International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 06 Issue: 03 | Mar 2019 www.irjet.net p-ISSN: 2395-0072

Modeling of an Energy Saving Solar Water Heating System for Industrial Low Temperature Applications

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Abstract - *The potential of solar thermal energy in industrial applications in Egypt is huge, even if it is not taking the same importance like photovoltaic modules and wind energy. The industrial section can benefit greatly from the use of solar thermal systems, especially, when it comes to low temperature applications. So, in order to encourage the adaption of solar thermal energy in industrial application, a system was designed using the program "TRNSYS 16", in order to estimate the true potential of solar thermal energy in Egypt, in particular, low temperature applications. A study was conducted for six different locations using the designed system by TRNSYS for the same flow rate demands for a low pressure boiler, covering most of Egypt from north to south. The system was simulated in each location, and the energy output of each location is presented. The results showed a huge gain in energy savings, and also, in the amounts of natural gas saved per year. The benefits of each location were also calculated according to the amounts of natural gas saved, as well as, the capital cost of the system in each location. The results reflect the importance of solar energy in industrial process heating.*

Key Words: Solar thermal energy, solar heating, Low temperature applications, Trnsys modelling, solar simulation

1.INTRODUCTION

At the end of 2016, the installed solar thermal capacity worldwide was about 176.8 GWth" Giga watt thermal" (221 million m^2). Compared with 170 GWth for wind, 69 GWth for geothermal and 9.5 GWth for photovoltaic (solar electric) [1], solar thermal has undoubtedly held a leading position among the renewable energy sources. Most of the current solar thermal plants today provide hot water to households, for both sanitary purposes and space heating. Although the residential sector has a tremendous potential for solar thermal energy applications, the industrial sector has amazing potential too. Electric energy and transportation energy have been in the forefront of public discussions of energy [2]. On the other hand, heat is accounted for 37% of energy consumption in mostly developed countries and in overall world consumption of energy around 47% [6]. Unfortunately, most of the policy makers and investors around the world think that solar energy is only associated with electricity-producing photovoltaic (PV) panels. And the investors that realize the existence of solar thermal heating associates it mostly with heating outdoor swimming pools and residential water in the United States [3]. Around 90 operating solar thermal plants around the world are constructed to provide process heating for various industries. The total capacity of these plants is about 25 MWth "Mega Watt thermal" or approximately 35,000 m^2 in area [7]. Comparing this 25 MWth capacity of the total installed capacity of solar thermal energy of 118 GWth, this leaves us with a very small fraction of (0.02%). This capacity shows how much is the wasted potential of solar thermal energy in industrial applications.

Figure 1 and Figure 2 shows the different installed capacities and number of operating plants that use solar thermal energy based on different industries and distribution by country.

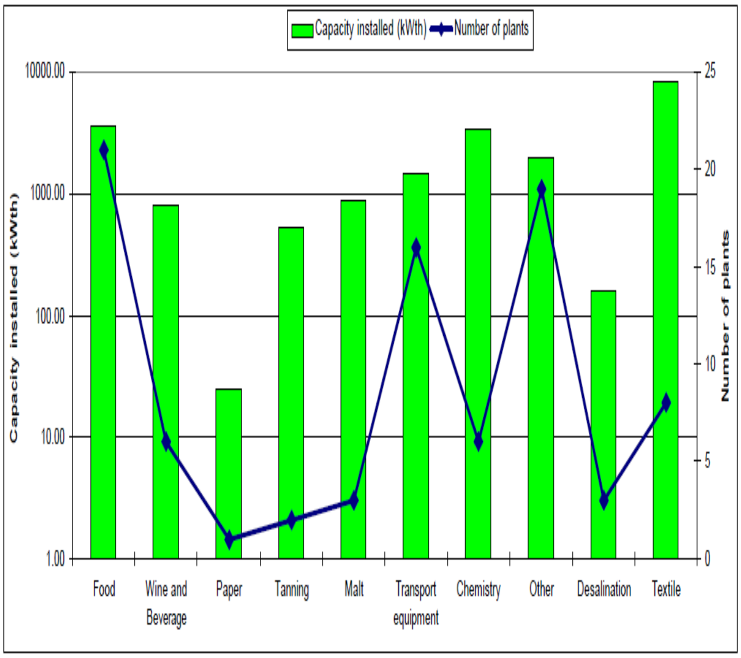

Fig. 1 Solar industrial process heat plants distribution by industrial sector [4].

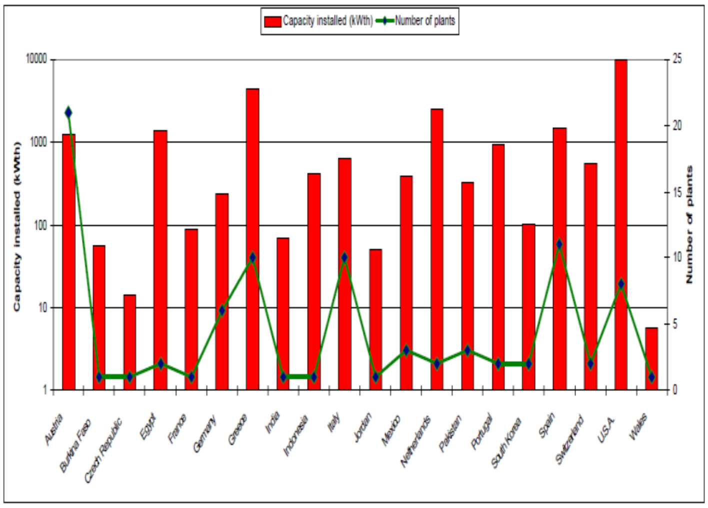

Fig. 2 Solar industrial process heat plants - distribution by country [4].

The second issue that needed to be discussed is the most suitable industrial sectors for the use of solar thermal systems, so that it could be maximized by the use of solar thermal heat. In these sectors, heat is constantly required throughout the year and these sectors have the kind of temperature levels that work very well with the existing efficiencies of solar thermal systems. These sectors include: Food, including wine and beverage, Textile, Plastic and metal treatment Some of the chemical industries, and Plastic treatment. Industrial heating can be divided into three main ranges. Most of them can be achieved by using solar thermal systems. The lowest range is any industry that uses heating applications at or below 80°C. A flat plate solar collector can reach this kind of temperature range and it's widely and commercially available. The second range is any heating application between 80°C to 250°C. And this type of application can be achieved by using evacuated tube solar collectors. The final Temperature range is any heating application above 250°C [8].

This range of temperatures needs a CSP" Concentrated Solar Power" system in order to achieve these kinds of temperatures. About 30% of the total industrial heat demand temperature range is in the first range at temperatures below 100°C and almost 57% in the range below 400°C [9]. The solar thermal industry is growing at a steady rate for the past decade. The global solar thermal market grew by 17% in 2007 and the growth continued until it reached 42% in 2008[4] because the residential heating section spiked at 45-50%. By the end of 2009, Both the United States and Canada accounted for 8.7% of the installed capacity worldwide [2]. China led the global market with 58.9% of installed capacity, followed by Europe at 18.9% [5]. 38 Firms have started using solar thermal systems for industrial process heating with projects that can be considered as large scale in Europe and China.

And as for the Egyptian level, that makes it even more appealing as the temperature ranges for industrial heat processes in Egypt mostly falls below the 250°C [9] combined with the good irradiation levels throughout the year. In 2011, Egypt has witnessed the first achievement of utilization of renewable energy resource, which was the completion of the first 140 MW solar thermal plants in Kuraymat, and connecting it with the national grid at the end of June of 2011[9]. This project was a collaboration of multi-international support and the Egyptian government. The Egyptian government planes to supply 20% of the electricity generation in the country by forms of renewable energy by 2022 and reached to 42% by the year of 2035 according to the announcement of Egyptian new & renewable energy authority "NREA". Egypt could supply more than half of its electricity demand by using renewable energy sources [9]. This paper discusses with detail, the potential of this type of energy by designing and optimizing a solar thermal system using the program "Trnsys 16" to simulate a solar thermal plant in different locations around Egypt to determine the range of useful energies per year in all those different locations. Due to the removal of subsidies by the government on fossil fuels, the cost of fuel will be higher than ever before in Egypt, on the other hand, the price of the locally manufactured solar thermal equipment became competitive to the fossil fuel equipment which consequently maximizes the benefits of a solar thermal system under these new conditions in Egypt. These expected impacts are not only on the Egyptian level, but for other countries with similar irradiation conditions that will adopt the usage of solar thermal systems. The expected impacts for this technology are:

- Contribution to Egypt's targets for renewables.
- Job creation.
- Fuel saving and cost reduction.
- Contributing to global warming reduction and carbon levels.
- Better future for our environment

2-THE DESIGNED SYSTEM AND SIMULATION

The system consists of two loops, the first one (solar loop) consisting of the storage tank and evacuated tube solar collectors and a pump with a controller. The second one (load loop) consists of the pump and auxiliary heating unit before the boiler, and boiler or required load. The two loops are connected via heat exchangers, the oil is heated from the solar collectors, stored in the storage tanks and used to heat the water used for the desired load.
The system consists of:

- Single speed and variable speed pumps.
- Evacuated tube solar collectors (without storage tank connected to it).
- Stratified storage tanks (no auxiliary heating is used inside the tank).

- Temperature differential controllers.
- Weather simulation files for EPW" Energy plus weather".
- Heat exchangers and waste heat recovery.
- Auxiliary heater.
- Flow diverters and flow mixers and tee-pieces.

The closed loop system for the collector-tank consists of four collector arrays. These collector arrays have the same exact design. This loop is split to four collector arrays for safety measures, and also, to prevent the system from completely shutting down if something happened to one of the collectors or piping. As the collectors might be connected in series, and if so, if one collector is damaged, it can stop the flow rate of the other connected collectors. Every collector array consists of a pump, storage tank, and a controller, and the evacuated tube collectors. The user can change the number of collectors used or even the type of collector if the demand is in a lower temperature ranges. The user can also control the collector array configuration for series or parallel based on the required design and flow rate. The tank size is based on the required amount of oil to be stored and can be adjusted also based on application and operating hours. It's possible also to use the auxiliary heater built in the stratification tank but, it is disabled in the current design because an auxiliary heating unit is used after the heat exchangers output. The collector's position can be adjusted by changing the tilt angle of the collector based on the latitude angle of the location. It is considered that the tilt angle of the collector is equal to the latitude angle of the location [10]. As shown in Fig. 3, the flow coming from the heat exchanger (cold output) enters a diverter, but, this diverter is connected to the controller. The diverter is used to divert the flow from the collector-tank loop in case the controller detects that the collector and tank are overheating above the max required design temperatures. And in this case, the flow is diverted to the tee-piece to cool the liquid coming from the tank and the collector before it enters the heat exchangers or mixers. And also for more safety measurements an expansion vessel is also used.

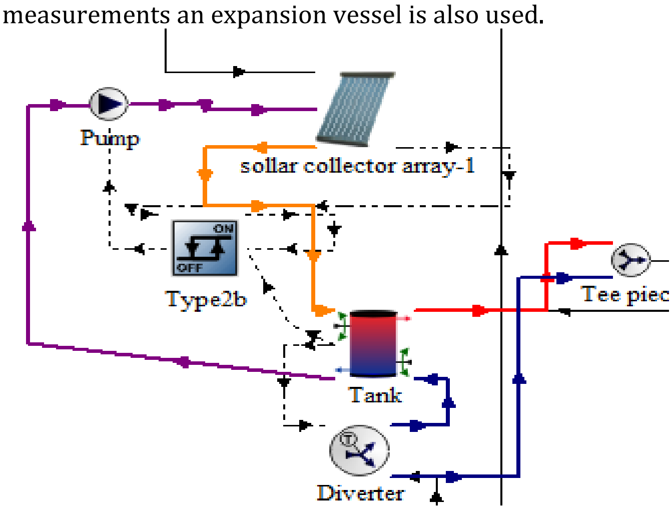

Fig. 3 Collector array configuration

The collector is also connected to the pump and tank and collector array. When the temperature of the oil leaving the collector is lower than the temperature set in the controller, the controller automatically shuts down the pump and the flow is only taken from the stored oil in the tank. This is used to preserve the heat in the tank as long as possible to be used in the heat exchangers. The stratified tank is separated into two levels. The first level in the bottom stores the cold oil, the second level stores the hot oil. This loop is repeated four times and it's the exact same design for each collector array. This design is great for energy saving and also for safety measures. The flow from the four collector arrays are mixed together and separated into two heat exchangers. The heat exchanger design is determined by the entering temperature of the oil coming from the collector array and required temperature for the load and the overall heat transfer coefficient and the number of shell passes. The heat exchanger is designed based on these parameters and these parameters can determine the required length and number of tubes and type of heat exchanger to be used. The outputs of the heat exchangers are mixed together. A controller is connected to the mixing point. This controller determines if the flow should move to the auxiliary heater or the waste heat recovery if the output temperature of the heat exchangers is less or more than the required temperatures of the load. The waste heat recovery output can be separated to two streams. A stream going to the actual load required, and a stream to any hot water application needed. As the extra heat can be useful and should not be wasted, the second stream can be used to heat the entering water before going to the heat exchangers in the first place.

Figure 4 shows the design of the heat exchanger and auxiliary and WHR" Waste Heat Recovery" and load loop in more detail. And also as a controller is connected to the two heat exchangers to divert the flow completely for anyone of them in case there's a failure or malfunction in one of them and it needs to be shut down. This is done to prevent the system from being completely shut down in case one of the heat exchangers fails. The weather file is also involved which is connected to the solar collector array and also as an environmental temperature for the storage tanks. Each equipment has three things:

- A parameter for certain conditions that need to be fixed like specific heat for a liquid used in the equipment, for example.
- Input to the equipment that is coming from the previous equipment like mass flow rate or inlet temperature.
- Output of the equipment that is connected to other equipment

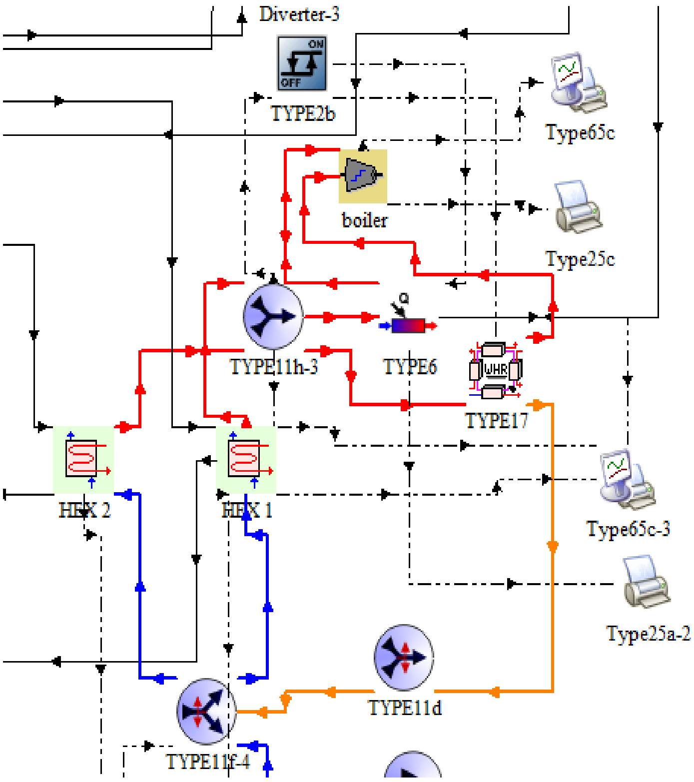

Fig. 4 The heat exchanger and load loop

After all these connections and mathematical models, the final configuration of the system design is shown in Fig. 5. The system is simulating the temperature output of the system all over the year Specifically, 8760 hours. The system output can present also any type of energy output from any equipment, as long as the connection is applied to the output printer. Which in turn, prints the results to an excel file where it can be utilized for data processing to be presented either in Figures, tables and charts. As mentioned before, the simulation is done in 6 different locations around Egypt. In this case the results of the output temperature of the solar system are presented against the time per hour in a year. The parameters that are fixed are: The area of the solar collectors at 4284 m^2, the flow rate of oil and water used in heat exchangers and collectors is 7295 kg/h and 12690 kg/h respectively.

These numbers are chosen based on a reference low pressure boiler system for a company named Savola Egypt, the oil flows through the four collector arrays and then stored in a stratified tank and the controller determines the amount of oil stored in the tank and when the oil stops from flowing to the collector array, the entered weather file is simulated across the year on the collector arrays, the hot oil enters the two heat exchangers and cold water is heated at the designed flow rates. If the temperatures acquired by the heat exchanger is exactly what is needed for the load, the auxiliary heater will not work, if the temperature is higher than needed, the flow of water will go through a waste heat recovery unit to extract the extra heat that is given by the solar system, if the temperatures are lowered than required the auxiliary will be used and losses are also calculated in the auxiliary in this case. Then the water flow enters the required load and the results are printed to the output file in the form of an excel file for all year long. All the modeling equations used for each equipment of the system are obtained at [11].

The study is based on the data obtained from the company as shown in Table. 1. And these data are used as a reference point for the simulation of the 6 locations in Egypt, as these data represent an actual low pressure boiler system that is currently used in the company Savola.

Table. 1 Data obtained from the company Savola Egypt.

data	consumption
Natural gas consumption	Based on working hours
water flowrate quantities	65.65 m^3 /operation cycle
steam flowrate quantities	About 7.295 ton /h.
Entering temperature for water	60 ^oC
Leaving temperature for steam	110 ^oC -120 ^oC
Average efficiency	70%
Volumetric size of the boiler	50000 liter

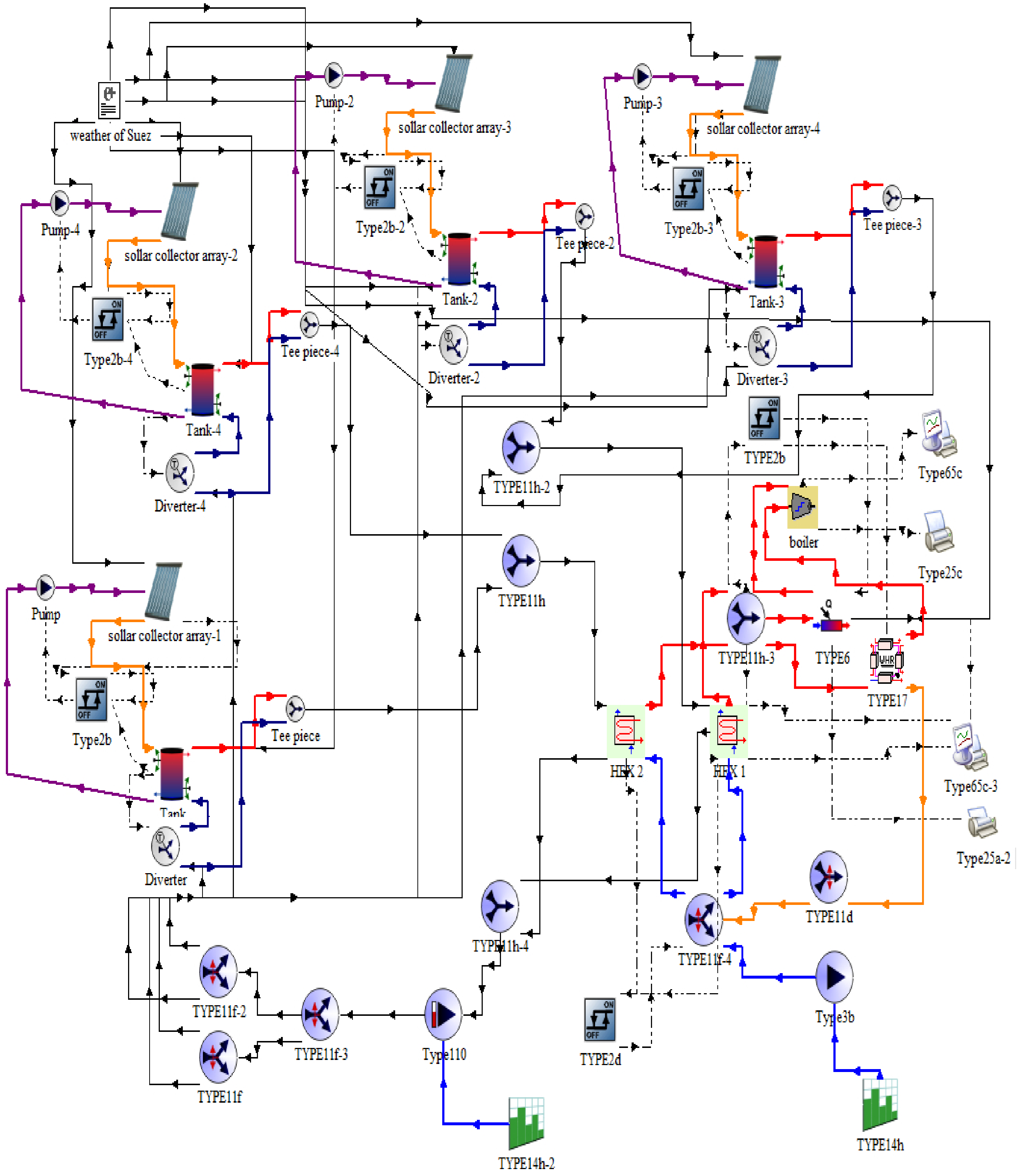

Fig. 5 System design configuration

3-RESULTS AND DISCUSSION

3.1. Results for various locations based on temperatures

The results show a huge difference in the consistency of the temperatures obtained by system in the various locations. Figures [6], [7], [8], [9], [10], and [11], show the consistency of the temperatures is different from location to location, this is mainly because of the difference in wind speeds and humidity levels in each location and also the amounts of radiation per year on each location. Aswan being the lowest in humidity and El Arish and Mersa Matruh being the highest. Also, the amount of shading is different between each location, which can vary the results. This difference in temperature levels affect the amounts of energy saved and energy needed for the auxiliary. The system can reach temperatures up to 175^{0}C in summer times of Suez, Giza, Aswan and El Gharbia, this can serve a great amount of industrial thermal applications and can save lots of energy, especially, in the summer times where radiation is at its peak.

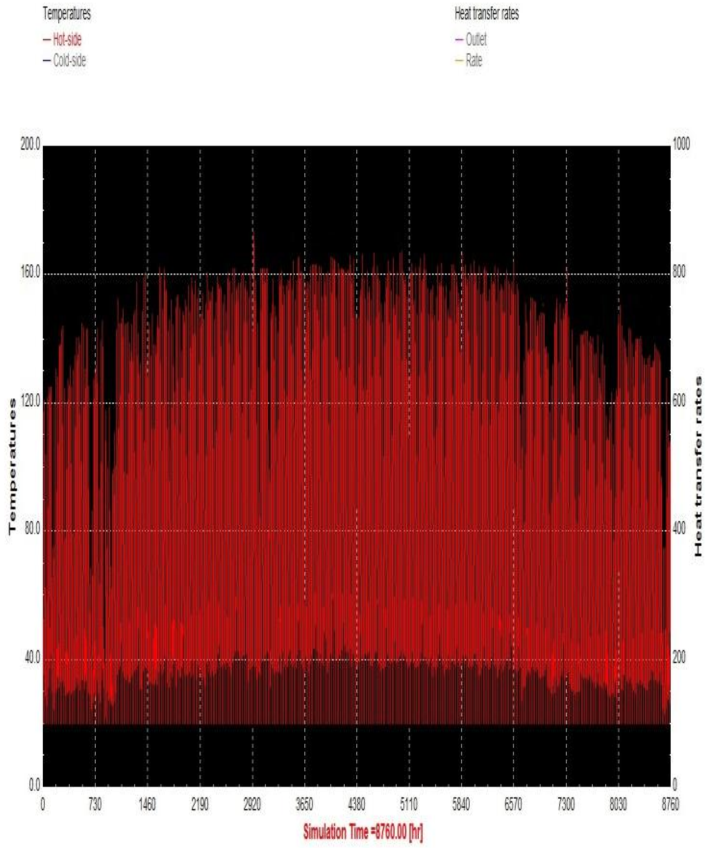

Fig. 6 El Arish hot side temperature results

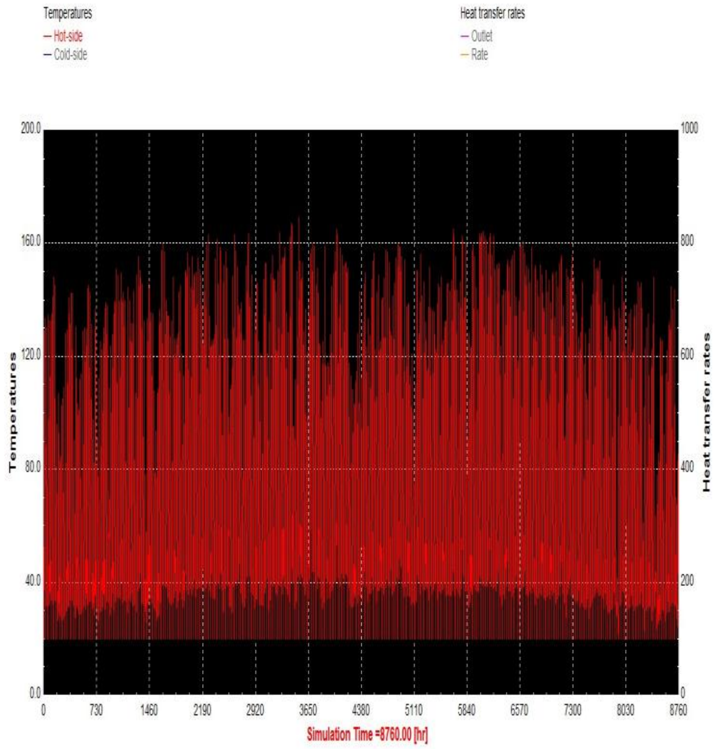

Fig. 7 Mersa Matruh hot side temperature results.

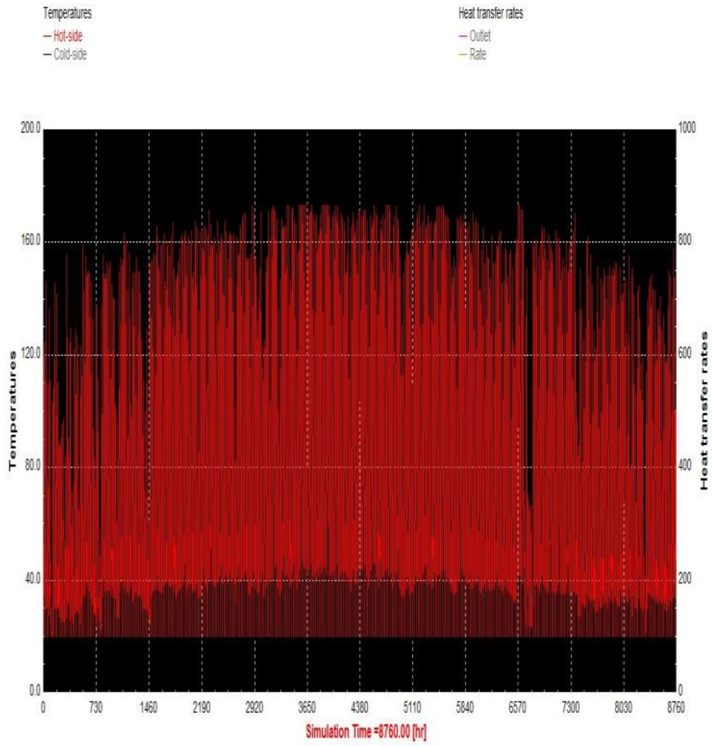

Fig. 8 Suez hot side temperature results

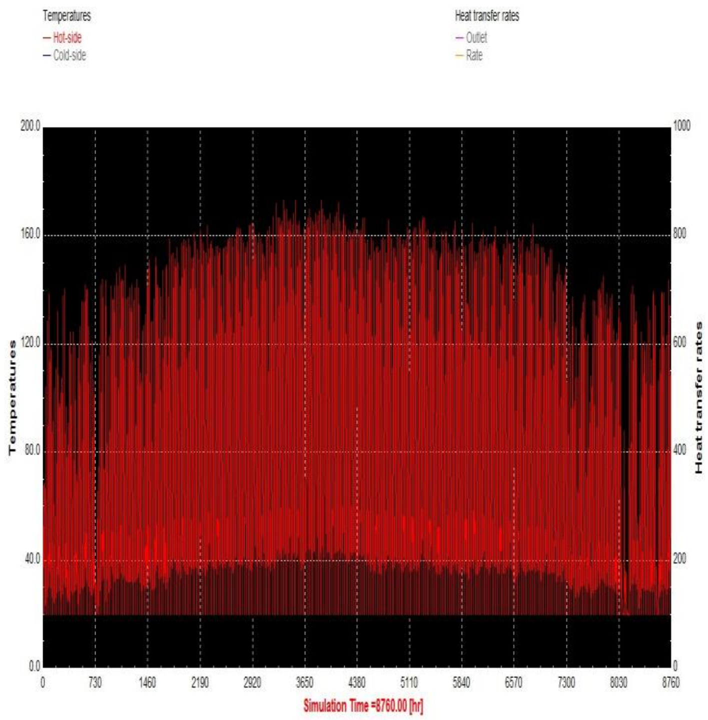

Fig. 9 El Gharbia hot side temperature results

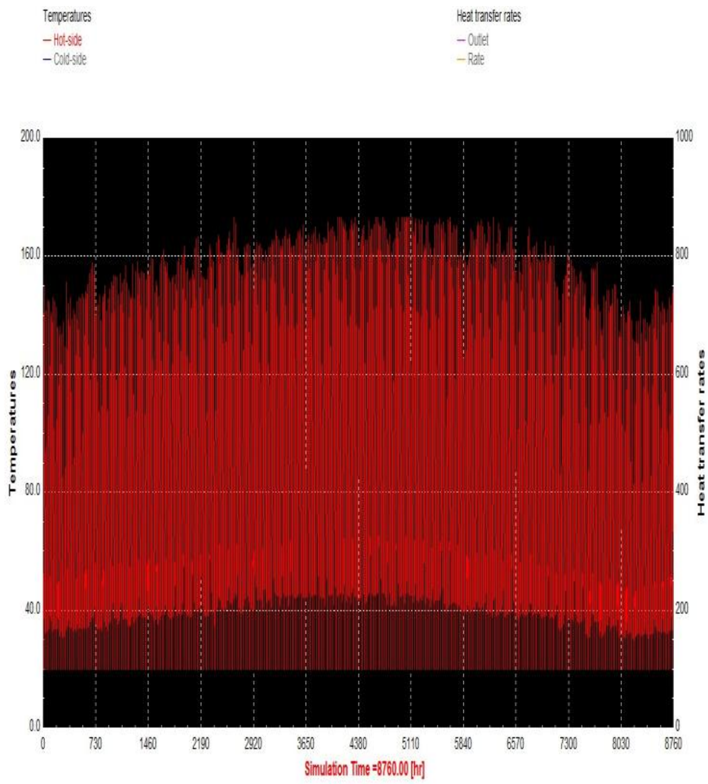

Fig. 10 Giza hot side temperature results

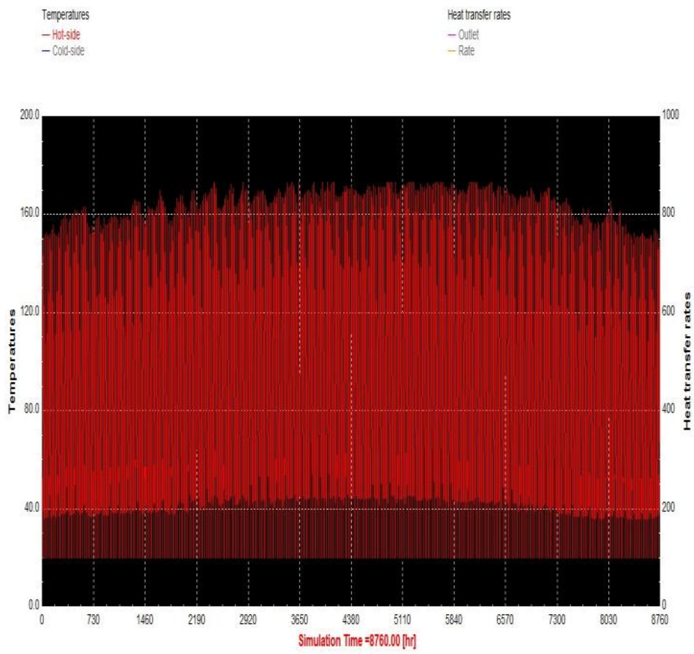

Fig. 11 Aswan hot side temperature results

3.2 Energy saved and energy needed for auxiliary heater based on area for different locations

Figure 12 shows the results of the saved energy per area of the collectors for different locations in Egypt and Fig.13 shows the results of the needed energy for the auxiliary heater per area of the collector for different locations in Egypt. The auxiliary energy is calculated directly from the output of the auxiliary heating from the system's simulation output file.

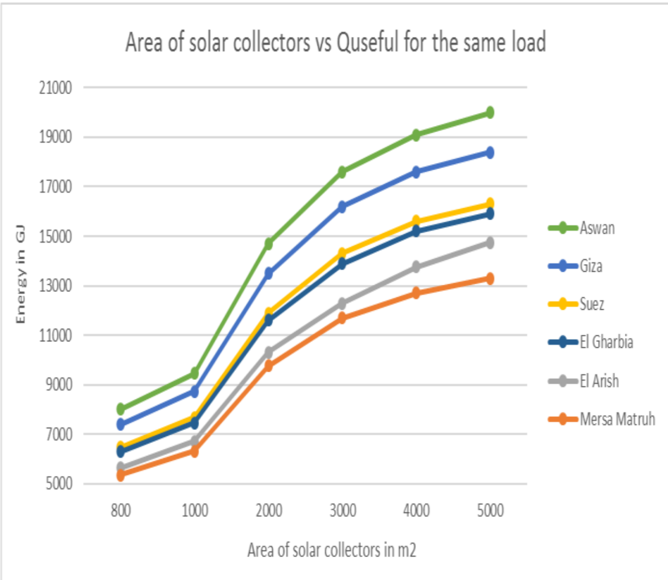

Fig. 12 Energy saved per area of collector for different locations

The energy output per year is in GJ" Giga joule", this curve shows the huge potential of solar thermal energy even in the locations with the lowest radiation in Egypt, the amount of energy obtained by the system is impressive. The lowest amount of energy saved by a system is at El Arish for a collector area of 800 m^2 at 5330 GJ and the highest energy saved by the system is in Aswan for a collector area of 5000 m^2 at 20000 GJ. The amount of energy in Suez and El Gharbia are similar. These results will reflect in the amounts of Natural gas that will be saved for each location based on the calorific value of the natural gas.

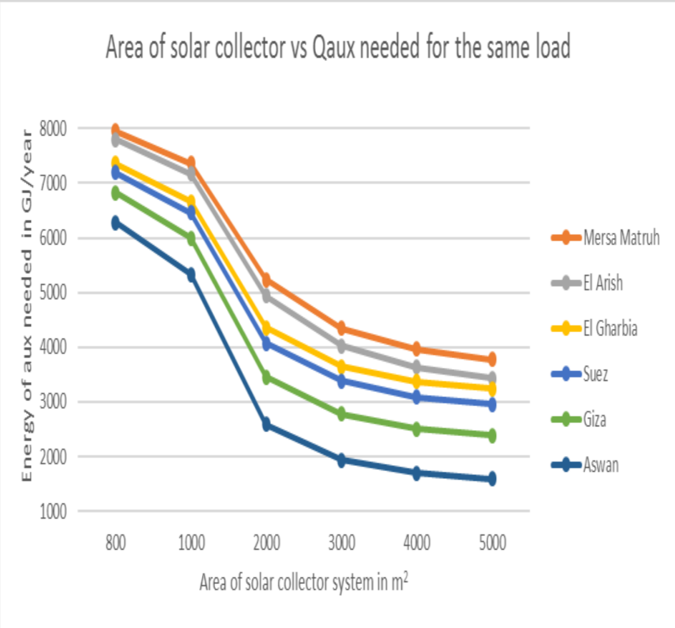

Fig. 13 Energy needed for auxiliary per area of collector for different locations.

3.3 Results for benefits for different locations based on area

In the current study, the benefits were determined for natural gas saved based on a calorific value of a boiler of efficiency of 70% [12]. The Egyptian government is removing the subsides on natural gas and petroleum products slowly overtime [13]. Which consequently provides considerable advantages of a solar thermal system to be competitive. The price of natural gas is estimated at $0.31 for meter cube of natural gas [13] based on current conversion rates of EGP to $ in 2019. The prices of natural gas in Egypt differ based on the type of industry and the consumption of natural gas. The calorific value of natural gas at 70% efficiency is 30100 KJ/m^3 of natural gas. The benefits were determined of each location by dividing the total energy saved over the calorific value of natural gas to calculate the amount of natural gas saved. Figure 14 shows the difference between the benefits based on each location. Mersa Matruh has the lowest value of money saved at $54893 /year and Aswan being the highest value at $205980 / year.

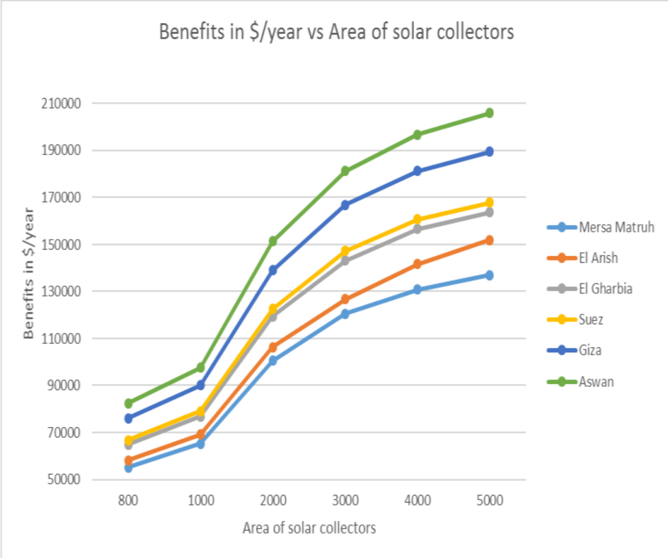

Fig. 14 The benefits of each location based on solar collector area

3.4 Results for capital cost based on location

The capital cost of each location was determined by the capital cost of the case study in Savola company as reference case in the system design. As the flow rates in Savola Egypt are used in the general study and the same design of the system is used, the cost per unit area of the system can be calculated by dividing the capital cost of the project / area of solar collectors used, to determine an approximation of the cost per m^2 for the solar system in each location. Figure 15 shows the difference in capital cost between El Arish or Mersa Matruh and Aswan is huge. El Arish and Mersa Matruh at $1079010 and for Aswan only at $383648. All these capital costs are calculated based on the areas of solar collectors for each location at 13000 GJ/year of useful energy output by the system.

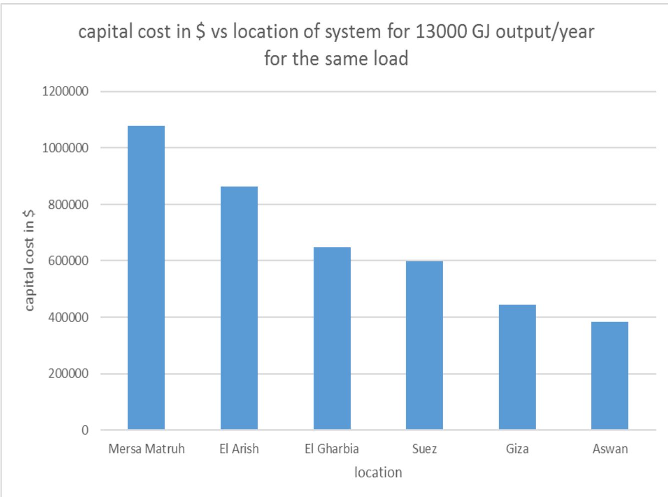

Fig. 15 The capital cost of the system for different locations

3.5 Results for cost of auxiliary for different locations based on area

Figure 16 shows the cost of the auxiliary declines with the increase in solar collector area due to the decline in the amounts of energy needed for the auxiliary heater. Mersa Matruh being the highest cost if auxiliary for 800 m^2 at \$81877/year, and Aswan being the lowest at only \$16375/year. The cost of the auxiliary system is calculated in the same way as the benefits, by losing the calorific value of natural gas of a boiler at 70% efficiency. The auxiliary energy calculated before is converted into natural gas consumption for each location.

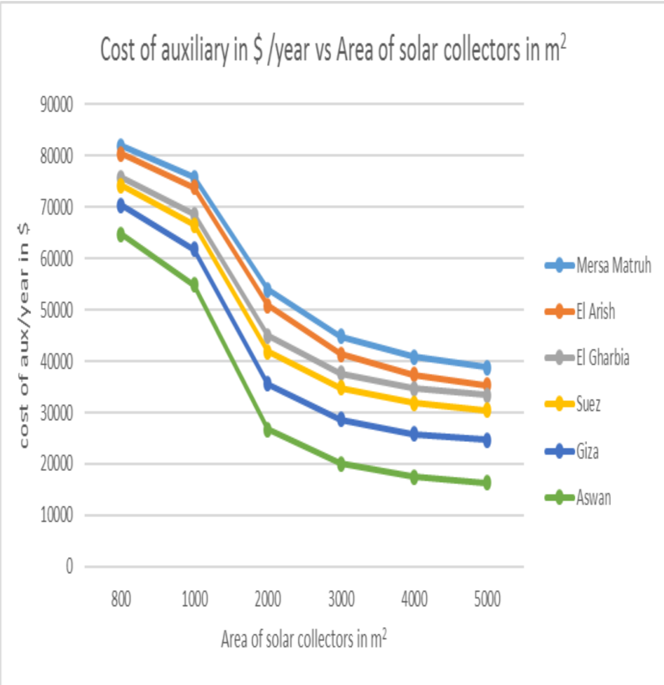

Fig. 16 The cost of auxiliary based on area for different locations

3.6 natural gas saved for different locations based on area

Figure 17 shows the natural gas amount for each location based on area is shown, and the calculations are done based on the calorific value of natural gas at 70% efficiency. The amount of natural gas is determined from the energy saved per year. The results show the same theme observed by the previous results, Aswan being the highest in amounts of natural gas saved at a tremendous value of 664000 m^3/year of natural gas saved, while Mersa Matruh and El Arish being the lowest at 178000 m^3/year, these numbers show how a solar system can affect the consumption of natural gas if it's connected to a low temperature thermal load.

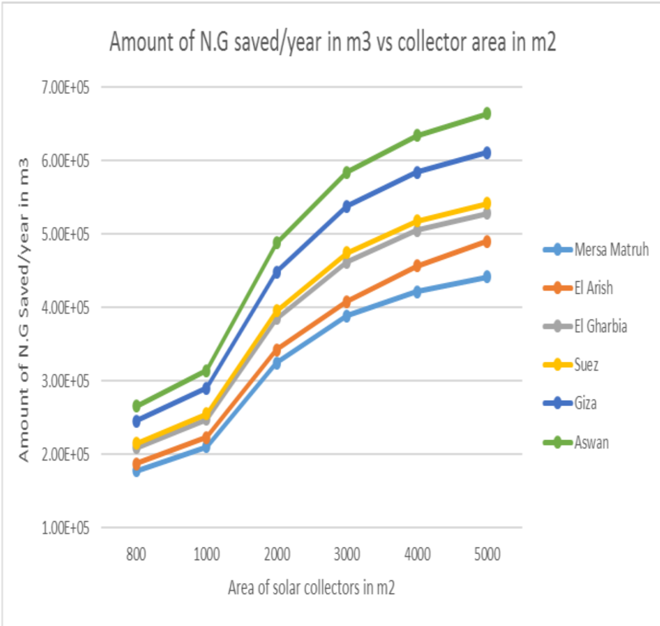

Fig. 17 The amounts of natural gas saved based on area of collectors for different locations.

3.7 Amount of natural gas needed for auxiliary for different locations based on area

As indicated by the results of the energy saved per year for each location, the energy for auxiliary can differ greatly based on the consistency of the system. Figure 18 shows that Mersa Matruh has the highest amount of natural gas needed at 259000 m^3/year for 800 m^2 solar collector area and Aswan is the lowest at 52800 m^3/year for 5000 m^2 solar collector area.

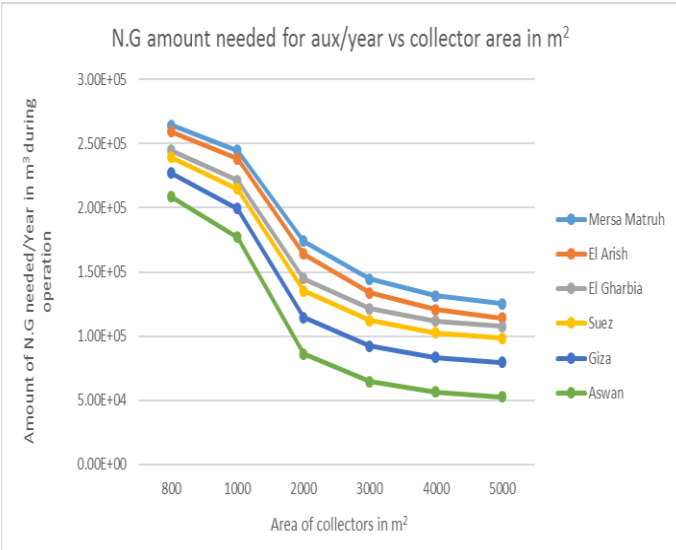

Fig. 18 The amounts of natural gas needed for auxiliary in each location

4-Conclusion

In conclusion, the potential for solar thermal project in Egypt for low temperature industrial applications is tremendous, and due to the increase in energy prices in the last few years due to the government removing the financial aid on conventional fuel, made the potential of solar thermal even higher than ever before. The designed system model by Trnsys helped us determine the potential of the solar thermal energy by simulating the weather conditions in each of the 6 locations in which the study was conducted. It showed the great potential of solar thermal energy in each of these locations. It also showed how much we can save on fossil fuels like natural gas if we opted to use solar thermal energy instead of conventional systems. The designed model was also used for the case study in Savola Egypt. The draw backs of solar thermal system are the huge upfront cost and the area required for the solar collectors, and also, the payback period for the solar system depends on the consistency of the location in delivering the required energy for a decent benefit.

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BIOGRAPHIES

Hamdy El-Ghetany is a Professor of Solar Energy, Head of Solar Energy Department, National Research Centre, Cairo, Egypt. Dr Hamdy awarded his doctoral degree graduated from Tohoku University, Japan 2000. He has an extensive experience in the field of mechanical engineering for 32 years either academically or professionally. Professionally, he is an electromechanical designer and reviewer for the pipe lines, storage tanks, heat exchanger, water treatment and solar energy systems of several projects. Academically, he is recognized both internationally and nationally in the area of solar energy applications. He is the author of more than 40 scientific research articles published in leading international journals and international and national conferences.

Ayman S. Abbas, Assoc. Prof graduated with a B.Sc. (Honours) in Design and Production Engineering in 1992 from Shoubra Faculty of Engineering, Zagazig University. He obtained his Ph.D. in 1998 from the University of Strathclyde, UK, in Computer Aided Design. Upon his return from the UK, he joined a private higher education institution in Egypt, where he helped develop the curriculum of the Mechatronics Engineering department. Dr. Abbas worked on several research projects and taught various design and automation courses at his last post.

Dr Abbas joined the BUE in 2006 to co-establish the Mechanical Engineering Programme. Since then, he was involved in the establishment of an up-to-date curriculum and its continuous review and development. Together with the Head of Department, their efforts culminated in the successful validation of the programme initially by Loughborough University and subsequently by London South Bank University, according to the QAA regulations which was achieved in August 2007 and sustained ever since. He acted as the departmental Teaching and Learning Coordinator since validation. From September 2013 to October 2017, Dr Abbas was appointed Programme Director for Mechanical Engineering. Dr Abbas has extensive experience in the areas of design education, kinematics and dynamics of machines and robotics and automation studies. He has several published journal and conference papers in these fields. Dr Abbas also acted as an initiator for Robot Contests in Egypt and has supervised teams successfully on the local, regional and international levels.

Nour A. Abou Ghattas, is a chemical engineer, graduated from El Shorouk Academy, currently preparing his master's degree in renewable energy sources, specifically solar energy. He is currently working as a teaching assistant at the Canal high institute of engineering in Suez, Egypt, He worked on several projects connected to his field and also the field of renewable energy, he's also one of the judges in the Intel ISEF "The Intel International Science and Engineering Fair". He also worked as a freelancer for software and web development work for both Google and Facebook through a company called Appen online. He's also responsible for online projects related to Victoria Institute Business development regarding the field of chemical engineering. He was also invited by Zewail City of Science and Technology to teach a subject in material science. He hopes to prepare his PHD in the field of solar energy and make significant work in the field.