pu}} = \frac{Q_f}{24 \cdot 450}(393000 + 10710 \cdot P_f \cdot 1.01325)$	Pump cost	(28)
$\mathrm{CC_{ERT}} = \frac{Q_c}{24 \cdot 450}(393000 + 10710 \cdot P_c \cdot 1.01325)$	ERT cost	(29)
$C_{mem.} = 1000$	Membrane cost	(30)
$C_{eq} = \mathrm{CC_{swip}} + \mathrm{CC_{pu}} + \mathrm{CC_{ERT}} + C_{mem.}$	Total equipment cost	(31)
$\mathrm{CC_{installation}} = 0.2 \cdot C_{eq}$	Installation cost	(32)
$\mathrm{CC_{site}} = 0.25 \cdot \mathrm{DCC}$	Site development cost	(33)
$\mathrm{CC_{land}} = 0$	Land cost	(34)
$\mathrm{DCC} = C_{eq} + \mathrm{CC_{installation}} + \mathrm{CC_{site}} + C_{land}$	Direct capital cost	(35)
$C_{fr} = 0.05 \cdot \mathrm{DCC}$	Overhead freight cost	(36)
$C_{con} = 0.15 \cdot \mathrm{DCC}$	Construction cost	(37)
$C_{ow} = 0.1 \cdot \mathrm{DCC}$	Owner cost	(38)
$C_{co} = 0.1 \cdot \mathrm{DCC}$	Contingency cost	(39)
$\mathrm{ICC} = C_{fr} + C_{co} + C_{ow} + C_{con}$	Indirect capital cost	(40)
$\mathrm{TCC} = \mathrm{ICC} + \mathrm{DCC}$	Total capital cost	(41)
$\mathrm{ACC} = \mathrm{TCC} \cdot Z$	Annual capital cost	(42)
$Z = \frac{i(i+1)^n}{(i+1)^n - 1}$	Amortization factor	(43)
$C_{Energy} = \dot{m}_{fuel} \cdot C_{fuel} \cdot 24 \cdot f \cdot 365$	Energy cost	(44)
$C_{rpm} = 0.2 \cdot C_{mem}$	Membrane replacement cost	(45)
$C_{rpp} = 0.1 \cdot CC_p$	Pump replacement cost	(46)
$C_{rpe} = 0.1 \cdot CC_{ERT}$	ERT replacement cost	(47)

(*Continued*)

Table 5 (*Continued*)

Equation	Describe	
$TRC = C_{rpm} + C_{rpp} + C_{rpe}$	Total replacement cost	(48)
$C_{chemical} = Q_f \cdot 365 \cdot f \cdot 0.018$	Chemical cost	(49)
$C_{maintenance} = 0.02 \cdot ACC$	Maintenance and spare parts	(50)
$C_{insurance} = 0.005 \cdot ACC$	Insurance cost	(51)
$C_{labor} = 365 \cdot \gamma \cdot f \cdot Q_p$	Labor cost	(52)
$AOC = C_{Energy} + TRC + C_{chemical} + C_{maintenance} + C_{insurance} + C_{labor}$	Annual operating cost	(53)
$TAC = AOC + ACC$	Total annual cost	(54)
$UPC = \frac{TAC}{Q_{annual-freshwater}}$	Unit product cost	(55)

3.5. Region III

As shown in Fig. 4, this region includes the parts of preheated temperature curves of 25°C $\leqslant T_{11} \leqslant$ 25.18°C placed in the right side of required preheated temperature curves. In this region, the preheated seawater values are greater than the required preheated seawater values. It means that the net power generation is less than the required power of RO system unit 1 to desalinate the preheated seawater. Therefore, additional preheated seawater is rejected back to the sea. It is apparent from Fig. 4 that the intake air compressor can be cooled until 15°C in this region. Fig. 7 shows variations of freshwater production with variations of T_2 and T_{11} when the system operates in region III. It can be obvious that the freshwater production can be increased to 103.3 kg/s as the seawater temperature increases from 25 to 25.17°C and the intake air temperature decreases from 35 to 15 °C. Using economic equations presented in Table 4, UPC of freshwater is calculated by 1.64 $/m^3 when the system operates with maximum performance.

3.6. Comparison of systems

The results of systems optimization in order to select the best system with maximum freshwater production are summarized in Table 6. According to Table 6, the maximum freshwater production by the system presented in Fig. 1 is 101 kg/s with UPC of freshwater 1.67 $/m^3. Also, the maximum freshwater production by the system presented in Fig. 2 when operated in regions I, II, and III is 136.2, 106, and 103.3 kg/s with UPC of freshwater 1.32, 1.61, and 1.64 $/m^3, respectively. From Table 6, it can be concluded that the system operated in regions I, II, and III can increase the freshwater production by 26, 4.7, and 2.2% and decrease the UPC of freshwater by 21, 3.6,

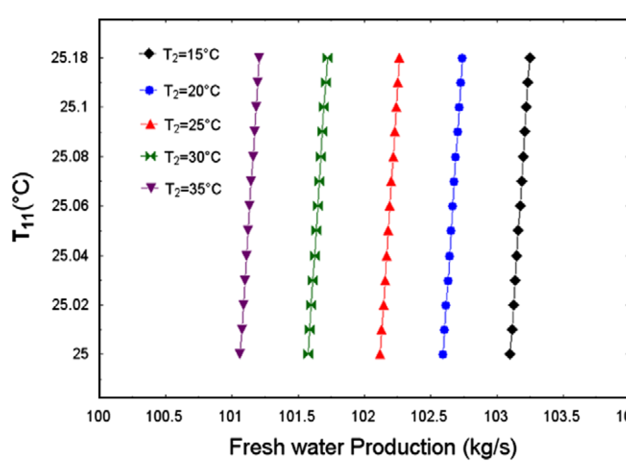

Fig. 7. Effects of T_{11} and T_2 on freshwater production for the new system (region III).

Table 6
Comparison of freshwater production and UPC with the base system and the new system

	Fresh water production (kg/s)	UPC of freshwater ($/m^3)
The base system	101	1.67
The new system (region I)	136.2	1.32
The new system (region II)	106	1.61
The new system (region III)	103.3	1.63

and 1.8%, respectively, as compared to the base system presented in Fig. 1. Among the investigated systems, the system presented in Fig. 2 which operates in region (I) is suggested to be the best system to couple the RO and GT power plant in order to maximize freshwater production (see Table 6).

4. Conclusion

In this study, two systems which couple an RO system and a GT power plant in order to produce freshwater have been analyzed and optimized. The following conclusions can be drawn:

(1) In this study, a new structure coupling an RO system and a GT power plant was modeled and optimized in order to maximize freshwater production.
(2) For the system with a refrigeration cycle, three structures based on preheated seawater values and net power generation were investigated: (i) a system with two RO units, (ii) a system with one RO unit, and (iii) a system with one RO unit and the rejection of additional preheated seawater back into the sea.
(3) The system with two RO units was suggested as the best system to couple an RO and a GT power plant and can save 21% in the production cost of 1 m^{3}of freshwater and increase freshwater production by 26% as compared to the base system.

Acknowledgments

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Nomenclature

A	—	membrane pure water permeability, kg/m^2 s pa
ACC	—	annual capital cost, $/yr
AOC	—	annual operation cost, $/yr
B	—	membrane salts permeability, kg/m^2 s
CC	—	capital cost, $
C.C.	—	combustion chamber
Com.	—	compressor of GT
C_p	—	specific heat capacity, kJ/kg °C
C	—	cost
DCC	—	direct capital cost, $
E.T.	—	expander turbine
E.R.T.	—	expander recovery turbine
FF	—	fouling factor
F	—	plant load factor
GT	—	gas turbine
h	—	enthalpy, kj/kg
ICC	—	indirect capital cost, $
i	—	interest
J	—	mass flux through the membrane
LHV	—	low heat value
$\dot{m}$	—	mass flow rate, kg/s
mem.	—	membrane
n	—	life cycle of plant, yr
P	—	pressure, kpa
Pu	—	pump
Q	—	flow rate, m^3/d
Ref.	—	refrigeration
RO	—	reverse osmosis
Rs	—	membrane salt rejection, %
Ru	—	universal gases constant, J/k/mol
R	—	water recovery rate, %
S	—	area, m^2
T	—	temperature, °C
TAC	—	total annual cost, $
TCC	—	total capital cost, $
TCF	—	temperature correction factor
TRC	—	total replacement cost, $
U	—	average velocity, m/s
UPC	—	unit product cost, $/m^3
$\dot{W}$	—	power, kw
X	—	salt concentration, ppm
Z	—	amortization factor
Subscripts		
B	—	bulk
C	—	concentrate
Co	—	contingency
Con	—	construction
eq.	—	equipment
F	—	feed water

Fr	—	overhead freight
Ow	—	owner
P	—	permeate
ref.	—	refrigerant
Rpe	—	ERT replacement
Rpm	—	membrane replacement
Rpp	—	pump replacement
S	—	salt
swip	—	seawater intake and pretreatment
W	—	wall
Annual-freshwater	—	freshwater production per year, m^3/yr

Greek

γ	—	heat capacity ratio
η	—	efficiency, %
π	—	osmotic pressure, kpa
ρ	—	density, kg/m^3
ΔP	—	transmembrane pressure, kpa
$\Delta\pi$	—	transmembrane osmosis pressure, kpa

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