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Modeling and Investigation of Wind Turbine Integrated System in Terms of Thermodynamic Perspective for Power, Heating, Cooling and Clean Water Production

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Abstract: In this work, a new wind turbine supported power, heating, cooling and fresh water generation plant is introduced, and thermodynamic performance evaluation is conducted. The examined system includes wind turbines, vapor compression cooling (VCC) system, which operates R744 refrigerants, and reverse osmosis (RO) desalination system. Also, the key objective of this paper is to meet the electricity need of the VCC's compressor and the RO's pumps, with the wind turbines and then to send the remaining electricity to the place of use. The overall thermodynamic analyses are executed with the Engineering Equation Solver (EES) computer program. The consequences of this paper indicate the total energy and exergy efficiency are figured as 0.66 and 0.61, respectively. In addition, fresh water production capacity of the suggested system is 60 kgs^{-1}.

Rüzgâr Türbini Entegre Sisteminin Güç, Isıtma, Soğutma ve Temiz Su Üretimi için Termodinamik Açıdan Modellenmesi ve İncelenmesi

Anahtar Kelime:
Soğutma,
ısıtma,
temiz su,
enerji,
ekserj,
rüzgar türbini

Öz: Bu çalışmada, rüzgâr türbini destekli güç, ısıtma, soğutma ve tatlı su üretim tesisi kombine bir sistemi önerilmiş ve termodinamik performans değerlendirmesi yapılmıştır. Önerilen bu çalışma, rüzgâr türbini, R744 soğutkanlı buhar sıkıştırmalı soğutma sistemi (VCC) ve ters ozmos (RO) alt sistemlerinden oluşmaktadır. Ayrıca bu çalışmanın temel amacı, buhar sıkıştırmalı soğutma sisteminin kompresörü ve ters su üretim sisteminde ki pompaların elektriksel güç ihtiyaçları rüzgâr türbininden elde edilen güç ile karşılanmasıdır. Tüm sistemin termodinamik hesaplamalarında EES adlı program kullanılmıştır. Önerilen sistemin, genel enerji ve ekserji verimi sırasıyla 0.66 ve 0.61 olarak hesaplanmıştır. Ayrıca, önerilen temiz su üretim sistemi ile 60 kg/s temiz su üretimi gerçekleşmiştir.

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1. Introduction

The global energy requirement in the world has been dramatically increase in recent years. To meet the increasing energy demand, it is very important to environmentally being, sustainable and use of the economical energy systems instead of fossil fuels. Fossil fuels are widely used in energy production systems and this causes many adverse environmental impacts[1]. It is evident that these fuels are not sustainable, and as a result of combustion, cause unresolved environmental problems such as acid rain and global warming. Therefore, it is inevitable that renewable energy integrated plants are more preferred to combat environmental problems.

Renewable energy resources are more attractive than conventional fuels for clean energy generation[2]. On the other hand, multigeneration systems can be defined to produce various useful outputs for example cooling, heating, power, fresh water and etc. with the same energy input. These integrated systems stand out for the aim of more efficient use of energy resources. Also, these systems have many advantages such as low cost, low energy, and exergy losses, high performance and low environmental emissions[3,4].

Wind energy, a renewable energy source, is an important resource for a sustainable future for reducing fossil-based fuel use. Also, this energy source can be defined as a continuous energy source, unlike solar energy. Integrated use of non-fossil energy sources, such as solar and wind energy, are also known to be important for

sustainable energy production. Therefore, scientists have done a number of studies on multigeneration systems subjects in recent years.
Luqman et al. [5] have investigated a thermodynamic assessment of an oxy-hydrogen combustor integrated energy production cycle. The total energetic and exergetic performance of their suggested plant are 50% and 34%, respectively. Sezer and Koc[6] have proposed a design and performance assessment of the solar, wind and osmotic power cycle for multipurpose. Their proposed system that produces hydrogen, oxygen, fresh water, and refrigeration along with electricity. The whole energy and exergy efficiency of their work are determined as 73.3% and 30.6%, respectively. Sorgulu and Dincer[7] have examined both solar and wind combined cycle for power, cooling, heating and hydrogen generation. They conducted a comprehensive thermodynamic investigation of the integrated plant and the hydrogen production rate is found as 0.035 kgs^{-1}. Devrim and Bilir[8] have studied the performance evaluation of wind, solar and fuel cell based combined plant. Their suggested system that including 3 kW, 3.4 kW and 1.2 kW wind turbine (WT), electrolyzer and photovoltaic panel. Their study results showed that the specified 5-hour electrolysis process could be carried out when using the photovoltaic panel area of 17.97 m^2, except November. Sezer et al.[9] have studied a solar and wind energy combined plant, which include reheat Rankine cycle, absorption cooling and thermal storage. Their proposed system's performance is found as 61.3% and 47.8%, respectively, based on energetic and exergetic efficiencies. Ishaq and Dincer [10] have suggested wind energy supported plant for hydrogen and ammonia generation. Their modeled plant's performances are calculated as 40.5% and 42.3%, respectively, in terms of energetic and exergetic efficiencies. Also, in the literature, there are numerous papers that the combined multigeneration system based on different renewable energy sources [11–14].

In this work, a WT integrated plant is suggested for producing power, cooling, heating and desalinated water generation. In addition, the main aim of the paper is to meet the electrical energy needed by the RO unit and VCC system with wind turbines, which are renewable energy sources. In this regard, a detailed thermodynamic analysis is investigated for wind energy-based desalination unit and VCC system. Additionally, the energetic and exergetic analyses, and also irreversibility and locations of the overall cycle are studied. The impact of some important limitations on system performance are discussed and presented graphically. The key purposes of this paper are listed as below;

- to examine the clean water production rate from the seawater
- to meet the electrical power requirements in the subsystems with WT
- investigating the performance and irreversibility rate of the modeled cycle and sub-systems
- to study the cooling and heating loads with VCC and power production rate with WT.

2. System Definition and Analyses

As seen in Fig.1, the suggested combined cycle that including a WT for power generation, a VCC for heating and cooling loads and RO unit for desalinated water production. In this proposed study, it was designed with inspiration from the works of Luqman et al. [5]. The general aim of this study is to meet the energy requirements of VCC and reverse osmosis (RO) systems with WT.

The R744 refrigerant VCC is used to meet heating and cooling loads. This subsystem consists of a compressor, a gas cooler, a throttle valve and an evaporator. The gas cooler is cooled by water and the heated water at point 5 is used to heat the building, which also the gas cooler is working as a heat exchanger. While the cooling load takes place in the evaporator part, the heating load is made with hot water coming from the gas cooler. the R744 refrigerant is preferred in this subsystem, because of its thermodynamic and environmental properties. Also, the RO method is preferred to obtain desalinated water from seawater. It was inspired by some of the studies in the literature to design the RO unit[15,16]. In general, in this study, it is designed that the electrical need of the VCC compressor, as well as the electrical need of the RO's LPP and HPP pumps, is to meet with WT. At point 1, where is the compressor inlet, the R744 refrigerant is assumed as the saturated vapor.

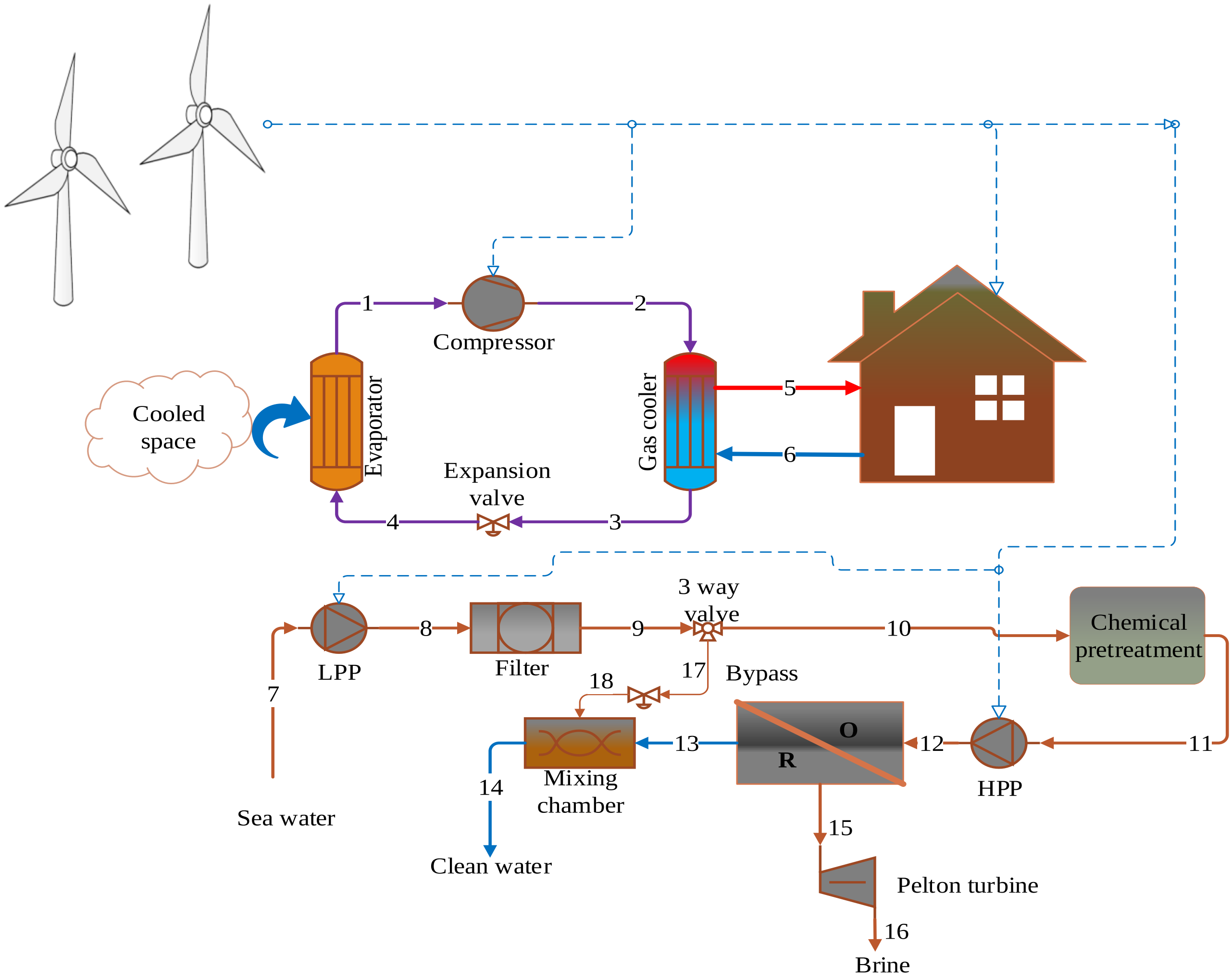

Fig.1 Schematic presentation of wind turbine combined system

The energy performance assessment of any thermal plant alone is not enough. Besides, exergy analysis that is related to thermodynamic second laws and offers many advantages. For more realistic results, energy and exergy analyzes should be carried out together. The thermodynamic analysis of a system is usually based on mass, energy, entropy and exergy balance relations[17–19].

The general thermodynamic equilibrium equations can be defined as;

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}\left(h_{in} + \frac{V_{in}^2}{2} + gZ_i\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}\left(h_{out} + \frac{V_{out}^2}{2} + gZ_{out}\right) \tag{2}$$

$$\sum \dot{m}_{in}s_{in} + \dot{S}_{gen} + \sum_{in}\left(\frac{\dot{Q}_k}{T_k}\right) = \sum \dot{m}_{out}s_{out} + \sum_{out}\left(\frac{\dot{Q}_k}{T_k}\right) \tag{3}$$

$$\sum \dot{m}_{in}ex_{in} + \dot{E}x^{\dot{Q}} + \dot{E}x^{\dot{W}} = \sum \dot{m}_{out}ex_{out} + \dot{E}x^{\dot{Q}} + \dot{E}x^{\dot{W}} + \dot{E}x_{dest} \tag{4}$$

Here, $\dot{Q}, \dot{W}$, h, s characterizes the heat transfer rate, work rate, specific enthalpy, specific entropy, respectively. Furthermore, the physical exergy, heat and work exergy rates can be written as;

$$ex_{ph} = h - h_o - T_o(s - s_o) \tag{5}$$

$$\dot{E}x_Q = \left(1 - \frac{T_o}{T}\right)\dot{Q} \tag{6}$$

$$\dot{E}x_W = \dot{W} \tag{7}$$

WT power production rate can be computed as given below [20,21];

$$\dot{W}_{wt} = \frac{1}{2}\eta_{wt}\rho_{air}A_{wt}C_{p,wt}V^3 \quad (8)$$

Here, $\dot{W}_{wt}$ is the WT power, η_{wt} is the WT efficiency, ρ_{air} is the density of air, and V is the wind speed[2]. The WT energy input rate is written as below;

$$Input = \frac{1}{2}\rho_{air}A_{wt}C_{p,wt}V^3 \quad (9)$$

Also, the consumed electrical power by the VCC's compressor and RO's LPP and HPP pumps can be calculated as below based on the thermodynamic first law.

$$\dot{W}_{compressor} = \dot{m}_1(h_2 - h_1) \quad (10)$$

$$\dot{W}_{LPP} = \dot{m}_7(h_8 - h_7) \quad (11)$$

$$\dot{W}_{HPP} = \dot{m}_{11}(h_{12} - h_{11}) \quad (12)$$

$$\dot{W}_{pelto\_turbine} = \dot{m}_{15}(h_{15} - h_{16}) \quad (13)$$

The net power generation of the modeled system can be written as below;

$$\dot{W}_{net,overall} = \dot{W}_{wt} + \dot{W}_{pelto\_turbine} - \dot{W}_{compressor} - \dot{W}_{LPP} - \dot{W}_{HPP} \quad (14)$$

$$\dot{Q}_{heating} = \dot{m}_2(h_2 - h_3) = \dot{m}_5(h_5 - h_6) \quad (15)$$

$$\dot{Q}_{cooling} = \dot{m}_1(h_1 - h_4) \quad (16)$$

The COP_{en} and COP_{ex} of the VCC system can be determined as;

$$COP_{en,heating} = \frac{\dot{Q}_{heating}}{\dot{W}_{compressor}}, COP_{ex,heating} = \frac{\dot{m}_2(ex_2 - ex_3)}{\dot{W}_{compressor}} \quad (17)$$

$$COP_{en,cooling} = \frac{\dot{Q}_{cooling}}{\dot{W}_{compressor}}, COP_{ex,cooling} = \frac{\dot{m}_1(ex_1 - ex_4)}{\dot{W}_{compressor}} \quad (18)$$

The general energy and exergy equilibrium equation of the overall cycle can be illustrated as;

$$\eta_{overall} = \frac{\dot{W}_{net,overall} + \dot{Q}_{cooling} + \dot{Q}_{heating} + \dot{m}_{14}h_{14}}{Input + \dot{m}_7 h_7} \quad (19)$$

$$\psi_{overall} = \frac{\dot{W}_{net,overall} + \dot{Ex}^{Q}_{heaxing} + \dot{Ex}^{Q}_{cooling} + \dot{m}_{14}ex_{14}}{Input + \dot{m}_7 ex_7} \quad (20)$$

3. Results and Discussion

In this part of the work, a comprehensive thermodynamic evaluation is conducted for WT combined with VCC and reverse osmosis cycle. The key aim of this paper is to meet the energy demands of the VCC compressor and RO's LPP and HPP pumps with WT, and also the power, cooling, heating and fresh water production. To determine of the thermodynamic calculation of this paper, some assumptions have been made as follows;

- The WT power coefficient is assumed as 60% [2].
- The heat loss and pressure drops are neglected
- The R744 refrigerant is assumed as statured liquid at input of the VVC compressor at state 1
- The reference temperature is 20 °C and reference pressure is 101.325 kPa.
- The sea water inlet temperature at point 7 assumed as 30 °C.
- The average wind speed is 5.2 m/s.

The thermodynamic performance results that is energetic and exergetic efficiency are specified in Table 1. As shown this Table, the energetic efficiency of the VCC for heating and cooling load are determined as 3.584 and 2.584, respectively. Also, the exergetic performance of the WT and RO unit are computed as 0.54 and 0.98, respectively. Lastly, the energetic and exergetic performance of the suggested study are 0.66 and 0.61, respectively.

Table 1. Thermodynamic results of the whole cycle and its subsystems

System and subsystems	Energy efficiency	Exergy efficiency
Wind turbine (WT)	0.60	0.54
VCC_for heating	3.584	0.92
VCC_for cooling	2.584	0.89
RO unit	0.63	0.98
Overall system	0.6621	0.61

The modelled plant is developed to beneficial productions such as cooling, heating, fresh water and power with use the sustainable method. The useful commodities of the suggested plant are computed and tabulated in Table 2. As shown in Table 2, in this study, approximately 60 kg / s of fresh water is obtained with about 100 kg/s sea water input. Also, the modeled system outputs can be ranking as, the net power production is 105.8 kW, the heating load 120.3 kW, and also the cooling load is 86.76 kW.

Table 2. The useful outputs of the proposed system

Net Power production (kW)	105.8
Heating capacity (kW)	120.3
Cooling capacity (kW)	86.76
Fresh water rate (kg/s)	60

Generally, the working fluid is superheated at the evaporator exit to prevent the liquid from reaching the compressor, in cooling systems. Therefore, the superheating term is very important parameter to design the cooling systems. Fig. 2 shows that the variation of the energetic performance coefficient (COP_{en}) and exergetic performance coefficient (COP_{ex}) of the VCC with changing the super heating temperature. In the VCC system, COP_{en} for heating and cooling loads increased about 1 with increment in the superheating temperature from 0 to 10 ^{o}C. With this increase in superheating temperature, it is clearly seen that COP_{en} increased from about 2.2 to about 3.3, for cooling application. The reason for this increase is that the energy consumed by the compressor decreases as a result of the superheating of the working fluid at the compressor inlet. On the other hand, COPex for heating and cooling loads decreased which is due to the fact that increase irreversibility.

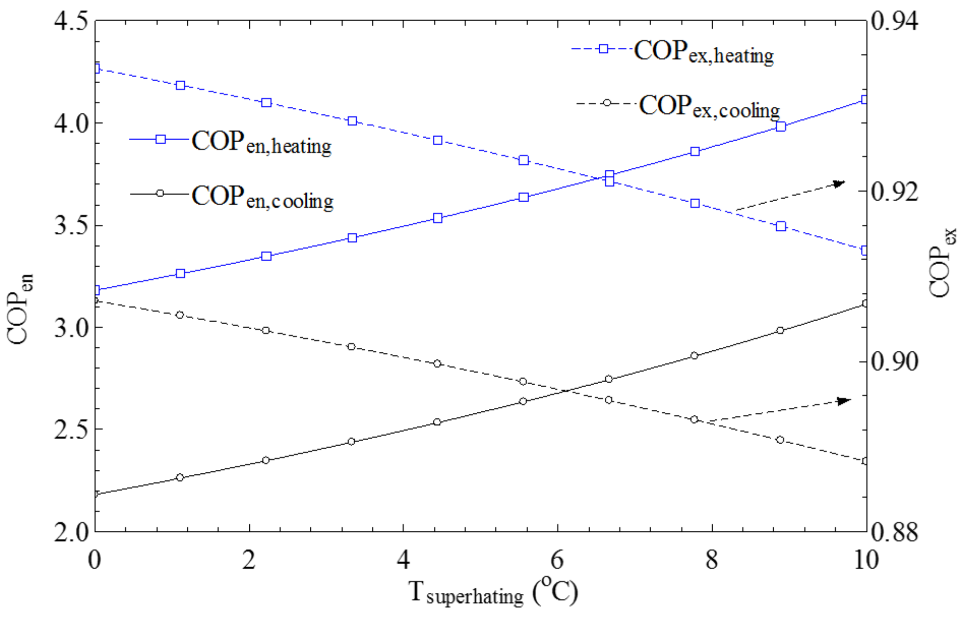

Fig.2. Variation of the COP_{en} and COP_{ex} of the VCC with changing the superheating temperature.

The influence of the dead state temperature on the WT power production rate and on the air density is demonstrated in Fig.3. It can be understood that the WT power production and air density is decreased with the rise in the dead point temperature. As the dead state temperature increases, the air density decreases and then the electrical power production rate obtained from the planned cycle also decreases, according to equation 8. It is noted that the power production rate of WT is directly proportional to the air density.

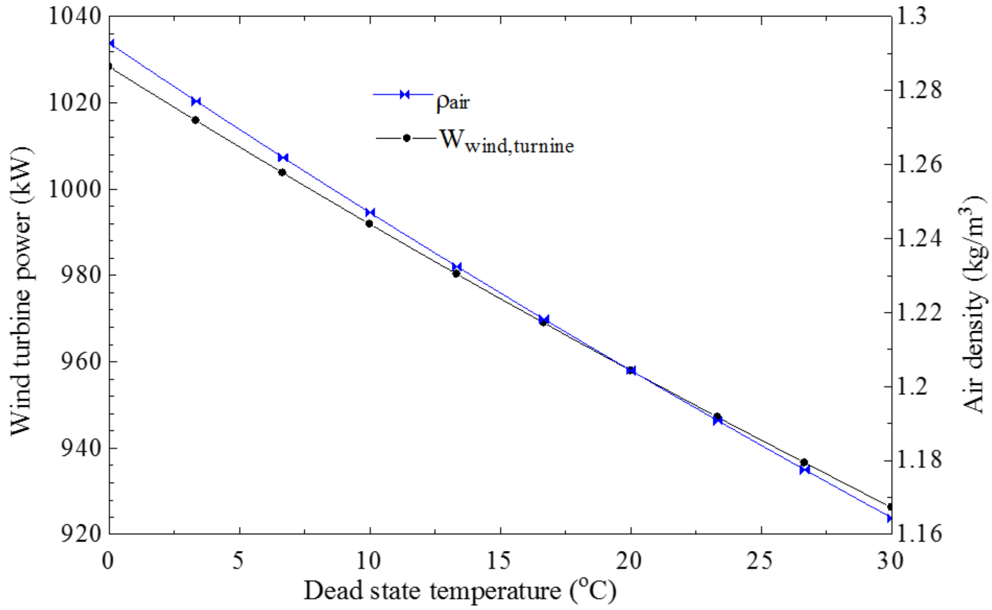

Fig.3. Variation of the density of air and power generation with changing the dead state temperature

Fig.4 expressions that the influence of chancing reference temperature on the overall plant's performance. The modeled plant's energy and exergy efficiency both drop with rising in ambient temperature. The cause for this condition is that the air density declines as the ambient temperature rises and thus drop in WT power production rate. System performance decreases correctly with the decrease of power generation produced. Looking at Eq. 8 above, this is clearly seen that the air density is direct proportion with the WT power production. In addition, the results showing the impact of environmental temperature change on the recommended study performance is consistent with Ozlu and Dincer [2] work results.

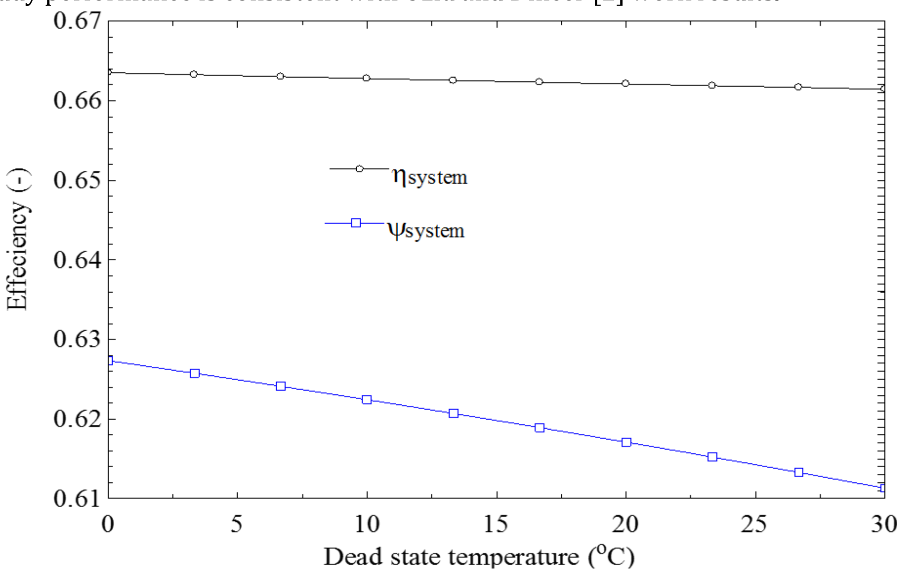

Fig.4. System efficiency versus with dead state temperature

The influence of the seawater temperature on energetic efficiency of the RO unit and planned system is seen in Fig.5. As clearly displayed in Fig.5, the rise in the seawater temperature has adverse effect of the RO unit and whole cycle efficiency. The increment in the seawater inlet temperature of approximately 20 °C reduces the energy performance of the RO system by about 6%.

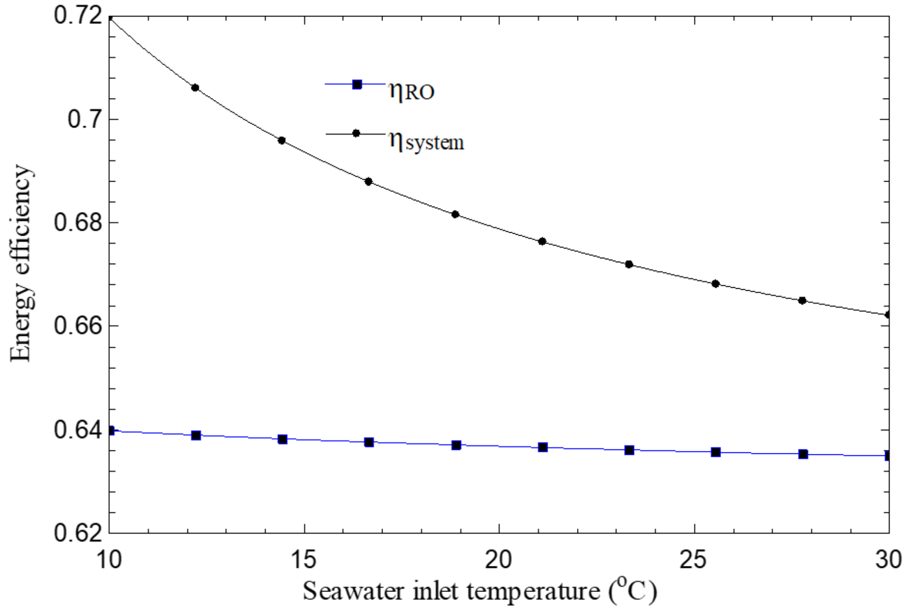

Fig.5. System and RO unit energy efficiency versus with seawater temperature

For this study, the wind speed is assumed that is to 5.2 m/s, at 50 m. As the elevation increases, the wind speed increases and therefore more power can be produced. So, Figs. 6 and 7 illustrate the impacts of the wind speed on the power generation rate, total irreversibility, and overall system performance. Increment in the wind speed from 5 to 12 m/s, the net power production rate and irreversibility increased, as shown in Fig.6. On the other hand, in this increase range of wind speed, the energy performance of the total system rises but exergy efficiency decreases, as in Fig.7. With this graph, the cause for the decrease in exergy efficiency can be stated as the increase in the wind speed and the total exergy destruction rate of the WT increase.

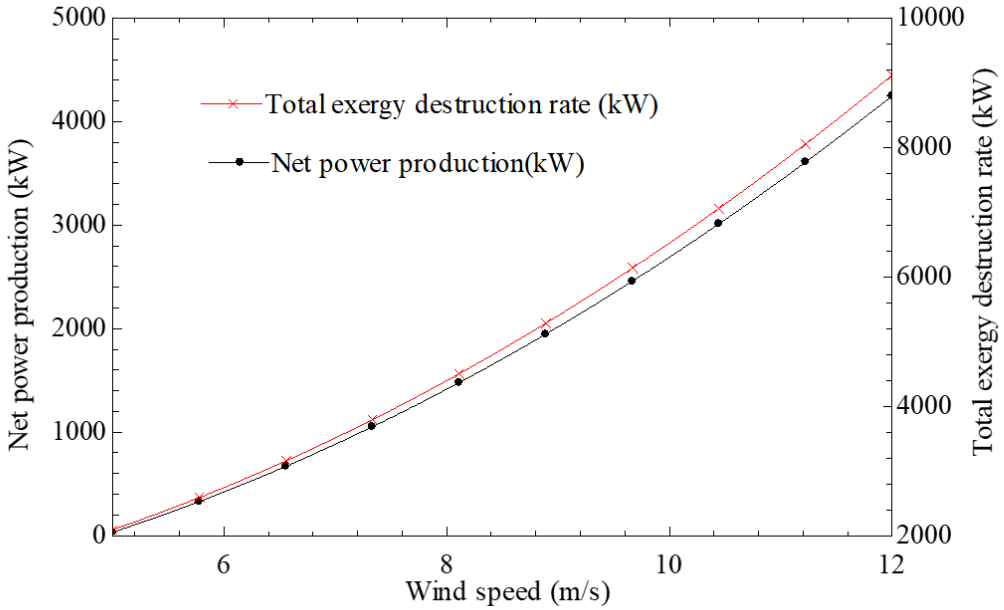

Fig.6. Influence of the wind speed on the net power production and total exergy destruction rate

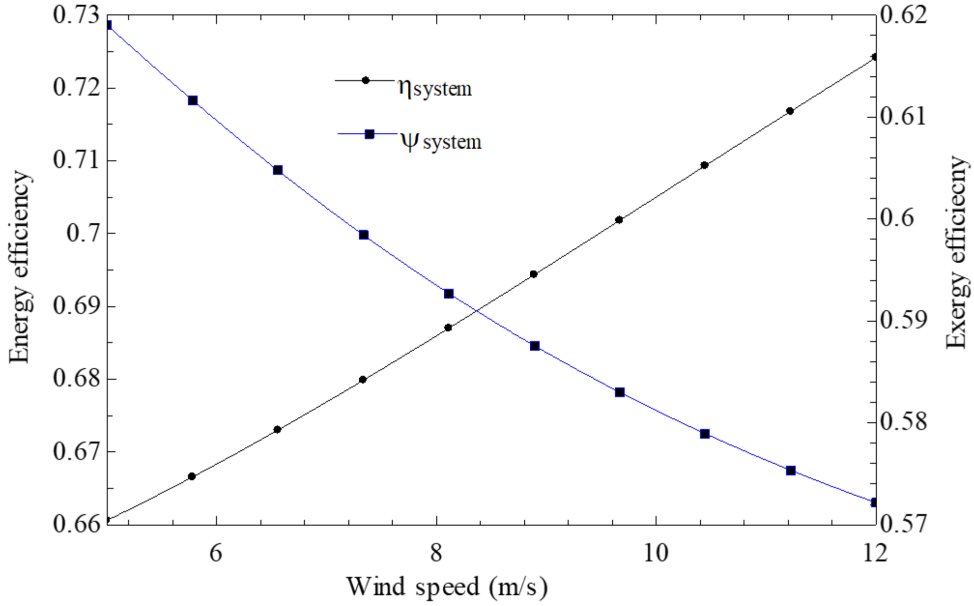

Fig.7. Influence of the wind speed on the total plant's performance

Finally, Fig.8 explains that the impact of the RO unit efficiency on the freshwater production and total energetic and exegetic performances of the system as well. It can be concluded that if the use of highly efficient RO unit, it will be produced more fresh water rate. Besides, it is clearly seen that the energy and exergy efficiency of the proposed cycle increases with the rise in clean water production. The cause for this rise graph can be stated as the direct proportional relationship between RO unit performance and clean water production.

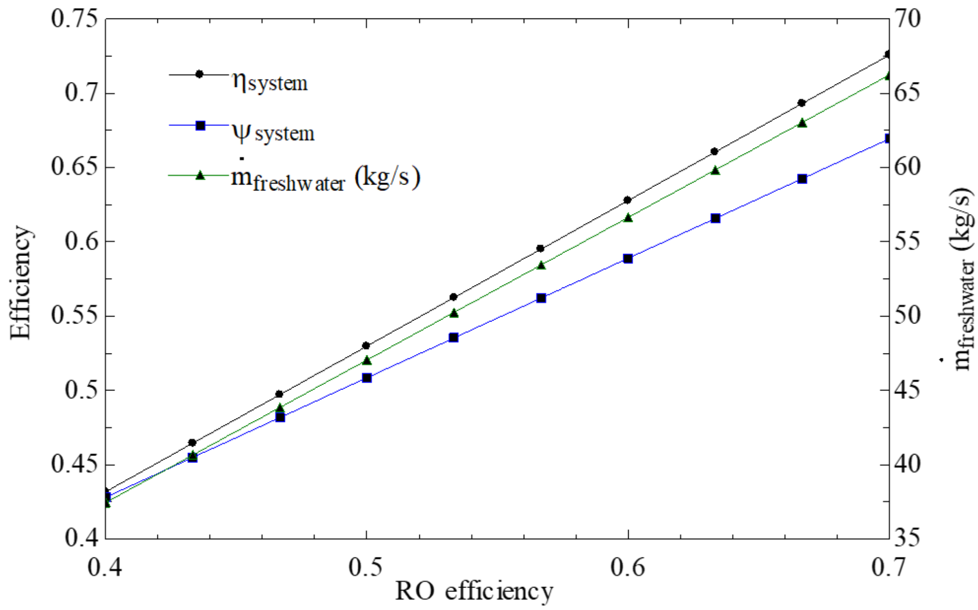

Fig.8. Variation of freshwater production rate and performance of the overall system with various RO unit efficiency.

4. Conclusion

The key purpose of this work is the examination of power, cooling, heating and fresh water generation, which is assisted WT. The generated power from the WT is designed to meet the requirements of the VCC system's compressor as well as the RO system's LPP and HPP pumps. The CO_2 refrigerant is used in the VCC as the working fluid because of its ODP and GWP values. Briefly, a system for heating, cooling, and electrical needs has been proposed with the support of the wind turbines, and comprehensive analysis has been made.

Results display that the desalinated water rate is calculated as 60 kg/s. Also, the heating and cooling capacities of the VCC sub-plant are 120.3 kW and 86.76 kW, respectively. The net power production rate of the suggested plant is 105.8 kW. Also, maximum irreversibility rate is shown in WT. The whole energy and exergy efficiency of the modelled cycle are to be 0.6621 and 0.61, respectively.

This paper shows that it is possible to the sustainable method for heating, cooling, clean water, and power generation, especially where wind speed is high at seaside. Considering that today most of the electricity request is fulfilled by natural gas or coal, thus sustainable and environmentally friendly technologies can be developed with different renewable energy supported systems.

Nomenclature

COP_{en}	energetic coefficient of performance
COP_{ex}	exergetic coefficient of performance
$\dot{Ex}$	rate of exergy (kW)
E	energy (kW)
ex	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
HPP	high pressure pump
LPP	low pressure pump
P	pressure (kPa)
RO	reverse osmosis
s	specific entropy (kJ/kg-K)
T	temperature (^oC)
VCC	vapor compression cycle
WT	wind turbine
$\dot{Q}$	heat transfer rate (kW)
$\dot{W}$	work rate (kW)
Greek letters	
η	energy/energetic efficiency
ψ	exergy/exergetic efficiency
Subscripts	
in	input
out	output
0	reference point

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