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Hybrid Thermoelectric Generators-Renewable Energy Systems: A Short Review on Recent Developments

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Abstract

The development of different renewable energy techniques has shown their ability in limiting the environmental crisis and meeting future needs. In recent years many efforts have been made in order to produce hybrid systems that work on integrating renewable energy systems with thermoelectric generators (TEGs) in order to increase energy efficiency. This review attempts to discuss and summarize different configurations of hybridizing TEGs with different renewable energy sources (solar, fuel cell, biomass) underlying the concepts and approaches used to reach these hybridizations. This review will give necessary information about this type of hybridization and encourage for future research due to its promising results.

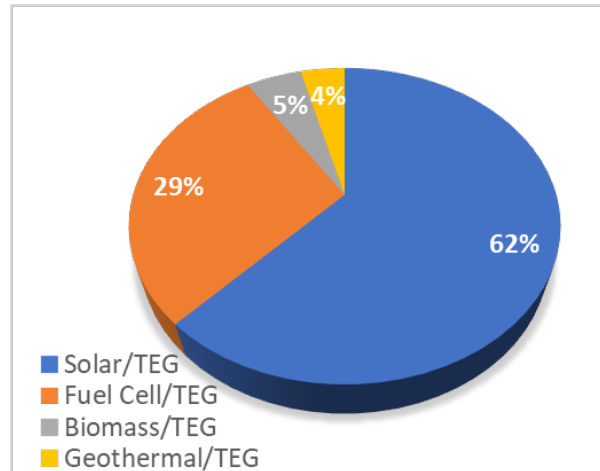
Keywords: Renewable Energy; Thermoelectric Generators (TEGs); Hybrid Systems.

1. Introduction

Recently, reducing environmental problems resulting from high energy demand has captured the global attention for finding some strategies that compensate for the usage of fuel and decrease the level of pollution crisis [1]. Accordingly, alternatives such as heat recovery [2,3], energy management [4,5] and renewable energy [6-8] have been adopted by many institutions and researchers all over the world in order to reduce energy costs as well as environmental issues. The utilization of renewable energy technologies such as solar [9], wind [10], geothermal [11], fuel cells [12] ... etc. as clean energy production is significantly increased in many countries. However, renewable energy sources are highly dependent on weather conditions like wind speed or solar irradiance [13,14]. To overcome the drawbacks of a single renewable energy source system and to increase its efficiency, coupling of various energy systems is introduced forming hybrid systems that are more reliable and environmentally friendly [15]. In this context, the hybridization of thermoelectric generators (TEGs) with a conventional power generation system has been extensively introduced [16,17].

Thermoelectric generators are solid-state semiconductor devices that can generate electricity due to temperature gradient using Seebeck effect [18,19]. These devices are characterized by their free gas emissions, simplicity in

Fig. 1. Studies performed on different renewable energy systems integrated with TEGs for the past 10 years.



maintenance with no moving parts which have the ability to generate power for a long-life span [20]. TEGs are widely used in waste heat recovery applications mainly that of photovoltaic cells where excess electricity can be generated and more than 23% efficiency enhancement might be reached [21,22]. From the literature, several researchers have investigated methods in order to enhance the power and performance for renewable energy systems upon integrating these systems with thermoelectric generators (Fig 1). This paper presents a short review based on recent studies that focuses on the applications of different renewable energy systems with thermoelectric generators. The paper is divided as follows: section 2 describes the development and working principle of thermoelectric generators. Section 3 presents the performance of TEGs when integrated with several renewable energy systems and section 4 will be dedicated to conclusions and future perspectives.

Nomenclature

TEG	Thermoelectric generator
FC	Fuel cell
ZT	Figure of merit
PV	Photovoltaic

2. Thermoelectric Devices and their working principle

Thermoelectric technology is one of many green technologies which is able to convert heat into electricity and vice versa. Seebeck effect which goes back to 1821 and is based on potential generation across a certain load due to temperature difference between two junctions (hot and cold) is the fundamental concept for a thermoelectric generator. Until 1990s, thermoelectric devices were uncommonly used due to their low processing efficiency. However, renewed interest in thermoelectric devices has been introduced into research due to global warming alerts and the need of a sustainable, durable and reliable electric source [23,24].

There are many types of thermoelectric materials that can be classified based on their thermal and electrical conductivities as well as seebeck coefficient such as BaUO₃, CoSb₃, SnSe, and many others. However, Bismuth Telluride (Bi₂Te₃) is the most commonly used one due to its high effectiveness at room temperature. The working principle of a thermoelectric device can be either as a power generator or as a thermoelectric cooler. These devices consist of flat arrays of P (charged holes h⁺) and N (charged e⁻) types that are connected electrically in series and thermally operating in parallel. As a power generator, the temperature difference causes the movement of both

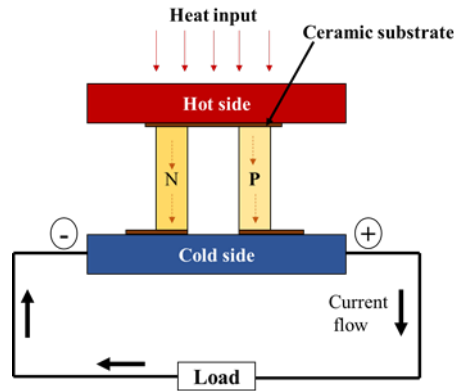


Fig. 2. Structure of a TEG based on Seebeck effect.

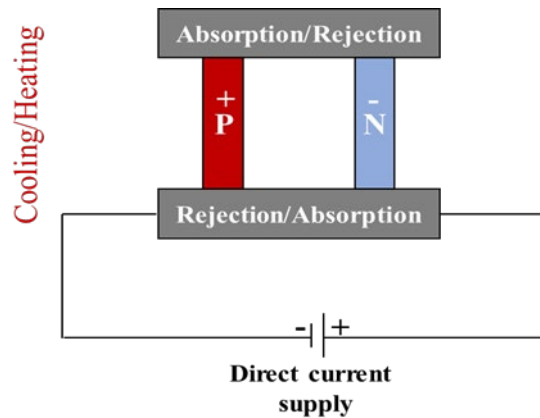


Fig. 3. Schematic for TE cooling or heating based on Peltier effect

electrons and holes from the hot side to the cold side resulting in a potential difference that will drive current through the device when it is connected to an external load (see Fig 2). The temperature gradient between the two junctions of a thermoelectric device directly affects the output power which can be increased by the increase of this gradient and the efficiency of the device. The efficiency of a thermoelectric generator is given as the ratio of the power supplied to the external load by the heat absorbed at the hot junction [25-28].

Thermoelectric cooler works opposite to thermoelectric generator using Peltier effect. In this case a direct current passing through the two junctions can produce or absorb heat based on the direction of the current as shown in Fig 3. This type is highly recommended upon controlling the temperature of a certain device or system however it is quite dependent on many parameters such as ambient temperature, thermoelectric properties and the current flow. Due to their ability to convert low amount of heat into electricity, optimizing a thermoelectric material in order to reach the best performance is crucial and highly dependent on the type of the material used. The performance of the TE device is estimated depending on its operating temperature and the figure of merit (ZT). Figure of merit depends on the seebeck effect, the thermal and electrical conductivity. Thus, improving the figure of merit and decreasing the thermal conductivity of a thermoelectric material can significantly enhance its performance. [29-32]

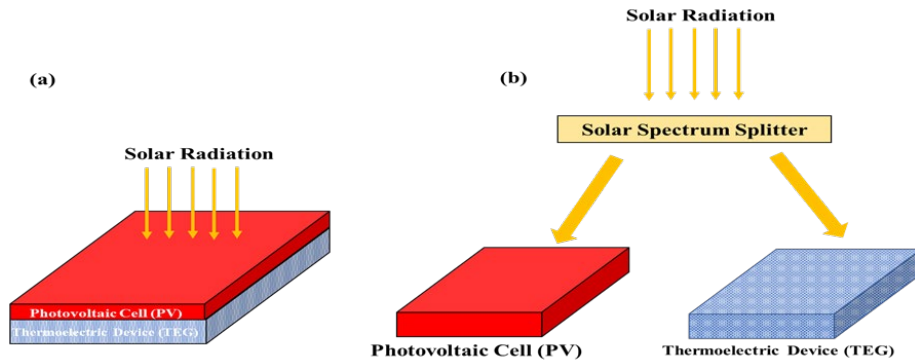


Fig. 4. Schematic of the hybrid PV-TEG: (a) combined (PV-TEG) system; (b) spectrum splitting (PV-TEG) system

3. Hybrid thermoelectric devices (TEG) – Solar photovoltaic systems

The solar renewable energy systems are the most widespread technologies due to high solar radiations available. To utilize the harnessed energy in useful applications, solar energy systems in its two versions solar thermal modules and photovoltaic cells (PV) are able to convert the solar radiation directly into thermal and electrical energy respectively. Solar photovoltaic system (PV) are excessively used and integrated into buildings due to their high-power density compared to other renewable energy technologies. In order to increase the conversion efficiency of a PV system, several cooling technologies that take into consideration the surface operating temperature have been utilized. Due to the fact that the rise in a PV surface temperature can drop its efficiency, thermoelectric modules are introduced in order to utilize the waste heat dissipated from the photons below or above the solar cell band-gap energy and convert it to electricity. [33-35]

Recently, integrating a PV solar cell with a thermoelectric module is widely performed and studied, where, the overall output power of the hybrid system is the total sum of the power of the PV and TE modules [36,37]. To date, the hybridization of PV/TE systems can not only increase the efficiency conversion of a solar cell, but also helps in reducing the heating up of these cells and consequently increasing their life span. The methods of developing an optimized hybrid PV/TE system can be merged with other additional components like cooling systems and can be classified into two designs; spectrum splitting PV-TE and a combined PV-TE as shown in Fig.4. As shown in Fig.4 (a), when the sunlight is subjected to the two parallel modules (PV and TEG), the PV works to absorb the UV regions and convert it directly to electricity. As for underlying TEG module it is able to absorb the rest of the radiations (IR region) and heats up the hot side of the TEG device [38]. A heat sink can be placed at the bottom side of the combined system to ensure a temperature gradient through the thermoelectric module. In Fig.4. (b) the solar radiations are divided into two parts; the solar radiation below the cut-off wavelength is absorbed by the PV cell and radiations above this wavelength are reflected to the thermoelectric device (TEG). [39]

Different approaches have been conducted by researchers for optimizing the PV-TE systems for a better performance. Studies take into consideration PV and TE parameters, additional systems (Heat sinks, cooling mediums or concentrators) in analysing any proposed system. Fig.5 shows the increase in the overall efficiency in a hybrid PV-TEG system compared to a stand-alone PV system based on the same operating conditions. The efficiency increment shows that the enhancement in the overall efficiency may exceed 30% for a certain design or condition. The optimization and developments of a hybrid PV-TEG system is based on modifications and enhancements regarding materials and operating conditions and designs of both PV cells and TEG modules that can affect the conversion efficiency of the combined system. Table 1 shows the effect of each operating condition on the performance of the system.

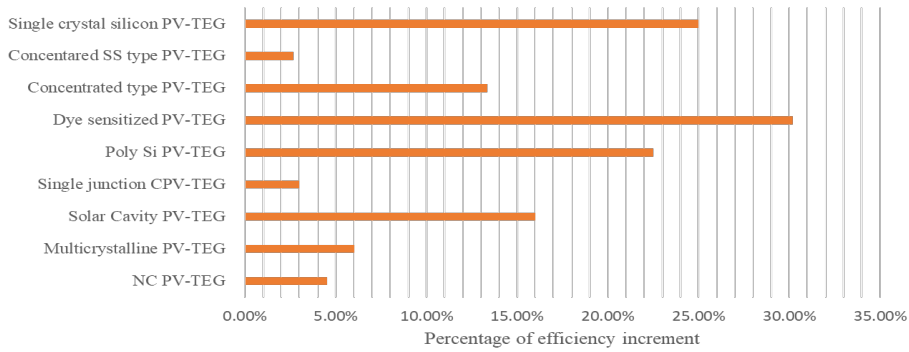


Fig. 5. Efficiency increment of a hybrid PV-TEG system compared to a stand-alone PV system

Table 1. The performance of a hybrid PV-TE system

Parameters	Effect on hybrid PV-TE performance
PV Type	Affects the conversion efficiency of the system. The most common types are: Silicon and dye sensitized PV cells.
TE Material	Depends on the figure of merits ZT . Optimal ZT can increase the hybrid system overall efficiency.
PV structure	Nano-structure surface of a PV cell and cooling system integration are essential for a better performance. Nanofluid proved their ability to remove excess heat more efficiently than water.
TE structure	Decrease in the thermoelectric leg length and surface area can increase the temperature gradient between the hot and cold side and consequently increase energy generation.
Concentration ratio	The overall efficiency varies with the increase of the CR depending on the PV-type used.
Solar irradiance	Its increase can increase the system power gain.
Ambient temperature	Conversion efficiency decrease with ambient temperature increase.
Power generation	The amount of output power of the hybrid system is relatively higher than stand-alone PV and TE modules.
Overall efficiency	Integrating the best way to couple the PV and TE modules for a better thermal resistance optimization based on the system's working conditions.
Cost	The hybrid PV-TE cost is significantly higher than a stand-alone PV. TE contributes the highest part of the total cost. Compared to the amount of energy generated by the TE device, the hybrid system is not economically feasible and needs more improvements.
Life cycle	Hybrid PV-TE increases the life span of the PV module.

4. Hybrid thermoelectric devices (TEG/TEC) – Fuel Cells

4.1. Fuel Cells

Fuel cells are electrochemical systems that use the chemical energy of the fuel in order to produce electricity and heat without any moving parts. These cells are characterized generally by their low emissions and high energy efficiency. A typical fuel cell consists of two electrodes, the anode and the cathode in addition to an electrolyte placed in between with high conductivity. The fuel oxidation (hydrogen) happens at the anode forming electrons flowing through the load circuit and releasing cations H^+ from the reactants and flow out through the electrolyte to the cathode (oxygen), where the electrons reduction takes place. [40-44] The electrochemical reaction occurring in the fuel cell results in water, heat and electricity production. As shown in Fig 6 the basic reactions taking place in a fuel cell model are as follows:

At the anode: $H_2 \rightarrow 2H^+ + 2e^-$

At the cathode: $1/2 O_2 + 2H^+ + 2e^- \rightarrow H_2O$

Overall reaction: $H_2 + 1/2 O_2 \rightarrow H_2O + \text{Heat} + \text{Electricity}$

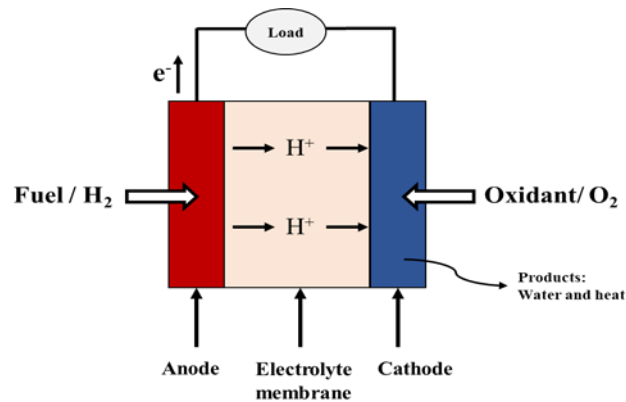


Fig. 6. Schematic diagram and operating principle of a fuel cell

Five different categories of fuel cells are classified in the literature depending on the type of the electrolyte used: Alkaline fuel cell (AFC), Phosphoric acid fuel cell (AFC), Proton exchange membrane Fuel cell (PEMFC), Molten carbonate fuel cell (MCFC), Solid oxide fuel cell (SOFC) and direct fuel cell that uses liquid fuel such as methanol, ethanol, etc. Generally, all fuel cell types are clean and sustainable energy sources and they are highly advantageous due to fuel flexibility. However, fuel cells can generate a significant amount of waste heat during their operation, so managing the operating conditions such as temperature and efficiency, and reducing losses such as ohmic, concentration losses and many others in a fuel cell are critical approaches in several thermal applications or heat exchangers for enhancing energy production. [45,46]

Hybridization of fuel cell with thermoelectric devices has been actually valid in 2010 where a modelled TEG-PEMFC system for recovering waste heat from the high temperature PEM fuel cell stack was presented. To support the co-design and co-optimization of the system a three-dimensional TEG module in ANSYS FLUENT has been implemented. In addition, an experimental validation was carried out in which the TEGs were installed at the exhaust pipe surface. However, this study didn't make a clear optimization of the performance or the operation of the system. Based on the reviewed state of arts, waste heat recovery, thermal management, efficiency improvements and cogeneration processes are main strategies that are studied within a fuel cell and thermoelectric device hybrid system

in order to improve its function and increase energy savings. Tables 2 shows some studies based on the hybridization between fuel cells and thermoelectric generator systems.

Table 1. Studies on the hybridization between TEG and fuel cells.

Reference	Hybridization	Research approach
[50]	FC-TEG	A 3-D finite element model developed in COMSOL Multiphysics that simulates both the FC and the TED subsystems. the proposed model can easily simulate the TED as both a thermoelectric generator (TEG) or as a Peltier device for cooling and heating.
[51]	FC-TEG	This study uses the thermoelectric device to further improve the exergetic and temperature performance of the conventional fuel cell based combined heat and power (FC-CHP) system.
[52]	FC-TEG	The hybrid system is superior to the stand-alone MCFC system as the bottoming TEG can effectively increase the maximum power density
[53]	MCFC-TEG	A new MCFC-based hybrid system to harvest the waste heat from MCFC for additional cooling production. the power density and efficiency of the proposed system is effectively increased by 3.4% and 4.0% comparing with the stand-alone MCFC.
[54]	FC-TEG	A thermoelectric device is proposed to recover the waste heat from a PAFC. Maximum power density and the corresponding efficiency are increased by over 2.0%.
[55]	FC-TEG	The equivalent maximum power density of the AFC can be increased by up to 23%. The effects of the operating current density, operating temperature, heat conductivity, and integrated parameter on the performance of the hybrid system are revealed.

[56]	TEG-FC	The system presents a thermal management system for a fuel cell who exploits the bi-directional characteristics of the TE device to achieve both temperature control and the possibility for energy harvesting when active control is not required.
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5. Hybrid Thermoelectric devices – Biomass Energy systems

The chemical energy that results from the burning biomass is considered as a promising and reliable alternative for heat production which can be directly converted to different energy forms (electricity, heating, agricultural uses, etc). Biofuel significantly competes coal, petroleum fuel or nuclear fuel as a recycled energy source that can help in preventing or reducing some environmental problems. Biomass energy systems differs from other renewable energy systems when it comes to their high dependency on weather conditions and changes like solar or wind energy. However, biomass power plants encounter many challenges like costs, capacity or location. Studies on biomass energy systems are based on their design to energy conversion system about their configuration size in addition to their hybridizations with other renewable energy system. Table 3 shows recent studies on the hybridization of biomass systems and TEGs.

Table 3. Recent studies on hybrid systems between biomass and TEGs.

References	Integration of TEG with biomass energy systems	Research approach	System performance
[57]	The TEG module is placed between two stainless steel plates. At the bottom of the plate a heat gun supplies the heat flow. The top plate is cooled by water.	Testing the feasibility of a biomass power plant and a TE device for the best integration.	The performance of the TEG is enhanced with a better contact between its surfaces and the cooling and heating structures. A better compression rate leads to a higher power output and surface heat uniformity.
[58]	The TEG system is placed on the surface of a catalytic reactor, which is used for cleaning which serve as a heat source of hot junction on the TEG.	Examine the wasted heat that is recovered from a biomass gasifier.	The maximum and minimum conversion efficiencies of the TEG ranges between 10.9% and 2.8% The performance of the TEG shows a maximum power output of 6.1W and a power density of 193.1 W/m ² .
[59]	The hot side of the TEG device is inserted into the flue gas duct, whereas a fresh air duct is placed at the cold side.	The electric energy amount that could be recovered by a TEG module when integrated to a biomass fired thermal oil heater.	Analysing different thermoelectric materials it has been found that the best material for the temperature range 300–573 K is the p-type (Bi,Sb) ₂ Te ₃ and n-type hot forged Bi ₂ Te ₃ .the maximum electrical power of the module is 4.4 W.
[60]	Adding the TE WHRSs at different locations of a system consisting of a gas turbine, ORC and domestic water heater.	Integrating a thermoelectric WHRS in a biomass power generation system for improving its performance.	The total output heat from the stack enter the WHRS the efficiency will improve by 0.35%, where it will increase by placing the WHRS at the condenser of the ORC. The operating parameters of the system significantly affects its performance.

6. Conclusions

Renewable energy systems and technologies have been developed in order to meet the worldwide energy demands. Introducing thermoelectric generators into renewable energy systems has been widely used in order to increase their efficiencies since they are highly relying on ambient conditions. Thermoelectric generators can be integrated with renewable energy sources like solar, biomass systems in order to implement a hybridized system with high efficiency. Further studies can be performed on the hybridization between thermoelectric generators and geothermal energy systems.

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