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Research paper

Recent developments in photovoltaic-thermoelectric combined system

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Abstract

The photovoltaic system converts solar radiation into electricity. The output of the solar photovoltaic systems is strongly depending on the operating cell temperature. The power output of photovoltaic system reduces as the operating cell temperature increases. Several techniques have been reported in the literature to maintain the low operating temperature of the solar cell by utilizing module heat for separate thermal application. Integration of photovoltaic thermoelectric (PV-TE) system is one of these techniques. In these PV-TE systems, the hot junctions of thermoelectric modules are coupled with the photovoltaic. The thermoelectric module uses heat from PV system and generates additional power. This PV-TE system not only generates more power but also improves the PV efficiency. The present article reports a comprehensive review of latest developments in the PV-TE systems. A detailed classification, key outcomes of published research and the future research scope are discussed in this article.

Keywords: *Photovoltaic; Thermoelectric; Indirect; Direct; BIPV.*

1. Introduction

Exhaustive and unprecedented extraction of minerals, metal ores, fossil fuels etc has brought conventional energy sources on the verge of extinction. It can be seen as the last call to the industrialized world to switch and explore other environmentally friendly energy sources. The world has been witnessing an upsurge in generation and utilization of renewable energy. It has also been anticipated that in next 6-7 decades, the renewable energy and its applications shall be one of the greatest revolutions of the 21st century. Solar energy systems, in particular, are widely accepted and used as of now due to its affordable economics, availability, handling ease and portability. Among the various source of renewable energy, the sun provides 4000 trillion kWh irradiation per day [1]. The solar energy available for harvesting at the earth is about 3.85 million kWh per year EJ [2]. Harvesting the solar energy is comparatively convenient provided that the challenges related to efficiency and effectiveness of solar power systems are addressed adequately. Various technologies that are available worldwide are capable of converting solar energy into useful work such as heat and electricity. Among all of these, Photo-voltaic (PV) solar modules are increasingly employed because of its capability in processing both the beam and diffused radiation. Till 2017, across India, about 29 GW of PV solar power capacities have been installed against estimated power potential of India i.e. about 700 GW. The annual growth rate of solar energy in India is estimated to be about 35 - 40% [3]. At the end of 2030, India is expected to produce 500 GW of electrical power entirely through solar energy [3]. However unlike anticipated, from the prevailing technology and procedures, it is observed that only 15-20% of solar radiations are converted into electrical energy by commercially available PV. The rest of the solar radiation causes thermal losses in the solar cell increasing its temperature. The output of the photovoltaic modules reduces when the operating temperature of the solar cell increases. Thus for better performance of solar cells, it is required to maintain a low operating temperature of the solar cells. The heat from the PV module can be extracted from several ways. PV-TE system is one of those techniques.[4] In the conventional PV-TE system the hot junction of thermoelectric modules was usually attached to the PV modules and the cold junctions are exposed to ambient. According to Seebeck effect, the TE module generates power. Thus in all the PV-TE system gives more power output and at the same time, TE module helps to maintain a low operating temperature of solar cells. The current paper describes the systematic review of recent developments in PV-TE systems.

1.1. Terrestrial solar spectrum

The solar spectrum is characterized by the surface temperature of the sun. Solar radiation spectrum is close to that of the blackbody with a temperature of 5800 K. This spectrum defines the corresponding spectral irradiance for all wavelengths of sunlight. About half of terrestrial solar spectrum is a visible short-wave and the other half is mostly in the form of infrared. Some of it is also in the form of ultraviolet spectrum. Visible light, with wavelengths between 0.4 μm and 0.75 μm, has a 46% share of the spectrum, infrared light 47%, and ultraviolet light is only 7% (Fig 1)[5]. The earth’s atmosphere reduces the irradiance that reaches the earth's surface. Ozone, water vapor, and carbon dioxide absorb radiation with certain wavelengths as it passes through the atmosphere. Absorption of solar radiation reduces the ultraviolet and infrared spectrum. The maximum value of solar radiation intensity is 2074 W/m^2
occurs at 0.48μm[5].

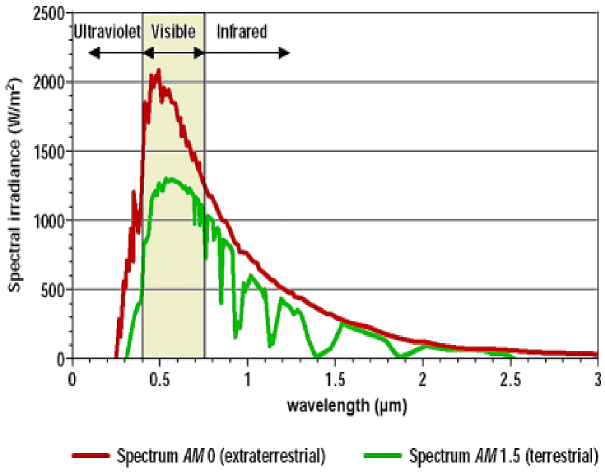

Fig. 1: Solar Radiation Spectrum[5].

1.2. Photovoltaic (PV) cell

A PV cell converts part of solar energy into electrical energy, however, most of the remaining part of solar energy gets converted into heat.[6][7][8] Fig.2 illustrates the working of the solar cell. Due to this, there are increases in the temperature of PV cell above the desired operating temperature(standard test condition (STC) solar irradiance of 1000 W/m^2, Air mass (AM) 1.5 and cell temperature of 25ºC) [9]. Therefore, there is a slight increase in cell current and a significant drop in voltage. The increase of PV cell temperature also leads to a sudden increase in reverse saturation current and the voltage drops are observed to be as high as approximately 2.2 mV per ºC rise in temperature. Since temperature rise is proportional to the resistivity of silicon, which is the material of PV cell. The overall conversion efficiency of PV cell reduces with the rising in temperature [10]. The maximum temperature in a PV system in field application is in the range of 80-150 ºC [11]. A few of the previous researchers have focused on utilization of heat in Photo-Voltaic Thermal (PVT) systems; however, there is still an appreciable scope for engineering research and technology development so as to recover the untapped and unutilized heat energy.

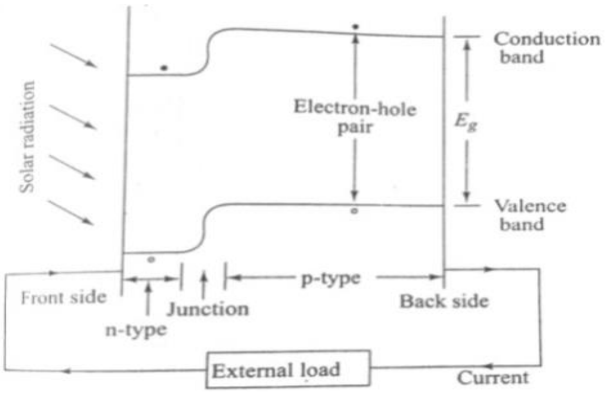

Fig. 2: Principle of Working of a Solar Cell[5].

1.3. Effect of solar cell temperature on PV output

The efficiency of the solar cell is one of the important parameters to establish the comparison between existing PV systems. The efficiency of PV module is depend on ohmic losses between solar cells, solar radiation, high module temperature, concentrating ratio[12][13], dust and packing factor.[14] Commercially available Mono and Polycrystalline solar cells have efficiencies in the range of 14-20% [3]. It is well known that solar cell made up of Ga-As material has the highest efficiency among all other PV solar module[15]. Table 1 shows the leading manufacturers of PV modules and corresponding efficiencies of PV Modules. It is observed from Table 1 that efficiency of PV module decreases with an increase of PV cell temperature.

Table 1: PV Manufacturers and Their Specification [16]

PV Manufacturer	Temperature Coefficient(%/ºC)	Module Efficiency (%)	Efficiency at 30 °C (%)	Efficiency at 35 °C (%)
Axitec	-0.4	16.9	16.83	16.77
Canadian Solar	-0.41	17.7	17.63	17.56
Hanwha Q CELLS	-0.39	18.3	18.23	18.15
Hanwha SolarOne	-0.41	16.2	16.14	16.07
Hyundai	-0.45	16.5	16.43	16.37
Kyocera	-0.45	16.1	16.04	15.97
LG	-0.41	18.6	18.53	18.45
Panasonic	-0.3	21.6	21.51	21.43
SolarWorld	-0.43	17.6	17.53	17.46
SunPower	-0.38	22.2	22.11	22.02

*[Temperature coefficient: coefficient expressing the relation between a change in physical property and the change in temperature].

Fig 3 shows the effect of temperature on Current and Voltage (i.e. IV characteristics curve. The area under IV curve shows the power output of PV cell, where Power = Voltage (V) X Current (I). The fig 3 shows that as the temperature of PV cell increases, current increases slightly but voltage drop is considerable so that overall power output decreases significantly. The temperature rise of PV cell leads to decrease in output power and efficiency of PV module. This phenomenon is caused due to the shrinkage of the band gap, as the temperature rise of PV module results in the drop of open circuit voltage [3]. The temperature of PV cell is given by Eq.1.

$$T_{pv}=T_a+c\ G \quad (1)$$

R. Bjork et. al[18]. have suggested a relation for variations in efficiency of PV cell as a function of temperature difference between PV cell and surrounding temperature, as per following Eq.2

$$\eta_{PV}=\eta_{Tref}\,(1+\beta\,(T_{PV}-T_a)) \quad (2)$$

Table 2 shows the observation of some researchers about the drop in conversion efficiency for the unit rise in temperature.

Table 2: Drop in Conversion Efficiency for Unit Temperature Rise

Reference	Efficiency decrease per unit temperature rise (%/ºC)
Khaled toffee et al.[19]	0.45-0.5
Shohreh sultana et al.[20]	0.5
Amit Sahay et al.[10]	0.5

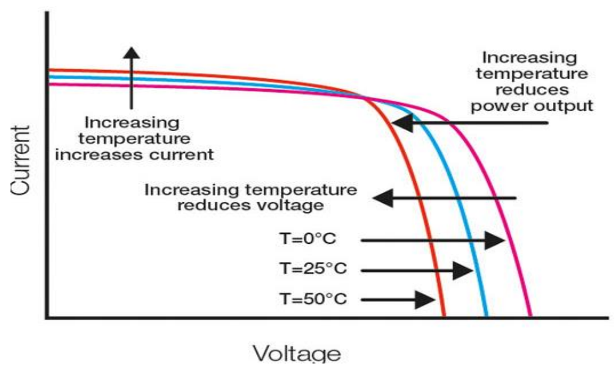

Fig. 3: Characteristics Curve for PV Cell [3].

1.4. Photovoltaic-Thermal (PVT) system

The PVT system is the integration of PV system and solar thermal system. The integrated system produces electricity and heat instantaneously from a single unit. The main aim of this integration is to extract heat from the PV module during photovoltaic operation and to increase the electrical efficiency of the system. This system produces low-grade thermal energy and it can be used in industrial, domestic applications. The integrated system provides space and cost advantage over the individual systems. Tushar et al.[21] have the reported the classification of PVT system as illustrated in fig. 4.

The PVT system is being developed for possible of parametric optimization to obtain better performance [21]. Further, few researchers are exploring to improve the conventional PVT system with the inclusion of air or water-based support systems and concentrator [22] [23]. Recently, the utility of heat pipe[24], nanofluids [25] [26], and phase change materials with PVT system had been reported in some literature [13-15]. Various literatures on PVT system are available to understand the recent development of PVT technologies and creating a platform for futuristic research and developments. This article presents a brief review about utilizing the thermal energy of PVT system emphasizing on the performance of the PV system influenced by PV module's surface temperature.

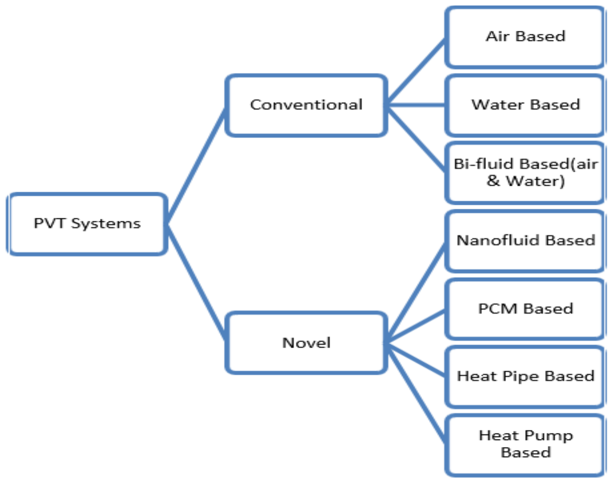

Fig. 4: Classification PVT Systems [21].

1.5. Developments of PVT

It is evident from the literature published in past couple of decades that tremendous advancement has been made in PVT system, which has lead to effective utilization of PV cell temperature. In 2010, Dutreuli et al. found that electrical efficiency of PVT system for a glass to glass with duct is more than that for glazing units. In another study by Zdrowski et al., it is observed that Building Integrated PVT (BIPVT) system has more efficiency than that of water-cooled PVT system. [30] [31].

In novel techniques, PVT system with heat pipe, phase change material(PCM), nano-fluids has been developed [21]. And it was noticed that many more techniques are available to improve the overall efficiency of PVT system by implying any thermal fluids which can absorb the heat energy of solar spectrum[32]. Water, oil, bi-fluid (air & water) treated as conventional PVT system.[33] But nowadays PVT based on refrigerant, natural circulation[34], PCM, nana-fluid, heat pump, tri-functional PV [35] [36] is developing .now the research area is focusing on how this heat energy can be directly utilized to convert effective power. [37] [38] Relevant to this work hybrid solar TEG modules are also developed. [39] [40]

2. Concept of PV-TEG

The PV-TEG system is different hybrid configuration developed to increase electrical energy and thermal extraction from the solar radiation[41]. In this system, TEG is located in the most desirable way with PV module to generate electric power by Seebeck effects. The excess heat of the PV module is used for power generation by using of TEG.

TEG is working on Seebeck effect which generates electrical power out on expenses of thermal energy that is temperature difference must present in two junctions. [42 - 44] Combining of TEG modules with Photovoltaic (PV) gives the hybrid system.[45][46] Now research is going to improve the efficiency of TEG module by changing its materials. [47] TEG is more useful in the field of electric power generation. [48 – 50] Alloys of bismuth, selenium, antimony, and tellurium having temperature difference generate the potential difference between junctions [51] [52]. The potential difference is directly proportional to temperature difference. The efficiency of the thermoelectric generator is the function of the figure of merit (ZT) and it can be estimated by Seebeck and joule Thompson effect in Eq.3

$$\eta = \left\{\frac{Th-Tc}{Th}\right\}\left\{\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+\frac{Tc}{Th}}\right\} \quad (3)$$

2.1. Previous review work

Table 3 shows the review article published on PV-TE hybrid system. Up to the date very few researcher reviews have been done. Most researchers focused on a mathematical modeling, thermodynamic analysis, experimental investigation, computer simulation on PV-TE hybrid system[53].

Table 3: Summary of Review Papers of PV-TEG System

Sr. No.	Summary	Year	References
1	This review paper describes the various approaches used to optimize hybrid photovoltaic/thermoelectric systems.	2016	Priscilla Huen, et al[54].
2	This review paper addresses the current progress of combustion driven TE and TPV systems.	2016	K.F.Mustafa et al.[55]
3	In this review, different heat utilizing methods are discussed such as PVT, solar thermal –TEG, PV-TEG. Relevant to this, the effect of natural and design parameter presented.	2017	C. Babu et al.[52]
4	The objective of this review is that to provide the analytical expression for thermal modeling and energy analysis of BIPV, BIPV-T air, and water collector also to provide suitable simulation software for BIPV and BIPV-T system.	2017	Mary debbarma et al.[56]

Rom the literature, it has been observed that many PV cell temperature management systems developed. However, hybrid PV-TE systems are developing as an additional power producing method. So that many researchers performed the mathematical modeling [57], computer simulation [58] thermodynamic analysis [59] [60], Exergy and energy analysis[61], experimental investigation[62] and transient modeling [47-48] [64], Geometry optimization [65], Thermal resistance analysis [66] [67] of PV-TE system to get most efficient systems. This review article presents the recently developed PV-TE hybrid system and proposing a novel technique to combine PV-TE system.

2.2. Classification of PV-TE system

Based on the literature reviewed, classification of PV-TE hybrid system is given. Mainly it is classified as the mode of contact between PV and TE i.e., direct or indirect contact. Fig.5 shows the detailed classification of PV-TE system.

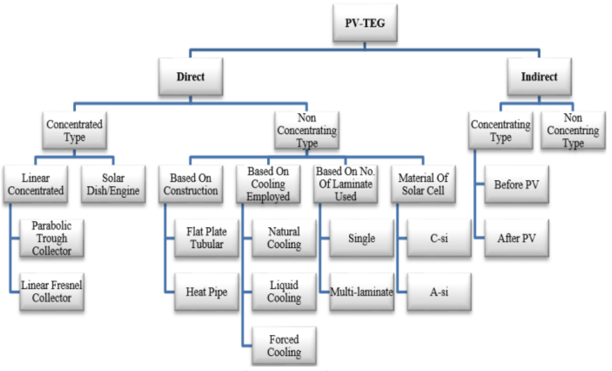

Fig. 5: Classification of PV-TEG System.

2.3 Review of recent developments of PV-TEG systems

2.3.1. Direct contact type PV-TEG systems

2.3.1.1. Non-concentrated type

According to the classification, different arrangements of PV-TEG systems are discussed below. R. Bjork et al. [18] Examined the performance of four different types of commercials PVs and commercial Bismuth Telluride TEG by the analytical method. In this system, TEG is mounted directly on the back side of PV. So that hot side temperature of TEG is equal to the temperature of PV. the observation shows that direct coupled PV-TEG is not a viable option for power production as long as PV performance decreases significantly with increase in temperature[18]. Vishal Verma et al.[68] developed an optimized cooling technology for an active cooling of PV module. This work includes modeling of PV module in MATLAB and integration of PV and TEG for PTH system. The simulation result shows that output power of TEG varies with the temperature difference. For temperature difference of 25K, 50K, 75K output obtained are 0.43, 1.26, 3.75W respectively [68 – 70]. Shohreh Soltani et al. [20] Developed a new nano-fluid based cooling for the hybrid photovoltaic-thermoelectric system. This work comprises of comparison of natural cooling, air-cooling, water cooling SiO_2/water nana-fluid cooling and Fe_3O_4/water nana-fluid cooling. The result shows that compared to natural cooling SiO_2/water nana-fluid yielded the highest power and efficiency improvement which is 54.29% and 3.35% respectively while Fe_3O_4/water nana-fluid improves power by 52.40% and efficiency by 3.13% [20]. Mohammad Javed Aberuee et al. [71] analyze the performance of thermoelectric generator working on solar energy to produce electric power, distilled water, and hot water. Also, Genetic Algorithm is used to optimize minimum thermodynamic irreversibility. The analysis shows that maximum energy and exergy efficiency of the integrated system is about 46 and 1.5 resp. [71] D.N. Kossyvakis et al. [17] [72] evaluated the performance of directly coupled PV-TE hybrid system. According to theoretical investigations, the corresponding performance enhancement achieved reaches 22.5% for poly-Si and 30.2% for dye-sensitized based hybrids respectively [17]. Jian Lin et al. [73] developed a thermodynamic model to investigate PV-TE hybrid system. Optimum operating regions of the maximum efficiency and power output of hybrid system are determined. The result obtained provides useful information for the optical design of real hybrid system driven by solar energy. Xiaodong et al. [74], [75] utilize the exhaust heat energy engine to generate power from TEG and solar energy from PV. The combined system used to track maximum power.100 W prototype has been built and tested. The proposed system will be very promising for different types of automobiles. Haijun Chen et al.[76] performed an experiment to utilize solar energy by combining two different types of solar cells with different absorption bands into a hybrid cell. And subsequently, the equivalent circuit model is used to optimize the structural design of PV-TE hybrid system. According to equivalent circuit analysis, maximum efficiency reaches 24.6% when a spacing between TE is 15μm. Guiqiang et al. [77] developed a conceptual novel PV-TE system based on flat plate micro-channel heat pipe. [77] Adham Makki et al. [9]numerically investigate the feasibility of heat pipe based PV-TE system.

2.3.1.2. Concentrated type

Khaled teffah et al. [19] Carried out an experiment on PV-TE system for high concentration solar energy (x300-1000). The experimental setup contains triple junction solar cells, thermoelectric cooler, thermoelectric generator, and these components were connected in thermally series. The design and modeling have been done on COMSOL MULTIPHYSICS software .the simulation result on MATLAB/SIMULINK show that temperature of TJSC cell is directly proportional to sun concentration ratio. For the sun concentration ratio of 300 and 1000 are 368.2K and 529K respectively. E.A. Chavez-Urbiola et al. [78] studied the feasibility of thermoelectric generators in the solar hybrid system. In this investigation, four systems were examined. They arranged PV cell, concentrator, TEG, Heat extractor in four different ways. The major finding shows that for a temperature difference of 155° K the output power of TEG is 3 W. Jin Zhang et al. [79] developed a thermal model to evaluate the performance of highly concentrated PV-TE hybrid system. The result shows that thermal design is dependent on two factors i.e., the thermal resistance between PV and TE and thermal resistance between TE and environment. Also signifies that efficiency of highly concentrated PV-TE hybrid system increases with the decrease of PV area. Dianhong Li et al.[80] proposed a 1D model for PV-TE analysis based on basic thermodynamic laws. Energy and exergy analysis was carried out on the solar cell and thermoelectric module. The calculation result shows that high concentration ratio and suitable PV cell used in the PV-TE hybrid system can increase the system output efficiency. Wei Zhu et al. [81], [82] developed a PV-TEG hybrid system and also they use SSA to enhance solar radiation .the hybrid system is placed in the enclosure to reduce the convection losses.

Table 4: Summary of PV-TEG System

Reference	Type of PV module	Method of TEG coupling	Type of work	Operating conditions		TEG properties			System performance	Remarks
				Irradiance (W/m^2)	Operating temperature (°C)	Material	Temperat-ure difference between hot & cold (°C)	Figure of merit (ZT)		
Shohreh soltani et al.[20]	Poly crystalline	Rear side flat plate PV	Experimental	500-1000	25	Bi_2Te_3	90	0.0085	SiO_2 improved power production by 0.971%. The cooling method mainly affect TE	Integration of PV with TE cooled by nanofluids could be used as power pro-

									performance Indirectly affects PV performance	duction.
Yuan deng et al.[81]	DSSC	Back side of PV	Numerical simulation	1000	25	Ceram-ic	27	-	The output performance of HGS de-pends on connection. Coupling of TEG en-hanced V_{oc} & I_{sc} from 0.3 to 0.86V and 0.024 to 0.07A	It is a best suitable technique for solar energy utilization with an improve-ment of thermoelec-tric device
R.Bjork et al.[18]	c-Si,a-Si,CIGS,CdTe	Rear side of PV	Analytical	1000	25	Bi_2Te_3	25	0.001	TEG produces a significant amount of power. Pv output can be increased by increasing concentration. Direct cou-pling will not always pro-duce a benefi-cial result.	Direct cou-pling is not a viable option for power production.
Sark [90]	Multi crys-talline	Rear side flat plate PV	Theoretical	1000	80	Bi_2Te_3	27	0.004	Electrical efficiency-14.03% TEG efficien-cy – 5% Overall effi-ciency 35%	Compare to PV.PV+TEG performance increased by 24.9% and 18.6% for Malaga and Utrecht cities in spain
Cotfas et al.[91]	Mono-crystalline	Rear side flat plate PV	Simulation (LABVIEW)	920	32.5	Bi_2Te_3	5.9	2.4	Power gain is 7% TEG gener-ate3.4mW Overall effi-ciency 16.71%	Fill factor of PV is 73.46
Ju et al.[86]	GaAs	Spectrum splitter projects to TEG	Numerical	1300	77	$CoSb_3$	85	1.4	TEG contrib-utes 10% in power output and 2% in efficiency	Optimized wavelength and heat transfer coefficient are specified
Kossyv-akis et al.[17]	Poly-crystalline	Connect-ed back side alumi-num absorber of PV	Experimenta-tion	1000	25-86	Bi_2Te_3	20	1	TEG gain 22.5% output and 2.26W Overall effi-ciency 33-40%	TEG module can be cooled by 1.6mm long length effec-tively
Li et al.[77]	Poly-crystalline	Back side of the micro-channel heat pipe	Numerical	100-1000	25	Bi_2Te_3	40	1	The electrical efficiency of TEG is below 3% Overall effi-ciency is 11.3%	System efficiency depends on wind veloci-ty and ambi-ent tempera-ture
Attivisi-mo et al.[92]	Poly crystal-line	PV back side with ceramic plate absorber	Simulation (MATLAB)	100-500	28	Bi_2Te_3	150	Less than 0.7	TEG contrib-utes 13.81% in total energy Overall effi-ciency 45-70%	TEG module posses addi-tional energy of 6.5-12.2%
Xing ju et al.[86]	GaAs	Spectrum splitting	Numerical	1300	227	$CoSb_3$	527	1.4	Maximum output power is achieved at 850-900 nm wavelength An output power of TEG decreases with	Spectrum splitting PV-TE hybrid system has a potential advantage over PV only system

	increase in wavelength

Introduction of copper plate served as a thermal concentrator and conductor guarantees a large temperature difference. The developed hybrid system achieves a peak efficiency of 23% which is 25% more than PV alone. Jin Zhang et al. [79] developed a theoretical model for evaluation of the efficiency of PV-TE direct hybrid system. A detailed analysis is carried out to study the influence of temperature on PV efficiency. Hybrid systems with four different photovoltaic cells are studied. The results show that polymer PV cell performed better for concentrating hybrid PV-TE system. Ershuai Yin et al. [66] [80] introduces thermal resistance theory in theoretical modeling of PV-TE hybrid system. This theory used to optimize the coupled system in terms of optical total conversion efficiency. Four types of PV cells with three types of cooling methods were investigated. Results indicate that for the concentrated hybrid system, amorphous silicon PV cell and polymer PV cell are superior. [66] Yusop et al. [83] and Yi-Hua Liu et al. [84]carried out MPPT analysis on hybrid system.

2.3.2. Indirect contact type PV-TEG system

K.P. Sibin et al. [85] designed and developed IAI multilayer spectrum beam splitter coating for PV-TE hybrid system. Whereas Xing Ju et al. [83-84] carried out numerical analysis and optimized spectrum splitting concentration PV-TE hybrid system. Yuanpei Xu et al. [88] proposed a novel ultra-broadband photon management for PV-TE hybrid system. Finite difference time domain method was used to investigate the optical behavior of structure in ultra-broadband(300-2500nm).numerical computation shows that high absorption in the solar cell can be obtained by in cooperation of antireflection and light trapping. M. Hajji et al. [89] proposed a novel hybrid system of indirect coupling of PV-TE. In this system, a setup is closed in an insulated chamber to reduce heat losses. When the solar radiation is imparted on PV module, due to its conversion capacity it converts some part of solar energy into electricity whereas remaining are transmitted through PV module. This transmitted energy is gets concentrated on the hot side of TEG module through the optical concentrator. And subsequently, another side of TEG is cooled. By producing a Seebeck effect electrical energy is generated. Tengfei Cui et al.[80] performed the experiment indirectly coupled PV-TE system. In this setup, they introduced PCM material between PV and TE. Investigated results show that comparing PV system, higher energy conversion efficiency can be obtained.

3. Discussions

A significant work is carried out in PV-TE system in the last two decades. The early work includes direct coupling of PV-TE systems. As demonstrated by R.Bjork et al. [16], the direct coupling of PV-TE systems is not viable all the time. For higher productivity of the TE systems, an indirect coupling of PV-TE is suggested by some latest studies. The key features of latest studies of PV-TE systems have been discussed in the subsequent text.

3.1. Developments & status of indirect type PV-TE system

Indirect coupling includes the photon management [88] [93 – 95], spectrum splitting before concentration [65] [75], light trapping [97], nano-structured thermoelectric [98], changing concentrator before PV [99] [100], spacing between PV and TE i.e., indirect coupling[89].Also, some researchers are focused on PV-TE hybrid system with and without glass cover. [101]
Photon management can be achieved by grouping the wavelength. In the range of 300-700nm i.e, shorter wavelength, photon absorption can be improved by using a composite surface structure having an effective refractive index. The absorption of larger wavelength (700-1100nm) can be improved by a plasmonic back reflector and metallic gratings on the back side. Different types of thin film PV device used in the hybrid system can also be beneficial by these photon management methods.
Spectrum splitting before concentration involves separation of solar radiation which is not in the range of solar cells band gap can be supplied to TEG so that due to thermoelectric effect electricity can be produced and overall efficiency of solar energy conversion can be increased.
Ying-Ying Wu et al. [101] generates thermal and electrical model to analyze the PV-TE hybrid system with and without glass cover. Main observation from the study is that Larger Z values are not always desirable for hybrid PV-TE system.

3.2. Key features of PV-TE indirect systems

The hybrid system i.e., PV module with thermoelectric generator provides additional energy 5-10% depending on TEG material, connection, combination. [52]. In space, the electric cogeneration carried out by TEG but there it is termed as radioisotope thermoelectric generators (RTGs). But this requires more temperature difference. Hybrid PV-TEG system is the most developing phenomenon compared to other hybrid technology related to PV. Fig 6 shows the indirectly coupled PV-TE system. Most of the authors are treating TEG as a PV cooling technique. [1] [10] [102-106].

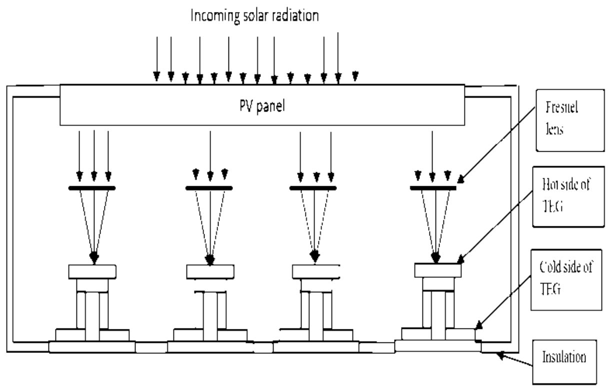

Fig. 6: PV-TE Indirect Coupled PV-TE System.

3.3. Advantages of PV-TE system

1) The power produced by the hybrid system is considerably greater than standalone PV system.
2) Energy generated per unit area will be higher than standalone PV system.
3) It does not increase the size of the module.
4) Both flat and concentrated hybrid systems are suitable for rooftop application and bulk power application

3.4. Disadvantages of the PV-TE system

1) PV-TE systems are difficult to design and coupling.
2) TEG has less efficiency and payback period.
3) As the manufacturing materials of TEG is expensive, the cost per unit electric power generated for TEG modules is high

4. Future scope & conclusions

Design of PV-TE still in research stage to enhance the power generation capacity. Manufacturing of TEG is not economical so that initial cost is very high. Research work is going on for suitable MPPT because PV power depends on voltage whereas TEG power depends on current. The hybrid system PV-TE are having a tremendous scope of research to increase overall performance, some of the future scope areas are specified.

A power output of hybrid PV-TE system depends on a material of PV cell and the spacing between PV and TE. So that to get maximum power output from the hybrid system, optimum spacing between TE and PV needs to be developed. It must ensure that the temperature drop between PV and hot side of TEG is minimum. It results in maximum power output from hybrid PV-TEG system.

Solar cells mounted on a plain glass substrate having a certain transmittance rate. This transmittance rate can be improved by a chemical etching method. So that total radiation falling of solar module can be utilized. A chemical solution used for etching must have high transmittance so that it can allow desired radiations.

The PCM material can be used in hybrid PV-TEG system. It can be used anywhere in the system. But the most suitable arrangement is PV-PCM-TE. By employing PCM material in between PV and TE, excess heat energy can be utilized to heat the hot side of TEG material. So that during a complete day hybrid system can work. In night time, PCM will release heat energy that can be useful for heating of hot side of TE.

TEG material must have both high electrical conductivity and low thermal conductivity. Most commonly bismuth telluride (Bi_2Te_3), lead telluride (PbTe), and silicon germanium (SiGe) are used. But these materials are very expensive because they contain rare elements. Today, the thermal conductivity of TEG materials can be lowered without affecting electrical properties by using nanotechnology. Better MPPT algorithm has to be developed for hybrid PV-TE system. It can easily track MPP from both PV and TE with a single algorithm, up till now fuzzy logic, hill climbing, controller and lock mechanism algorithm used in the simulation.

In this paper, different PV module temperature management systems are presented. The overall efficiency of PV-TE system depends on natural and design parameters. The natural parameters are solar radiation intensity, ambient temperature, wind velocity, and tilt angle which affects the overall efficiency by 10%. The additional design parameter is spacing between the module and concentrator and also the spacing between the concentrator and hot side of TEG. TEG parameter such as location, properties, integration type and thermal resistance between the absorber plate and TEG junction decides the power output. PV-TE system generated additional 10-20% energy with the increase in overall efficiency of 40-50%. The PV-TE system with PCM improves the overall efficiency by 1-2%.

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