Feasibility Study of Solar Energy Steam Generator for Rural Electrification

Mouaaz Nahas[1], M. Sabry[2,3], Saud Al-Lehyani[2]

[1]Department of Electrical Engineering, College of Engineering and Islamic Architecture, Umm Al-Qura University, Makkah, KSA
[2]Department of Physics, College of Applied Sciences, Umm Al-Qura University, Makkah, KSA
[3]Solar Research Department, National Research Institute of Astronomy and Geophysics, Cairo, Egypt
Email: mmnahas@uqu.edu.sa

Abstract

In Middle East region, where there are plentiful amounts of solar radiation and great desert areas, solar energy can play a potential role in replacing conventional fuel-operated electricity generation methods with a cost-effective, sustainable solution. This paper presents a feasibility study of a low-cost solar energy steam generator for rural areas electrification. The proposed system is based on the use of trough concentrator which converts solar radiation into thermal energy in its focal line (where a receiver pipe is installed with a fluid flowing in its interior). The aim of the paper is to predict the feasibility and potential for steam generation using a stand-alone solar concentrator with a small dimension for domestic and small-scale electricity generation. The study presented here is based on modelling of the system to determine the points at which the system is expected to produce sufficient steam energy at the tube outlet to drive a steam engine for producing electricity. Results are presented in graphical forms to show the operating points and the effect of changing selected input parameters on the behavior of the system in order to set some limits (boundaries) for such parameters. Results show that among the three input design parameters selected, the tube diameter is the most dominant parameter that influences steam energy, then the tube length and finally the flow rate of the water passing through the tube. The results of this paper can provide a useful guideline for future simulation and/or physical implementation of the system.

Keywords

---

1. Introduction

A continuously rising energy demand along with increasingly limited natural resources is challenging energy suppliers, industry as well as consumers to rethink how energy can be produced and used efficiently. Energy efficiency, smart energy use, and energy savings are keys to meet this challenge in a sustainable way [1] [2].

State power grid systems supply electricity to the majority of the population living in state capitals and industrial centres [3]. It is highly uneconomical to extend the electrical power grid system into the sparsely populated regions. Hence, there are many small remote communities that need an independent source of electrical energy, especially in the Middle East region. These locations represent a significant potential for renewable energy applications. The importance of using renewable energy not only will be confined to meet the demands of remote sites, but also can contribute to the national grid, helping to meet the peak-load demand during the summer months [3].

Renewable energy is becoming the focus of concern to both oil and non-oil producing countries. Nowadays, many countries around the world are keenly interested in taking an active part in the development of new technologies for exploiting and utilizing renewable sources of energy. The main motivation as to why renewable energy is given much attention is because of its contribution to reduce harmful emissions to the environment, especially carbon dioxide. There are rising concerns around the globe over the high oil and gas prices because of growing demand as well as the aspect to reserve oil for the next generation [4]. In countries located within the equatorial "Sun Belt" (where more solar radiation hits the earth than any other part of the globe), there is a massive amount of freely available solar energy which can be exploited. Besides receiving a lot of solar energy, desert countries in the Middle East have other competitive advantages when it comes to the potential of developing solar energy markets and technology. For instance, there can be lots of open lands, and more importantly, lots of sand which might contain a high percentage of silicon, the starting material for silicon solar "photovoltaic" (PV) cells and panels as well as semiconductor chips. Also, such countries have a relatively fast-growing young and educated population, many of whom are looking for good private sector jobs and careers (for further details, see [2]).

Middle East, Arabia and Gulf area present very high solar radiation potential especially Direct Normal Irradiance (DNI), *i.e.* the fraction of solar radiation which is not deviated by clouds, fumes or dust in the atmosphere and that reaches the Earth's surface as a parallel beam [5]. The regional DNI map is shown in **Figure 1**. Clearly, DNI in such region is amongst the highest values in the world. Moreover, in this region, there are fewer restrictions in space available due to desert areas, while some of the rural areas have not been electrified yet or are under electrification with decentralized ways of connection. The large space combined with the abundant solar resources has made this region one of the promising areas for the installation of solar energy plants for providing electricity [6].

Rural electrification is a global challenge in the developing countries especially those whose area is huge and has low population in scattered communities or tribes as is the case in most countries of the mentioned region. The socio-economic development processes revolve around suitable and sustainable power supply. In fact, it is the nucleus of operations and subsequently the engine of growth for all sectors of the economy. It also determines the living standard of the people and stops the immigration to urban areas as well [7].
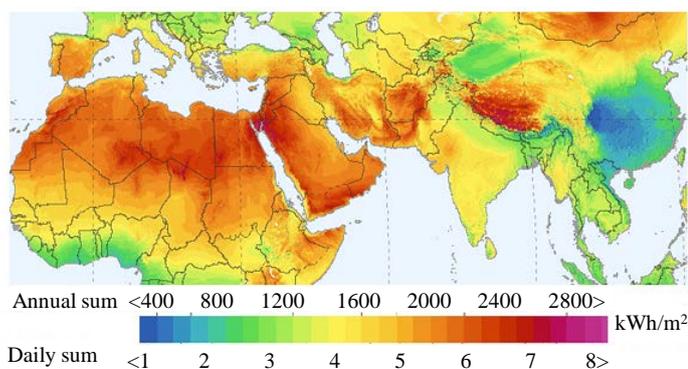

Figure 1. Solar radiation distribution over the Middle East, Arabia and gulf.

Amongst various renewable resources, solar energy could contribute in solving energy-deficiency problems like using electric-powered wells to obtain clean water for domestic use and/or some related activities in such rural communities and tribes.

Solar radiation incident could be concentrated using different imaging or nonimaging solar concentrators like Lenses, Parabolas, Troughs, etc. The only sunlight component that can be concentrated is the "Direct Normal Irradiance" (DNI) component—those rays which come directly from the sun without any scattering by dust or sands suspended in the sky. The other component, the diffuse solar radiation component cannot be concentrated because it occurs due to scattering by suspended particles in the sky. Increasing the percentage of direct solar radiation means that one can use solar concentrators effectively.

Concentrated sunlight has been used to perform useful tasks since long time ago. History mentions that the first one who used concentrated sunlight was Archimedes who used it on the invading Roman fleet and repelled them from Syracuse [8]. In 1866, Auguste Mouchout used a parabolic trough to produce steam for the first solar steam engine.

The first patent for a solar collector was obtained by the Italian Alessandro Battaglia in Genoa, Italy, in 1886. Over the following years, inventors such as John Ericsson and Frank Shuman developed concentrating solar-powered devices for irrigation, refrigeration, and locomotion. In 1913, Shuman finished a 55 HP parabolic solar thermal energy station in Meadi, Egypt for irrigation.

Giovanni Francia (1911-1980) designed and built the first concentrated-solar plant which entered into operation in Sant'Ilario, near Genoa, Italy in 1968. This plant had the architecture of today's concentrated-solar plants with a solar receiver in the centre of a field of solar collectors. The plant was able to produce 1 MW with superheated steam at 100 bar and 500 degrees Celsius [9].

Different types of concentrators produce different peak temperatures and correspondingly varying thermodynamic efficiencies, due to differences in the way that they track the sun and focus light. New innovations in "Concentrated Solar Power" (CSP) technology are leading systems becoming increasingly more cost-effective.

CSP systems use mirrors or lenses to concentrate a large area of DNI onto a small area. Electrical power is produced when the concentrated light is converted into heat, which drives a steam turbine that is connected to an electrical power generator [10].

The main focus of this paper is to study the feasibility of developing an electrical generator system based on the use of efficient solar concentrator. The solar concentrator is mainly used for heating the fluid that will produce the steam (vapour) through the receiving of solar radiation. Our study will involve determining a particular set of concentrator parameters that can be used to design the sought system, keeping in mind that the system should be able to work efficiently in regions located near the equatorial (*i.e.* Middle East) as well as being simple, safe, portable, and cost-effective. Before determining the design parameters of our proposed concentrator-based system, it is important to understand its structure and how it works. This is carried out in the next section.

2. Solar Energy Steam Generator System

This section describes—in brief—the proposed solar energy electrical generator system for which the feasibility study detailed in this paper is carried out. The proposed system idea is based on collecting solar energy by using solar concentrator which concentrates solar radiation on its focus by using a stationary nonimaging trough horizontal concentrator as shown in **Figure 2**.

Concentrators can absorb perpendicular incidence and scattered radiation in the received range causing the work temperature to reach 250°C or even higher. An example of trough solar concentrator is the Compound Parabolic Concentrator (CPC) having a pipe set in the focus as shown in **Figure 3(a)**. Optical concentration ratio of a solar concentrator X_c is defined as [10]:

$$X_c = \frac{\text{Collector aperture width}}{\text{Receiver diameter}} \tag{1}$$

In the system proposed, a copper tube is situated exactly on the concentrator focus, which is heated by means of the concentrated solar radiation falling homogeneously over its external surface. The tube inlet is connected to a liquid reservoir, which passes through the tube till it reaches the tube outlet.

The liquid has to be chosen with a low boiling point such that when passing through the hot tube, its temperature increases till it reaches boiling point and converts to steam with relatively high pressure (hence speed)
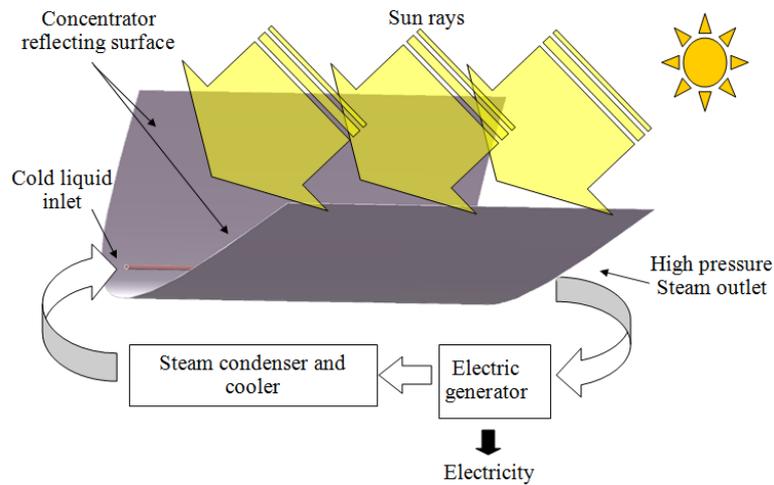
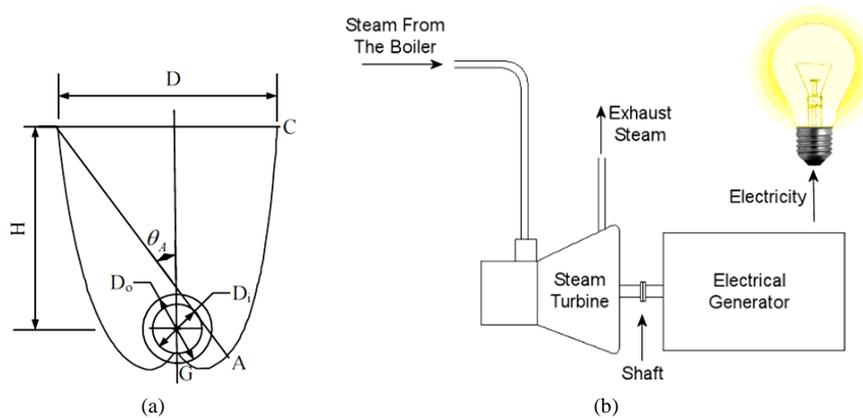**Figure 2.** Flow diagram of the proposed system.

(a)

(b)

Figure 3. (a) Cross sectional view of a CPC; (b) Steam generator model.

before reaching the tube outlet. Generated high pressure steam is then directed to a steam turbine, which rotates generating electricity for use in various applications (see **Figure 3(b)**).

The study presented here is based on mathematical modelling of the system to determine the parameter values at which the system would produce sufficient amount of power (*i.e.* sufficient steam quantity which will rotate the turbine).

3. Methodology and Mathematical Models

The study presented in this paper was carried out using MathCAD to develop mathematical models (equations) for calculating both energy absorbed by the water flowing in the tube and energy of the steam generated at the tube outlet to investigate the generated steam quantity and energy.

The input parameters examined in this study are:

1) Incident solar radiation intensity.

2) Diameter of the tube (0.005, 0.01 and 0.015 m).

3) Length of the tube (1, 2, and 3 m).

4) Flow rate of water inside the tube (15, 10, and 7 kg/hr).

Then, various graphs were generated to define the points at which the system would operate effectively (*i.e.* points at which the system is expected to produce sufficient steam energy at the tube outlet to drive the steam engine). Graphs were also used to demonstrate the effect of changing each parameter on the behaviour of the system in order to set some limits (boundaries) for the input design parameters (more details are provided in Section 4).

In this section, we develop some equations to calculate the output steam energy in terms of the various input system parameters stated above.

The velocity of the water inside the tube is defined as the rate of flow of water over a specific area. Mathematically, the velocity vel is calculated in m/s as:

$$\text{vel} = \frac{4\text{FR}}{\pi d^2} \tag{2}$$

where FR is the flow rate in L/s and d is the diameter in m.

The energy absorbed by the water inside the tube E_{abs} is calculated as:

$$E_{\text{abs}} = \text{Rad}_{\text{conc}} \cdot U_{\text{area}} \cdot t_p \tag{3}$$

where Rad_{conc} is the concentrated radiation in W/m², U_{area} is the unit side area in m², and t_p is the passage time of the water inside the tube; assuming that tube absorptivity is unity.

The energy of the steam generated at the tube outlet E_{steam} is calculated as:

$$E_{\text{steam}} = E_{\text{abs}} - \left(E_{\text{boil}} + E_{\text{ltnl}} \right) \tag{4}$$

where E_{boil} and E_{ltnt} are the boiling energy and latent energy of water (respectively).

Therefore, steam energy E_{steam} is calculated as:

$$E_{\text{steam}} = \pi^2 d^2 \cdot X_c \cdot \text{Int} \cdot \frac{\text{len}}{4\text{FR}} - \frac{\pi}{4} \cdot \rho \cdot d^2 \left(C_p \Delta T - E_{\text{ltnt}} \right) \tag{5}$$

where d is the tube diameter in m, Int is the intensity of incident radiation in W/m², FR is the flow rate in L/s, len is the tube length in m, ρ is the density of water in kg/m³ and C_p is the specific heat capacity of water in J/kg·K. The collector aperture width is assumed to be a constant value of 1 m throughout this study.

Clearly from Equation (5), the steam energy is proportional to the square of the tube diameter, whereas its relation to the tube length and flow rate is directly proportional and inversely proportional (respectively). An intuitive schematic diagram showing the flow of calculations is demonstrated in **Figure 4**.

4. Results

This section presents the results obtained in this study using graphical forms. The main aim of the presented graphs is to show the effect of various input parameters (*i.e.* tube length, tube diameter and flow rate) on the output of the system, namely the steam energy. The graphs are also used to determine the points at which the system is expected to produce sufficient steam energy at the tube outlet to drive a steam engine for producing electricity. From such graphs, it is possible to set some limits (boundaries) for the input parameters for practical implementation and/or simulation of the system.

We begin by showing the effect of tube diameter and tube length on the velocity and/or passage time of the water traveling in the tube. This is to begin to understand how such parameters will affect the energy of the steam produced at the tube outlet. **Figure 5** shows the effect of tube diameter on the velocity and passage time of the water flowing in the tube for different flow rates. It is clear that as the tube diameter increases the velocity decreases and the passage time increases. Also, increasing flow rate results in increasing velocity and reducing passage time at each tube diameter.

Figure 6 shows the effect of tube diameter on the passage time of the water for different tube lengths. The figure clearly shows how the increase of tube length results in increasing the passage time at each tube diameter.

Figure 7 shows the effect of flow rate on the energy of steam generated for different tube. Clearly when flow rate increases, the energy of the produced steam decreases since the water does not spend enough time to heat up while traveling in the tube. Moreover, for different tube lengths, the steam energy will increase as the tube length increases at a given flow rate. This is simply because the water will travel for longer period of time in the tube and hence absorb more energy while traveling. The figure also shows the flow rate points above which the system will produce steam for the different tube lengths considered. For example, when using 1 m tube, only the three lowest flow rates will produce steam. As the tube length increases the steam will be produced with the higher flow rate values. For example, with 3 m tube, all flow rates considered here are expected to produce steam at the tube outlet. Note that the zero-line shown in the graph presents the threshold level above which the system is expected to produce steam and under which it will not produce any steam. This threshold value de-
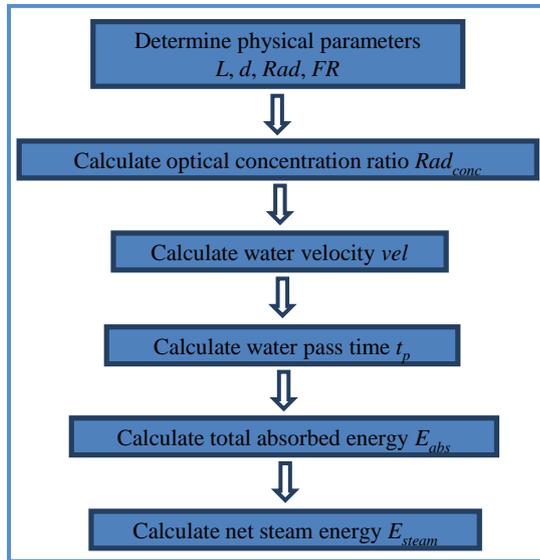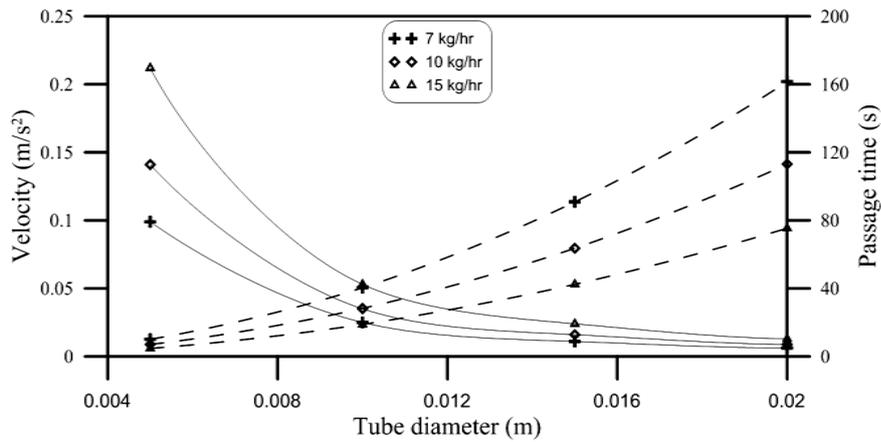
Figure 4. Intuitive schematic diagram.

Figure 5. Effect of tube diameter on the velocity (solid) and passage time (dotted) for different flow rates.
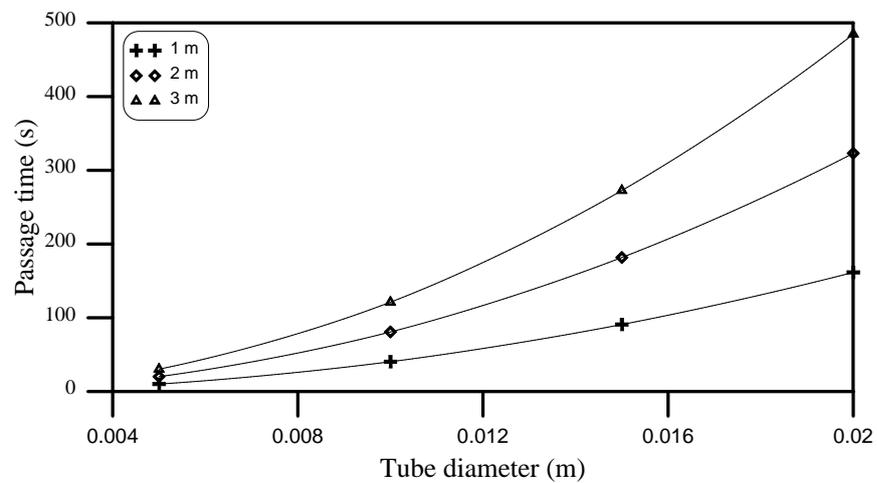

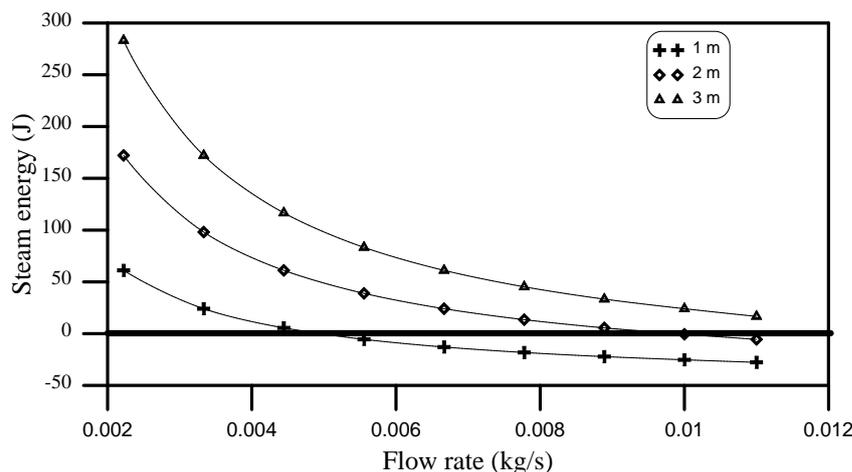**Figure 6.** Effect of tube diameter on the passage time for different tube lengths.

Figure 7. Effect of flow rate on the steam energy for different tube lengths.

pends on concentration ratio X_c, solar radiation intensity Int and rise in the inlet temperature ΔT. At this level, the absorbed energy is equal to the sum of boiling energy and latent energy of water, hence, the steam energy becomes zero; see Equation (4) above.

Figure 8 shows the effect of flow rate on the energy of steam generated for different tube diameters when the tube length is fixed to 1 m. Also here, it is clearly shown that as tube diameter increases, more energy will be produced from the system at a given flow rate. However, when increasing the tube diameter, steam energy grows faster than the case of increasing the tube length (compare with **Figure 7**). This is simply because the steam energy is squarely proportional to the tube diameter while it is directly proportional to the tube length, as in Equation (5). Moreover, it is clear that with all tube diameters considered, only flow rates below 0.004 kg/s will produce steam. Again this depends on the other operating conditions like tube length, incident radiation intensity and inlet temperature.

Figure 9 shows the effect of radiation intensity on the energy of steam generated for different flow rates.

Here, the tube length and diameter are set to 1 and 0.005 m (respectively) with an inlet temperature of 30˚C. Obviously, steam energy increases linearly as radiation intensity increases. Moreover, as flow rate decreases, steam can be produced by lower radiation intensity values. For example, using 7 kg/hr flow rate, the system will produce steam at all radiation intensities considered except at the lowest one (which is 100 W/m^2). Obviously, this is due to the low velocity and high passage time of the water inside the tube which makes it possible to convert into steam even with low radiation intensities. In contrast, for the 15 kg/hr flow rate (which is relatively high, resulting in high velocity and low passage time), the minimum radiation intensity needed to produce steam is 400 W/m^2. With lower intensity values, the water inside the tube will not absorb sufficient energy to convert into steam before reaching the tube outlet end.

Figure 10 shows the effect of radiation intensity on the energy of steam generated for different tube diameters. Here, tube length is set to 1 m and water flows with a rate of 15 kg/s. Again, steam energy increases linearly as radiation intensity increases. However, when increasing the tube diameter, steam energy grows faster than the case of increasing the flow rate (compare with **Figure 9**). Recall that the steam energy is squarely proportional to the tube diameter while it is inversely proportional to the flow rate, as in Equation (5). Also from the graph, with all tube diameters considered, the minimum radiation intensity needed to produce steam is 400 W/m^2 at the abovementioned operating conditions.

To investigate the system's performance under realistic operating conditions, a daily profile of solar radiation intensity has been chosen along with ambient temperature. Then, steam generated from the different combinations of the abovementioned system parameters were calculated and compared.

Figure 11 shows the daily profile of radiation intensity and ambient (which is set equal to the inlet) temperature in a selected day in the concerned region.

Figure 12 to **Figure 14** show the total accumulated steam energy for all input parameters considered in this study over that selected day from 8 am to 6 pm. The aim of these graphs is to investigate the effect weight of each parameter against the other parameters. More particularly, **Figure 12** shows the total accumulated steam energy
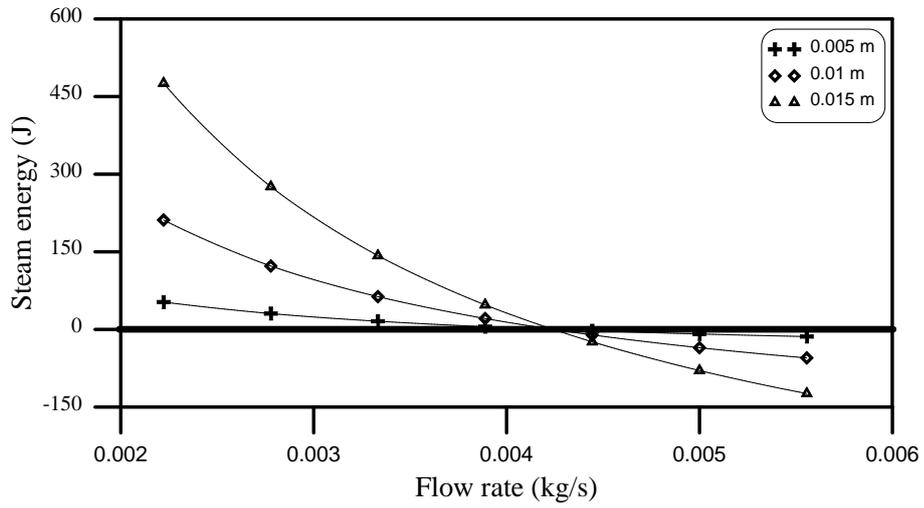
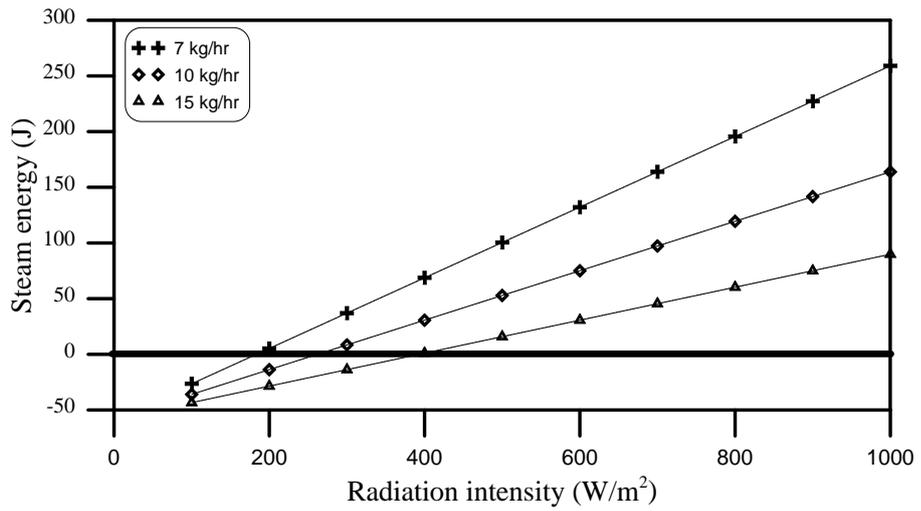**Figure 8.** Effect of flow rate on the steam energy for different tube diameters.

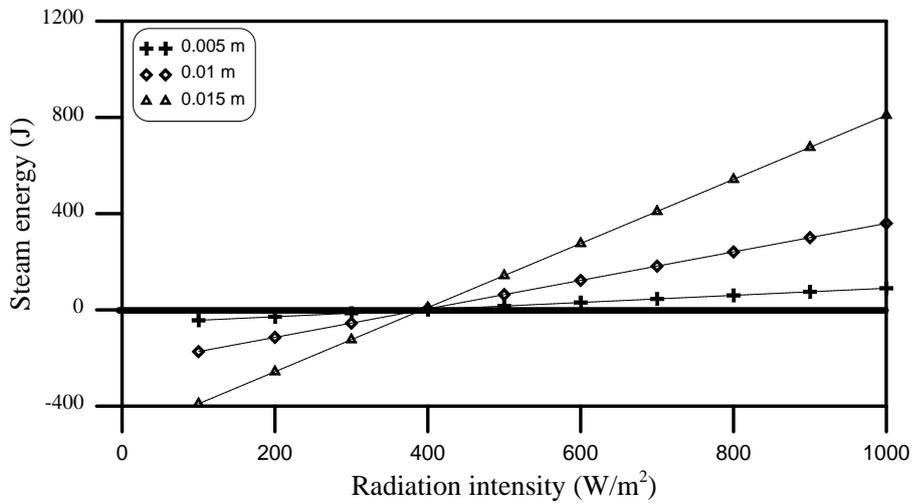**Figure 9.** Effect of radiation intensity on the steam energy for different flow rates.

Figure 10. Effect of radiation intensity on the steam energy for different tube diameters.
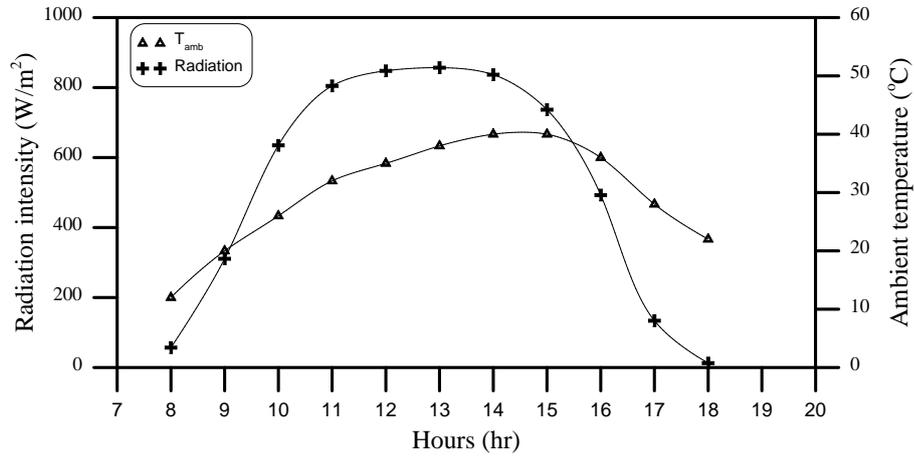
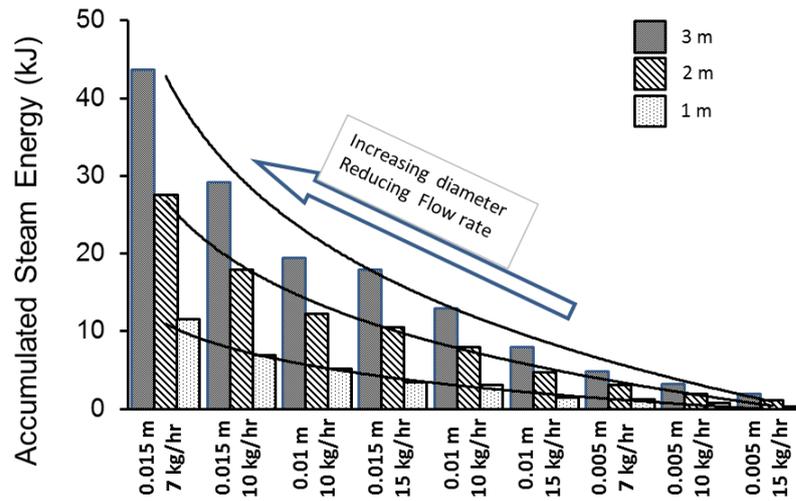**Figure 11.** Daily profile of radiation intensity and inlet temperature.

Figure 12. Accumulated steam energy for all flow rates and tube diameters considered when fixing the tube length.
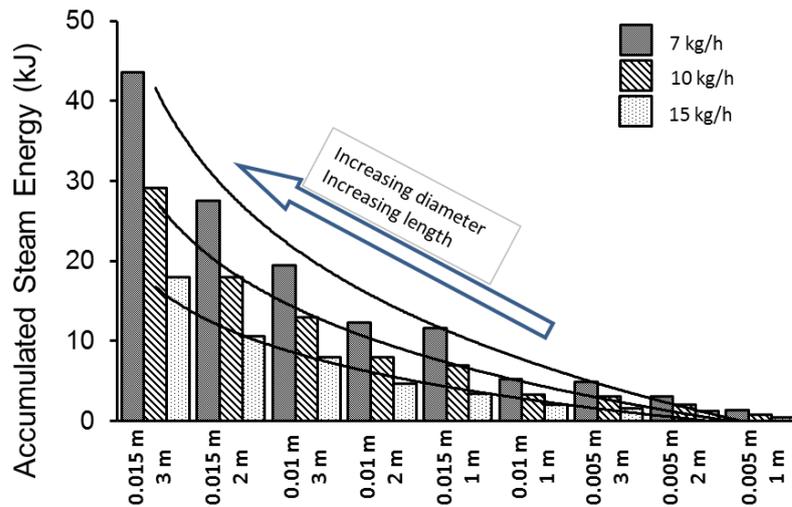

Figure 13. Accumulated steam energy for all tube lengths and tube diameters considered when fixing the flow rate.
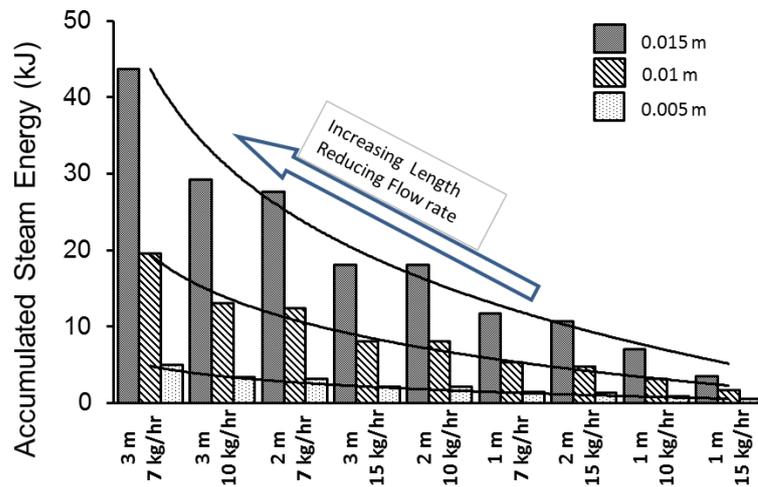
Figure 14. Accumulated steam energy for all tube lengths and flow rates considered when fixing the tube diameter.

for all flow rates and tube diameters considered when fixing the tube length. Similarly, **Figure 13** shows the total accumulated steam energy for all tube lengths and tube diameters considered when fixing the flow rate, and **Figure 14** shows the total accumulated steam energy for all tube lengths and flow rates considered when fixing the tube diameter.

The three graphs clearly show that the best steam quantity over the day is achieved with the largest tube diameter, largest tube length and lowest flow rate (and vice versa). However, by looking at the details, it can be noticed that:

1) For a given tube length, the effect of changing tube diameter overwhelms the effect of changing flow rate. Moreover, the total accumulated steam energy increases linearly with increasing the tube length.

2) For a given flow rate, the effect of changing tube diameter overwhelms the effect of changing tube length. Moreover, the total accumulated steam energy increases linearly with decreasing the flow rate.

3) For a given tube diameter, the effect of changing tube length overwhelms the effect of changing flow rate. However, the total accumulated steam energy increases nonlinearly (squarely) with increasing the tube diameter. It can also be noticed that with the very low tube diameters (such as the case of 0.005 m tube), total accumulated steam energy is not affected much by manipulating the other parameters.

5. Conclusions

The study outlined in this paper intended to investigate the feasibility of designing a small-size, stand-alone solar energy steam-based electric generator to use for domestic and small-scale electricity generation purposes. The proposed system was based on using nonimaging "Compound Parabolic Concentrator" (CPC) in which a copper tube is placed on the concentrator focus and heated up by receiving homogeneous concentrated solar radiation on its external surface. A fluid (chosen here to be water) is injected in the hot tube that will pass through it—while being heated up—till it converts from liquid to steam before reaching the tube outlet end.

The study was based on developing mathematical equations to calculate the energy of the steam produced from the concentrator system in terms of four main parameters: radiation intensity, tube length, tube diameter and water flow rate. The three parameters—tube length, tube diameter and flow rate, were considered to be the main input design parameters of the system. Graphs were then presented mainly to show the effect of changing input design parameters on the quantity of steam generated at the tube outlet. In addition, graphs were also used to determine the values at which the system is expected to produce steam so as to set initial boundaries for the input design parameters for further design processes of the system.

Overall, the results obtained demonstrate that among the three input design parameters, tube diameter is the most dominant parameter that influences steam energy, then the tube length and finally the flow rate. This implies that for achieving better steam quantity the designer shall begin by increasing the tube diameter before increasing the tube length or reducing the flow rate at last. Such results can provide a guideline for simulating and/or im-

plementing the system in practice.

It is worth noting that, in this study, the steam produced from the proposed system was only analyzed quantitatively since qualitative analysis cannot be performed by the approach considered in this study which is based on mathematical calculations. It is therefore suggested to conduct a computer simulation of the system using appropriate Computational Fluid Dynamics (CFD) simulation software. As such, the results presented here can be used effectively in the initial design (or modelling) phase of the system that is to be simulated.

Acknowledgements

References

[1] Rahman, F., Rehman, S. and Abdul-Majeed, M.A. (2012) Overview of Energy Storage Systems for Storing Electricity from Renewable Energy Sources in Saudi Arabia. *Renewable and Sustainable Energy Reviews*, **16**, 274-283. http://dx.doi.org/10.1016/j.rser.2011.07.153

[2] Al-Ammar, E. and Al-Aotaibi, A. (2010) Feasibility Study of Establishing a pv Power Plant to Generate Electricity in Saudi Arabia, from Technical, Geographical, and Economical Viewpoints. *International Conference on Renewable Energies and Power Quality* (*ICREPQ*'10), Granada, 23-25 March 2010,

[3] Said, S.A.M., El-Amin, I.M. and Al-Shehri, A.M. (2004) Renewable Energy Potentials in Saudi Arabia. *Beirut regional Collaboration Workshop on Energy Efficiency and Renewable Energy Technology*, American University of Beirut, Beirut, 76-82.

[4] Alnatheer, O. (2006) Environmental Benefits of Energy Efficiency and Renewable Energy in Saudi Arabia's Electric Sector. *Energy Policy*, **34**, 2-10. http://dx.doi.org/10.1016/j.enpol.2003.12.004

[5] Fernández-García, A., Zarza, E., Valenzuela, L. and Pérez, M. (2010) Parabolic-Trough Solar Collectors and Their Applications. *Renewable and Sustainable Energy Reviews*, **14**, 1695-1721. http://dx.doi.org/10.1016/j.rser.2010.03.012

[6] Tsikalakis, A., Tomtsi, T., Hatziargyriou, N.D., Poullikkas, A., Malamatenios, C., Giakoumelos, E., Jaouad, O.C., Chenak, A., Fayek, A., Matar, T. and Yasin, A. (2011) Review of Best Practices of Solar Electricity Resources Applications in Selected Middle East and North Africa (MENA) Countries. *Renewable and Sustainable Energy Reviews*, **15**, 2838-2849. http://dx.doi.org/10.1016/j.rser.2011.03.005

[7] Afa, J.T. (2013) Problems of Rural Electrification in Bayelsa State. *American Journal of Scientific and Industrial Research*, **4**, 214-220. http://dx.doi.org/10.5251/ajsir.2013.4.2.214.220

[8] Africa, T.W. (1975) Archimedes through the Looking-Glass. *The Classical World*, **68**, 305-308. http://dx.doi.org/10.2307/4348211

[9] Butti, K. and Perlin, J. (1980) A Golden Thread: 2500 Years of Solar Architecture and Technology, Vol. 514. Cheshire Books, Palo Alto.

[10] Rabl, A. (1976) Comparison of Solar Concentrators. *Solar Energy*, **18**, 93-111. http://dx.doi.org/10.1016/0038-092X(76)90043-8