The Potential of Solar Thermoelectric Generator STEG for Implantation in the Adrar Region

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ABSTRACT

A solar thermoelectric generator STEG is a system similar to photovoltaics in the specificity of converting solar energy directly into electrical energy without the need for a mechanical transaction. However, compared to photovoltaics, its introduction into large-scale solar power generation has never been achieved, largely due to the low efficiency of the main component of STEG, the thermoelectric TE module. In contrast to other sectors where TE technology is emerging and growing a rapid development that consequently leads to the discovery of new materials, more TE efficient and adapted design engineering. From this reality, STEG has the potential to become a competing alternative technology to the dominant solar photovoltaic systems, especially in hot regions where the PV system suffers from the progressive and precocious degradation of its original properties, leading to a decrease in lifetime and efficiency due to thermal fatigue caused by the excessive heating of the cells by solar infrared radiation that is useless for PV conversion. The concrete example of our study is in Adrar region (south-west Algeria) which is among the hottest and sunniest areas in the world. A selective analysis of the most suitable STEG system for the Adrar region is proposed, based on state-of-the-art data of STEG systems realized and simulated in the scientific literature.

I. Introduction

A solar thermoelectric generator (STEG) is a system which absorbs heat from solar radiation by using a thermal collector and in turn diffuses it's through a thermoelectric generator TEG. This latter transforms heat directly by the Seebeck effect into electrical energy due to the movement of the charge carriers induced by the temperature difference created through the TEG[1]. The discovery of thermoelectricity began two centuries back. [2]. Its applications can be found in several fields, such as the space sector [3],medical domain [4], petroleum industry [5],in micro and macro cooling [6], in the recovery of waste heat from transport means [7] [8] [9], industry [10], nature [11], and many other commercially available applications targeted to human comfort [12].

The first work on the STEG dates back in 1888 with a patented device [13] consisting of a combination of a thermopile (TEG), a storage battery and a lens to focus solar radiation on the thermopile. Later in 1910 another solar thermoelectric system was made by a company named Sun Electric Generator Company[14].

Before 1922, the work on the STEG lacked data of appropriate quality, from which Koblenz was able to measure the efficiency of a STEG device that reached 0.01% [15]. The evolution of STEG continued his progress by a work of [16] which demonstrated an efficiency of 0.63% without solar concentration and 3.35% with a solar concentration of 50 × sun. At present, research on the solar thermoelectric generator is oriented towards the development of mathematical 444s and experimental devices. In this study, A selective analysis of the most suitable and efficient STEG system to be implemented in the Adrar region are presented, based on state-of-the-art data of STEG systems realized and simulated in the scientific literature.

II. Composition of a STEG

According to the definition already mentioned, a STEG can be divided into three important parts, 1- Thermoelectric generator, 2- Solar thermal collector, 3- Heat transport and dissipation system.

II.1. Thermoelectric generator TEG

The Figure 1 illustrates a typical configuration of a thermoelectric module which consists of n- and p-type thermoelectric elements connected in series by conductive pads, and thermally in parallel by sandwiching them between two ceramic coatings. The temperature gradient acting between its two ceramic layers converts thermal energy into electrical energy following the principle of the Seebeck effect.

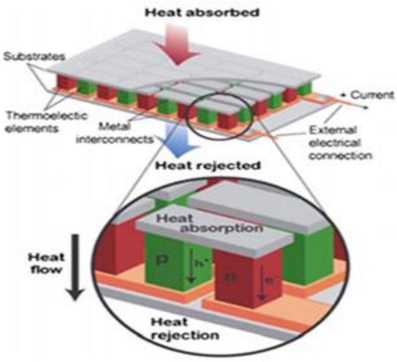


Figure 1. Schematic of a typical thermoelectric device [17]

This planar architecture is the most widely used and marketed, compared to other special module designs, which are designed according to specific technical requirements of the research project, such as the module in cylindrical, flexible, thin or thick film shape [18]. Another more relevant configuration is the Direct Contact Thermoelectric Generator (DCTEG), which decreases the overall thermal module resistance by the direct contact of the TE elements with the exchange media [19] [20].

The thermoelectric efficiency of TE materials is evaluated by the dimensionless thermoelectric figure of merit $ZT = S^2\sigma T/K$, where S ($V.K^{-1}$) is the Seebeck coefficient, σ ($S.m^{-1}$) is the electrical conductivity, T (K) is the temperature in Kelvin, and K ($W.m^{-1}.K^{-1}$) is thermal conductivity. In order to maximize ZT of a material, a number of parameters must be privileged. (1) low thermal conductivity to keep a large temperature difference between the two sides of the material, (2) high electrical conductivity to minimize the internal resistance of the material, and (3) a high Seebeck coefficient is required to obtain a high voltage[21] [22]. The efficiency of converting heat directly linked into electricity by thermoelectric processes is found from 2% to 6% [23], however the reliability and compactivity of the thermoelectric system can overcome this disadvantage [24], furthermore, theoretical predictions suggest that the efficiency of TE materials can be significantly improved by Nanostructure Engineering [25].

II.2. Solar thermal collector

Solar Thermal collectors are divided into several families of sensors with or without optical concentration. The systems with concentration are based on cylindrical lenses, Fresnel lenses, parabolic mirrors, flat mirrors or parabolic concentrators. The non-concentrated solutions are mostly limited to flat plate collectors, evacuated or not, and vacuum tubes[26].

Another method of classification is based on the collector motion, either stationary, or pivoting on one axis, or on two axes as illustrated in table (1).

Table 1. solar thermal collectors [27].

Motion	Collector type	Absorber type	Concentration rate	Temperature range (°C)
Stationary				
	Flat plate collector (FPC)	Flat	1	30-80
	Evacuated tube collector (ETC)	Flat	1	50-200
	Composite parabolic collector (CPC)	Tubular	1-5	60-240
Tracking on one axis			5-15	60-300
	Linear Fresnel Reflector (LFR)	Tubular	10-40	60-250
	Parabolic trough collector (PTC)	Tubular	15-45	60-300
	Cylindrical tank collector (CTC)	Tubular	10-50	60-300
Tracking on two axes				
	Parabolic reflector (PDR)			
		Pointed	100-1000	100-500
	Heliostat field collector (HFC)	Pointed	100-1500	150-2000

II.3. Heat absorption and dissipation system

The important parameter to have a high electrical conversion efficiency of a STEG is not only a high temperature on the hot side of the module, and/or a low heat loss, but also the fast and efficient absorption of this heat from the cold side of the module to be either released in nature or exploited [28] [29]. This technic is used to preserve a stable and high temperature difference between the two sides of the TEG. The evacuation is done by a heat carrier fluid which can be air, water, an antifreeze mixture, a phase change fluid, or even an oil with a high vaporization temperature for applications requiring high temperatures. The hot side of the TEG is either bonded or integrated or thermally connected to the solar thermal collector by a heat transfer fluid.

III. State of the art STEG systems

Research and development on STEG encouraged and accelerated activities of thermoelectric technology. The paper provides a general overview of the present state of research and development on experimental thermoelectric technology. Kraemer et al.[30] have used nano-structured thermoelectric materials to develop flat panel solar thermoelectric generators (Figure 2), which achieve a maximum efficiency of 4.6% under conditions of 1 kW.m-2. The efficiency is 7 to 8 times greater than the best value earlier cited for a flat panel display.

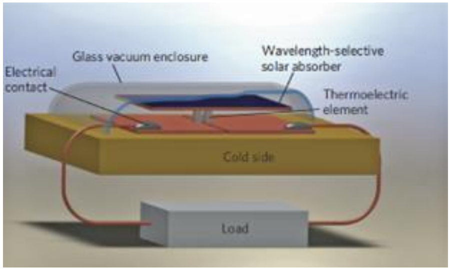


Figure 2. Illustration of a STEG cell composed of a pair of p and n thermoelectric elements.

A group of researchers built and tested at the laboratory scale a new concept called "The Thermoelectric Roof Solar Collector (TE-RSC)". The idea of this project is to reduce heat accumulation in houses and improve indoor thermal conditions, through a heat evacuation system powered by 10 thermoelectric generators stuck on a 0.0525 m^2 copper plate to be installed on the roof of a house. Test results show that TE-RSC could generate about 1.2 W with a simulated solar intensity of 800 W/m^2 and an efficiency of 1 to 4% was found. This electrical power is enough to drive the fan to cool the cold side of the thermoelectric modules and at the same time to evacuate the heat from the house. Finally, economic calculations have shown that the TE-RSC amortization is 4.36 years and the internal rate of return is 22.05% [31]. Lertsatitthanakorn et al. [32] have carried out a performance study and an economic analysis on a hybrid thermoelectric solar water heater system, the principle consists in gluing the TE modules on the absorber plate of a regular solar water heater as presented in the figure 3. The experiments results shown that the overall efficiency of the system increased when the water flow reaches a maximum rate between 74.9% to 77.3% corresponding to a water flow rate of 0.33 Kg/s. The electrical energy generated was 3.6 W at the temperature difference of 27.1°C which results in an efficiency of 0.87%. In addition, the economic study showed a payback period and an internal return rate of the TE solar water heater of 6.1 years and 18.52% respectively for a high-water flow rate used of 0.33 kg/s.

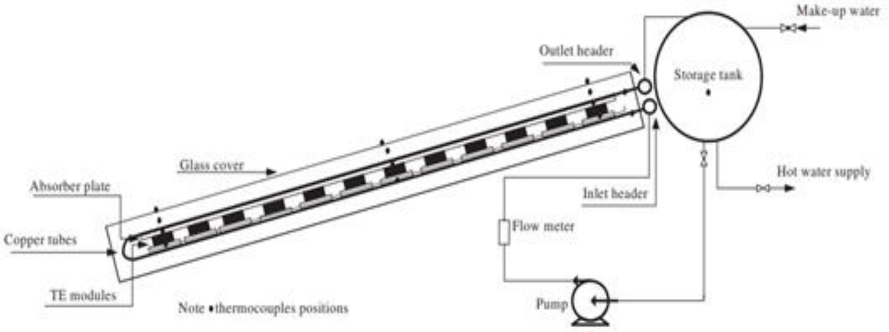


Figure 3. Diagram of the Thermoelectric Hybrid Solar Water Heater

In another experimental study[33], the authors investigate the thermal and electrical performance of a double-pass TE solar air collector with twenty-four TE modules and a collector area of 1.5m^2.Their results showed that the increase in thermal efficiency is proportional to the increase in airflow. In parallel, the electrical power and conversion efficiency depended on the temperature difference between the hot and cold sides of the TE modules. At a temperature difference of 22.8°C, the unit achieves a power output of 2.13W. He et al. [24] conducted a theoretical and experimental study on the incorporation of thermoelectric modules with vacuum solar heating pipe collectors (SHP-TE) as shown in the Figure 4. Their prototype have an electrical efficiency of 1%, a little less than a system with an organic Rankine cycle, but, the SHP-TE system is simple and has no moving parts and its parts are easily replaceable. On the same concept another innovative study has been made with the use of a parabolic solar concentrator [34].

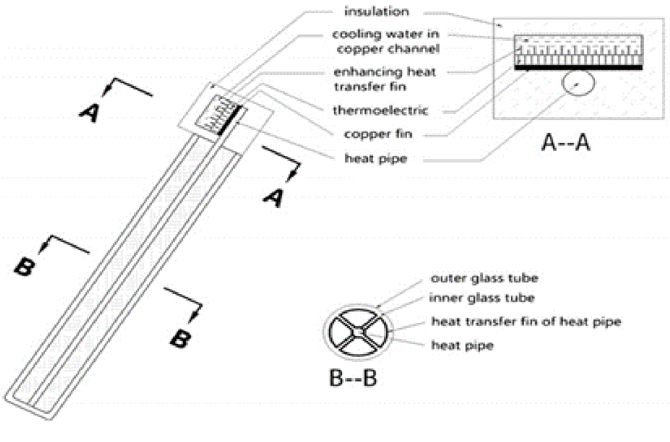


Figure 4. Schematic of an integrated HPS-TE system

Li et al. [29] tested a prototype of a solar concentrated thermoelectric generator (CTG) with a Fresnel lens as presented in the figure 5. The results obtained show that the maximum efficiency of the CTG can reach 9.8% for Bi_2Te_3, 13.5% for skutterudite and 14.1% for LAST alloys (silver antimony lead telluride). The experimental results of this prototype is used to validate their interesting model for the evaluation of solar concentration STEG[35]. The model is based on several real system design and operation parameters, which the author expects to provide a great model contribution to the design and performance evaluation of any

SCTEG system for a variety of applications. Amatya and Ram [36] investigated the possibility of substituting a PV panel by a commercial Bi_2Te_3 module combination with a low-cost parabolic concentrator (solar concentration of 66x suns) for the production of micro-energy. A system efficiency of 3% was measured and an output power of 1.8 W, with a peak power price of $1.67/Wp against a PV cost of $4/Wp. The authors have proposed a new thermoelectric material that will be able to increase the conversion efficiency by 5.6% for a 120x sun STEG.

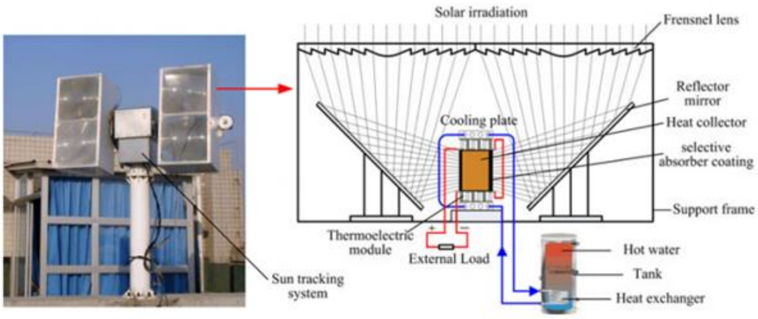


Figure 5. The Concentrated Solar Thermoelectric Generator System a) An experimental prototype of the CTG System. b) Details of the CTG unit.

Miljkovic et al. [37] have modelled and optimized a thermoelectric parabolic solar concentrator with the use of a thermosiphon to allow passive heat transfer (see figure 6). The thermosiphon is used to transfer heat from the cold side of the TE modules to a bottom tank. Several TE materials and different combinations of heat transfer fluid were simulated over a temperature range of 300-1200 K from a solar concentration of 1-100. The best result obtained was 52.6% overall efficiency for a solar concentration of 100 which gives a bottom tank temperature of 776 k. Limpahan et al. [38] have designed and built a parabolic-cylindrical solar concentrator that provides a high heat source to the eight series-connected thermoelectric modules measuring 40 mm x 40 mm x 3.5 mm, inserted between the absorber plate of the collector and the cooling water inside a square tube. The innovative idea behind this work is the addition of a cooling tower to maximise the temperature difference across the modules. The system generated up to 21 Watts at 12.7 Volts with 28°C maintained on the cold side and 125°C on the warm side which is worth a temperature difference of 97°C across the thermoelectric module. According to the authors thermoelectric technology has considerable potential for renewable and sustainable energy production, especially when integrated with cooling towers for medium- and large-scale thermoelectric power generation.

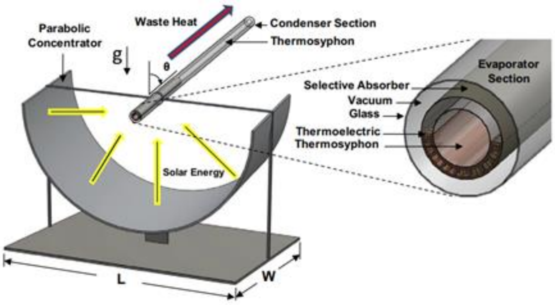
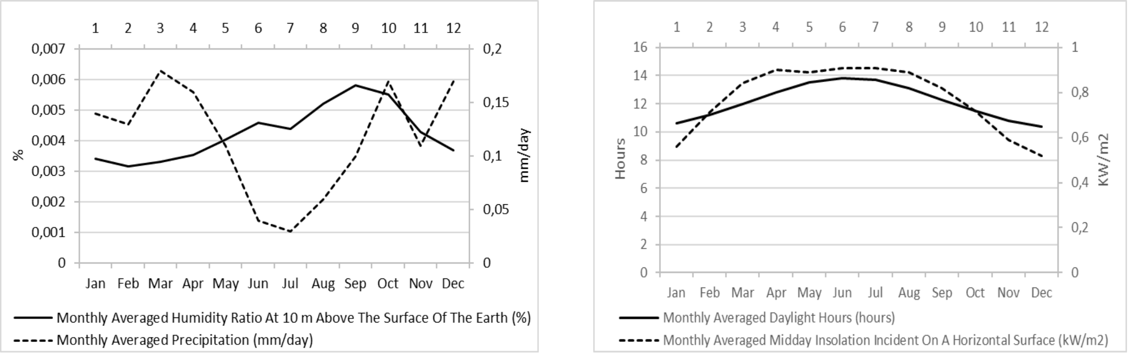


Figure 6. Schematic of a thermoelectric parabolic solar concentrator

IV. Selection of the appropriate STEG system for the Adrar region

Adrar has a hot desert climate typical of the hyper-arid Saharan zone, with a torrid, very long summer and a short, warm temperate winter. In order to choose the most suitable STEG system for the Adrar region, it is necessary to analyze the climate data. As shown in the figures figure 7 and 8, the climatic parameters of Adrar are very suitable for the implementation of a STEG system based on the temperature and the duration of insolation or irradiation, which are at high levels. Likewise, the wind speed is stable and high throughout the year, which can be very useful when using cooling with natural convection, adding to this the humidity rate, which is close to zero throughout the year, which is an important factor in minimizing the cost of using stainless materials and anti-corrosion maintenance. On the other hand, the infrared radiation contributes in rapid degradation for PV for conversion, this is justified by a study done by [39] who found that the lifetime of a PV module (with an output power close to 50%) in open circuit condition in the Adrar region could be reduced to 4 years, which would have a significant impact on its amortization. However, according to a study on a TE module exposed to thermal cycles of +146 to -20°C every 60s on one side and the other side is maintained at a constant temperature of 23°C gives a reduction of 20% after 40,000 thermal cycles and drop to 97% at 45,000 cycles [40]. Another assimilated study [41] with a cycle from 30°C to 160°C every 3 minutes resulted in an 11% reduction in output energy after 6000 cycles. If we consider a thermal cycle for a STEG is 24 hours, a simple calculation gives us that after 20 years of probable operation the STEG will undergo 7300 thermal cycles. The comparison notes that the degradation of a polycrystalline PV module is 20% over a 17-year lifetime [42] and other results show a degradation of 0.5% to 1% per year [43].



(a) (b)

Figure 7. Monthly average values of 22-year average in Adrar region [44-45], (a) humidity and precipitation, (b) daylight hours and midday insolation incident on a horizontal surface,.

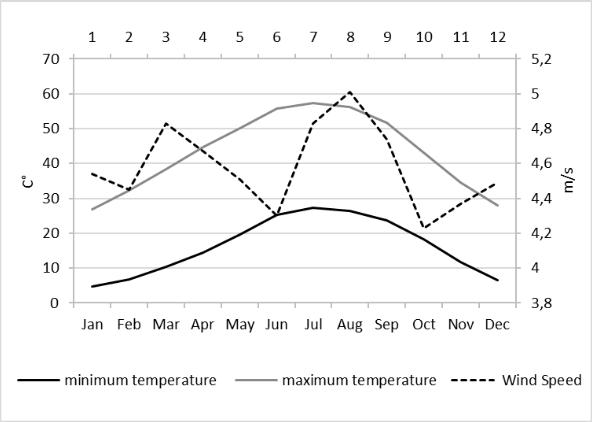


Figure 8. Average Minimum, Maximum Of The Daily Mean Earth Temperature (°C) and Monthly Averaged Wind Speed At 10 m (m/s) (10-year Average in Adrar region) [44-45].

Flat collector STEGs (concentration 1) are not preferred for large and medium scale applications, as their efficiency is very low due to the small temperature difference generated between its two sides, so the installation of such systems are very expensive since the TEG surface area required for one watt produced will be very large and the cost of producing a TEG is currently high. Nonetheless on a domestic scale it can be very beneficial, if it is used for the autonomous ventilation of localities, or used the heat released from the TEG for the thermal energy needs, which makes the overall efficiency of the system more efficient. On the other hand, the use of a vacuum collector can significantly improve the overall efficiency even if it involves additional costs.

The STEGs with solar concentrator are the promising solution for the production of electricity on a medium and large scale. It remains to be seen what type of solar concentrator is required, for that a techno-economic study would be necessary in this case. An analogy can be made with a technical-economic study done by [46] on the evaluation of a Stirling CPS parabolic concentrator in Algeria. The study showed that the implementation of the CPS in the southern regions of Algeria (Adrar is one of them) is competitive to PV especially in remote areas. The idea is to use TEG instead of Stirling, although the efficiency of a Stirling generator is much higher than TEG, but according to the studies of [47-48], this system is very promising. For large-scale production the parabolic-cylindrical or Fresnel mirror concentrator is suitable for hybridization with TEG, as the cost is relatively low compared to other concentrating systems. Their operating temperatures exceed 300°C which is perfectly appropriate for the operating range of new high efficiency TE metals such as TeAgGeSb (TAGS) to obtain high performance, the combination with a cooling tower is favorable[49].

V. Conclusion

In this paper, we presented a description of the solar thermoelectric generator followed by an the most important state of the art of the applications studied theoretically and experimentally to make a selective analysis of the most adequate STEG system for an arid zone (our case study is the region of Adrar south-west Algeria), based on the meteorological data of the region. The general contributions of the study are:

1- Solar thermoelectric generators with flat-plate collectors are suitable for domestic applications.

2- STEG with a parabolic concentrator is very beneficial for medium-scale power generation,

3-, Hybrid parabolic cylindrical collectors with thermoelectric generator cooled by cooling tower is the ideal solution for large scale production.

Power generation utilizing the thermoelectricity effect still has subjects to address, such as the fact that the materials are expensive and power generation efficiency is too low to justify general use. Consequently, researches and technology are being made for developing new materials that can increase the power generation efficiency and reduce costs through mass-production.

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