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Utilization of waste heat of a high-capacity wind turbine in multi effect distillation desalination: Energy, exergy and thermoeconomic analysis

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ABSTRACT

An integrated system in which the required steam of multi effect distillation (MED) desalination, used for producing potable water, is provided by using the waste heat of a high-capacity wind turbine (WT). This system is used in the areas with shortage of potable water supplies and high wind energy potential. In addition, energy, exergy and thermoeconomic analysis are performed. The results revealed that in the areas with average wind speed of 11 m/s, the waste heat in a 7580 kW WT is 231 kW at 140 °C. The produced steam at 100 °C and 101.3 kPa is enough to produce 45.069 m^3/day potable water, which is sufficient for the daily use of 4507 people if each person consumes 10 L. Furthermore, the findings indicated that the maximum exergy destruction and exergy destruction cost are related to the second effect of MED desalination. Also, the cost of potable water is estimated as 16.676 \$/m^3. Using the waste heat of the WT increases the exergy efficiency of the integrated system 7.34%. Considering the cost of potable water, average rate of return and payback period are estimated as 6.76% and 6.33 years, respectively.

1. Introduction

Scarcity of potable water is one of the most serious problems of many people in the world, especially in remote and coastal areas [1]. Desalination could be a feasible suggestion for solving this problem. However, producing potable water needs considerable capital investment cost (CIC) and energy. Most of the time, fossil fuels are used to provide the required energy of desalination units, although they are not recommended regarding the numerous problems such as pollution, shortages of resources, inaccessibility to remote areas and impossibility of transferring them to some distant areas. Renewable energies (RE) are designated as an appropriate alternative to fossil fuels because they are free, and also, they do not have environmental pollution [1], despite their remarkably high CIC. Considering the necessity of producing potable water in remote and dry areas and impossibility of using fossil fuels, the use of REs is the best option [1]. Employing RE, we need to choose a system which provides the necessary energy of producing potable water, and at the same time to be inexpensive in comparison with other systems. Wind energy (WE) is one of the REs that needs less CIC than other REs [2]. In addition, using of high-capacity wind turbines (WT) in off-grid areas is more economical due to less space occupancy and high production capacity [1,3,4]. On the other hand, thermal desalination methods are more suitable than membrane methods, regarding the quality of produced water [5].

As stated, it is essential to use WTs for providing energy in thermal desalination systems to reduce costs and supply potable water in remote and coastal areas with a significant population and high salinity levels in seawater.

The most common use of WE in a WT is the use of electrical and mechanical energy in the desalination systems. In [1,2] two methods were proposed to use WE to produce potable water. In the first method, the generated electric power by the WT is used in Electro Dialysis (ED), Reverse Osmosis (RO) and Motive Vapor Compression (MVC) desalination. In the second method, the mechanical force of the WT shaft was used in RO and MVC desalination. Forstmeier et al. [6] in their empirical research considered two conventional desalination units (MVC and RO) whose energy were provided by WT. The results revealed that energy consumption in RO is less than MVC, on the other hand, RO and MVC systems are suitable for the areas with accessibility and inaccessibility to the grid, respectively. In [7–9] WT were used to supply electric power in RO, MVC, and ED desalination systems. Tizen and Morris [7] compared RO and MVC desalination systems and indicated that for the inlet seawater of the desalination unit, both MVC and RO methods are suitable, but for water with low salt concentration, the usage of RO method is more prevailing. Intermitting WE is one of the problems of using WE in RO desalination system, because supplying continuous required energy of RO unit is necessary. To solve this problem, a battery bank is often used to save generated electricity

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produced by WTs at times when there is no power consumption. Another way to solve the problem of intermitting wind is to use a water storage tank. Bilstad et al. [10] carried out two pilot projects in which the needed energy of RO unit was provided by a WT. Both a water tank and a battery bank were examined. The findings revealed that use of a water tank is more economical than a battery bank. [11] did not use any energy storage system in their research, instead, they designed a control system to deal with the intermitting wind problem. Applying the control system, the maximum output of the RO unit was obtained. [12] used aquifer to store water. One of the advantages of this method is providing water for a long time (about one month) which is consumed when water is not produced. Another way to solve the intermitting WE problem is to use another RE along with WE. One of the solutions is the use of photovoltaic cells to absorb solar energy. [13,14] are researchers who investigated the use of combined WT and photovoltaic cells to produce potable water with the RO system. [13] concluded that the CIC in combined using photovoltaic cells and WT is lower than that of using photovoltaic cells alone. Some researchers focused on the economic analysis of integrating WT with desalination unit. [15] focused on designing a RO system and WT. Their results showed that the CIC is reduced if the design of the two systems is done with regard to the required water and energy. [16] examined the RO unit economically, and their findings indicated that climate conditions, nominal power of WT, salt concentration, desalination design, configuration, operating conditions and system capacity influence the system economy.

Unlike most studies that only considered electric power and mechanical energy of WT, some researchers used WTs to generate heat. [17,18] directly used WE to generate heat. In the first study, a new maritime lifesaving distiller was designed to produce potable water consumed for one person per day, without using any manpower. In this study, the diameter and length of the WT were about 0.15 and 0.35 m, respectively. Due to friction between the attached shaft to WT blades and the brakes installed around it, the mechanical energy of the WT is converted directly to the heat. By using of the same mechanism, [18] designed a system in which the produced heat is stored in a thermal energy storage system to produce steam in the Organic Rankine Cycle. In this way, it can be used for the days when there is no wind. Other researchers like [19,20] also indirectly used WE (using the generated electric power of WT) to produce heat. In both researches, WE provided the required power of a geothermal pump, and then the heat from the depths of the ground was used to heat the space or greenhouse uses.

The aforementioned research showed that using the WT electrical power has been the most prominent method used for producing potable water. In some other studies, the researchers used a mechanism to generate heat directly. Although high-capacity WTs generate significant heat due to the friction between mechanical parts including gears, bearing and due to electrical resistance in wire windings and control system, this heat is wasted without any use. [3,4,21,22] approximately calculated the amount of the waste heat in the Nacelle's equipment, which is variable due to the wind speed (WS). [21] estimated the waste heat of a 2 MW WT on the average between 95 and 125 kW, and they indicated that the waste heat of WTs is significant and this heat could be used for heating purposes. [22] assessed that the waste heat of a 8 MW WT is 571 kW and also in Tong's study [4] the waste heat of a 1.4 MW WT was calculated 65 kW.

As mentioned earlier, there is a significant amount of waste heat in the high-capacity WTs. However, in the previous studies, this heat has not been considered to produce potable water. In this work, the authors intend to use the thermally noticeable waste heat of a 7580 kW WT (Enercon-E126) at an area with strong wind (like WZ I,WZ II,WZ III and WZ IV, reported by ASCE 7) to produce the required steam in a multi effect distillation (MED) desalination system. For instance, an area with the annual average wind speed (AWS) of 11 m/s is shown in Fig. 1. More areas with annual AWS of above 11 m/s are shown in wind maps of ref. [23, 24]. Referring to the Enercon website, it is revealed that the

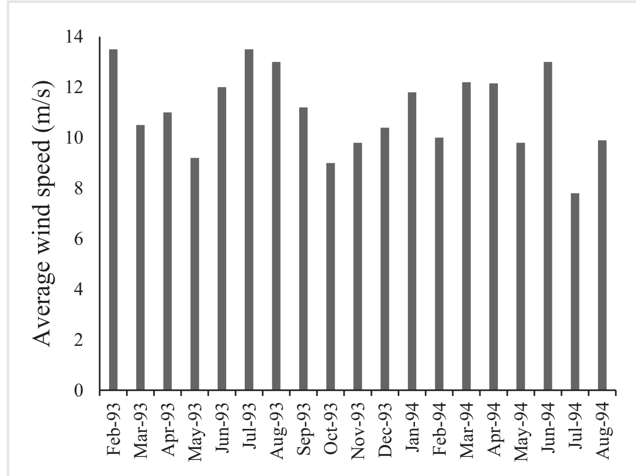

Fig. 1. Monthly average wind speed of Koudia Al Baida [27].

E-126/7580 WT is currently available and is being produced [25]. The WT which is studied in this work has not been used at a specific location. While the previous model of the high capacity WT of this company has been used extensively. The Enercon E126/7500 is the previous model of Enercon E126/7580. It has similar dimensions (hub height and swept area) and approximately the same capacity to the considered WT. According to ref. [26], the Enercon E126/7500 model has been used in Noordoostpolder (Netherlands), Diepenau (Germany), Potzneusiedl (Australia), Estinnes-au-Mont (Belgium), etc. It should be noted that the mentioned model (E126/7500) has not been produced anymore [26]. For this reason, the Enercon E126/7580 model, which has been replaced with the previous model and also is currently produced, is considered in this work.

The summer operating mode is adopted as the design condition for proposed system (the required power of the seawater pump is maximum) and the waste heat of the WT reaches 140 °C. The MED system has some requirements like low-pressure steam, electricity for pumps and vacuum devices. The low-pressure steam at 100 °C and 101.3 kPa is provided by using the waste heat of WT and the required power of pumps are also provided by WT output power. In addition, the analysis of energy, exergy, and thermoeconomic of the combined WT and MED desalination system is carried out.

2. System description

WTs with 0.5 MW or higher capacity are usually called high-capacity WTs in which the cooling system is regarded as an essential component. The waste heat of cooling systems of all high-capacity WTs is valuable and is proportional to their output power. In this work, WT (Enercon-E126) with output power of 7580 kW is selected as a high-capacity WT. It is suitable to be used in WZ I, WZ II, WZ III and WZ IV wind zones, as reported by ASCE 7.

In the selected high-capacity WT in this work, circulated oil around the generator and other rotating components reaches 140 to 150 °C [22,28]. For the AWS ranging from 8 to 12 m/s, the waste heat of the WT varies between 122 and 269.9 kW (with WT generator efficiency of 93% [29]) and the temperature reaches 140 °C. It should be noted that the integrated system can work properly without any limitation due to the changes of environment temperature in summer and winter (assuming that the temperature does not drop below 0 °C), however, the exergy efficiency and cost of produced water will be increased in summer, due to the increase of the power for the seawater pump.

In areas where the temperature in winter drops below 0 °C, a heater [30] or a de-icing system (it is similar to the one that used in the rear window of a car) [28] is used. If the mentioned systems are used, the