

Design and Development of Solar-Based Water Heating System with Mechanical Sun Tracking

Mohammed S. Al-Soud

Department of Electrical Power Engineering and Mechatronics, Tafila Technical University, Tafila, Jordan
e-mail: msoud@ttu.edu.jo

Received: February 12, 2018

Accepted: February 24, 2018

Abstract— In this work, the effect of integrating a mechanical sun tracking system on the performance of a solar heating system was investigated. The heating system consists of a copper pipe in the form of rectangular vortex. The solar tracking system is designed and constructed mechanically through a water float associated with a tow pulley to the gearbox. The gearbox is connected to a pulley on the shaft that is connected to the parabolic trough. A programming method to control the pumping system as a function of time is used. An experimental study was conducted to investigate the performance of the solar heating system with and without tracking. The results of experimentation indicate that in the case of exposing solar heating to the sun for 15 minutes, the heating system with mechanical tracking increased water temperature from 24° C to 84° C, while the heating system without tracking increased water temperature from 24° C to 55° C.

Keywords— Heating system, Mechanical sun tracking, Parabolic trough.

I. INTRODUCTION

Jordan is among the highest in the world in dependency on foreign energy sources, with 96% of the country's energy needs coming from oil and natural gas imported from neighboring Arab countries. At the same time, a renewable energy potential analysis in Jordan shows that solar energy is by far a renewable source with the largest theoretical potential 1,642 GW [1]. A side from its economic and environmental benefits reduces dependence on imported energy; Jordan needs to invest in alternative and renewable energy sources, especially solar and wind energies.

Water heating systems are popular solar applications in Jordan especially in the rural areas where no electricity is currently available. The maximum extractions of solar energy can be made using a sun tracking system [2]. Solar water heating industry in Jordan is well developed. By 1999, about 25% of homes had been fitted with solar water heaters.

Solar tracking systems have been investigated and studied by several researchers with different modes and electromechanical models to improve the efficiency of solar systems. The efficiency of a solar heating system depends on many factors. Climatic conditions such as solar radiation and ambient temperature constitute one factor. Basically, tracking systems could be either an electro-mechanical system consisting of the electrical, electronic and mechanical element (active type) or a mechanical system without any electrical and electronic elements (passive type) [3]. Passive trackers are less favorable and applicable due to their complex design and low accuracy [4].

Many experimental and theoretical studies have been conducted on sun tracking systems with different applications to improve the efficiency of solar systems [5]-[8]. In [9], the comparison between a mechanical and an electromechanical solar tracking system shows that the mechanical sun tracking system consumes zero energy from the produced energy and thereby it increases the overall efficiency by 5-8%.

Clifford and Eastwood [10] presented a passive solar tracker system which integrates two bimetallic sections made of steel and aluminum and placed symmetrically on either side of a central horizontal axis of the wooden frame. The efficiency of the solar panel of this system is increased by 23%. Abouzeid [11] presented a tracking system based on a step movement of either 15° or 7.5°. A programmable logic controller and an EEPROM carrying all necessary commands are used for various operation situations.

Rubio *et al.* [12] showed a hybrid tracking system which consists of a combination of open-loop and closed-loop tracking methods based on solar movement models and a dynamic feedback controller. The results show the benefits of the new method contrasted with those of a classical open-loop strategy.

GAJJAR [13] designed, fabricated and installed the dual axis solar tracking system using LDR sensors. The solar cell operates efficiently with the dual axis solar tracker. Power increases up to 17.53% compared to the fixed mount solar system.

Sungur [14] designed and constructed a multi-axes sun tracking system with programmable logic control. The function of both the solar azimuth angle and solar altitude angle is to follow the sun's position. He found that the energy obtained from the two-axes sun-tracking system is 42.6% more than that of the fixed system.

The purpose of this research is to construct and investigate a mechanical sun tracking heating system mainly for remote areas where no electricity is available to meet the household heat water needs.

II. SYSTEM DESIGN

A special mechanical tracking system was constructed to drive the structure which carries the parabolic trough with a heating unit. The structure is designed to carry the whole system loads including the force applied by the wind. The whole mechanical design has been simulated before implementation to eliminate system breakdown.

The proposed mechanical design will satisfy such conditions as the sun rays which must be reflected to the specified receiving line; secondly, the mechanical tracking system depends on the sun position; and the mechanical system moves along the east-west axis. Therefore, the mechanical design is divided into three parts: a mechanical structure with a mechanical tracking mechanism, a parabolic trough and heating pipes.

A. Design and Construction of the Tracking System

A.1. Supporting Framework

The supporting body is designed to rotate around its east-west axis, which is designed and fabricated of iron tubes with a square cross sectional area (0.5x5x5cm). The horizontal bars are used to reinforce the structure from deflection. The main components of the mechanical tracking solar system are shown in Fig. 1.

The supporting structure transmits motion from the gear box to the parabolic trough, which consists of a shaft pulley, shaft, and float wire. The wheels are holding the system. They are used for maintaining easy motion and system balance. The bearings in the top are of a heavy-duty type used to offer simple rotation of the upper part of the system. The positioning of these bearings is very sensitive since it may affect the balance of the whole system and cause misalignment.



Figure1. The main components of the mechanical tracking solar system

A.2. Description of the Mechanical Solar Tracking System

A mechanical solar tracking system works on the principle of mechanical clock; and it consists of gear box and control unit. A gear train operating system with the help of potential load is employed to rotate the solar concentrator with the movement of the sun

The gear box consists of three types of pulleys: two toothed pulleys with a diameter of 4.5cm having 15 teeth; three toothed pulleys with a diameter of 13.5cm having 14 teeth, and non-toothed pulley as shown in Fig. 2.

The control unit consists of two tanks in the system. The upper tank is the tank which contains water float. The lower tank contains the linkage water flowing from the upper tank through an adjustable water valve. Both tanks have a dimension of 0.8x0.5x0.4m as shown in Fig. 3. In addition, control unit controls the duration of revolving i.e. 8 or 10 hours depending on whether it is winter or summer. The water float also controls the rotation speed of the trough.



Fig. 2. Gear box unit with three types of pulley

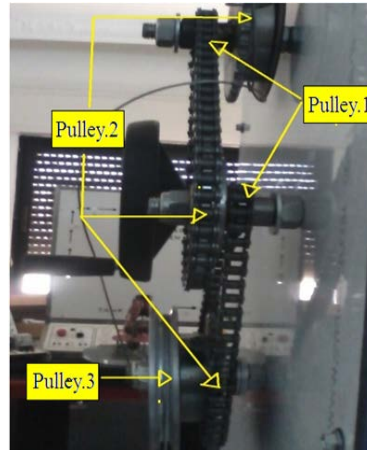


Fig. 3. Control unit of the system

A.3. Parabolic Trough

The designed surface is based on the general equation for the parabola. The system is designed to set the focal point 1m from the vertex. The aperture of the system is 1.5m long. The parabolic shape is formed using 19 adjustable reflective plates/mirrors. Each reflective plate can change its tilt angle to reflect the incident radiation into the focal line. The width of each mirror is about 0.1m, so that a straight surface is sufficient without having concave mirrors. Although this solution will decrease radiation losses due to the missed reflective rays and decrease unreflective areas between mirrors bisections, it is a reasonable approach. Coating is made of a mixture of cobalt, aluminum, rubber and silica that reflects about 94% of the solar radiation.

A.4. Mechanical Design of Solar Heating Pipes

The solar heating coil consists of a copper pipe, which is black painted and formed into a rectangle spiral shape. The coil is placed on the frame of the rectangle. The pipe is approximately 54 meters in length, with a diameter of 16 mm and a separation of 2 mm between adjacent lines. Fig. 4 shows solar heating pipes with the mechanical sun tracking system.

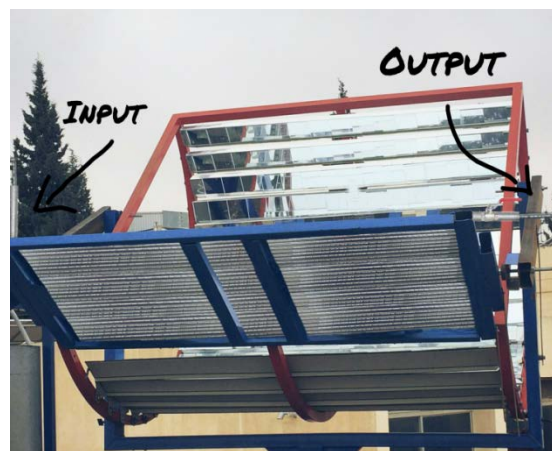


Fig. 4. The proposed heating system

B. Working Principle of the System

The mechanical tracking system operates as follows: in the morning, the system is oriented manually to face the sun in the east. The water float is linked to the gearbox and then to the shaft pulley to transmit motion to the shaft then to the collector to keep facing the sun during the whole day. The float is hanged up; and the upper tank is filled with water. The suggested tracking system works on the principle of water balance between the upper and lower tanks. The flow of water from the upper tank increases the height of the pontoon, which is inside the lower tank. The pontoon is mechanically linked to the rotation of the hub. The higher the volume of water, the higher the pontoon and thus the rotation of the hub to the west [15]. The slow cyclic motion of the collector, introduced from the slow downward motion of the water float caused by a leakage of water to the lower tank, is controlled by the adjustable valve fixed to leak water during 10 hours. The gear box converts the linear motion of the float water into cyclic; and it increases the permissible motion angle.

This motion is transmitted to the collector through a float wire connecting the gear box to the pulley, which is fixed on the shaft of the collector. In the morning of a new day, the water float is hanged up again; and water goes back from the lower tank to the upper tank using a manual pump.

The solar heating system operates in the following manner: from the input tank a pump, driven by a 12 VDC; 50W motor pumps cold water into a solar heating pipes. In this design, the DC motor is powered by a photovoltaic module with the following specifications: Maximum power (P_{max}) 50W, Voltage at P_{max} (V_{mpp}) 17.5V, Current at P_{max} (I_{mpp}) 2.90A, Short circuit current (I_{sc}) 3.20A, Open circuit voltage (V_{oc}) 21.8V, Module efficiency 11.1%, and Nominal voltage 12V.

The input water remains in the heating system for 15 minutes, before this time the input tank drains hot water through the hot water outlet into the collection tank. This mode of operation of the heating system was achieved by designing a of a programmable logic controller (PLC-LOGO-24RC-Siemens) [16], [17]. A schematic hardware circuit and the functional PLC program for this pumping system are shown in Fig.5 and Fig .6.

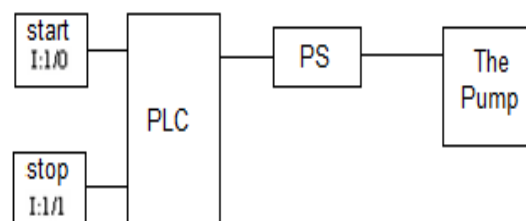


Fig. 5. The schematic of hardware components of a pumping system

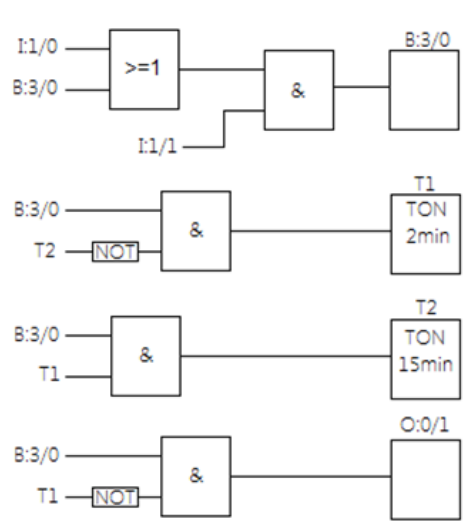


Fig. 6. The functional PLC program for the pumping system

Where PS is the power supply (PV-module); I: 1/0 is the push button to start automatic cold water supply; I: 1/1 is the stop push button; B: 3/0 is the internal memory as a master power; T1 is the timer for ON duration; T2 is the timer for OFF duration; and O: 0/1 is the output which represents the pump.

III. EXPERIMENTATION AND RESULTS

To ensure measuring experiments at the same environmental conditions, two identical systems were designed. The first one is a fixed system with a tilted angle of 28° , which is the suitable tilt angle for Tafila area. The second system is with a continuous mechanical sun tracking mechanism (Fig. 7).

The system was installed and tested at Tafila Technical University in Tafila, Jordan on latitude 30.47° and longitude 35.43° with an annual mean daily global solar radiation on a horizontal surface of 5 to 7 kWh/m²-day [18], [19]. Jordan has wind speed of an average of 5-9m/s. Wind speed and system weight create the main load on the experimental design [20]. The mechanical sun tracker was designed using a clockwork mechanism.

The proposed system has been implemented to evaluate the mechanical sun tracking system for heating purposes. Experiments on the solar heating pipes with one axes sun tracking system were carried out on the 2^{ed} and the 3^{ed} of August 2017 from 8:00 AM to 4:00 PM local time at Tafila. The global solar radiation on the horizontal surface was measured using Kipp and Zonen pyranometer. Temperature measurements were carried out using a K-type thermocouple coupled to digital thermometer with a range of measurement from -50 to 150° C. The proposed system operates in the following manner: cold water is supplied into the system through the cold inlet of the rectangular tube, where cold water will be exposed to solar radiation for 15 minutes. After that, the heated water will be pumped out through the hot water outlet of the rectangular tube. The volume of the water inside the heating system is approximately 9.5 liters. The flow rate of the used pump (12 VDC, 50 W) is 4.75 L/min.



Fig.7. Two systems working in parallel for the same weather conditions

Fig. 8 shows the ambient temperature measured at the site during the test period for the day in which the experimental part was conducted.

Figs 9, 10 and 11 show the measured hourly variation of inlet cold water temperature values, the hourly variation of outlet hot water temperature values and the hourly variation of the heating system surface temperature values. The figures show an increase in the outlet water temperature during the early hours of the day until it reaches the maximum value around noon and then decreases as the sun sets. In addition, the curve corresponding to hot water temperature at the outlet of the solar heating coil with one axes tracking system shows an increase in water temperature from 24°C to 84°C after exposure to the sun for 15 minutes. However, the system without tracking increases water temperature from 24°C to 54°C . Moreover, water temperature at the outlet of the solar heating pipes can reach higher rates on hotter summer days.

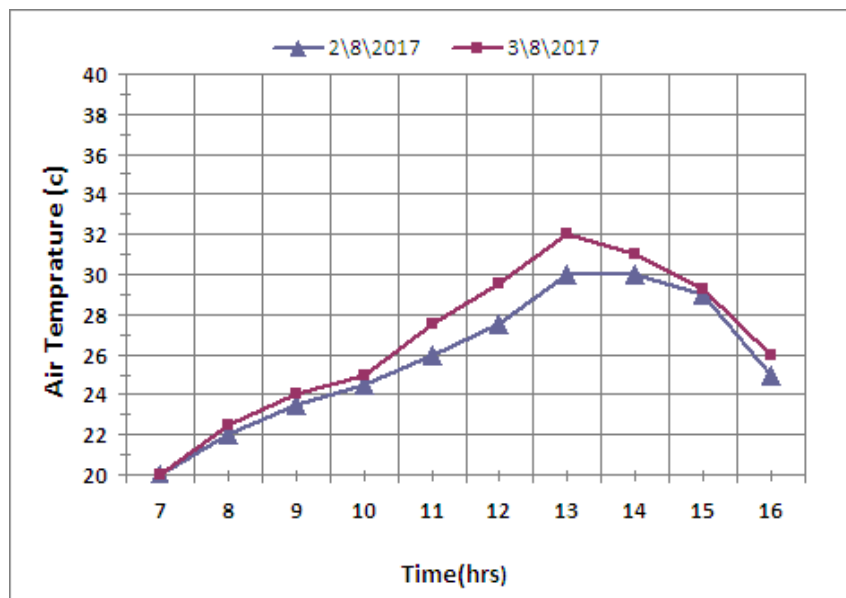


Fig. 8. Variation of air temperature as a function of time

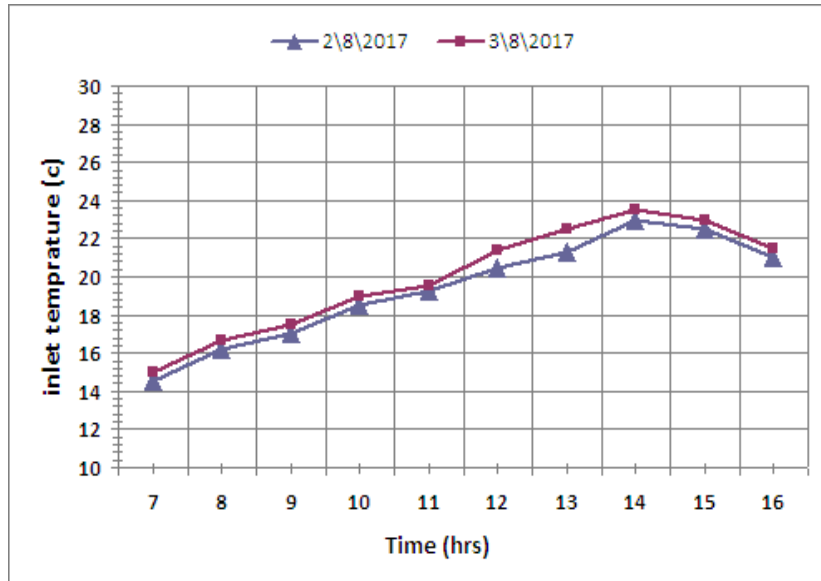


Fig. 9. Variation of the inlet cold water temperature as a function of time

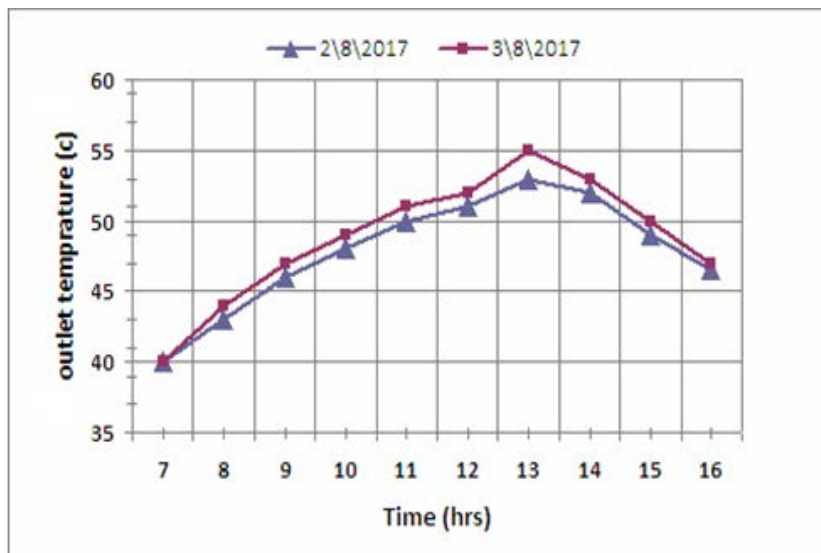


Fig. 10. Variation of the outlet hot water temperature as a function of time for a fixed system with 28° tilted angle

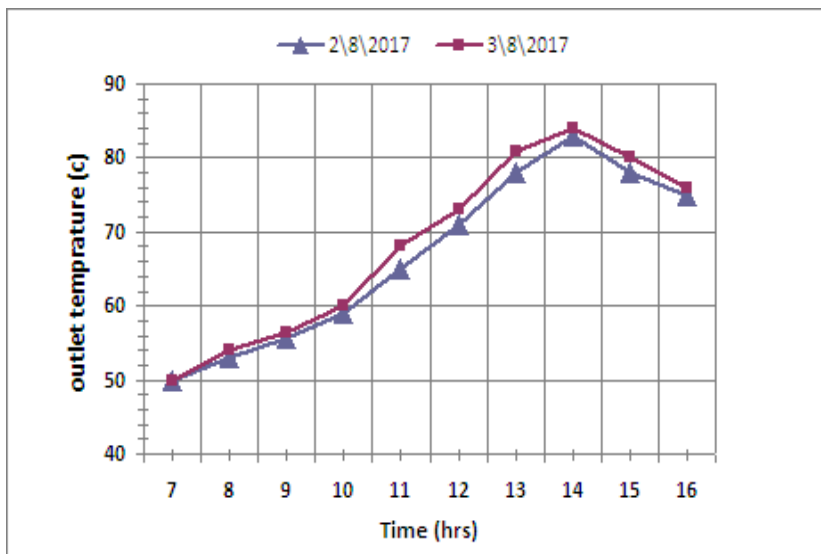


Fig. 11. Variation of the outlet hot water temperature as a function of time for a mechanical sun tracking system

IV. CONCLUSIONS

In this proposed system, the pure mechanical sun tracking heating system was implemented to produce heat energy for different applications. Mechanical tracking mechanism is based on the concept of water float, which is linked through a tow pulley to the gearbox. The gearbox is connected to a pulley on the shaft that is connected to the parabolic trough. The comparison between the mechanical tracking system and electro-mechanical solar tracking system shows that it consumes zero energy and thereby increases the overall efficiency. The result of the proposed water heating system shows that the heating system provided better results. The maximum outlet water temperature of the parabolic trough for the fixed system reached 55° C on summer days from a registered inlet temperature of 24° C, while the heating system with a tracking system recorded a maximum outlet temperature of 84° C from an inlet temperature of 24° C. The experiment was conducted during a typical summer day. This temperature gain is considerable and sufficient for many domestic and industrial applications.

REFERENCES

- [1] M. Al-Soud and Q. Alsafasfeh, "Economical evaluation for various renewable energy products in Jordan," *Proceedings of the Renewable Energy Congress*, pp. 1-4, 2015.
- [2] B. Huang, Y. Huang, G. Chen, P. Hsu, and K. Li, "Improving solar PV system efficiency using one-axis 3-position sun tracking," *Energy Procedia*, vol. 33, pp. 280-287, 2013.
- [3] A. Khalifa and S Al-mutawali, "Effect of two axes sun tracking system on the performance of compound parabolic concentrators," *Energy Conversion and Management*, vol. 39, pp. 1073-1079, 1998.
- [4] N. Parmar, A. Parmar, and V. Gautam, "Passive solar tracking system," *International Journal of Emerging Technology and Advanced Engineering*, vol. 5, no. 1, pp. 138-145, 2015.
- [5] P. Roth, A. Georgiev, and H. Boudinov, "Cheap two axis sun following device," *Energy Conversion and Management*, vol. 46, no. 7-8, pp. 1179-1192, 2005.
- [6] M. Koussa, M. Haddadi, D. Saheba, A. Malek, and S. Hadji, "Sun tracking mechanism effects on flat plate photovoltaic system performances for different step time and main parameters affecting the obtained gains: case of north africa and mediterranean site," *Elsevier Energy Procedia*, vol. 18, pp. 817-838, 2012.
- [7] R. Agarwal, "Concept of mechanical solar tracking system," *Journal of Mechanical and Civil Engineering*, pp. 24-27, 2014.
- [8] S. Bushong, "<http://www.solarpowerworldonline.com>. [Online]. Available: <http://www.solarpowerworldonline.com/2016/05/advantagesdisadvantages-solar-tracker-system/>, 2016.
- [9] M. Sarker, M. Beg, M. Hossain, M. Islam, and M. Zaman, "Design of software controlled two axis automatic solar tracking system," *Mechanical Engineering Research Journal*, vol. 5, pp. 32-36, 2005.
- [10] M. Clifford and D. Eastwood, "Design of a novel passive solar tracker," *Solar Energy*, vol. 77, no. 3, pp. 269-280, 2004.
- [11] M. Abouzeid, "Use of a reluctance stepper motor for solar tracking based on a programmable logic array (PLA) controller," *Renewable Energy*, vol. 23, no. 3-4, pp. 551-560, 2001.

- [12] F. Rubio, M. Ortega, F. Gordillo, and M. López-Martínez, "Application of new control strategy for sun tracking," *Energy Conversion and Management*, vol. 48, no. 7, pp. 2174-2184, 2007.
- [13] V. Gajjar, "An experimental study on dual axis solar tracking system," *International Journal of Mechanical and Production Engineering*, vol. 5, no. 3, pp. 86-91, 2017.
- [14] C. Sungur, "Multi-axes sun-tracking system with PLC control for photovoltaic panels in Turkey," *Renewable Energy*, vol. 34, no. 4, pp. 1119-1125, 2009.
- [15] M. Al-Soud and A. Akayleh, "Development of a solar water distillation system with a mechanical sun tracker," *International Journal of Ambient Energy*, pp. 1-6, 2017.
- [16] E. Manado, J. Macros, S. Perez, *Programmable Logic Devices and Logic Controllers*, Prentice-Hall, 1996.
- [17] Siemens Company Catalogue of LOGO 24 RC.
- [18] M. Louy, Q. Tareq, S. Al-Jufout, Q. Alsafasfeh, and C. Wang, "Effect of dust on the 1-MW photovoltaic power plant at Tafila Technical University," *Proceedings of the Renewable Energy Congress*, pp. 1-4, 2017.
- [19] E. Hrayshat and M. Al-Soud, "Potential of solar energy development for water pumping in Jordan," *Renewable Energy*, vol. 29, no. 8, pp. 1393-1399, 2004.
- [20] M. Al-Soud, "Assessment of wind characteristics and wind potential energy yield in the Jordanian southern region," *Energy and Power Engineering*, vol. 9, pp.348-357, 2015.