Chapter 14
Power Extraction from Several Interconnecting Solar PV Networks for an Electrically Integrated TEG System Under Weather Fluctuation

Sasmita Jena, Sambit Tripathy, Keshav Krishna, and Sanjeeb Kumar Kar

Abstract With the extensive demand for energy harvesting systems from various renewable resources, researches have been carried out in several areas among which thermoelectric generator (TEG)-based system is an emerging one. In this paper, eight solar PV modules are interconnected in numerous fashions in order to investigate the behavior of the hybrid system. The transiency of the solar PV modules inside the network has been examined under healthy irradiance and sectional irradiance. Rise in solar concentration tends to decrease the solar PV module efficiency, and this curse to solar PV becomes the boon to the TEG giving rise to higher power output at the terminals. Incorporation of solar photovoltaic (SPV) and thermoelectric (TE), termed as Solar photovoltaic-thermoelectric (SPV-TE) hybrid system is found be a very promising technique to broadening the utilization of solar spectrum and enhancing the power output effectively-cum-efficiently. This hybrid architecture caters electrical energy with additional thermal energy that signifies upon harnessing of solar insolation in an exceptional way.

Keywords Hybrid system (SPV+TEG) · Thermoelectric generator · Operating temperature · PV networking · Power generation

1 Introduction

Lower quantum efficiency is found to be a major demerit of solar photovoltaic cells in these days. Though only a smaller portion of incident radiation is converted into electricity directly, efficiency is found to be a crucial factor to be improved, so that the popularity will be gained for solar photovoltaic cells [1, 2]. Further the non-convertible radiations will heat the panels that reduce the efficiency. Hence, at present, cooling systems have been integrated, so that the temperature could be decreased to a greater extent and enhancing efficiency of the solar panels. Therefore, realization

S. Jena (✉) · S. Tripathy · K. Krishna · S. K. Kar
Department of Electrical Engineering ITER, Siksha O Anusandhan Deemed To Be University, Bhubaneswar, Odisha, India
e-mail: sasmita.jena500@gmail.com

S. Mahapatra et al. (eds.), *Advances in Energy Technology*, Advances in Sustainability Science and Technology, https://doi.org/10.1007/978-981-15-8700-9_14

of photovoltaic-thermoelectric systems comes into picture [3]. Direct conversion of sun light into electrical energy is an effective-cum-efficient way in this renewable era. Furthermore, some significant part has been absorbed as heat; to get rid of this some of the heat recovery system has been proposed in combination of conventional solar photovoltaic cells. Thus, TEG has come into picture, so that the non-convertible radiation which is dissipated as heat can be further converted to electrical energy. Researches have been going on such hybrid system for gaining popularity upon the renewable-based generation system [4]. The concept of solar energy spectrum energy utilization by a solar PV-thermoelectric module and finding of an optimized geometry for SPV-TE based hybrid systems has been outlined. Current SPV-TE module-based hybrid systems are mostly based upon dye-sensitized solar cells(DSSC), a Si-based solar cells for the solar PV part while Bi–Te modules for the thermoelectric part. Also maximum power point tracking plays a vital role in all solar PV based systems. Such combination-based systems are generally relying upon absorption of light spectrum by solar cells and secondly on the optimum operating temperature of the TE modules [5]. Many researchers are also working upon Perovskite solar cells which are found to be reasonable choice for SPV-TEG based hybrid system. It has been found that the temperature coefficient of the Perovskite solar cells is lower than 2%, and this is found to be advantageous for Perovskite solar cells-TE based systems. There is nearly about 1% difference in Perovskite solar cell-TE based system (18.8%) and only Perovskite solar cells (17.9%). Also by altering the thermal concentration, the volume of thermoelectric material can be lowered, and at the same time, cost will be cut off remarkably. For analyzing such influence of thermal concentration upon the desired hybrid system, a 3D numerical model has been also developed [6].

In this paper, the solar PV modules are connected in parallel in order to form an array which is helpful in system requiring higher amount of power. In this paper, eight modules are connected in several manners in order to analyze and predict the system performance. The array thus formed by the SPV modules is connected with TEG in order to produce power. Solar panels receive solar irradiance to generate power which can be termed as conversion of light energy into electrical energy. But the demerit lies upon the heat lost at the panel surface which causes rise in surface temperature. This in turn declines the solar PV performance at a greater rate, and panel suffers from lower quantum efficiency. Thus, the TEGs use this lost heat and converts this heat energy into electricity. Hence, the power generated using solar irradiance and power generated by using the excess heat of panel gives a significant output at the solar panel terminals. This system also aims to provide another perspective of understanding the volatility of SPV-TEG hybrid module under partly cloudy conditions. The system is tested for single SPV module integrated with TEG and then tested upon five different types of SPV networking structure with integrated TEG. The entire study has been carried out using eight solar PV modules with networking namely:

- Network-I
- Network-II

The entire study is subjected to be tested under two types of irradiance namely:

- Healthy irradiance (HI)
- Sectional irradiance (SI).

Though daily solar insolation which is an inevitable part of solar energy to generate power is very reliant to time, factually it has impact upon the temperature of SPV-TEG hybrid system, consequently the power generation and hence the efficiency of the system. Therefore, light has been put upon the implication of changing weather condition on the system performance and power generation. This sectional irradiance (SI) is further subdivided into two parts such as:

- 3/4th (75% shaded)
- Fully shaded (100% shaded).

The paper organization is as follows. In Sect. 2, the hybrid PV-TEG system is modeled, and hence, the theoretical approach is outlined. Sect. 3 is followed with the interconnection of solar PV panels with TEG integration. Section 4 consists of power generation from the hybrid interconnection.

2 System Modeling and Description

The modeling of thermoelectric generator (TEG) and solar PV modules (SPV) have been performed by insertion of corresponding number of modules in parallel and series as per the requirement. After being designed individually, both the systems have been combined in order to perform the study upon the hybrid system. The power generated from SPV array, i.e., conversion of light energy into electrical energy, and power generated from TEG, i.e., conversion of lost heat into electrical energy, is added in order to obtain the required power from the hybridized SPV-TEG system. Generally, inconstancy nature of weather specifically partly cloudy condition plays a vital role on the system's cohesion and hence marking critical issues like power generation, efficiency, etc. The model is described in individual subsection namely:

- Modeling of solar PV array
- Modeling of TEG

2.1 Modeling of Solar PV Array

Solar irradiation and temperature on the solar PV module surface are solely responsible for the characteristics of SPV array. As the solar irradiance upon the SPV array is increased, the power generated from SPV array is also increased. In order to construct an SPV array, number of SPV modules need to combine in particular fashion either in series or parallel to obtain the requisite power. The equivalent circuit of the solar cell is shown in Fig. 1.

The output current of the solar PV module, i.e., I_{pv}

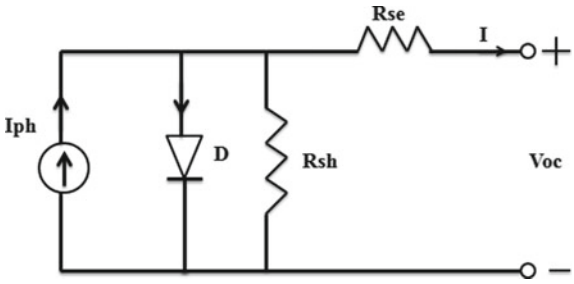


Fig. 1 Equivalent circuit of solar PV module

Table 1 Specification of solar PV module used (WAREE solar PV modules)

Parameters	Values
Maximum power voltage	17.47 V
Maximum power current	2.86 A
Maximum power	50 W
Short-circuit current (I_{sc})	3.1 A
Open circuit voltage (V_{oc})	21.57 V

$$I_{pv} = N_p * I_{ph} - N_p * I_o\left[\exp\left\{\frac{q * \left(V_{pv} + I_{pv}Rs\right)}{N_s A_{kt}}\right\} - 1\right] - I_{sh} \tag{1}$$

where k = Boltzmann's constant = $1.3805 * 10^{-5}$ J/K, A = ideality factor of the solar PV cell depend on PV manufacturing technology, and some of them are presented in Table 1, T = operating temperature of the module, $q = 1.6 * 10^{-19}$ C.

2.2 *Modeling of Thermoelectric Generator*

The working of TEG constitutes of three elementary thermoelectric effects with two accessorial effects. The three elementary effects are named as: Seebeck effect, Peltier effect, and Thomson effect, while the accessorial effect can be named as: Joule effect and Fourier effect. Seebeck effect is responsible for electromotive force (EMF); and Peltier heat, Thomson heat, and Joule heat are caused by the effect of Peltier, Thomson, and Joule, respectively. As a matter of fact, Peltier effect is not an interface effect; it produces heat only at the end sides of the semiconductors. Volumetric effects like Thomson and Joule heat production are pretended to be uniformly transferred to the cold and hot junctions of the semiconductor elements. Though Thomson effect is very small, it is often neglected in many cases.

For steady-state analysis at cold and hot junction of TEG, an energy balance equation is used which can be expressed as follows:

Mathematically'

$$Q_h = \propto * T_h * I - k_{tc}\Delta T - 0.51^2 R \tag{2}$$

$$Q_c = \propto * T_c * I - k_{tc}\Delta T + 0.5I^2 R$$

The electrical current can be expressed as follows:

$$I = \frac{\propto \Delta T}{(1+n)R} \tag{3}$$

The short-circuit current is the maximum current at a load voltage of zero, i.e., $V_L = 0$, and hence, can be written as follows:

$$I_{SC} = 2I_m = \frac{2W_m}{V_m} \tag{4}$$

Finally, the voltage of TEG can be expressed by using Ohm's Law, and the corresponding equation obtaining short-circuit current and current through TEG, i.e.,

$$V = -R(I - I_{SC}) \tag{5}$$

A model of TEM specified by TEPI-12656–0.6 has been used over here to model the hybrid system, and the behavioral analysis has been conducted. The parameter specifications of the thermoelectric module (TEM) have been listed in Table 2. The constraints that have been considered for modeling are presented in Table 3.

Table 2 Parameters for thermoelectric generator

Parameters	Values
Open circuit voltage (V)	8.8
Cold junction temperature (°C)	30
Hot junction temperature (°C)	300
Load resistance (Ω)	1.25
Load output voltage (V)	4.27
Load output power (W)	15
Load output current (A)	3.52
Heat flow density (W/cm^2)	~ 12
Heat flow across the module (W)	~ 370

Table 3 Thermal parameters specification

Parameters	Symbols	Corresponding values
Seebeck coefficient	$\propto$	0.035 V/K
Resistance	Ω	1.22
Thermal conductivity	k_{tc}	20.91 W/K
Figure of merit	Z	$0.387 * 10^{-6} K^{-1}$

3 Results and Discussion

The solar PV panel receives solar irradiation and generates electricity directly through the photovoltaic effect. Though solar panel is considered as less quantum efficient due to excess heat absorption at the surface, the heat recovered from the module surface is considered to be reused and generate power. Thence, thermoelectric generator comes into picture that effectively as well as efficiently use this lost heat and produce electricity. The solar PV modules and the TEG combined deliver substantial amount of power. This makes the solar PV modules much more efficient-cum-effective. The system is tested under two types of irradiance namely:

- Healthy irradiance (HI)
- Sectional irradiance (SI)

The HI shows the system receiving sunlight at standard testing condition (STC), i.e., at 1000 W/m^2, and the modules receiving solar irradiance generate power, and subsequently the heat absorbed by the modules is further reused by the TEG that are connected in parallel. The system is tested for only solar PV based, only TEG based, and both SPV-TEG based sources in order to verify the results. All the connections have been subjected to be tested under sectional irradiance (partly cloudy condition). The following types of sectional irradiance (SI) are considered over here. (Figs. 2 and 3).

- 3/4th (50% shaded) and
- Fully shaded (100% shaded).

3.1 Type-I Network: Table 4

Healthy irradiance (HI) means system performance during non-shading condition. During the experiment, the irradiance varies from 900–1000 W/m^2; that is why the theoretical analysis is also done at 1000 W/m^2 in MATLAB/Simulink. The power obtained from hybrid SPV and TEG system is much significant than that of only SPV based or only TEG based system which can be seen in Fig. 4. The result for every subconditions of SI is shown in Figs. 5, 6, 7, 8. It can be interpreted from the graph that every time shading occurs, power is decreasing gradually. It can also be seen that the power obtained from SPV and TEG based hybrid system is always

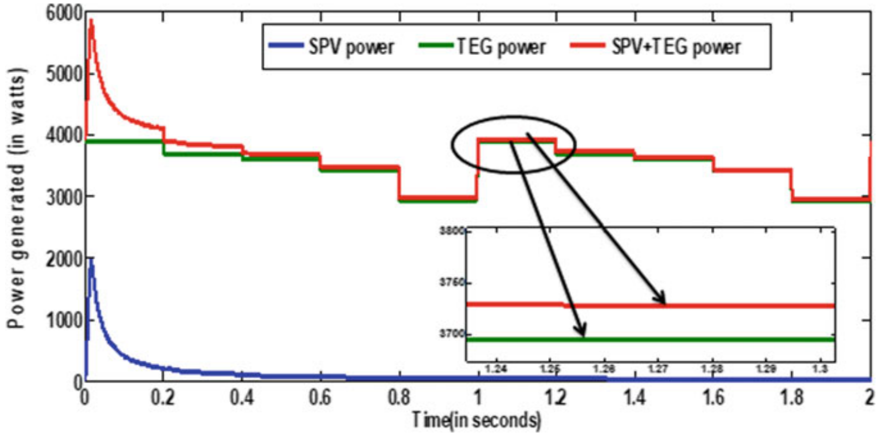


Fig. 2 Power obtained using Type-I network at healthy irradiance (HI)

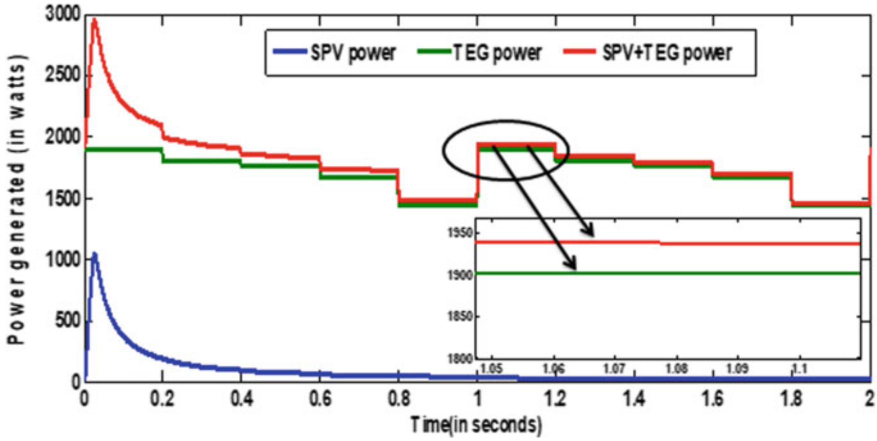


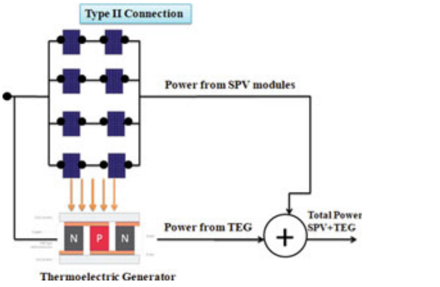
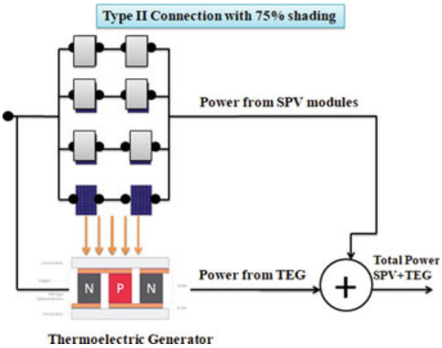
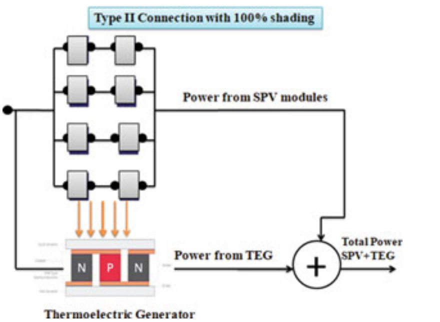
Fig. 3 Power obtained due to sectional irradiance (SI)-3/4th of shading

very significant than that of only SPV based system and only TEG based system, no matter what type of shading occurs.

3.2 Type-II Network: Table 5

The connection diagrams have been shown with values that are obtained experimentally and theoretically that can be seen in Table 5. The modeling has done by using MATLAB/Simulink, and the experiment has been carried out at the rooftop of ITER, Siksha O Anusandhan (Deemed to be university).

Table 4 Type 1 network

Type of connection	Connection diagram	Output values obtained	
		Experimental	Theoretical
At healthy irradiance (non-shading condition)		1. Only SPV 20.54 W 2. Only TEG 3881 W 3. SPV + TEG 3901.4 W	1. Only SPV 20.72 W 2. OnlyTEG 3886 W 3. SPV + TEG 3907 W
		Experimental	Theoretical
At sectional irradiance 3/4th section (75% shading)		1.Only SPV 18.85 W 2. Only TEG 1897.57 W 3.SPV + TEG 1916.42 W	1. Only SPV 19.15 W 2. OnlyTEG 1902 W 3. SPV + TEG 21921W
		Experimental	Theoretical
At sectional irradiance Whole section (100% shaded)		1. Only SPV 17.77 W 2. Only TEG 1556.77 W 3. SPV + TEG 1574.54 W	1. Only SPV 18.32 W 2. Only TEG 1571 W 3. SPV + TEG 1590 W

It can be interpreted from the graph that every time shading occurs, power is decreasing gradually. It can also be seen that the power obtained from SPV and TEG based hybrid system is always very significant than that of only SPV based system and only TEG based system, no matter what type of shading occurs. It can also be outlined that the TEGs work according to the sun light incident on the SPV modules. During HI, the solar irradiance has incident on panel that in turn raising the temperature of the SPV module surface, and hence, yields a significant amount

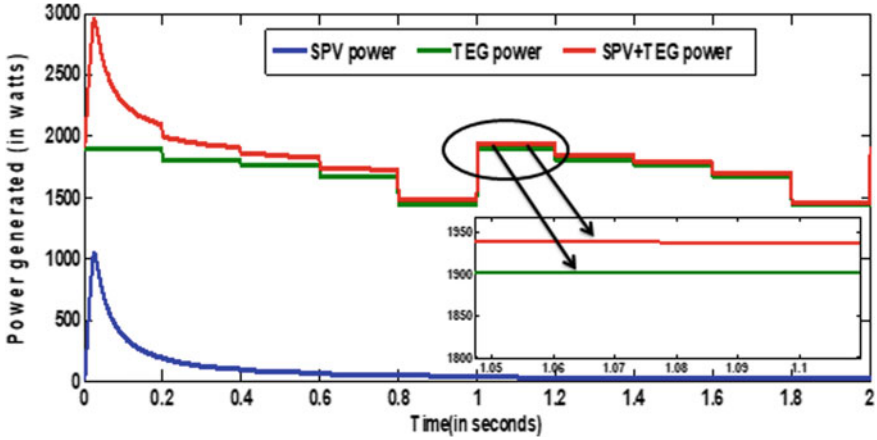


Fig. 4 Power obtained due to sectional irradiance (SI) 100% of shading

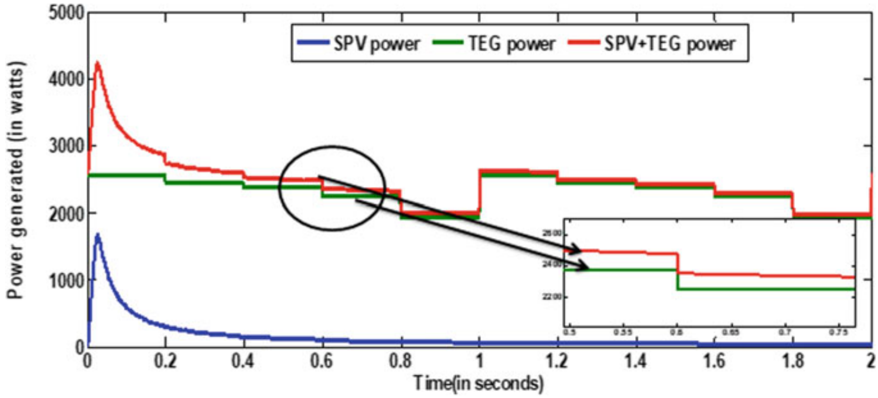


Fig. 5 Power obtained using Type-II network at healthy irradiance (HI)

of power from the hybrid system such as for Network = 4212 W (4.212 Kw) and Network-IV = 4010 W (4.010 Kw), respectively. However, during SI, the solar irradiation became lesser than that of HI; this leads to lesser power generation from TEG and consequently from hybrid SPV + TEG. Because lesser is the irradiance, lesser heat will be absorbed and lesser will be the power generation.

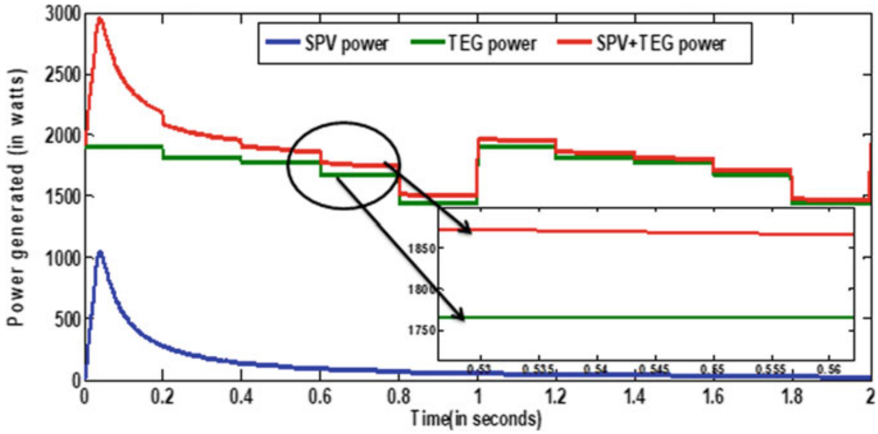


Fig. 6 Power obtained due to sectional irradiance (SI)-3/4th of shading

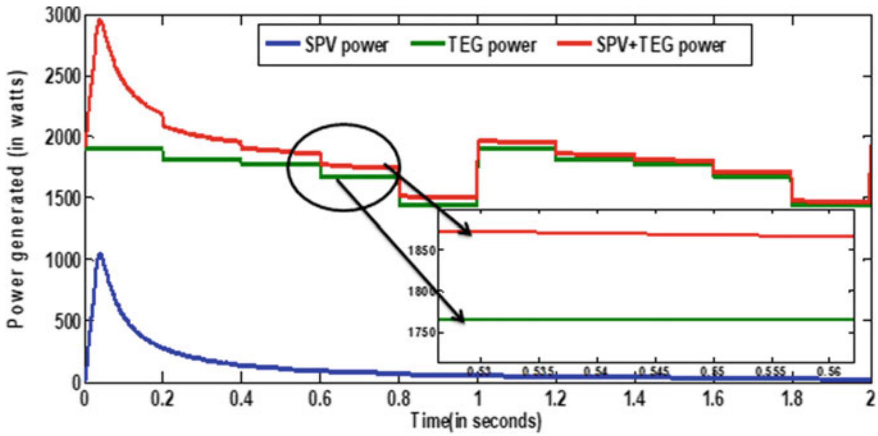


Fig. 7 Power obtained due to sectional irradiance (SI) 100% of shading

4 Experimental Setup for the Proposed Solar PV Networks

The experimental was carried out at the rooftop of ITER, Siksha O Anusandhan (Deemed to be University), Bhubaneswar, India. Eight PV modules are interconnected under earlier mentioned networking structures namely Network-I and Network-II. All the modules are interconnected as per the connection diagram given in Tables 4 and 5. The experiment was carried out under HI and SI. Under HI, the irradiance was found to be varied in between 850–950 W/m^2. The experiment has been conducted in April though in summer, the irradiance received by the solar PV module is higher consequently rising the surface temperature. This in turn lowers the module efficiency. To overcome this lowering of quantum efficiency, the TEG

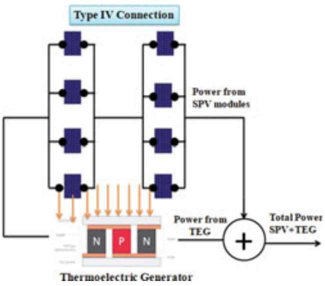
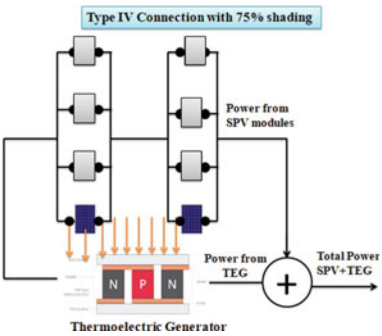
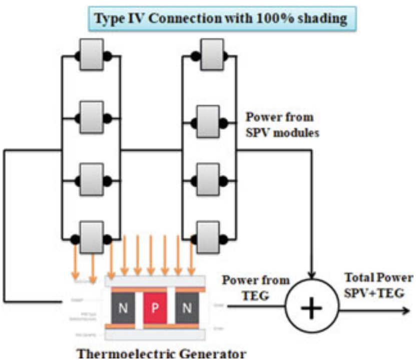
Fig. 8 Field setup for proposed solar PV network at the rooftop

is connected in order to use the higher temperature and generate power. The power obtained at the output terminals will be the combination of power generated from solar PV module using photovoltaic effect and power generated from TEG using thermoelectric effect.

5 Conclusion

Thermoelectric generator is integrated with solar PV system in order to process the lost heat by thermoelectric effect. The conversion of light energy into electricity by photoelectric effect and converting heat into electricity by thermoelectric effect combined generate significant amount of power from solar PV array**.** During HI, the power generated is much higher than that of SI conditions. Because the irradiance thud incident on the modules during HI is higher that tends to excessive heat absorption at the junction of TEG. The experimental and theoretical evaluation has been conducted in order to verify the output power for only SPV based system, only TEG based system, and hybrid SPV-TEG based system. This study clearly states that the power during hybridization is much significant as compared to other two. The augmentation of the solar concentration decreases the SPV module efficiency and this in turn helpful for TEG for increasing its efficiency. This concept has been validated in this study. Employment of hybrid SPV-TEG based system delivers steady power for varying weather condition than only SPV/only TEG. Elementary understanding of overall output performance of the studied system has been made by consideration of thermoelectric effect and can be implemented in the places where rapid fluctuation of solar insolation and partly cloudy conditions degrades the solar PV array output with procurement of stability.

Table 5 Type 2 network

Type of connection	Connection diagram	Output values obtained	
		Experimental	Theoretical
At healthy irradiance (Non-shading condition)		1. Only SPV 29.98 W 2. Only TEG 3881 W 3. SPV + TEG 3911.98 W	1. Only SPV 31.06 W 2.OnlyTEG 3886 W 3. SPV + TEG 3917 W
		Experimental	Theoretical
At sectional irradiance 3/4th section (75% shading)		1. Only SPV 26.89 W 2. Only TEG 1897.57 W 3. SPV + TEG 1924.46 W	1. Only SPV 28.67 W 2. Only TEG 1902 W 3. SPV + TEG 21931 W
		Experimental	Theoretical
At sectional irradiance Whole section (100% shaded)		1. Only SPV 25.45 W 2. Only TEG 1556.77 W 3. SPV + TEG 1582.22 W	1. Only SPV 27.46 W 2. OnlyTEG 1571 W 3. SPV + TEG 1599 W

References

1. Jena S, Kar SK (2019) Setting a fostered energy network by decarbonizing the grid: hybridization, control, and future solutions upon storage. Int J Energy Res 43(1):455–474
2. Jena S, Kar SK Demonstrating the benefits of thermoelectric-coupled solar PV system in microgrid challenging conventional integration issues of renewable resources. Int J Energy Res
3. Jena S, Kar SK (2019) Employment of solar photovoltaic-thermoelectric generator-based hybrid system for efficient operation of hybrid nonconventional distribution generator. Int J Energy Res

4. Jena S, Kar SK, Satpathy PR Encapsulating the challenges of storage in solar PV based microgrid. ISBN: 978–3–659–35285–0
5. Senthilkumar J, Charles Raja S, Srinivasan D, Venkatesh P (2018) Hybrid renewable energy-based distribution system for seasonal load variations. Int J Energy Res 42(3):1066–1087
6. Wu YY, Wu SY, Xiao L (2015) Performance analysis of photovoltaic–thermoelectric hybrid system with and without glass cover. Energy Convers Manage 93:151–159