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Economic feasibility of alternative designs of an RO-ORC desalination plant using solar energy for Libya

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Abstract: The fresh water has become a challenging problem for many countries, especially in arid and semi-arid regions, with population growth and a shortage of water resources. This problem let the desalination plants become the main source of potable, industry, and irrigation. Libya is one of these countries. In this paper first and second thermodynamics laws were used to investigate the exergy and economic analysis of proposed desalination plant in Waddan City in Libya to provide desalination technique to be used in this area, as the source of brackish water is available. The model and simulation results for single pass SRO with PX powered ORC using solar energy has been carried out in this paper, IPSEpro software was used. Libyan environmental data for brackish water at Waddan City were used in this model, to produce about 8208m^3/day for the local community. a comparison between electricity from grid and ORC powered by solar energy. The results showed that using ORC better than using electricity from grid.

Keywords: *Exergy efficiency, economic analysis, RO, ORC and solar energy.*

Introduction

Utilization of the solar energy to power the ORC, which was found competitive choice with the other sources, this due to a good thermal efficiency at low temperature. Moreover, it is considered environmentally.

Many researches have been carried out to investigate and study performance enhancement of these technologies. A comparison between an ORC energized by thermal energy absorbed by a parabolic trough collector, a flat plate collector and a compound parabolic concentrator using MatLab/SimuLink code Nafey et al. [1]. The generated electrical power from the ORC was supplied to operate Reverse Osmosis (RO) desalination; the results showed that the parabolic trough collector, flat plate collector and compound parabolic concentrator are considered cycle (ORC). IPSEpro software is used to model the ORC unit and model is validated against existing ORC refrigerants; R134a, as well as single pass reverse osmosis (SRO) powered by ORC with solar energy.

1.1 ORC cycle modelling and validation

The most suitable ORC refrigerant can utilize the low thermal temperature grade such as the one that is recovered from the geothermal is R123a. This refrigerant was characterized compared with other working fluids by high molecular weight, low vaporization heat and non-flammability. In addition, environmentally, they have less impact, no ozone depletion potential and small greenhouse warming potential.

The IPSEpro refrigerants library was used to create the ORC model for an existing ORC unit utilizing the heat from underground hot spring in Chena, Alaska to power a 250 kW ORC unit. ORC model validation step took place through the comparison between the model results and existing units. The result showed that, the model predicated very close estimation of the actual ORC unit with heights deviation of 3.27% at condenser cooling water flow. Model accuracy was gained less deviation from the study conducted for same unit, based on this result the model was used in this study, figure 1 shows a diagram from ORC cycle in IPSEpro.

1.2 Single pass RO

The IPSEpro desalination library was used to create the SRO model for an existing RO unit, and validated against actual data. The result showed that a good agreement between the model result and actual data, figure 2 shows the diagram of the model.

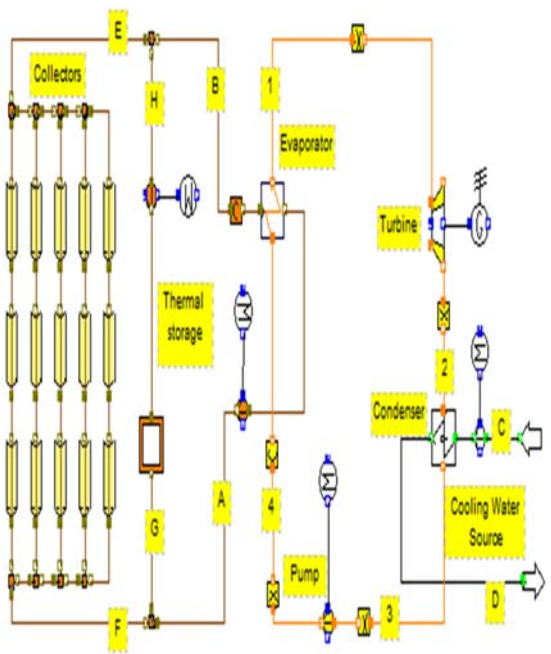

Figure 1: A diagram from IPSEpro of the ORC cycle [23].

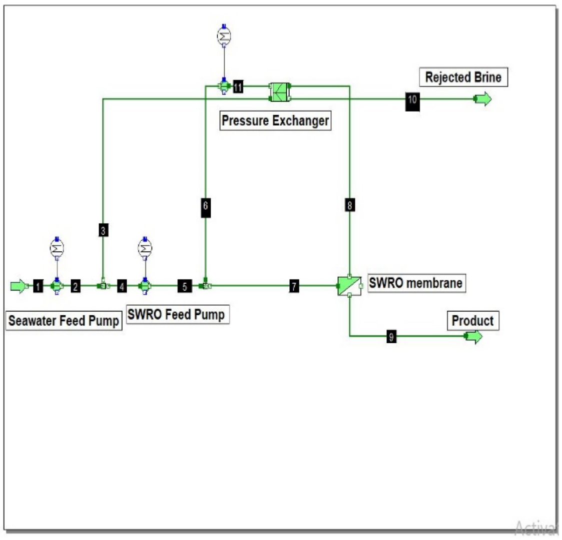

Figure 2: Diagram from IPSEpro of the SRO desalination plant

In present study, Waddan City in Libya is chosen as a case study where a source of geothermal brackish water is available SRO (as opposed to seawater). RO is now a leading technology in the desalination industry worldwide, both in small and large-scale applications [1, 2 and 3]. RO desalination is popular among fresh water supply companies due to its lower start-up and delivery time, lower environmental impact, easier operation and maintenance, lower capital and operating costs, and a significant drop in energy consumption due to the latest energy recovery devices [4].

On the other hand, RO technology is not generally favoured for seawater desalination of high saline waters (45,000ppm) with high temperatures (40 ℃), such as occur in the Arabian Gulf [5]. Membrane fouling is also a problem so pre-processing of the feed water is important.

The main improvements in RO desalination technology have been focused on the membrane technology, to reduce the fouling and increase the membrane life, and on high pressure pumps to reduce their electrical power consumption [3 and 6]. Furthermore, a number of recommendations from recent studies have suggested conducting the further research on the operation of commercial RO plant and renewable energy [7-10].

The main purposes of this study are: to produce distillate water from brackish water, find the best optimal selection to provide distillate water to this City which suffers from lack of drinking water and fill the research gap in such conditions, of the source to drive RO.

2. Methodology

The Organic Rankine Cycle (ORC) is similar to the steam turbine cycle expected the working fluids in the ORC are the refrigerants. As shown in figure 1, each number in the cycle represents the state of the stream.

The ORC turbine work resulting from the expansion process of the refrigerant mass is (mg):

Where the isentropic from gothermal and heat rejected from condenser to the water cooling, work performed by the refrigerant circulated pump.

Therefore, ORC net power production can be estimated as subtraction of the power generated from the ORC turbine from power consumed by refrigerant pump and condenser cooling pump:

Exergy analysis of ORC will be similar to the power plant in the cogeneration system.

The methodology can be divided into sections:

2.1 First section thermodynamic analysis:

Exergy is defined as the maximum obtainable useful work when a stream is moved from its initial state to the dead state at the temperature T_0 and pressure P_0 of the environment [6, 11, 12 and 13]. Exergy efficiency can be defined as the ratio of network output to fuel exergy and the thermal system.

$$E_x = E_{ph} + E_{ch} + E_{ke} + E_{pe} \quad (1)$$

Neglecting the small potential and kinetic terms.

$$E_x = E_{ph} + E_{ch} \quad (2)$$

$$e_{ph} = (h_i - h_0) - T_0(s_i - s_0) \quad (3)$$

$$e_{ch} = \sum_{i=1}^{n} w_s(\mu_1^* - \mu^0{}_i) \quad (4)$$

The overall exergy efficiency is defined as the ratio of the minimum separation work required to the total input exergy [6, 12 and 14].

$$\eta = \frac{W_{min}}{E_{input}} \quad (5)$$

Where W_{min} is defined as “the residual exergy when they move to the date state at (P_0, T_0)” [14]. The specific power consumption was calculated based on electrical power consumption per m^3.

2.2 Second section economic analysis:

To assess economic analysis for the two desalination systems, the payback period (PBP and net present value (NPV), the average rate of return (ARR) and profitability index (PI) are calculated as follows:

The PBP takes account of the period of investment before breaking even and making a profit. The PBP can be defined as the period required to return the Total Capital Investment (TCI) [15]. This can be calculated as follows:

$$TCI = \sum_{j=1}^{PBP} CFN_j \quad (6)$$

where: TCI is the Total Capital Investment, and CFN is the recurrent Net Cash Flow.

Net Present Value (NPV).

The net present value is known as the difference between the sum of all the net cash inflows and the initial investment cost over the project lifetime discounted so that all values are compared at a single point in time (the present). The value of NPV can be positive or negative. A positive value means that the income to the project is higher than the investment, which is preferable in any project. On the other hand, a negative value shows that the project could not recover the investment costs and should be avoided. The NPV is calculated mathematically as follows [15].

$$NPV = \sum_{j=1}^{r} \frac{CFN_j}{(1+r)^j} - TCI \quad (7)$$

where CFN is the net cash flow over the lifetime t and r is the discount rate.

Average Rate of Return (ARR)

The average rate of return is defined as the ratio of the average annual net profit to the total capital investment. It can be worked out as follows:

$$ARR = \frac{\overline{NP}}{TCI} \quad (8)$$

where $\overline{NPV}$ is the average annual net profit.

Profitability index (PI). The profitability index is defined as the net present value of the future net cash flow to the total capital investment [16].

3. Parametric study

After the validation of the models (ORC and SRO), the parametric study was carried out to investigate the influence of environmental data (salinity and temperature) on SRO desalination plant.

In this study the parametric study was foucu only on the SRO desalination plant, the proposed SRO model has been investigated. The model was studied using Libyan environmental data for brackish water. A thermodynamic analysis was carried out for model.

This technology was studied to produce about 8208m^3/day for the local community. The effect of feed water temperature shows that as the feed of the brackish water in the tank cannot be controlled, it necessary to study the effect of this variation on the system's performance. Figure 3 shows the effect of feed water temperature on exergy efficiency and specific power consumption for SRO. The exergy efficiency increased with feed water temperature for both techniques (membrane pore size increased and the feed water passes more easily for SRO).

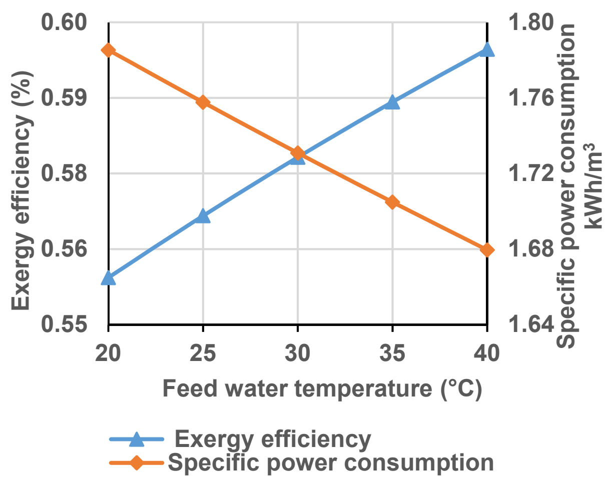

Figure 3: Effect of feed temperature on exergy efficiency and specific power consumption for SRO at salinity 1.96 g/kg

Raising the feed water salinity increases exergy efficiency for SRO (Figure 4) due to increase in the inlet enthalpy [5], where the specific power consumption increased.

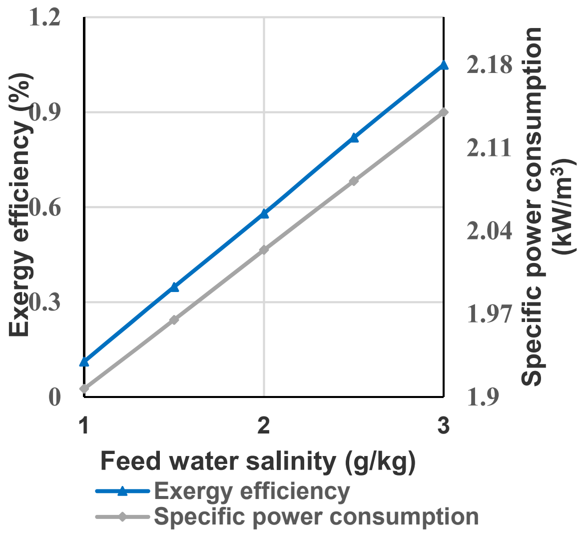

Figure 4: Effect of feed water salinity on exergy efficiency and specific power consumption for SRO at 25°C

3.1 Annual Cash Outflow and Inflow

The annual cash outflow covers the money spent for operation and maintenance (O&M). It has been calculated as a function of plant capacity per year. All proposed systems are assumed to operate at 85% per year [17]. SRO O&M costs are $0.126/m³ [18] and 19083/year ORC O&M.Revenue or sales income profit is represented by the annual cash flow balance of O&M costs against revenue income. In this study, the products sold is potable water. The potable water selling tariff is $2.5/m³ for domestic consumers [19]. The revenue for each model was calculated according to Libyan prices and in order to compare the effect of different sales prices on annual revenue, to find at what selling price the project is not economic a variations in the prices of potable water will be considered from $1.25/m³ to $2.75/m³.

3.2 The solar hybridised system RO-PX description

The potential of utilising solar energy in libiya to drive the combined RO-PX system was investigated to match the libyan weather conditions. Therefore, two different solar configurations have been conducted in this paper, the RO stnadlone and the combined system. The combined system is powered by a solar energy system from a solar collector to power the RO-PX unit. The second configuration utilises an organic Rankine cycle as a source of electricity and heat to power the combined system. The electricity which is generated by the ORC plant powered the combined system pumps and. The parabolic trough collector, which is used to drive the ORC, contains 148 collectors and Therminol VP-1 was used as the absorber oil to transfer the heat. The local climatic libyan conditions were taken into account. The thermal analysis was conducted with an ambient temperature of 25 °C and direct irradiance of 833 W/m². The type of collectors is LS-2 with efficiency 0.76. The results show that the total solar radiation incident on the collector is 34.4 MW and the total absorbed energy is 26.1 MW. Furthermore, the efficiency of the collector for all the components is higher than 55% when using solar radiation of 833 W/m², as shown in figure5. However, to maximize the overall efficiency of the thermal solar system, the useful heat gain must be increased for constant incident solar radiation. Solar radiation impacted on the efficiency of PTC components; the efficiency increased at the receiver and collector-receiver. There is a difference between energy received and delivered due to the solar radiation scattering. The collector received 26.8 MW energy but delivered only 20.3 MW at 0.9 kW/m² day, the difference is approximately 24%, 22% and 41% at collector, receiver and collector-receiver respectively. The required power of the standard RO system is 2.1 MW when the system works without a recovery device. However, 1 MW is required to energise the pressure exchanger. This power obtained by solar collector area

10055 m^2 for the standard RO, 4788 m^2 for the RO-PX. Thus, the RO-PX system is an optimum design to produce fresh water for drinking combined with the ORC-PTC solar system.

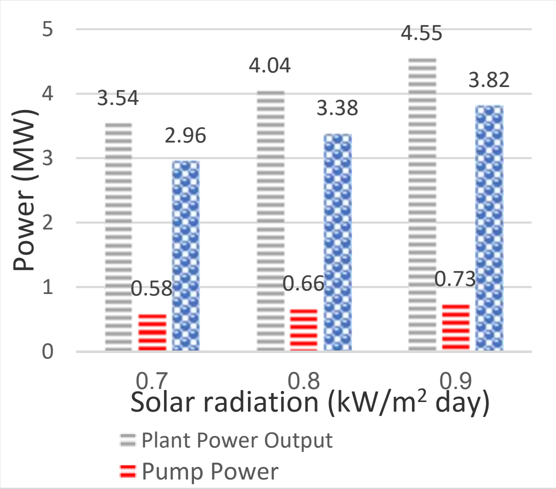

Figure 5:Effect of solar radiation on the ORC output

3.3 Plant Costs

3.3.1 ORC cost

The ORC system is assembled commercially as one unit mounted on skid or in a package. The ORC unit capacity is 625kW. The ORC unit specific prices (£/kW) have been analysed in many studies and decrease as unit capicity increase, in thuis stduy, the ORC produce 625kW with unit specific cost found 2279£/kW. Annual operation and maintenance cost of the unit was 19083 £/year.

3.3.2 Single-pass RO

The cost of the proposed single-pass unit with pressure exchanger (PX) to produce 8208 m^3/day of potable water from brackish water (BW) is estimated [20] as $2.5 million. whereas the O&M costs are $0.126/$m^3$ [21].

3.4 Profitability Evaluation

Economic assessment is performed for each proposed system to find its profitability. The SRO is chosen to produce distillate water from brackish water, where the ORC is powered by solar energy to provide electricity to drive the SRO plant to produce 8208m^3/day.

3.5 Sensitivity Study

The sensitivity of the economic analysis was investigated in terms of the effect of potable water prices because the most common factors affect the economic analysis. A number of studies were conducted where the proposed model was assumed to operate at full load in ISO conditions with brackish water temperature set at 25°C with 85% capacity factor.

3.6 Sensitivity Study for SRO

The sensitivity analysis of SRO was performed, to find which the optimal selection can be used to produce distillate water from brackish water. In this section there is only one parameter could affect the desalination system economically, potable water selling price.

4.5.1 Effect of water selling price

The impact of water selling price on payback period (PBP) and net present value (NPV) was investigated with change in potable water selling price. The results show that as the selling price increase the PBP decrease where, the NPV increase, also the results showed that when the SRO powered by ORC the BPB is less than when it is powered by the electricity from the grid (general company of electricity), as well as the NPV is higher, as shown in figures (6 and 7) respectively. These results are compatible with thermodynamic analysis.

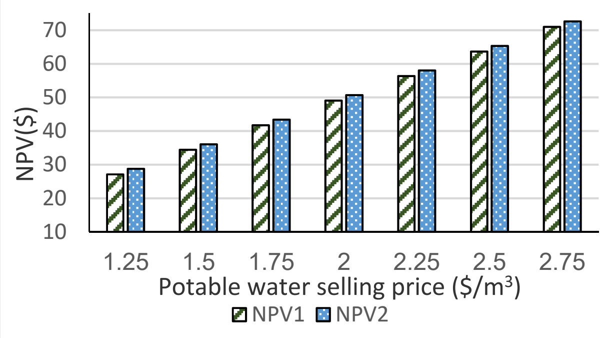

Figure 6: Net present value against the selling water selling prices variation

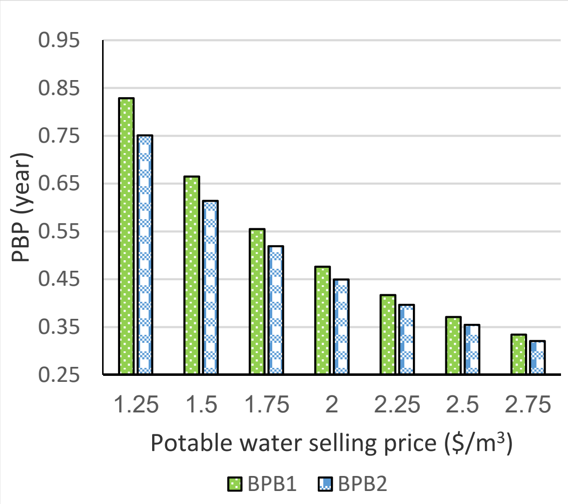

Figure 7: Payback period against the selling water selling prices variation

4. CONCLUSION

This paper has studied the exegetic and economic analysis of single pass reverse osmosis powered by ORC using solar energy compared with SRO powered by electricity from grid, to find the optimal alternative can be used to produce potable water from brackish water in Waddan City, Libya. The effect of variation in feed water temperature and salinity on exergy efficiency, specific power consumption and economic aspects were studied. It can be concluded that as the feed water temperature increased the exergy efficiency increased and specific power consumption reduced. The effect of feed water salinity on specific power consumption showed that as the feed salinity increased the specific power consumption for SRO rose, whereas the exergy efficiency and specific power consumption almost remain constant with plants capacity change. The economic analysis showed that SRO powered with ORC is better economically than when electricity used from grid which is less payback period and high net present value.

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