Hybrid desalination and power generation plant utilizing multi-stage flash and reverse osmosis driven by parabolic trough collectors

Nour A. Moharram a, Seif Bayoumi a, Ahmed A. Hanafy a, Wael M. El-Maghlany b,*

a Mechanical Engineering Department, College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
b Mechanical Engineering Department, Faculty of Engineering, Alexandria University, Egypt

ARTICLE INFO

Keywords:
Cogeneration
Hybrid CSP plant
Thermo-economic study
Sea water desalination

ABSTRACT

This investigation represents the optimum operation of a co-generation plant producing water and electricity at a specified geographical location in Ras Gharib, Egypt. A model has been set employing Parabolic Trough Collectors (PTC) utilizing molten salt as the working fluid for the solar island which exchanges heat with a simple steam Rankine cycle. Thereby, the steam turbine generates an adequate amount of electricity used to cover all the plants' requirements including the Reverse Osmosis (RO) water desalination unit demand. Moreover, the Multi-Stage Flash (MSF) plant acts as a condenser for the proposed system, taking full advantage of hot steam exiting the turbine unit to desalinate seawater. The results are displayed considering the optimum operation of the plant along the year anticipating the amount of freshwater and electricity produced all year long using MATLAB/Simulink package. Monthly assessments yield that maximum production of 16000 m³/day and 2000 m³/day of fresh water can be produced from the MSF and RO plants respectively in July together with 12.65 MW can be supplied to the grid after meeting all the plant demands.

1. Introduction

Egypt is seeking innovative approaches to tackle water and energy escalating demands using abundant renewable energy resources available due to its geographical location. The necessity for water and energy is mainly due to the soaring population growth rates and to the rapid industrial growth needed for development. Solar energy implementation has been the main scope for development by the New and Renewable Energy Authority (NREA) due to Egypt's high solar irradiance and suitable climatic conditions needed for harnessing energy especially using Concentrated Solar Power (CSP) collectors. There are four main technologies of CSP collectors used; Parabolic Trough Collector (PTC), Linear Fresnel Reflector (LFR), Concentrated Solar Tower (CST), and Parabolic Sterling Dish. Numerous experiments and numerical studies have been carried to determine the most mature and efficient technology yielding that parabolic trough collectors are superior in comparison to other technologies concerning reliability, level of maturity, modularity, and cost efficiency when implemented in Egypt [1–7]. Parabolic troughs are capable of being hybridized with steam power stations generating electricity or acting as a heat source for solar desalination producing freshwater. Thereby, solar desalination serves as a
significant solution for water shortage in Egypt. Seawater desalination could be classified into two major classes: thermal desalination and membrane desalination. The performance of both desalination techniques has been intensively investigated experimentally and theoretically by several researchers, concluding that Multi-Effect Desalination (MED) and Multi-Stage Flash (MSF) have a noticeable primacy over most thermal desalination techniques when considering reliability, recovery rate, and capital cost investments in large scale production [8–12]. However, thermal desalination is an energy-intensive process requiring an alternative heat source other than fossil fuels. Several studies have focused on presenting innovative approaches to supply thermal desalination plants with high energy demands requirements utilizing renewable energy sources, for example; the use of solar and nuclear energy [13,14]. Moreover, Reverse Osmosis (RO) is categorized as the most mature membrane desalination technique which can be commercially implemented simply when compared to other membrane desalination techniques [15–17]. Furthermore, the RO desalination technique has superiority as it operates at high pressure utilizing the smallest membrane pore size when compared to other membrane desalination techniques yielding a higher membrane separation efficiency [18].

In this study, a state-of-the-art solar cogeneration plant is described and simulated using the MATLAB/Simulink software package. The novelty of this study is the establishment of a prediction tool anticipating the output productivity of the proposed plant signifying
the feasibility of implementing such a plant in a specific location.

2. Scope, objective, and methodology

From the previous survey, more attention has been focused on merging power stations, utilizing solar energy as a heat source, with desalination plants whether thermal by using high steam temperatures exiting the turbine or membrane desalination by using a share from the produced electricity. A considerable number of studies concentrate their focus on co-generation solar plants generating fresh water and electricity in parallel [19–23]. These studies and many more conclude the feasibility of hybridization between solar power plants and desalination plants and their benefit/cost superiority particularly in developing countries as Egypt. Therefore, the main objective of this study is to investigate the practicality of implementing a cogeneration plant working on the principles of solar steam Rankine cycle, combined with an MSF desalination plant acting as a condenser for the system.

Also, a reverse osmosis plant is added to act as compensation for freshwater productivity during low solar irradiance seasons. Illustrated in Fig. 1 the proposed system schematic diagram for the hybrid plant consisting of parabolic trough collectors feeding the system with hot molten salt in which it is stored in two tanks providing heat supply to the model during the night. The molten salt is then passed through a heat exchanger to transfer the heat to the steam flowing to the turbine unit. Consequently, the superheated steam entering the turbine expands and exits the turbine at a temperature (113 °C–120 °C) suitable for MSF plant operation in which it acts as a condenser. Moreover, the electricity generated by the steam turbine is used to cover all the model requirements including the RO load, and the remaining electrical production is supplied to the grid.

3. Mathematical model and data reduction

The proposed model is sub-divided into six different units running in parallel. The following section shows the mathematical model for each unit separately which are clustered together in the established MATLAB model.

3.1. PTC model

The collector is the heart of any solar energy system. The performance of such solar energy systems is largely dependent on the portion of solar insolation that is transferred to the working fluid, which can be expressed using the collector instantaneous efficiency as a function in solar irradiance, mean collector, and ambient temperatures as in Eq. (1) [24].

$$\eta_{PTC} = 0.75 - 4.5 \times 10^{-5} \times (T_{col} - T_{amb}) - 0.039 \times \left(\frac{T_{col} - T_{amb}}{G}\right) - 3 \times 10^{-4} \times \left(\frac{T_{col} - T_{amb}}{G}\right)^2$$

(1)

Substituting the PTC efficiency in Eq. (2) yields in calculating the useful thermal power available [25].

$$Q = A_{PTC} \times \eta_{PTC} \times G = m_{col} \times \Delta h_{h-o}$$

(2)

Fig. 1. Proposed system Configuration.
3.2. Storage tanks

Storage tanks are implemented in the system to assure production continuity at night. The storage volume required expressed in Eq. (3) is calculated based on thermal load demand, operating hours, and the state of molten salt stored in it. Moreover, the storage tank pump work required is calculated as shown in Eq. (4) [26].

\[ V_{stg} = \frac{Q \times OH}{\rho \times C_p \times T_{stg}} \]  
(3)

\[ W_{p_{stg}} = \frac{100 \times m_{stg} \times (P_{stg} + P_{loss})}{\rho \times \eta_p} \]  
(4)

3.3. Heat exchanger

The heat exchanger is in charge of supplying the steam turbine with the thermal power required. Thus, utilizing energy balance, the steam mass flow rate required is calculated. Also, based on the effectiveness of the heat exchanger, the outlet molten salt temperature is determined using Eq. (5) [27].

\[ T_{ms_o} = T_{ms_i} \times \epsilon_{evp} \times \left( T_{ms_i} - T_{evp} \right) \]  
(5)

3.4. Turbine unit model

For the proposed model approach, it is crucial to assign the outlet steam enthalpy of the turbine to match the optimum steam temperature entering the desalination plant. Therefore, the turbine work is calculated using Eq. (6) based on the steam mass flow rate [28].

\[ W_t = m_{st} \times (h_{t_{in}} - h_{t_{out}}) \]  
(6)

3.5. Multi-Stage Flash desalination plant

The governing equations for the MSF model can be expressed using the formulas obtained from the mathematical model illustrated in “Fundamentals of Salt Water Desalination” by El-Dessouky and Ettouney [29]. For a known salinity ratio between brine water and feed water, the volume flow rate of the distillate product is obtained using Eq. (7). Thus, the brine volume flow rate can be expressed as in Eq. (8) [30].

\[ M_d = \left( \frac{S_b - S_f}{S_b} \right) \times M_f \]  
(7)

\[ M_b = M_f - M_d \]  
(8)

Stage temperature drop expressed in Eq. (9) is calculated based on the assigned top brine temperature (TBT), last stage brine temperature (T_n), and the number of stages (N) [31].

\[ T_{stage} = \frac{TBT - T_n}{N} \]  
(9)

From Eqs. (7) and (9), the recycle brine flow rate is calculated as shown in Eq. (10). Accordingly, the recycle brine salinity is expressed based on the salt concentration balance equation in Eq. (11) [31].

\[ M_r = \frac{M_d}{1 - \left(1 - \epsilon_s \times T_{ms} \right)^N} \]  
(10)

\[ S_r = \left( S_f \times M_f + (M_r - M_d) \times S_b - M_b \times S_b \right) / M_r \]  
(11)

3.6. Reverse osmosis unit

The formulas used in RO unit simulation are based on the basic configuration for RO desalination plants, which are principally based on membrane recovery ratio and feed water properties [32,33]. The feedwater flow rate is calculated according to the demanded distillate water as expressed in Eq. (12). Moreover, the distillate salt concentration is determined as indicated in Eq. (13) using the salt rejection percentage according to the type of membrane used in the system.
used in Eq. (15) to calculate the power rating for the pump used in the RO unit [34].

\[ \Delta P = \left( \frac{M_t \times \text{TCF} \times FF \times \Delta \rho \times N_t \times k_x}{3600} \right) + \Delta \Pi \]  

(14)

\[ \text{HPP}_{\text{Pump}} = \frac{M_t \times \Delta P}{3.6 \times \rho_f \times \eta_p} \]  

(15)

3.7. Economical study

In order to decide whether the proposed plant is feasible and cost-efficient, an economic assessment is crucial to compare the plant with traditional alternatives. Therefore, investment, operating, and maintenance costs analysis is performed for each component in the plant. For that purpose, the amortization factor is estimated based on the following relation in Eq. (16).

\[ A_f = \frac{i \times (1+i)^{LT_p}}{(1+i)^{LT_p} - 1} \]  

(16)

where \( i \) is the interest rate and set as 5%, \( LT_p \) is the plant lifetime and set as 25 years [29].

The following formulas in Table 1 represent the investment, operation, maintenance, and the total capital costs for PTC, steam turbine, pump unit, and heat exchanger respectively, representing the solar Rankine cycle implemented in the system [25, 35, 36].

Moreover, the direct capital cost for the utilized desalination plants is a function of its productivity as shown in Eqs. (17) and (18) [37]. However, the indirect cost can be estimated approximately as a percentage of the direct capital cost as indicated in Eqs. (19) and (20) [38, 39].

\[ \text{DCC}_{\text{MSF}} = 2000 \, \text{$/m^3/ day \times Plant \, Capacity_{MSF}} \]  

(17)

\[ \text{DCC}_{\text{RO}} = 1000 \, \text{$/m^3/ day \times Plant \, Capacity_{RO}} \]  

(18)

\[ \text{IDCC}_{\text{MSF}} = 25 \% \times \text{DCC}_{\text{MSF}} \]  

(19)

\[ \text{IDCC}_{\text{RO}} = 27 \% \times \text{DCC}_{\text{RO}} \]  

(20)

Therefore, the Annual Fixed Charges (AFC) can be calculated using Eq. (21). Also, operation and maintenance costs are represented as a percentage of the total capital cost as shown in Eqs. (22) and (23). It is noticeable that the operation and maintenance costs percentage is higher than the MSF plant due to extra charges due to consecutive membrane replacements [40].

\[ \text{AFC}_{\text{MSF, RO}} = A_f \times (\text{DCC}_{\text{MSF, RO}} + \text{IDCC}_{\text{MSF, RO}}) \]  

(21)

\[ \text{OMC}_{\text{MSF}} = 0.02 \times (\text{DCC}_{\text{MSF}} + \text{IDCC}_{\text{MSF}}) \]  

(22)

\[ \text{OMC}_{\text{RO}} = 0.05 \times (\text{DCC}_{\text{RO}} + \text{IDCC}_{\text{RO}}) \]  

(23)

Annual chemical cost and labor cost varies according to the capacity and type of the desalination plant. From previous studies, the load factor of most desalination plants is nearly 0.9, and the specific labor cost is constant at 0.1 $/m^3, whilst the specific chemical costs vary accordingly with values of 0.025 $/m^3 and 0.04 $/m^3 for MSF and RO plants respectively. Consequently, the annual chemical and labor costs can be expressed as in Eqs. (24) and (25) [30, 40].

\[ \text{ACC}_{\text{MSF, RO}} = \text{SCC}_{\text{MSF, RO}} \times LF \times \text{Plant \, Capacity}_{\text{MSF, RO}} \times 365 \]  

(24)

### Table 1

DCC, O&M and TCC costs for solar Rankine cycle.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DCC ($)</th>
<th>O&amp;M ($)</th>
<th>TCC ($)/y</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PTC</strong></td>
<td>( 150 \times (A_{\text{col}})^{0.95} )</td>
<td>( 15% \times \text{ICC}_{\text{col}} )</td>
<td>( A_f \times (\text{DCC} + \text{O&amp;M})_{\text{col}} )</td>
</tr>
<tr>
<td><strong>Steam Turbine</strong></td>
<td>( 4750 \times (W_p)^{0.75} )</td>
<td>( 25% \times \text{ICC}_i )</td>
<td>( A_f \times (\text{DCC} + \text{O&amp;M})_i )</td>
</tr>
<tr>
<td><strong>Pump Unit</strong></td>
<td>( 3500 \times (W_p)^{0.47} )</td>
<td>( 25% \times \text{ICC}_p )</td>
<td>( A_f \times (\text{DCC} + \text{O&amp;M})_p )</td>
</tr>
<tr>
<td><strong>Heat Exchanger</strong></td>
<td>( 150 \times (A_{\text{hex}})^{0.8} )</td>
<td>( 25% \times \text{ICC}_{\text{hex}} )</td>
<td>( A_f \times (\text{DCC} + \text{O&amp;M})_{\text{hex}} )</td>
</tr>
</tbody>
</table>
\[ ALC_{\text{MSF,RO}} = SLC \times LF \times \text{Plant Capacity}_{\text{MSF,RO}} \times 365 \]  
(25)

\[ TAC_{\text{MSF,RO}} = AFC_{\text{MSF,RO}} + ACC_{\text{MSF,RO}} + ALC_{\text{MSF,RO}} + (OMC_{\text{MSF,RO}} \times A_f) \]  
(26)

\[ TPC = TCC_{\text{col}} + TCC_{\text{hex}} + TCC_p + TCC_t + TAC_{\text{MSF}} + TAC_{\text{RO}} \]  
(27)

\[ TWP = \frac{TPC}{(\text{Plant Capacity} \times 365 \times LF)} \]  
(28)

The total annual cost for the MSF plant can be presented by Eq. (26), which is then substituted in Eq. (27) to deduce the total plant cost per year. Thus, the unit freshwater produced from the MSF plant is expressed by Eq. (28).

4. Model validation

This study proposed a novel approach for cogeneration plants utilizing the coupling of solar thermal steam power plant with two different desalination techniques (MSF and RO). There are no experimental nor theoretical results for the proposed system configuration in the previous literature. Therefore, the main model components are validated solely to certify the authentication of the created MATLAB model. Firstly, the solar field employing parabolic trough collectors model is validated with ISCC Al kuraymat solar power plant after applying the modifications needed according to the input conditions of Al kuraymat plant as it consists of 1920 PTCs with mirror aperture area near to 130800 m\(^2\) using 40 loops, each loop consists of 4 collectors with a total of 160 collectors [41, 42]. The model is tested using the same reference day mode conditions of 700 W/m\(^2\) direct solar irradiance and an ambient temperature of 20 °C. The heat transfer fluid nominal mass flow rate is 250 kg/s having an inlet temperature of 293 °C and outlet temperature of 393 °C. Similar conditions are applied to the presented model, and the outlet temperature is calculated, recording a value of 395.95 °C with an error of 0.75%. Moreover, the MSF plant model is validated with Nafey et al. [43] Visual Basic model, which is successfully proven against the Eoun Mousa MSF desalination plant in Egypt. The plant consists of one brine heater as a heat source, 17 stages for the heat recovery section, and three stages for the heat rejection section. Similar input conditions are applied to the presented model to calculate the amount of fresh water produced per day. The result conceded productivity of 4986.97 m\(^3\)/day, which is when compared with the existing plant productivity of 5000 m\(^3\)/day, will result in an acceptable error of 0.26%.

5. Case study

The Red Sea coast is the recommended area of the project execution, where most of the adjacent land area of the Red Sea is mostly arid with inadequate resources of groundwater either in quantities or qualities. In the study at hand, the previously described proposed model illustrated in Fig. 1 was tested under climatic conditions of Ras Gharib city, which is located on the coast of the Gulf of Suez.

The location was mainly suggested as it has the highest potential weight among other Red Sea Governate cities due to its optimum weather profile suitable for solar projects. Also, Ras Gharib represents one of the leading centers of petroleum production in Egypt; as a
result, water demands are peaking due to development in industrial activities in the Red Sea Government [44].

5.1. Climatic input data

Cedar Lake Ventures, Inc [45], offers a detailed report of the weather of Ras Gharib based on a statistical analysis of historical hourly weather reports and model reconstructions from January 1, 1980, to December 31, 2016, from El Tor station. Moreover [46], delivers local weather information of high quality worldwide, including 30 years of hourly historical weather data for Ras Gharib. Monthly mean values for ambient temperatures have been collected and illustrated in Fig. 2, including the average seawater temperature in the specified region. Furthermore, indicating the average sunrise and sunset times is a necessary input parameter in the proposed model to calculate the monthly average solar time, aiding the adjustment of the storage tanks' capacities maintaining sustainability. Last but not least, the average hourly solar profiles are gathered for each month based on data collected from the Global Solar Atlas in the specified location of Ras Gharib as visually demonstrated in Fig. 3 [47].

5.2. Design input parameters

The input parameters required for designing the cogeneration plant are exemplified in Table 2. The desalination plant capacities are assigned based on water demand in Ras Gharib according to the data supplied from the Red Sea Governate addressing the amount of water which the city should cover relying on desalinating seawater [44]. The government is willing to invest in mega projects to decrease the reliance on River Nile water transported through old pipelines to the city [48]. Therefore, introducing a hybrid plant generating both electricity and freshwater to this region will a great development opportunity for the Red Sea Governate. Moreover, the parabolic trough collectors in use are EuroTrough collectors model ET100, which have been fully qualified in 2002 at the Plataforma Solar in Almeria with independent performance test certificates from the research laboratories [49]. The Solar field area is directly proportional to the amount of heat gain and plant productivity. Although in this study, the area for PTCs was fixed with a value of 250,000 m$^3$, which was the area available for implementation determined by the New & Renewable Energy Authority (NREA) in Egypt. This obligatory constraint in the location of implementation has two opposing effects. The first is limiting the productivity of the proposed plant, whether in terms of desalinated water or power production. The second is lowering the capital costs of the plant which will reflect in lowering the unit production cost; due to the high land costs in Red Sea Governorate as it is one of the best tourist locations in Egypt. Moreover, the sizing of the RO plant was based on iterative scenarios determining the productivity of the MSF plant operating under the worst conditions. Considering that freshwater demand in the location is approximately 12,000 m$^3$/day, the RO plant capacity was set to 2000 m$^3$/day to assure coverage of demand together with freshwater produced from the MSF plant. Increasing the RO plant capacity will yield higher water production rates, on the other hand, decreases the amount of electricity supplied to the grid. Therefore, it was decided to produce an adequate amount of fresh water to cover the demand and prioritize peaking the amount of power supplied to the electricity grid which is connected to all Egyptian governorates.

6. Results and discussion

The results of the proposed configuration applied for cogeneration of power and water utilizing concentrating solar power (CSP) plants will be discussed to evaluate the performance of the plant along the year and providing an economic assessment addressing the unit electrical and water costs. The productivity of the plant was investigated under obligatory boundary conditions and constraints considering the climatic data of the region and the design input parameters, which have standards regarding commercial availability.
6.1. Water productivity

The results were obtained with the previous constraints put into consideration to ensure maximum water output and minimum unit water production cost. The total water productivity was obtained by operating both desalination plants at their maximum capacities. MSF desalination plant has a restricting constrain to ensure optimum operation which is the inlet steam temperature must be in the range of 113 °C–120 °C. Having the solar area fixed along the year, varying monthly solar irradiance and climatic data consequently; the MSF productivity is confined within those constraints yielding to the results demonstrated in Fig. 4 representing the water productivity from each desalination technique and the total productivity per day. The Reverse Osmosis Pant is set to operate at a full load of 2000 m³/day all year long to contribute to the MSF plant in water productivity, aiming to fulfill the demand needed in the region. On one hand, the results yielded total maximum productivity of 16000 m³/day during July, utilizing 14000 m³/day and 2000 m³/day.

![Fig. 4. Monthly water productivity.](image-url)
from the MSF plant and RO plant, respectively. On the other hand, the least water productivity was in January, recording 10250 m$^3$/day and 2000 m$^3$/day from MSF and RO plant, respectively, with a total of 12250 m$^3$/day. Additionally, to ensure full load operation for the MSF plant, a standard deviation of 15% was set to guarantee lower production costs and higher efficiency. Demonstrated in Fig. 5, the mean value for freshwater productivity and the monthly allowable range for deviation.

6.2. Power productivity

The purpose of this section is to determine quantitatively the amount of power generated by the steam turbine implemented in the proposed model. There are no restricting constraints about the amount of electricity produced, as Ras Gharib is directly connected to the general electrical grid in Egypt. Therefore, the extra load supplied to the grid acts as a comprehensive contribution to the power generation plants in Egypt after considering total coverage of the plant’s demands. The electrical requirements for the plant can be represented as two main loads: reverse osmosis desalination plant and different pumping units implemented in the system power requirements. Although RO plant productivity is constant throughout the year, its power requirements slightly vary due to seasonal changes in climatic conditions and seawater salinity throughout the year. The results demonstrated in Fig. 6 are obtained after running several iterations assuring the turbine outlet temperature matches the standards of MSF plant inlet steam temperature and the solar area available by the parabolic troughs collector is fixed throughout the year. As shown in Fig. 6, the consumed power in the plant is mainly due to pumps load representing approximately 25% of the total power generated by the steam turbine. Eight different pumping units are employed in the proposed model with power consumption share as shown in Table 3.

6.3. Economic study results

The water unit production cost is calculated for the proposed plant yielding a mean value of 0.487 $/m^3$, which proves the feasibility of the plant when compared with conventional water desalination units in Egypt. Besides water production, the total plant costs have been distributed among the price of electricity supplied to the grid, which is sold to the consumers at subsidized prices. Therefore, the unit electrical cost has recorded a mean value of 0.0458 $/kW.h which is slightly less than the unit electrical cost from a traditional steam turbine plant. Demonstrated in Fig. 7 a chart representing the monthly variations considering water and electricity prices due to adaptation of the system to climatic conditions and seasonal variations. It is noticeable that production costs are inversely proportional to solar irradiance throughout the year. Solar intensity reaches its peak in July which subsequently records the least production costs, whether for freshwater or electricity, while in January when the solar intensity is the least, the plant’s economic analysis deduces the highest unit production costs. This occurs due to higher productivity rates with high solar irradiance; therefore, the plant’s total cost is distributed over larger amounts of products.

6.4. Summary of results

Table 4 summarizes the major output data for the proposed cogeneration plant. Yearly averages for water and power productivity
were calculated to emphasize the feasibility of the plant. Additionally, annual unit production costs for fresh water and electricity were computed to indicate the feasibility of the plant.

7. Conclusion

A MATLAB model has been established to examine the practicality of combining a concentrated solar power plant with two different water desalination techniques running with optimum operating conditions in Ras Gharib, Egypt. In this study, the proposed model consists of parabolic trough collectors acting as a heat source to the steam Rankine cycle via exchanging heat between molten salt and steam. The utilization of thermal storage tanks was crucial in the location of Ras Gharib, considering the coverage of the total freshwater demand. Two thermal storage tanks are integrated into the system to ensure continuous production, whether at night or at low solar irradiance times. In locations where freshwater demand is low, direct steam generation schemes can be integrated with small thermal desalination plants serving variable output productivity throughout the year. The steam turbine is coupled with a thermal desalination plant, which is employed in the system to act as the condenser to the Steam Rankine Cycle. An auxiliary reverse osmosis plant is connected to the generator of the plant, aiming to increase freshwater productivity to meet the demands in the region. Results have been demonstrated in graphs to determine the expected output of the system on monthly basis. The parametric study yields that a solar field of 250,000 m$^2$ is proficient in supplying a total of 16,000 m$^3$/day of desalinated water in addition to 12.65 MW delivered to

![Fig. 6. Power distribution among plant loads.](image-url)
the grid at its best conditions in July. Though, in January, water productivity was down to 12,250 m$^3$/day and 9.0 MW, which is the minimum production rate considering the worst operational conditions. The annual average water productivity is computed, resulting in 14,054 m$^3$/day with an average unit production cost of 0.487 $/m$^3$; while the average electrical productivity supplied to the grid throughout the year is approximately 10.8 MW daily, having an average unit cost for electricity of 0.0458 $/kW.h which is an acceptable value after meeting all the plant’s requirements to decrease the pressure on the main electricity network. In conclusion, the proposed cogeneration system is proven to be technologically and economically feasible at Ras Gharib, Egypt.

Credit author statement

Nour A. Moharram  
Conceptualization, Methodology and results output analysis.

Seif Bayoumi  
Methodology and review editing.

Ahmed A. Hanafy  
Writing and review editing.

Wael M. El-Maghlany  
Conceptualization, Methodology and results output analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References