DEVELOPMENT OF SOLAR THERMOELECTRIC GENERATOR

Taleb M. Maslamani
Abdu Idris Omer, PhD
Majid M. A.
Majmaah University , Kingdom of Saudia Arabia

Abstract

Concentrating solar power (CSP) is a unique renewable energy technology. CSP systems have the ability to provide electricity, refrigeration and water purification in one unit. This technology will be extremely helpful in improving the quality of life for many people around the world who lack the energy needed to live a healthy life.

A thermoelectric generator is a solid-state device that converts a heat flux into electrical power via the Seebeck effect. When a thermoelectric generator is inserted between a solar-absorbing surface and a heat sink, a solar thermoelectric generator is created which converts sunlight into electrical power.

This project describes the design and optimization of solar thermoelectric generators, with a focus on systems with high optical concentration which utilize multiple material systems to maximize efficiency over a large temperature difference. a single-stage generators are considered, over an optical concentration range of 0.1 to 1000X. It is shown that for high-concentration solar thermoelectric generators, conversion efficiencies of 13% are possible with current thermoelectric materials and selective surfaces. The assembled system as the concentrator thermo electric generator CTEG is able to produce electric power of up to 5.5W under the temperature difference of 35°C.

The experimental results showed a considerable agreement with the mathematical model as well as its potential application

Keywords: Solar thermoelectric, Seebeck effect, Concentrating solar power

1.Introduction

The sun is the most plentiful energy source for the earth. All wind, fossil fuel, hydro and biomass energy have their origins in sunlight. Solar energy falls on the surface of the earth at a rate of 120 petawatts, (1 petawatt

= 1015 watt). This means all the solar energy received from the sun in one days can satisfied the whole world's demand for more than 20 years.

We are able to calculate the potential for each renewable energy source based on today's technology. However, the worldwide demand for energy is expected to keep increasing at 5 percent each year (see Figure 1). Solar energy is the only choice that can satisfy such a huge and steadily increasing demand.
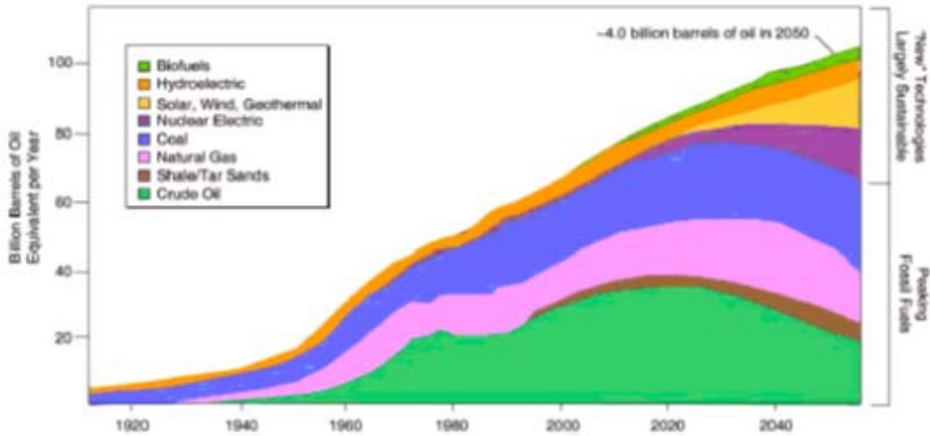
Sources: Lynn Orr, *Changing the World's Energy Systems*, Stanford University Global Climate & Energy Project (after John Edwards, American Association of Petroleum Geologists); SRI Consulting.

Figure (1): Word Energy Demand and Forecast

There are several applications for solar energy, for instance: electricity generation, photochemical, solar propulsion, solar desalination, and room temperate control. The collection of solar energy and its transfer to electricity energy will have wide application and deep impact on our society, so it has attracted the attention of the researchers.
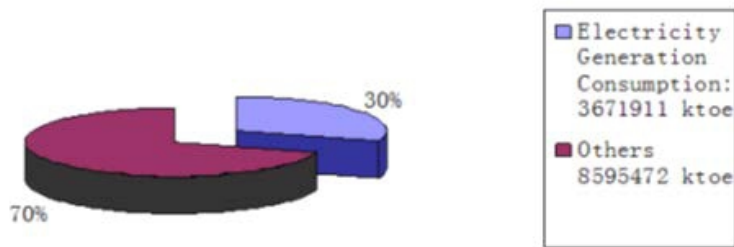
Source: Energy Balance for World, International Energy Agency

Figure (2): Electricity Energy Consumption Percentage of Total Production in 2008

The two most prominent solar energy technologies are photovoltaic (PV) and concentrated solar power (CSP). PV systems are beneficial because they can be scaled to any size, but they are costly and solely produce electricity. CSP systems can provide electricity as well as thermal power.

The drawback to these systems is that the most efficient solar thermal systems currently have an installation cost of $10,000/kW An economic CSP system could provide rural areas with electricity and energy needs to dramatically improve their quality of life.

2. Brief History of Solar Thermal Power

Concentrating solar power is a method of increasing solar power density. Using a magnifying glass to set a piece of paper on fire demonstrates the basic principle of CSP. Sunlight shining on the curved glass is concentrated to a small point. When all the heat energy that was spread across the surface of the magnifying glass is focused to a single point, the result is a dramatic rise in temperature. The paper will reach temperatures above 232 C and combust. CSP has been theorized and contemplated by inventors for thousands of years. The first documented use of concentrated power comes from the great Greek scientist Archimedes (287-212 B.C.). This is considered the beginning of modern solar concentration. Solar concentrators then began being used as furnaces in chemical and metallurgical experiments . They were preferred because of the high temperatures they could reach without the need for any fuel.

3. Solar Technologies (Figure 3)

There are several kinds of solar techniques that are currently available. However, each of them is based on quite different concepts and science and each has its unique advantages. Analysis and comparison between different technologies will help us to adopt the most efficient and beneficial technology given a specific set of conditions.

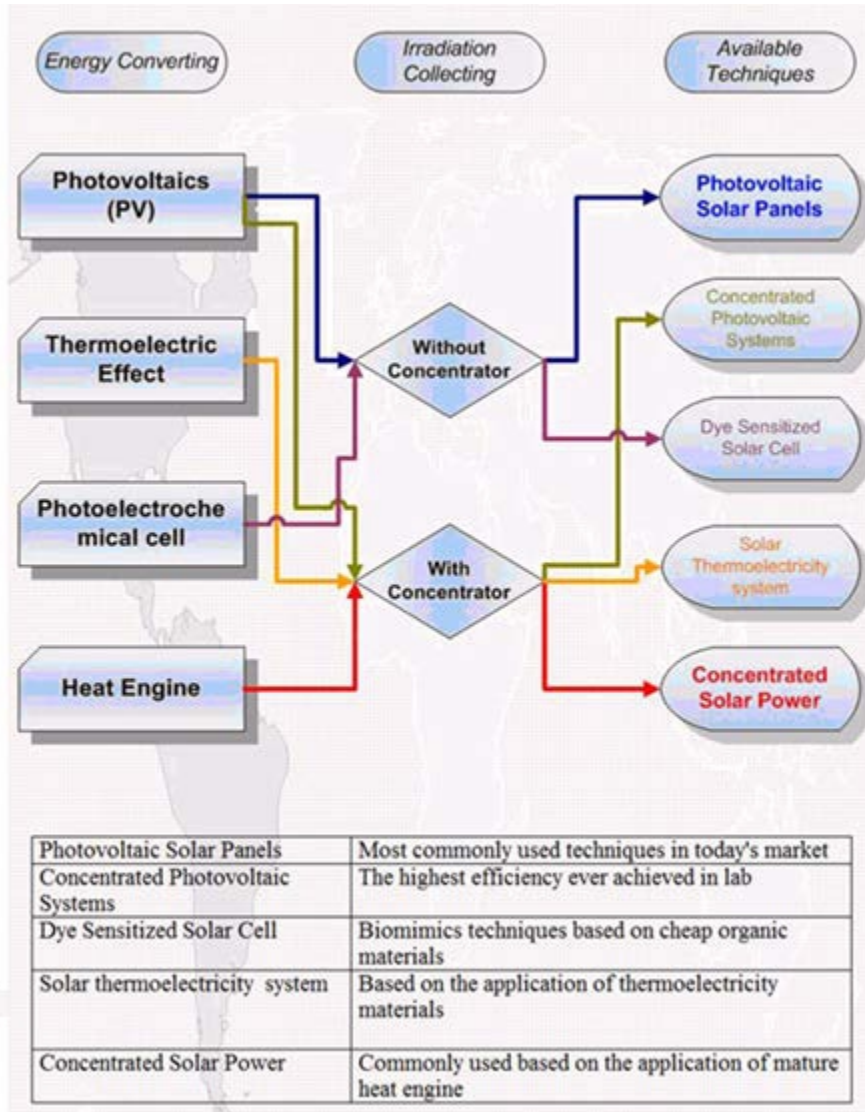| Photovoltaic Solar Panels	Most commonly used techniques in today's market
Concentrated Photovoltaic Systems	The highest efficiency ever achieved in lab
Dye Sensitized Solar Cell	Biomimics techniques based on cheap organic materials
Solar thermoelectricity system	Based on the application of thermoelectricity materials
Concentrated Solar Power	Commonly used based on the application of mature heat engine

Figure (3): Over View of Solar Technologies

Generally speaking, non-concentrated photovoltaic solar panels (PV) and concentrated solar power (CSP) are the two most mature technologies. They have been commercialized and expected to experience rapid growth in the future, thus our emphasis will be on these two technologies.

Their mechanisms will be discussed, and their advantages and drawbacks will be listed. Then, concentrated solar power will be discussed in detail, including their technologies, subcategory, structures, deployment and trend of improvement in future.

4. Solar Thermoelectricity

Solar thermoelectricity uses parabolic disc technology to capture thermal energy basted on the thermoelectric effect. Electricity is produced through a concentrator thermoelectric generator (CTEG) A thermoelectric device is divided into two parts it produces energy by converting differences in temperatures in the two parts into volts using a semi-conductor.

Conversely, when a voltage is applied to the device, it creates a temperature difference. At the atomic scale, an applied temperature gradient causes charged carriers in the material to move from the hot side to the cold side. This effect was discovered since 182 and has been developed in recent years. Now we are able to see that it works in astronautic devices and automotive engine systems.

4.1 Thermoelectric

The relatively low heat-to-electricity efficiency (typically around 5%) of thermoelectric converters has restricted their use in the past to specialized applications only. In the 1950's and 1960's the main application area was space exploration by the USA and the former USSR where autonomous long-life power generators were required. At the time the only existing technology were thermoelectric generators powered by radioisotope heat sources. In recent years, an increasing public awareness of environmental issues, in particular global warming, has resulted in broad based research for alternative commercial methods of generating electric power. With advances in the material research, thermoelectric generators have emerged as a promising new alternative. Today, thermoelectric power generation has attracted increasing attention as a green and flexible source of electricity able to meet a wide range of power requirements.

5. Seebeck effect

An n-type semiconductor bar is connected between a hot and a cold temperature reservoir Th and Tc, respectively, yielding the temperature difference ΔT, as shown in Figure 4. The temperature gradient in the semiconductor bar induces a gradient of the electron concentration, and a voltage difference ΔU across the bar is established. This phenomenon is called Seebeck effect. The voltage difference can be expressed in terms of the temperature T and the temperature-dependent and material-specific Seebeck coefficient S by:

$$\Delta U = \int_{Tc}^{Th} S(T)dT \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots . (1)$$
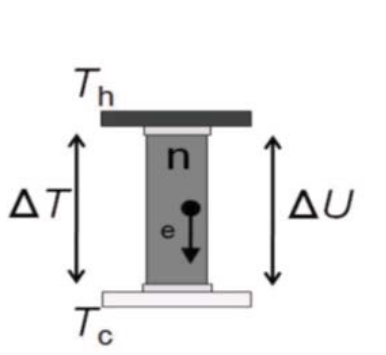
Figure 4:An n-type semiconductor bar

6. Schematic of a thermoelectric converter module

A thermoelectric converter (TEC) module comprises p-type and n-type semiconductor legs sandwiched between a hot and a cold plate at hot (T_h) and cold (T_c) temperature reservoirs, respectively, and connected thermally in parallel and electrically in series, as shown in Figure 5, for a single p/n-type leg pair. Then the induces a voltage difference ΔU between the cold terminals. When an external load is connected, an electric current (denoted by J) flows and power can be extracted.
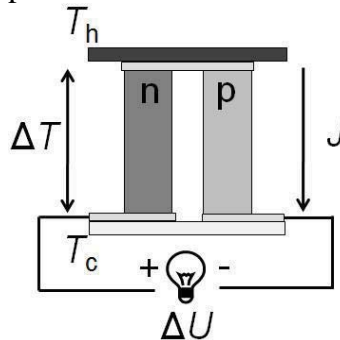

Figure 5: A thermoelectric converter module comprises p-type and n-type semiconductor

The performance of the thermoelectric material is characterized by its figure-of-merit
defined as:

$$ZT = \frac{S^2 T}{\rho . k} \quad\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where S is the Seebeck coefficient, ρ the electric resistivity, κ the thermal conductivity and T the mid temperature between the hot and cold temperature, given by $T = 0.5 \cdot (T_h - T_c)$. Then the maximum heat-to-electricity efficiency of a TEC module can be expressed in terms of the hot temperature T_h, the cold temperature T_c, and the figure-of-merit ZT by:

$$\eta mod = \frac{Th - Tc}{Th}(\sqrt{1+ZT} - 1)/(\sqrt{1+ZT} + \frac{Tc}{Th})$$

The first factor of the latter equation represents the Carnot efficiency, which depends only on the temperature difference of the two temperature reservoirs T_h and T_c, and the second factor embodies the figure-of-merit ZT . The higher ZT , the higher is the maximum module efficiency, approaching the Carnot efficiency for ZT   ∞.

As an example, a Bi-Te-based module having ZT = 1 and operating at 200 K temperature difference reaches the maximum module efficiency of 5%.

6.1 Advantages

A simple system that can be deployed on roof tops is able to work in harsh environments, quiet in operation, capable of virtually endless shelf life, the thermoelectric part has simple structure without any moving parts, extremely reliable and can be driven by low grade heat energy.

6.2 Drawbacks

Drawbacks of the system can be summarized as: the efficiency of the thermoelectric materials is still very low, the recently achieved figure of merit is only 1.3~2.0.

Also, like most of the other solar technologies with concentration requirements, this system is unable to collect diffuse irradiation and must rely on direct radiation only.

Moreover, in order to have sufficient output, high temperatures are needed to make it work efficiently (~200˚ C based on Carnot or thermal efficiency), which lead to higher concentration ratio of the collector (10~100 suns) and more precise tracking systems. Higher concentration collector will increase capital cost and maintenance cost. thermoelectric material like Bismuth telluride is toxic and expensive. Cooling systems are required to decrease the temperature of the cold side in order to increase to total efficiency.

7. Horizontal Coordinates

The first coordinate system discussed here is Horizontal, or alt-azimuth. In this system a person standing on the surface of the Earth takes their perceived horizon to be a flat plane. The line normal to this surface, directly above the person, is called the zenith. The altitude angle describes the angle a body is above the horizontal plane. Everything above the plane is positive, and everything below the plane is negative. The other parameter, azimuth angle, describes the angle a body is from a plane parallel to zenith

connecting celestial north-south. This plane is chosen to be 0° azimuth. Positive angles run in the clockwise direction, making this a left-handed system. In Figure 6, we can see γ_s represents positive azimuth, and represents negative azimuth. Also in Figure 16 we see that α_s represents the altitude angle. With these two angles, the direction normal to the Sun can be found.

8. Equatorial Coordinates

The second coordinate system reviewed is called equatorial. In the equatorial coordinate system, the fundamental plane lies along the celestial equator. The normal vector in this system is the rotational axis of the earth. The celestial sphere is partitioned into sections analogous to our geographical coordinates. Declination (δ) describes the angle above or below the celestial equator like latitude. The other coordinates, which is likened to longitude, is called hour angle (H). The hour angle uses units of hours, minutes, and seconds to partition the 360° sphere into 24 hours. One hour angle equals 15° of arc. Following these coordinates simplifies the apparent motion of the sun. The change in hour angle is constant throughout the day at 1° every 4 minutes. The declination changes by no more than 4 tenths of a degree per day. To convert between the two coordinate systems we may use Equations 3 and 4. These equations give altitude and azimuth angle for the sun given the observers latitude (Φ), declination (δ) and hour angle (H).

$$\sin\alpha = \sin\alpha \times \sin\Phi + \cos\delta \times \cos\Phi \times \cos H \qquad \ldots\ldots\ldots\ldots\ldots\ldots.3$$

$$\text{Cos}\gamma \times \cos\alpha = \cos\Phi \times \sin\delta - \sin\Phi \times \cos\delta \times \cos H \ldots\ldots\ldots \quad \ldots\ldots\ldots.4$$
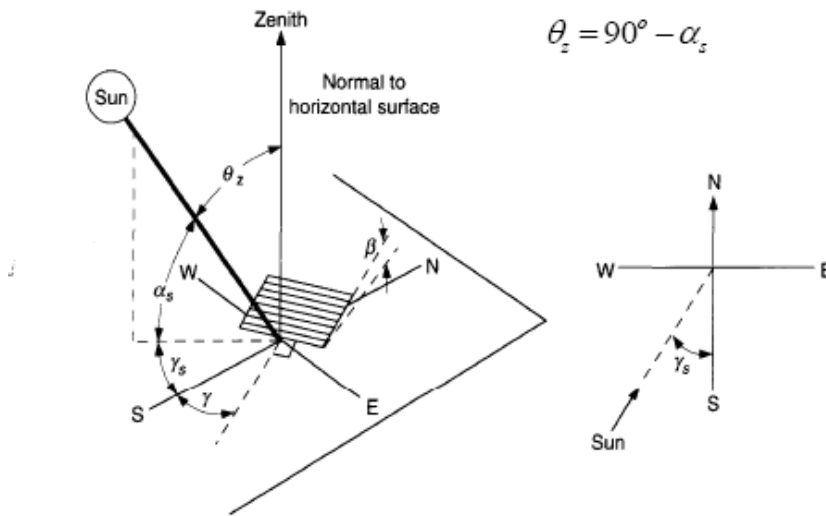

Figure 6: Horizontal Coordinate System

9. Optics Concentration

The concentration ratio of a parabolic concentrator (PC) is given by Equation 5 .

A_d is the projected area of the concentrator and A_r is the receiver area.

$$CR = \frac{Ad}{Ar} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.5$$

9.1 Refection and absorption

The manipulation of light and other EM waves can be achieved in a number of ways; it can reflect off of a surface, transmit through a material without effect, or be absorbed by the surface. With absorption, the EM waves increase the energy of the impinging surface.

Equation: 6 describes a particular surface depending upon it's coefficient of reflectivity, ρ, transmittance, τ, and absorptivity γ, . Each coefficient describes the relative effect the surface has on the radiation that impinges upon it. For example a surface with τ = 1 would transmit all radiation through the material and none would be reflected or absorbed. Coefficients of a material change depending on radiation wavelength, surface temperature and incident angle.
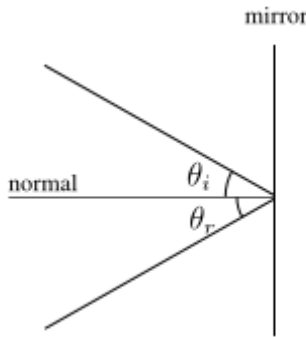

Figure 7: specular Reflectance

To simplify analysis, coefficients are averaged for regions of interest and given a single value.

$\gamma + \tau + \rho = 1$ …………………………6

10. Expermental Setup

An experimental prototype of concentrator thermo electric generator using parabolic dish concentrator of 0.3 m^2 projected area (CTEG), heat sink cooling system and Peltier thermo electric generator is being fabricated at the center. See Figure 8.

Figure 8: Concentrator thermo electric generator (CTEG) elements

11. Results and Discussion

This chapter contains results and analysis for testing performed at STEG facilities in the autumn of 2013. Tests were performed to determine the thermal conversion efficiency of the concentrator system. Solar energy was concentrated to central receiver where it was heated and temperature rise of the hot side of the TEG.

With this information the thermal collection efficiency for the system was found. The system was characterized by estimating thermal losses for each sub-component.

11.1 Theoretical results

We have $G = 1100$ W/m^2 [Meteorological Department of Jordan]Since the dish is always tracks the sun, the sun's zenith angel α is always = 0 degree

Reflective paper coefficient ρ = 60% and Absorption coefficient of the hot surface γ = 70%. The $T_{dish} = 25$ C [At steady state conditions]

T_h=110 C [At steady state conditions], and T_c= 75   [At steady state conditions]

Area of the front view of the dish= a×b×π [projected area of the ellipse]

Where a,b are : a=350mm, b=300mm
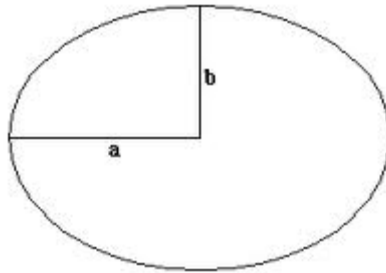
Figure 9: aperture area of the parabolic dish

A_{dish}=350×300×π = 329.8×10^{3}mm^2 =0.3298 m^2, Area of the hot side = $\frac{\pi}{4}$ D^2 = $\frac{\pi}{4}$×0.1^2 = 7.583×10^{-3} m^2. = $q_{reflected}$ =G× ρ × γ = 1100×0.6×0.7=462 W/m^2

Q_{in}= $q_{reflected}$ × A_{dish} = 462×0.3298=152.36 W, Q_{losses}=Q_{conv}= h×A_h×(T_h-T_{air})   Where h= 12 W/ m^2.C   [ASHRAE], Q_{losses}=22.4×7.583×10^{-3}×(110-17) = 27.7W. Q_h=Q_{in} – Q_{losses}=152.36 – 27.7 =124.66 W. Q_c= Ŋ$_{fin}$×h×$A_{heat\ sink}$×(T_c – T_{air}). Ŋ$_{fin}$=75%, h=22.4 W/ m^2.C   [ASHRAE], $A_{heat\ sink}$=N_{fines}×A_{fine} = 50×40×30×2=120×10^3 mm^2 =0.12 m^2 , Q_c = 0.75×22.4×0.12×(75 – 17) =116.928 W. Ŋ=(Q_h - Q_c)/ Q_h, = $\frac{124.66-116.928}{124.66}$

=0.062 = 6.2% and Ŋ$_{with\ fan}$ =(Q_h - Q_c - P_{fan})/ Q_h =$\frac{124.66-116.928 - 3.36}{124.66}$ = 0.035 =3.5%

Where: Q $_{reflected}$ –the power that reflected from the reflective paper .
Q$_{in}$ – the power that inter the hot side .
Q $_{losses}$ – the power that dissipated to the air .
Q $_h$ – the power that delivered to the hot side .
Ŋ – efficiency symbol

11.2 Experimental results

P_{output}=V×I =5.5×1=5.5 W, Ŋ= P_{output}/Q_h = $\frac{5.5}{124.66}$ = 0.044 = 4.4%, Ŋ$_{with\ fan}$= (P_{output} - P_{fan})/Q_h = $\frac{5.5-3.36}{124.66}$ =0.017 = 1.7%

12. Conclusion

In this project, the potential of thermo electric cells combined with concentrator solar energy as a power generation system has been tested and illustrated. An experimental prototype of concentrator thermo electric generator using parabolic dish concentrator of 0.3 m^2 projected area (CTEG), heat sink cooling system and Peltier thermo electric generator is being fabricated at the center.

It was expected that was formulated on the basis of energy balance predicted that maximum power of 7.7 W can be produced from the 0.3 m^2 dish while maintaining the cell temperature below 110 °C.

The assembled system as the CTEG is able to produce electric power of up to 5.5W under the temperature difference of 35°C. The experimental results showed a considerable agreement with the mathematical model as well as its potential applications.

In summary, further testing about the full understanding of the

CTEG should be studied, and the perspective applications for such power system is strongly depend on the development of the thermoelectric material, therefore, research about testing the latest TE material under the current CTEG system is recommended so that for this particular area, the concentrator thermo electric generation can be considered as a perspective candidate of the renewable energy based power source.

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