Sustainable Energy Technologies and Assessments 43 (2021) 100932

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Original article

Economic analysis of hybrid Photovoltaic Thermal Configurations: A comparative study

Challa Babu, P. Ponnambalam [*]

Siddartha Institute of Science and Technology, Puttur, Andhra Pradesh, India
School of Electrical Engineering, VIT, Vellore, Tamilnadu, India

ARTICLE INFO

Keywords:
Hybrid Photovoltaic Thermal configurations
Economic aspects
Levelized Cost of Energy
Cost analysis

ABSTRACT

The research focus immersed on the renewable power generation is moving more expeditiously than the conventional power generation schemes. Additionally, apart from all other hybrid systems, Photovoltaic Thermal Systems (PTS) possesses the unique advantage of utilizing the maximum incident solar energy emanating from the radiant sun. Ordinarily, various PTS configurations implement different thermal extraction and heat utilization methods. This exhaustive work majorly concentrates on the flat plate PTS configuration commercialization concepts. Nevertheless, the current research scenario for each specific configuration, such as liquid type PTS, air type PTS, Phase Change Materials (PCM) based PTS, Thermoelectric Generator (TEG) integrated PTS, and other hybrid configurations are withal discussed. In the commercialization aspect, the specific major constrain is economic considerations. However, there is a lack of literature studies on the financial issues of various PTS configurations. The main objective of the proposed work is to develop a theoretical economic model for the hybrid PTS configurations with a single reference frame. Therefore, this notable work considers the Levelized Cost of Energy (LCOE) for calculation of economics involved in the different PTS configurations and it compares with the standard PV model. Furthermore, theoretical results show that the LCOE of TEG based PTS configuration has exceptionally 8.71% higher LCOE than the standalone PV system, similarly for liquid, air, PCM and Nanofluid based arrangements is 43.5%, 24.24%, 28.40%, and 28.40% higher than the standalone PV systems.

Introduction

In recent times the power generated by renewable sources has incremented expeditiously. As a matter of fact, in renewable sources, solar power contribution is so high when compared with other sources. The sun is the most immensely colossal source of energy engenderment than any other renewable source. However, the amount of energy coming from solar radiation has not been completely converted into an effective form of energy. Therefore, there are many pieces of research on maximum energy tracking, extraction, and generation. The Photovoltaic (PV) panels engender electrical power by utilizing the light energy of the solar radiation but withal absorb the thermal energy, so it makes panel sultry. Consequently, this heat energy causes 0.5%/°C electrical efficiency loss per every degree temperature increment after 25 °C [1]. There is a great desideratum for abnegating the heat in the module to amend the electrical efficiency of the PV panel, i.e., cooling. Here, the term cooling refers to the reduction of PV panel temperature with the coolants.

The Photovoltaic Thermal System (PTS) configurations come with the principle of PV cooling, and it utilizes the repudiated heat for thermal applications like a domestic water heater, space heating, water distillation, etc. [2]. Notably, the PTS configurations are simple designs to extracts the heat energy from the PV panel, and it avails to truncate the temperature of the PV module. The complete analysis in this work is circumscribed to flat plate configurations because of its feasibility for the rooftop systems. Moreover, the performance of various PTS configurations is presented in the review [3] and research article [4]. But only liquid PTS configurations have emerged as a commercial product having the manufactures of Solimpeks, Turkey [5], DualSun, France [6], energy-xprt, USA [7]. The advantage of PTS configurations is that it engenders more energy than the stand-alone PV systems [8]. The proven results show the PTS configurations develop more energy than the PV system [9] but a simple question is “why many of the hybrid Photovoltaic Thermal configurations has it not emerged as a reliable commercial product?” till date. To find the solution to this question,

---

* Corresponding author.
E-mail address: ponnambalam.p@vit.ac.in (P. Ponnambalam).

https://doi.org/10.1016/j.seta.2020.100932
Received 22 June 2020; Received in revised form 8 November 2020; Accepted 20 November 2020

Nomenclature

a-Si	amorphous Silicon
BOS	Balance of System
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
COP	Coefficient of Performance
c-Si	crystalline Silicon
CSP	Concentrated Solar Power
DSSC	Dye-Sensitized Solar Cell
GaAs	Gallium Arsenide
LCE	Life Cycle Analysis
LCOE	Levelized Cost of Energy
NOCT	Nominal Operating Cell Temperature
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
PCM	Phase Change Material
PCM	Phase Change Materials
PTS	Photovoltaic Thermal System
PV	Photovoltaic
TEG	Thermoelectric Generator

Parameters

d	depreciation rate (%)
E_t	Energy generated (kWh/year)
G	Solar Irradiation (W/m^2)
I_0	Investment cost ($/kW)
M_t	Maintenance cost ($/kW/year)
O_t	Operational cost ($/kW/year)
r	rate of discount (%)
T	lifetime of the project (years)
T_a	Ambient temperature (°C)
T_m	Module temperature (°C)
W	Wind velocity (m/s)

subsisting literature and theoretical methods are utilized for various PTS configurations.

The PTS configurations performance is analyzed concerning the transmutation of different design parameters such as glazing [10], reflectors [11], PV silicon wafer type [12], absorber plate [13], flow type [14], single-pass/dual-pass [15], by considering the input changes, i.e., solar irradiation, ambient temperature and wind velocity of the location. Furthermore, the performance measures for assessing the PTS configurations are net efficiency, Coefficient of Performance (COP), and Life Cycle Analysis (LCA) [16]. Major researchers are concentrating on the performance amendments by making incipient design configuration along with the heat pipes, microchannel, concentrators, and reflectors. But there's some lack within the economic analysis for several design configurations [17]. In this article, the financial report of significant design configurations of the photovoltaic thermal system by utilizing the benchmark economic tool Levelized Cost of Energy (LCOE) is highlighted.

In the literature, authors [18] formulated a mathematical model to calculate LCOE of PV and Concentrated Solar Power (CSP) systems individually, and it shows that CSP power generation is not economical as the PV power generation in 2030. In the same way, the authors [19] developed an economic model of PV/T configuration utilizing the Life cycle cost (LCC) computation by considering the necessary expenses of the system. Nevertheless, this method didn't provide a clear economic projection than the LCOE. The authors [20] performed a dynamic simulation of PTS configuration for heating the swimming pool; the cost functions are considered for separate systems of PTS to calculate the tariff. Consequently, the results show that the economic feasibility for PTS configuration for indoor and outdoor swimming pool models has to improve by adopting the thermal feed-in tariffs.

The authors [21] produced the LCOE analysis of individual PV (20 MW), CSP (30 MW), and hybrid PV-CSP (50 MW) plants with fifteen hours of thermal storage systems by simulating up to 2050 for the Atacama Desert, in Chile's climatic conditions. Consequently, the LCOE simulation results for PV, CSP, and hybrid PV-CSP plants by considering the blue map scenarios 2014 to 2050 are 12.88 & 8.43 cUS$/kWh, 15.29 & 9.02 cUS$/kWh, and 14.69 & 8.57 cUS$/kWh respectively. Comparatively, the LCOE simulation results for PV, CSP, and hybrid PV-CSP plants by considering road map scenarios 2014 to 2050 are 10.74 & 7.79 cUS$/kWh, 14.93 & 7.57 cUS$/kWh and 13.88 & 7.74 cUS$/kWh respectively. The authors [22] have carried out the preliminary economic Analysis of Thermoelectric Generator (TEG) integrated microchannel PTS configuration, and the outcomes highlight the concerning energy and economics payback period. The authors [23] considered the LCOE analysis of various PV material plants, and the results show that the Heterojunction with Intrinsic Thin-layer (HIT) has the lower LCOE of 0.15$/kWh when compared with other five different PV configurations. In the same way, authors [24] made the economic analysis by utilizing analysis of variance (ANOVA one way) tool for the PV system by considering cooling consequences, and the outcomes show, that the heat exchange PV system is having more economic feasibility than the sprinkle cooling PV system.

The authors [25] have done the LCC analysis for a building integrated PTS configuration with two varied approaches in designs, which are i) Individual PV and Individual Solar Thermal (ST) and ii) Liquid type PTS configuration. Comparatively, the cash payback time for a liquid type PTS configuration is 0.72% lower than the individual PV and ST systems.

The authors [26] presented the LCOE analysis of microporous TEG integrated PTS configuration, and the results show that the microporous TEG minimizes up to 13.89% of the regular TEG cost. The author [27] produced an LCOE analysis of liquid type PTS configuration, and it's far as compared with the flat PV and solar thermal system. Notably, the result shows that the liquid type PTS configuration has more economical feasibility for rooftop power and hot water generation.

In recent instances, numerous PTS configurations had been researched that may generate/extract more energy with scarcely higher efficiency than the stand-alone PV by using water [28], air [29], Nanofluids, Phase change material [30], and Thermoelectric generator [31]. The objectives of the proposed work are considered to give direction for the commercialization of PTS configurations.

1. To check the commercial viability of PTS configurations
2. To develop a financial model for all PTS configurations for the same reference frame
3. To evolve the economic feasibility of all PTS configurations.

The above-said objectives can be achieved with a help of developing a theoretical model for different PTS configurations such as liquid type, air type, nanofluid type, PCM type, and TEG type PTS configurations with the help of literature. The economic values of each PTS configuration are considered for a single reference frame and are compared to identify the commercial feasibility of PTS configurations. In many portions of the literature, the financial Analysis of PTS configuration is attempted by amalgamating both the economic values of PV and Solar thermal. Additionally, theoretical/experimental analysis is carried out for the liquid type PTS configuration concerning LCOE and LCC. Still, newly, TEG integrated PTS, Phase Change Material (PCM) based PTS, and Nanofluid type PTS configuration gain extra attention in

Table 1
Temperature co-efficient for different PV modules [32].

Temperature coefficient parameters	Mono-Crystalline silicon (m-Si (B-C))	Copper Indium Selenide (CIS)	Heterojunction with Intrinsic Thin layer (HIT)	Multi-Crystalline silicon (mc-Si)	Amorphous silicon and microcrystalline silicon (a-Si & μc-Si)
Short circuit current temperature coefficient I_{SC} (%/°C)	0.059	0.01	0.03	0.036	0.056
Open circuit voltage temperature coefficient V_{OC} (%/°C)	−0.19	−0.30	−0.24	−0.33	−0.39
Maximum power temperature coefficient P_{Max} (%/°C)	−0.38	−0.31	−0.30	−0.47	−0.35

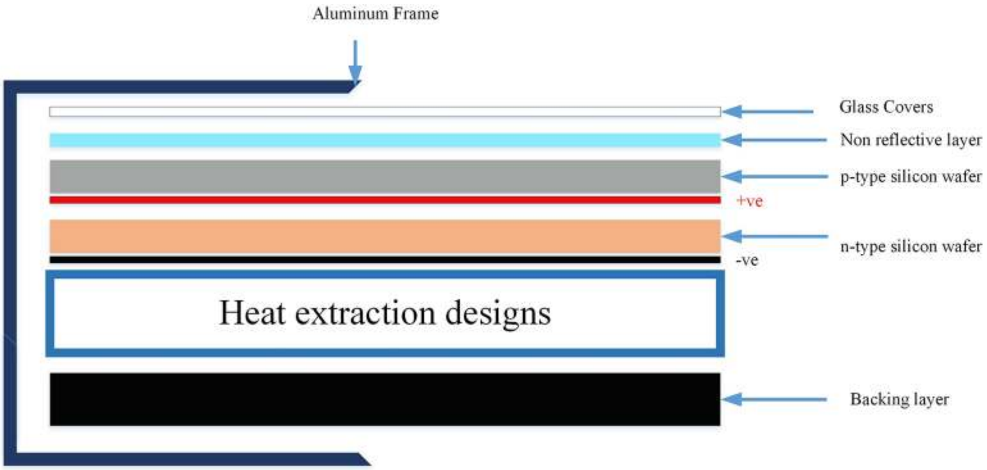

Fig. 1. PTS cross-sectional diagram [19].

the direction of the energy generation. The ratings, size, and location of all the literature studies are divergent. Hence, in this work, a posit has been made on PTS configurations that all are considered in the same location (Vellore, Tamilnadu, India) and size (5 kW) with surmised economic values. This study avails to find the economic feasibility of various PTS configurations in the direction of product development and its commercialization.

This article is prepared as, in Section 2, the essential need for PTS configurations and its types in keeping with coolant flow are offered. Section 3 describes the LCOE of various PTS configurations. The summary of the LCOE is utilizable for the production and utility sectors to develop/implement PTS configurations. Section 4 describes the current studies demanding situations in PTS configurations, and it gives direction for future researches.

Photovoltaic thermal configurations

In all the PV module datasheets, the temperature coefficient of short circuit current or open-circuit voltage and a maximum power of PV parameters are mentioned by the manufacturers. In general, variants of PV cells and their temperature coefficient parameters are shown in Table 1. Hither, the construal of a temperature coefficient is the percentage of increment or decrement in any parameter concerning the increment or decrement of temperature. Wherein, the positive sign denotes the magnitude of an increase in I_{SC} for every 1 °C increment of temperature above the 25 °C, and the negative sign betokens the amplitude of decrement in V_{OC}, P_{Max} for every 1 °C increment of temperature above the 25 °C. In all the cases, maximum power is indicated with a negative sign, and it betokens that the module power truncates with the increment in temperature above 25 °C. However, the rooftop PV modules reach around 95 °C during the summer, which leads to a reduction in power by 17.5% of its maximum potential. The temperature coefficient for different PV modules is shown in Table 1.

PV module temperature

The sun is a significant wellspring of warmth and light. Moreover, solar radiation is divided into three types and is direct, diffuse, and reflect (albedo) radiation. In detail, the direct radiation hits the solar panel surface, the PV semiconducting materials convert the photon energy to DC power, and the PV assembly absorbs the radiated heat energy. On the positive side, this heat energy serves as the source of hybrid thermal systems. Further, Fig. 1 shows the flat plate PTS cross-sectional diagram.

Some of the parameters influencing the PV module temperature are listed below

1. The natural parameters like the ambient temperature of the location, wind velocity, and solar irradiation are the significant parameters of the solar module temperature [9].
2. The number of glass covers on the top of PV additionally affects the thermal extraction in solar radiation. The glass cover act as a primary sentinel from the external conditions, and transmits uniform energy throughout the surface of the silicon layer [33].
3. The backing layer materials withal transmute the heat energy accumulated at the backside of the PV module [8].
4. The temperature coefficient of different PV materials transmutes the magnitude of energy generated by the PV system [34].

The electrical efficiency of the system can be increased by reducing the heat in the PV panel. Notably, the PV panel temperature can be evaluated by numerous correlations. To enumerate, in one of the literature, the temperature of the PV panel can be predicted by a relationship given in Eq. (1) [35]. In the same way, another popular estimation of the heat of the module is by the Nominal Operating Cell Temperature (NOCT) of the panel, and that is provided in Eq. (2) [36].

$$T_m = 0.943T_a + 0.0195G - 1.58W + 0.3529 \quad (1)$$

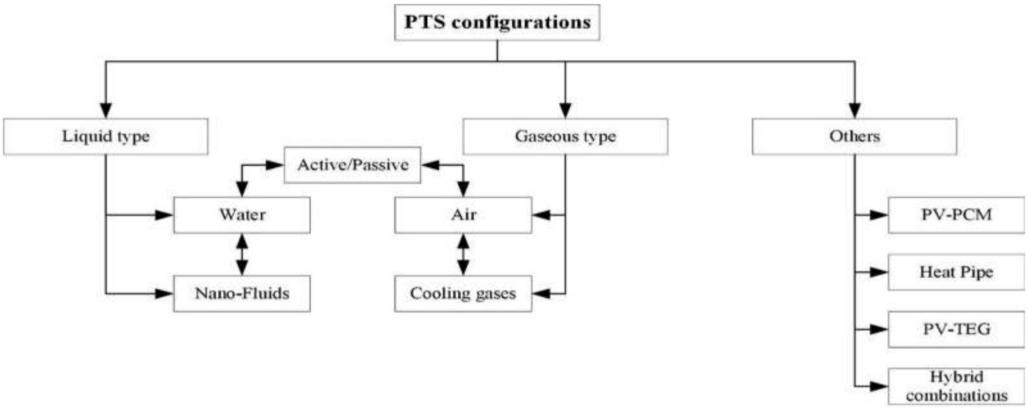

Fig. 2. Classification of PTS configurations.

Table 2
Different PTS module design parameters.

Design parameter	Available configurations	Remarks
Coolant flow	Natural/Forced	The thermosiphon model for natural liquid flow is possible. Forced air configuration needs additional setup.
Coolant type	Liquids/Gaseous	Liquids such as water, Nanofluids, and gases such as air is used in PTS systems
PV module material	Crystalline silicon (sc-Si/mc-Si), thin-films (a-Si/ CdTe, CIS, CIGS), Dye-Sensitized Solar Cell (DSSC), and organic solar cells.	The selection PV wafer depends on its electrical efficiency and cost. The commercial PV wafer efficiency at STC conditions varies from 10% to 30%.
Collector type	Flat-plate / Concentrated	Flat plate configurations generate more electrical and fewer heat energies and concentrated systems produce more heat and less electrical energy.
Covers	Glazed / Unglazed	Glazing increases the optical losses, but a proper tradeoff has to be done for selecting the optimal glazing thickness, which has a less optical loss and provides excellent protection.
Absorber plate	Aluminum/copper	Copper is a good heat absorber than aluminum.

$$T_m = (T_a + (NOCT - 20))\frac{G}{800} \tag{2}$$

where T_a is the ambient temperature in °C

G is the irradiance in W/m^2

W is the Wind velocity in m/s

The temperature difference between the cell temperature and the back surface of the module is denoted as ΔT. Moreover, the temperature for the thermally insulated surface is zero, and for the flat-plate module, open rack mounting is 2 to 3 °C at standard solar irradiation. And, for concentrating type, this quantification is between the back surfaces and the finned heat exchangers (heat sink).

Classification of PTS configurations

The PTS configurations represent the latest technology to utilize the PV panel’s unutilized temperature for different heating applications. Generally, in a PTS configuration, the heat energy is absorbed by a coolant (that flows below/above the PV panel) which minimizes the temperature of the PV panel so that the electrical efficiency of the PV panel increases [37]. Besides, the cooling process is done through conduction or convection, or radiation processes. There are several mechanisms used to lessen PV panel heat. In this context, the concerns for discussions are the PV panel heat reduction and the heat utilized by different PTS configurations. Correspondingly, Fig. 2 shows several settings developed in PTS.

The PTS modules are structured from multiple points of view by picking the correct absorber plate, coolant type, and flow type. Some of

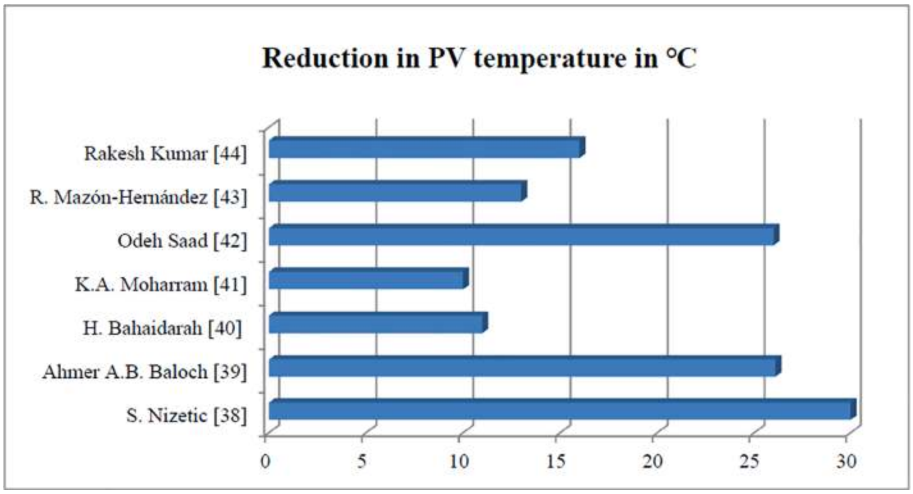

Fig. 3. Active type heat reduction of PV panel (See references mentioned above for further information).

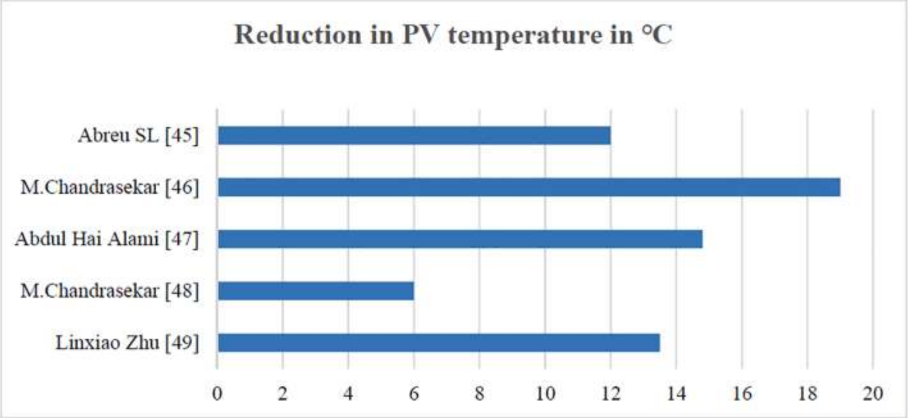

Fig. 4. The passive type heat reduction of PV panel (See references mentioned above for further information).

the design parameters considered for the design of PTS modules are listed in Table 2.

The different design parameters in PTS configurations influence the module temperature. In this article, coolant flow is taken as the parameter for classification to introduce various PTS configurations in the sub-sections. In particular, the active and passive types of PTS reduces the module temperature by changing the design parameters like flow rate to single-pass or dual-pass.

Active methods

In the active PTS, external pumping force is used to make the coolants to flow in the rear side of PV. Moreover, in the active type, majorly air and Nanofluids are used as coolant. In particular, the active coolant flow methods are more suitable for the flat plate configurations rather than the concentrated because of its constructional feasibility. Altogether, the amount of heat reduction by the active systems presented in the literature is shown in Fig. 3.

Active air pass configuration

The air type coolants flow through single or dual passes to extract maximum heat from the absorber surface. Notably, the amount of heat extraction from the active air systems is intense because of the direct coolant contact between the heating surface and the air. After all, the heated air is collected by the pressurized tank to be utilized for heating applications. In some of the active airflow systems, the fin constructions are used to enhance the heat extraction. As well as, in some of the air type PTS configurations, the heated air is directly utilized for drying purposes without any storage tank.

Active Nanofluid configuration

The nanofluid type active systems are designed with a closed-loop pipe arrangement. In the first place, the selection of this type of nanofluid configuration for the thermal extraction depends on the available heat energy. Comparatively, the nano fluid-based PTS works with maximum efficiency than any other PTS configurations because it is good in heat conductivity, convective heat transfer coefficient, and its magnetic & electrical characteristics.

Passive methods

The passive PTS are the natural coolant flow systems. The natural flow occurs through the thermosiphon principle. Currently, water is used as a passive coolant fluid for the experimental works. Albeit in recent advancements, for the natural flow systems, the nanofluid configurations are implemented. To summarize, the amount of temperature reduction by the natural flow liquid PTS is shown in Fig. 4.

Other PTS configurations

Apart from the above mentioned active and passive systems, other popular configurations are stand-alone PV with PCM, TEG, and the coalescence of both PCM & TEG. In like manner, there are, in addition, some hybrid configurations by combining the TEG, PCM, and heat pipes to the existing configurations. Albeit the direct energy conversion type, such as PV integrated TEG, PV integrated PCM are active research areas in the current scenario. Nevertheless, the other configurations are still in design, prototype experimentation for the optimum system design configuration. However, the dynamic control type configurations demand more attention to the heat exchanging control.

The above-said configurations are classified as per the coolant flow (Active/Passive/other). Notably, the active configurations have the advantage of a high rate of heat removal and ease in control. While the passive configurations have the advantage of simple construction and reduced cost, indeed, these configurations have more precedence than the stand-alone system. Still, the primary reason for the commercialization is cost, i.e., the amount to be invested in extracting the additional energy.

Many literature studies demonstrated the different types of PTS configurations in various approaches such as theoretical simulations, numerical models, and experimental setups. It is difficult to make the economic model for all types of PTS configurations which are presented in the literature. To make the objective of the proposed work more specific by considered the PTS configuration which is having more commercial feasibility. The liquid type, air type, nanofluid based, PCM based, TEG integrated PTS configurations are having more commercial feasibility than the other PTS configurations.

Economic aspects of PTS configurations

This section articulates a clear view of the economic aspects of PTS configurations. Undoubtedly, the economic aspects are one of the primary concerns for commercializing any system. To enumerate, the cost of any system represents the sum of material cost, production cost, operation & maintenance cost (O&M), interest & depreciation cost. In particular, some of the patented design works emerged as a commercialized product in PTS configurations. Still, many configurations are not yet released by any manufacturers due to the economic validations. Specifically, in this work, the Levelized cost of energy (LCOE) is considered for various PTS configurations, due to the lack of data availability in the investment, O&M costs of PTS configurations.

The economics in each PTS configuration represent fundamentally the sum of the cost incurred for PV and thermal extraction medium and its configuration designs. The PV system is the primary source for electricity generation, and the thermal design fortifies the PV system to enhance its overall efficiency. Indeed, in this economic analysis, five different PTS configurations are considered, and they are i) liquid type PTS ii) air type PTS iii) Nanofluid PTS iv) PCM based PTS and v) PV with Thermoelectric Generator (TEG). Another PTS configuration combination of any two or more PTS configurations leads to the development of hybrid configurations.

To achieve the Net Present Value (NPV) of zero when doing the discounted cash flows with assumptions the suitable method is the Levelized cost of energy (LCOE). The sum of the present value cost is achieved by multiplying the Energy generated annually (E_t) with LCOE and is shown in Eq. (3) [18].

$$\sum_{t=0}^{T}\frac{(LCOE_t)\times(E_t)}{(1+r)^t}=\sum_{t=0}^{T}\frac{(Costs_t)}{(1+r)^t} \tag{3}$$

By writing the LCOE from Eq. (3)

$$LCOE=\sum_{t=0}^{T}\frac{(Costs_t)}{(1+r)^t}/\sum_{t=0}^{T}\frac{(E_t)}{(1+r)^t} \tag{4}$$

where $Costs_t$ is called the discounted Costs which includes discounted Investment cost (I_0), Operational (O_t), and Maintenance (M_t) costs from zero years to a lifetime. The denominator is the discounted energy generated from zero years to a lifetime. It has to note that, the Investment cost of the project consider only at the time of beginning, so it has to separate from the summation in $Costs_t$ and is shown in Eq. (5). The energy generated at the begging year is zero and also considers the degradation in the energy concerning time and is shown in Eq. (6).

i.e.,

$$Costs_t=\begin{cases} I_0 & t=0 \\ O_t\&M_t & t>0 \end{cases} \tag{5}$$

$$E_t=\begin{cases} 0 & t=0 \\ max[E_0(1-d)^{t-1},0] & t>0 \end{cases} \tag{6}$$

The Levelized cost of energy (LCOE) written as

$$LCOE=\frac{I_0+\sum_{t=0}^{T}(O_t+M_t)/(1+r)^t}{\sum_{t=0}^{T}E_t/(1+r)^t} \tag{7}$$

In these,
I_0 is the initial Investment cost ($/kW)
O_t is the Operational cost ($/kW/year)
M_t is the Maintenance cost ($/kW/year)
E_t is the Energy generated (kWh/year)
T is the lifetime of the project
r is the rate of discount (%)
d is the depreciation rate (%)

In major literature works, the economics assessment has been performed for the PTS configurations by taking into account the structural cost discretely for stand-alone PV systems and the solar thermal system. However, in this theoretical analysis, considered the net cost of PTS configuration represents the sum of PV cost and the adscititious thermal extraction cost influenced on all costs, as the thermal system is going to be implemented with the stand-alone PV system structure. While in the sub-sections specifies the operational and maintenance expenses of different PTS configurations.

In this theoretical model, some of the assumptions are taken into the account concerning financial and technical aspects [50]. The nominal discount rate of all PTS and PV systems is 5%. The baseline values of PV and additional thermal extraction costs that affect LCOE are presented in Appendix A. The operation and maintenance costs of PTS configurations are considered according to their materials of design and their properties of the NREL-CREST Cost of Renewable Energy Spreadsheet Tool [51]. The Efficiency of the PV module and the thermal systems are to be constant (irradiance, ambient temperature, and module temperature) and only vary concerning annual degradation.

Table 3
Economic aspects of a PV system.

Economic parameters	Value
Investment cost	3000 $/kW
Lifetime	25 years
Discount rate	5%
Operational cost	10 $/kW/year
Maintenance cost	10 $/kW/year
depreciation rate	0.4%/year

All PTS configurations consist of a Multi crystalline PV module having a glass polymer back sheet operated at the roof top having a fixed tilt at a location of Vellore, Tamilnadu, India. Various PTS configurations have disparities in the costs influencing parameters such as front layer cost, back layer cost, extra components cost, O &M cost, Balance of System (BOS) power & area costs, and supplemental components cost. Consequently, these cost parameters influence the module cost and installation cost of the system. In essence, the energy yield and efficiency of the system are based on the sum of electrical and thermal energy extracted/utilized by the PV/T configurations, and this influences the LCOE of the system.

The front layer cost includes the cost of glass covers on the PV surface, and it is quantified in $/m^2. Generally, the cell cost is influenced by the type of PV cell (i.e., PV wafer cost) utilized in the system, and it is quantified in $/m^2. This cost varies for different silicon wafers. The back layer cost includes the cost of the polymer or polymer glass utilized in the PV module. The Non-cell module cost consists of the cost of encapsulation, cell interconnection, junction box, leads, connectors, nameplate, frame, and it's testing, which is quantified in $/m^2. The extra component cost for PV is zero, and for the PTS configurations, and it varies according to the design configuration, it is quantified in $/m^2. The O & M cost includes the cost of troubleshooting, repairs, and cleaning considered per year, and it is quantified in $/kW/m^2. The BOS cost, power-scaling, includes the cost of inverters and electrical components regardless of physical size, and it is quantified in $/W. The BOS cost, area-scaling, consists of the cost of racking, wiring, and installation labor, which is quantified in $/m^2. The performance of the system is analyzed depending on the energy yield and its efficiency. In particular, the electrical efficiency of the system is quantified at the STC conditions, and the thermal efficiency varies concerning the time. Altogether, the overall efficiency is the sum of both electrical and thermal capabilities per annum, and it is expressed in (%). The energy yield in PV/T represents the sum of the electrical and thermal systems. The electrical yield is calculated as per the datasheet and its annual degradation. The thermal energy is quantified in Btu/hr, and it is converted into respective units of kW. Overall, the total energy yield of PTS configurations represents the sum of electrical and thermal energy yields.

The PV system considered for all the PTS configurations is a multi-crystalline silicon PV cell with a glass-polymer back sheet package installed in the rooftop having a fixed tilt. In general, cell technology influences the cell cost, efficiency, energy yield, degradation rate, and Balance of System (BOS). is Individual, in the present work, a multi-crystalline silicon PV cell considered, and it provides an efficiency of 18% with a 0.4% depreciation rate. For various PTS configurations, the depreciation rate varies, relying upon its constructional structure arrangement.

On account of a 5 kW PV framework, it requires a base territory of 38 m^2, and it produces a typical month to month vitality of 490kWh to 1190kWh of alternating power with average daylight of 7 h out of each day. Since the initial cost of the project is applied at the time of starting so, the rebate rate ought not to consider any significant bearing for a lifetime. Individually, in this analysis, LCOE is regarded as a 5 kW PV system possessing the mean capital, O & M costs, which are taken from the (NREL) database [52]. The economic aspects of a PV system are shown in Table 3.

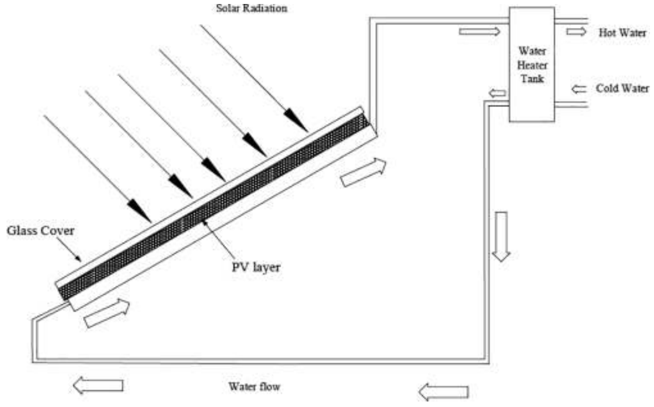

Fig. 5. Passive type Liquid PTS configuration.

The module cost is the sum of all the module components and 15% marginal profit to the manufacturer [52] and is given by Eq. (8)

$$\text{Module cost} = \text{Cost of module parameters} + 15\%\ \text{Profit} \quad (8)$$

The cost of module parameters is the sum of front layer cost, cell cost, back layer cost, and extra components costs [53]. The energy output for all PTS configurations is electrical and thermal energy. Moreover, the thermal energy (BTU/hr) is converted into equipollent electrical energy (W) to get the total energy yield of the PTS configuration. In the present work, the energy yield of all PTS configurations is shown in percentage and is referred to as the magnitude of energy gain as compared with the stand-alone PV system. In this comparative study, the displayed images are not the 5 kW PTS configurations and are shown to grasp a conception about its design configuration. The cost parameters of all PTS configurations vary due to its design and operations. The cost metric methodology [54] of each system is described at the respective PTS configuration.

Liquid type PTS configuration

One of the liquid PTS configurations is shown in Fig. 5. The investment and O & M cost of liquid PTS configuration is high as compared to the stand-alone PV system. While the liquid PTS configuration is shown for a single module, for an extensive system like 5 kW, it requires a bulk water tank, control valves, and piping system, which are mentioned in ref [25]. So the investment cost increases as 1000 $/kW power generation and operational cost increases by 7 $/kW/year, operations and maintenance cost is increased by 7 $/kW/year due to rusting and damaging of piping and control valve structures. To sum up, the net value of the system increases by 30 to 40% of the investment as compared to the stand-alone PV system. Therefore, the depreciation rate of the configuration is increased by 0.1% [55]. Important to realize, the quantity of thermal energy extracted from the liquid type configuration depends on the parametric values such as the type of the absorber plate and the flow rate of water.

Nonetheless, in this analysis, a PTS configuration that has a constant flow rate with a copper absorber plate to extract the maximum thermal energy from the module is considered. As might be expected, the removal of heat causes the increment in electrical power generated by PV, and the heat extracted from the module is converted into its equivalent energy in Watts. The combined energy derived from the liquid type PTS configuration is 15 to 18% depending on its configuration type [56].

The cost of the liquid type configurations varies depending on its configuration type, such as active or passive. The dynamic (active) systems cost 0.1% higher than the passive systems because of its force pumping add-ons. In general, the passive configurations work with the thermosiphon principle to flow the coolant from the tank. Furthermore, this type of arrangement demands more attention while designing for a particular location as the tilt angle, average temperature, and flow pipe diameter vary for different areas. After all, electrical and thermal energy gain leads to an increase in the combined utilizable energy up to 15% of the stand-alone PV system [57]. Table 4 show some of the assumptions made in the economic aspects of liquid type PTS configurations.

Table 4
Assumptions in Economic aspects of liquid type PTS configurations.

Economic parameters	Value	
	Active	Passive
Investment cost	4400 $/kW	4000$/kW
Lifetime	25 years	25 years
Discount rate	5%	5%
Operational cost	18 $/kW/year	17 $/kW/year
Maintenance cost	18 $/kW/year	17 $/kW/year
depreciation rate	0.5%/year	0.5%/year
Energy gain	18%	15%

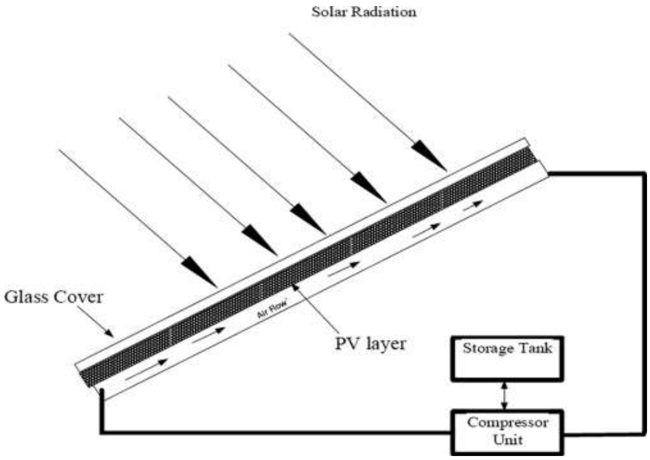

Fig. 6. Air type PTS configuration.

Air type PTS configuration

In air type PTS configuration, only a dynamic (active) method is appropriate to extract the heat from the module. In the active air type configuration, there are two types of arrangements that are more popular i) single-pass ii) dual-pass. To illustrate, Fig. 6 shows the dynamic (active) single-pass system. Considering the investment aspects, the cost of a single and dual-pass varies marginally, and O&M depends upon the storage. A blower is essential to force air inside PV layers in both single-pass and dual-pass system. In a single pass, hot air is accumulated at one end by a reservoir, in dual-pass, air coerced IN in one layer comes OUT through another layer. Hence, making the designs to collect the hot air at the same end becomes crucial. The investment cost of the system increases by 0.1% due to air compression storage [58]. Albeit, this cost is omitted in the case of non-storage configurations. Significantly, the life span of this configuration is higher than the liquid type system. Moreover, the degradation rate is withal equipollent to the PV because it doesn't impact any physical components like the liquid type. Undoubtedly, the maintenance cost is high for the storage-based configurations as compared with the non-storage arrangements.

Some of the significant applications of the air type PTS configurations are space heating, agriculture drying. While some air type configurations like space-heating need hot air storage, some other arrangements like agriculture drying don't need any room (storage). Indeed, the cost varies depending on the warm air storage. The magnitude of energy extracted from the air type PTS configuration depends on the airflow rate of a single-pass or dual-pass setting. To enumerate, in

Table 5
Assumptions in Economic aspects of air type PTS configurations.

Economic parameters	Value	
	With storage	Without storage
Investment cost	4400 $/kW	4000 $/kW
Lifetime	30 years	30 years
Discount rate	5%	5%
Operational cost	15 $/kW/year	12 $/kW/year
Maintenance cost	15 $/kW/year	12 $/kW/year
depreciation rate	0.4%/year	0.4%/year
Energy gain	22%	18%

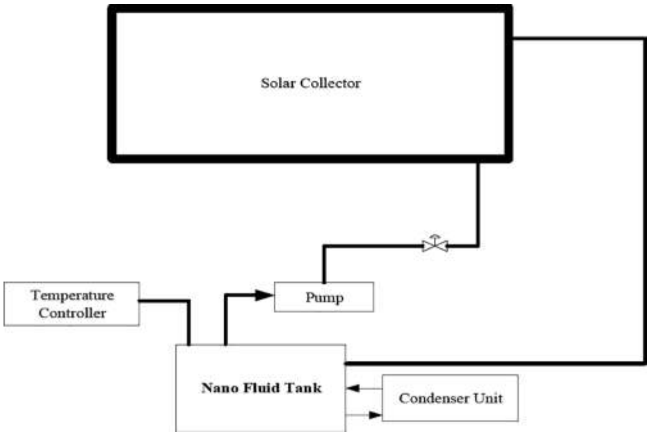

Fig. 7. Nano fluid-based PTS configuration.

Table 6
Assumptions in Economic aspects of Nanofluid type PTS configurations.

Economic parameters	Value
Investment cost	4500 $/kW
Lifetime	25 years
Discount rate	5%
Operational cost	15 $/kW/year
Maintenance cost	15 $/kW/year
depreciation rate	0.4%/year
Energy gain	20%

this air type PTS configuration, the thermal energy extracted from the module is 8% higher than the liquid type configuration. Consequently, the total energy gain by the air type PTS configuration is 18 to 22% as compared to the stand-alone PV system [59]. Table 5 shows some of the assumptions made in the economic aspects of air type PTS configurations.

Table 7
Assumptions in Economic aspects of PCM based PTS configurations.

Economic parameters	Value
Investment cost	4500 $/kW
Lifetime	25 years
Discount rate	5%
Operational cost	12 $/kW/year
Maintenance cost	16 $/kW/year
depreciation rate	0.5%/year [63]
Energy gain	12%

Nano fluid-based PTS configuration

The Nano fluid-based PTS configuration remains the advanced method in extracting the heat from the module. In this configuration, using an external force, the nanofluids such as Al_2O_3, CuO, Graphite, CNT, TiO_2, and Cu are commixed with the base fluids such as water, oil, and acetone are made to flow in the system as indicated in Fig. 7. Significantly, the cost of nanofluid depends on the particle size and fraction of the mix of particles. Hence, the investment cost of this configuration is higher than the liquid and air type configurations [60]. Moreover, the operation and maintenance of the Nanofluid setting are the same as the storage-based air type PTS. However, the lifetime of this system depends on the degradation of Nanofluid properties. Altogether, the calculation for the magnitude of thermal energy extracted in Nanofluid PTS configuration depends on the thermal storage temperature. Comparatively, the heat abstraction rate for the Nanofluid is 10% higher than the air and water [61]. Albeit the rate of heat abstraction is more elevated than air, the amount of thermal energy extracted is 3% lower than wind (air-type) because of Nanofluid properties. Table 6 shows some of the assumptions made in the economic aspects of nanofluid type PTS configurations.

PCM based PTS configuration

The Phase Change Mater (PCM) based PTS configuration utilizes the PCM to accumulate the thermal energy. There are two types of PCM available in the market they are organic and inorganic. In recent years organic-based PCMs are used, such as Rubitherm RT20, RT21, RT25, RT27, RT31, RT35, RT42, RT44, RT60, RT10HC, RT18HC, RT25HC, RT35HC, SP220A, Walksol A, and Calcium chloride hexahydrate. Notably, the investment cost of PCM based PTS configuration is high because of the closed-loop control design of PCM flow, storage structures, and safety measures. The operational cost is the same as the PV system. Still, the Maintenance cost increases due to the supersession of PCM and the requisite of regular inspection of the system flow. Nevertheless, the lifetime of the PCM based PTS is high because there is no dynamic operation in the system [62].

The energy density of PCM based PTS configuration is 8% higher than the liquid and air type configurations. Overall, the energy

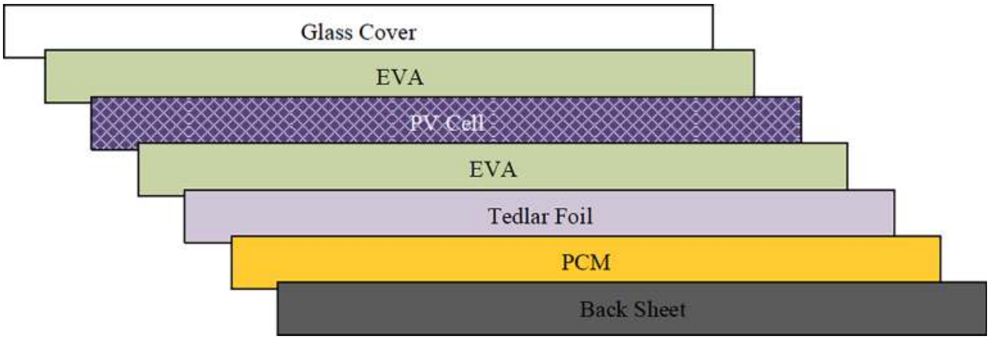

Fig. 8. PCM based PTS configuration.

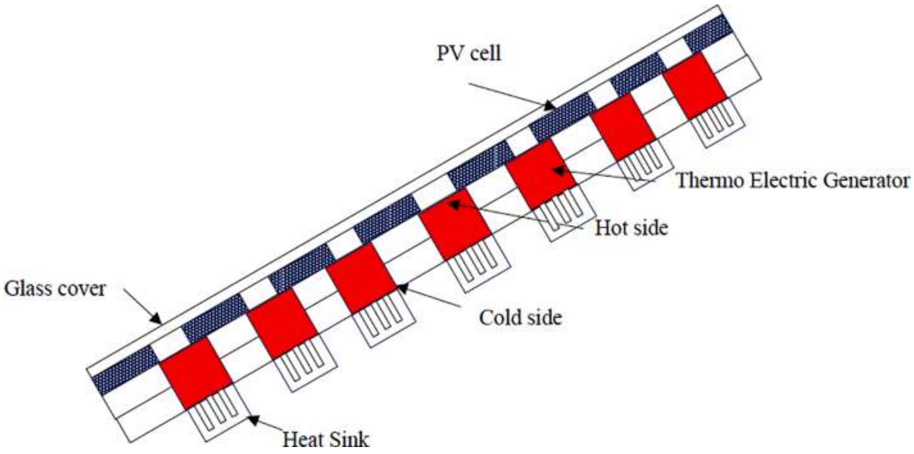

Fig. 9. TEG based PTS configuration.

Table 8
Assumptions in Economic aspects of TEG based PTS configurations.

Economic parameters	Value
Investment cost	3300 $/kW
Lifetime	30 years
Discount rate	5%
Operational cost	11 $/kW/year
Maintenance cost	11 $/kW/year
depreciation rate	0.4%/year
Energy gain	15%

efficiency of this configuration is 20 to 25% higher than the stand-alone PV, depending on the PCM materials, PCM location, and its integration. The degradation of PCM material depends on the number of energy cycles. The commercially available PCM has 20 years of life span with 5400 energy cycles [63]. Fig. 8 shows a typical PCM based PTS configuration. Table 7 shows some of the assumptions made in the economic aspects of PCM based PTS configurations.

TEG integrated PTS configuration

The TEG integrated PV is the most straightforward configuration compared to all other settings listed above because it doesn't have any dynamic controls and complex closed-loop systems. In either case (PV and TEG), the energy conversion process transpires with the fundamental inputs of photons and heat without any external forces [64]. The investment cost of this configuration increases with the expense of Thermoelectric Generators. However, there is no desideratum for any additional operational and maintenance costs for TEG. Furthermore, the lifetime of TEG is about 30 years, and the degradation rate is low.

The energy density of this configuration depends on the rating and quantity of TEGs connected at the rear side of PV [65]. Notably, in this PTS configuration, supplemental energy engendered is only electrical energy; there is no thermal energy extracted or stored. The TEGs utilizes the module temperature to produce electrical energy, which is 20% higher than the stand-alone PV system [22]. Comparatively, the TEG integrated PTS configuration has direct energy conversion systems such as PV and TEG so that net efficiency is 2% higher than the dynamic type PTS configurations. Fig. 9 shows the TEG based PTS configuration. Table 8 shows some of the assumptions made in the economic aspects of TEG based PTS configurations.

Other hybrid configurations

Apart from the above, five configurations, the hybrid configurations are implemented to enhance the magnitude of energy engendered from the overall system such as PV with PCM & TEG, Liquid type PTS with TEG, and Nanofluid PTS with TEG. These combinations enhance the net efficiency from 5 to 10% than the stand-alone configurations. Comparatively, the investment cost of Nanofluid PTS with TEG is high due to the Nanofluid structure. At the same time, the liquid type PTS with TEG is moderate due to the fluid flow structure, whereas PV with PCM & TEG is low as compared with the remaining two configurations.

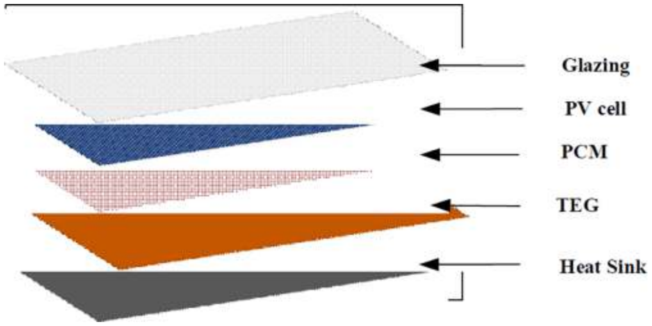

Fig. 10. hybrid PCM-TEG PTS configuration.

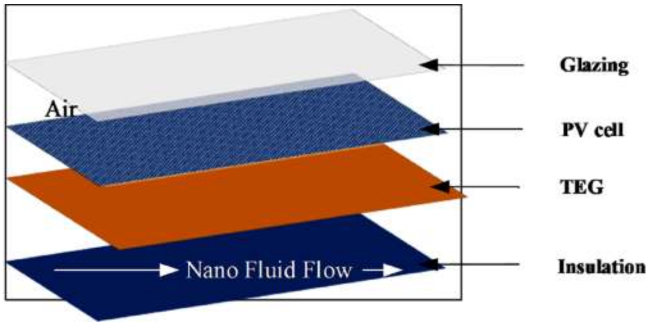

Fig. 11. hybrid TEG Nanofluid PTS configuration.

The quantity of energy generated by the hybrid PTS configuration depends on the type of integration and its design configuration. In the case of PCM-TEG arrangements, the energy density for PCM is high. At the same time, the TEG converts low-grade heat into a valid form of energy, so total energy gain by integrating TEG with PCM type PTS configuration is 40%, which is shown in Fig. 10. In the case of Nanofluid PTS configuration, combined with TEG engenders supplemental energy of 30% than the Nanofluid PTS configuration and Fig. 11 shows the hybrid TEG Nanofluid PTS configuration. Water is used, in the case of

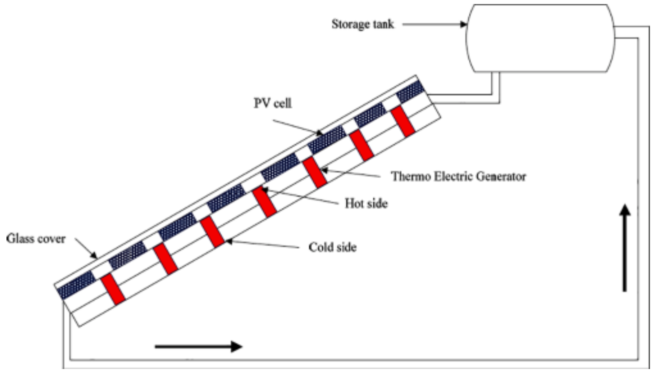

Fig. 12. liquid type PTS with TEG Configuration.

Table 9
Assumptions in Economic aspects of hybrid PTS configurations.

Economic parameters	Value		
	PCM-TEG PTS	liquid type PTS with TEG	TEG- Nanofluid PTS
Investment cost	5200 $/kW	4800$/kW	5200 $/kW
Lifetime	30 years	25 years	30 years
Discount rate	5%	5%	5%
Operational cost	20 $/kW/year	25 $/kW/year	20 $/kW/year
Maintenance cost	20 $/kW/year	25 $/kW/year	20 $/kW/year
depreciation rate	0.4%/year	0.5%/year	0.4%/year
Energy gain	20%	17%	22%

Table 10
The LCOE, Module cost, Total installed cost of PTS configurations.

S. No.	Configuration		LCOE $/kWh	Module cost $/W	Total installed cost $/W
1.	PV		0.264	0.36	1
2	Liquid type PTS	Active	0.382	0.39	1.69
		Passive	0.376	0.37	1.67
3	Air type PTS	With Storage	0.354	0.51	2.11
		Without storage	0.302	0.52	2.05
4	Nano fluid-based PTS configuration		0.332	0.41	1.64
5	PCM based PTS configuration		0.339	0.36	1.5
6	TEG based PTS configuration		0.287	0.36	1.18
	Other hybrid configurations	PCM-TEG PTS	0.467	0.58	2.36
		liquid type PTS with TEG	0.503	0.55	2.38
		TEG-Nanofluid PTS	0.459	0.56	2.37

TEG integrated liquid PTS configuration, to cool down the cold junction of TEG to increase the temperature difference between the two terminals. The total energy gain by the liquid type PTS integrated with TEG engenders 70% of supplemental energy as compared to the fluid (liquid) PTS configurations Fig. 12 shows the liquid type PTS with TEG Configuration. Regardless of, the efficiency (η) of all hybrid configurations are just marginally higher than the basic PTS configuration because hybrid configurations involve multiple conversion process, this causes a decrease in the net η of the system. The energy density of these hybrid coalescences is high due to the integration of 2 or more conversion sources. In essence, the net efficiency of this configuration increases remotely as compared to the individual setting. Table 9 shows

Table 11
Research scope of PTS configurations.

Configuration	Research Scope areas	Remarks
Liquid PTS configuration	Develop the exergy based studies of each configuration. The efficient location of the heat pipe and its rating has to be optimized. Develop the flow rate management systems felicitous for domestic/ commercial applications.	The Liquid type PTS configurations are more apt for high thermal absorption applications. These configurations have maximum efficiency with good exergy, and also possible to implement more possible configurations such as Microchannel heat pipe configurations.
Air type PTS configuration	Develop the compressed air storage system’s safety and standards. The excellent (optimum) ratings of the blower and the storage tank capacity for the felicitous application have to be derived. Design the flow rate of air and its control over the density in the storage tank.	The air type configurations with storage are apt for the space heating applications, while, without storage, the type is harmonious for the agriculture drying applications.
Nano Fluid based PTS configuration	The selection of Nanofluid for the applications has to be specified. The flow control and the storage capacity of Nanofluid and base fluid has to be optimized. Describe the environmental and safety measures for the Nanofluid systems need in government policies.	Most congruous for commercial and industrial applications. Comparatively, the energy yield of this configuration is higher than the liquid and air type configurations.
PCM based PTS configurations	Implement the optimum location and integration method of PCM. Organic PCM research is needed to increase the energy density of PCM. Effective heat energy extraction from the PCM needs to be improved. There is a need for research in energy density and its exergy efficiency.	This configuration has more commercial viability than others due to its simple operation and construction. Again, the cycles of energy storage and extraction are limited.
TEG based PTS	To calculate the optimal number of TEGs required for a flat plate PV area. To design the optimal location of TEG and its connection configuration to extract maximum power. To design the efficient integration method to minimize thermal conductance between absorber and TEG. New materials have to come up with high energy density felicitous for low heat energy applications.	This configuration has the advantages in the connection, integration to access distribution generating system, and high energy density. Comparatively, the electrical energy generated by this configuration is high because of direct energy conversion, and the generation of electrical power using heat energy.

(*continued on next page*)

Table 11 (*continued*)

Configuration	Research Scope areas	Remarks
Other hybrid configurations	To implement the energy and exergy analysis with the overall efficiency. Develop the integration type and method for PCM-TEG based configurations. To develop the design flow to extract maximum power from the system.	These configurations are felicitous for domestic/ commercial consumers because of the efficient utilization of low energy. Notably, the energy gain and the density is higher than all other PTS configurations.

some of the assumptions made in the Economic aspects of hybrid PTS configurations.

Summary of LCOE of all PTS configurations

The LCOE calculated for all PTS configurations is by considering all the costs for energy generation [66]. The module cost represents the sum of front layer cost, PV Cell cost, back layer cost, and other than cell modules cost, while the components cost is extra. The total installed cost depends on the BOS cost of power-scaling, BOS cost of area-scaling, and the overall efficiency of the system configuration. For making all PTS configurations on the same scale of 5 kW rooftop having multi-crystalline PV cells integrated with polymer back sheet, the cost of each set is shown in Table 10. Appendix A shows the module cost and the Total installed cost parameter values, which are considered by various parameters associated with the setup.

The above cost table limpidly shows that the TEG based PTS configurations offer a low LCOE of 0.287 $/kWh with a module cost of 0.36 $/W at a low installation cost of 1.18 $/W. Though, in this configuration, just the electrical efficiency is increased by 3% when compared with other arrangements.

Research challenges of PTS configurations

In literature, the focuses of some of the works are on the new advantages of PV/Thermal systems [67] concerning the energy, exergy, Economic, Environmental aspects and its R & D progress on the specific configurations such as water heating & distillation, air PTS operated for Building-integrated systems, TEG based PTS, Nanofluid based PTS and PCM based PTS. These studies are on any single configurations/applications. Nonetheless, this section gives the design and economic analysis for prospective investors in the field of microgrid systems.

In the process of commercialization of any product, it has to pass through three different engineering steps. The first one is design models of the system, the second is the optimization of design parameters, and the third is economic and environmental aspects. Apart from that, other standard and safety validations have to be passed by concerned regime policies of nations; at that point, just any novel configuration can emerge as an efficient commercial product. There are liquid type PTS accessible in the market by just a couple of providers; however, hardly these are known as the independent PV system. The PTS are currently facing constraints in the optimization of design parameters because each design configurations has different optimization parameters needed in the application perspective. Table 11 shows different PTS configurations having a specific change in design, either in coolant or flow or storage, with its applications.

Table 11 shows the different configuration's LCOE, module cost, and installation cost. The cost of PV, TEG based PTS, and PCM based PTS maintains a marginal difference in module cost due to its design considerations. The installation cost of TEG based PTS is low compared to all other configurations. The LCOE of all the PTS configurations increases from 8.7% to 90% as compared to the stand-alone PV system. Nevertheless, the energy gain by the PTS configurations is 10% to 50% as compared to the self-contained PV system. This metric shows that the cost per unit generation increases by 3% to 12% for the PTS configurations. The utility sectors people are observing the following issues in the PTS configurations i) profit gain period is high, ii) less lifetime compared to PV iii) O & M cost high for liquid and air PTS configurations. In the future, the PTS configurations will surmount these by making the most feasible design with minimum O & M by the soft computing based control strategies. The profit gain period increases when there is an increment in the magnitude of energy generated per m^2 area.

From the above observation, the upcoming PTS configurations must consider the design aspects of particular PTS configurations along with the energy, exergy, economic analysis for the novel PTS configurations. There is a plethora of scope for the research in the PTS configurations for leading exploratory approvals to make a more reliable flat plate system within the economic considerations of the domestic rooftop system.

Sensitivity analysis

In the literature, study authors made the sensitivity analysis for individual PV and concentrated solar power systems [18]. In the proposed work authors attempted sensitivity analysis of PTS configuration concerning energy and economic parameters. The solar irradiance and ambient temperature are the energy yield parameters, which creates a significant impact on the LCOE of PTS configuration. The economic parameters such as Investment cost (I_0), Operation and maintenance cost (O_t & M_t), and other costs are grouped as system costs which are

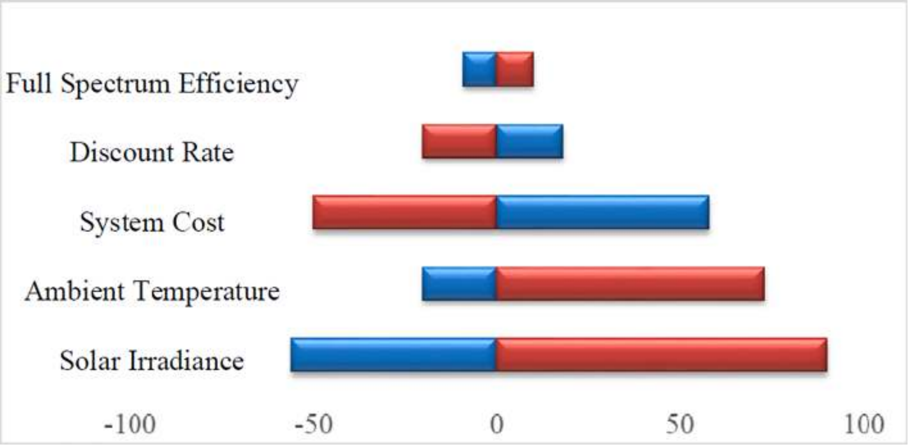

Fig. 13. Tornado analysis of PTS configurations.

Table A1
LCOE calculation Parameters.

Parameter	PV	Liquid type	Air type	Nano fluid	PCM based	TEG based	Hybrid systems
Front layer cost	Glazing	Glazing	Glazing	Glazing	Glazing	Glazing	Glazing
PV Cell cost	Multi crystalline	Multi crystalline	Multi crystalline	Multi crystalline	Multi crystalline	Multi crystalline	Multi crystalline
Back layer cost	Polymer	Absorber plate	Fins, channels assembly	Nanofluid flow assembly	Absorber plate	Absorber plate	Absorber plate, flow assembly
Other than cell modules cost	Junction box, leads, test and encapsulation	Water flow arrangements, water pump	Airflow structure, blower	Nanofluid, the base fluid	Phase change material	Thermoelectric generator	PCM, Nanofluid, TEG,
Extra components cost	–	Storage tank, piping assembly, flow control	Storage tank, pressure controls	storage tank, flow rate control	PCM energy extraction schemes	Integration, connection of TEG,	Storage tank, pressure controls piping assembly, flow control
O & M Cost	Inverter and other parts	Water flow structures, Inverter and other parts	Air compressor, Inverter and other parts	Flow system, Inverter and other parts	PCM energy cycles, Inverter and other parts	Inverter and other parts	System parameter and other parts
BOS cost of power scaling	Inverters	Inverters, auxiliary heaters	Inverters, compressed air chambers	Inverters, Auxiliary equipment	Inverters,Heat extractors	Inverters,TEG interconnections	Inverters, Auxiliary heaters, Pumps, extractors
BOS cost of area-scaling	Racking, wiring, labor	Racking, integration, cabling, labor	Racking, integration, cabling, labor	Racking, Integration, cabling, labor	Racking, cabling, integration, labor	Racking, wiring, integration, labor	Racking, integration, wiring, labor

impacting the LCOE of PTS configuration [68]. The discount rate also majorly impacts the LCOE of the system. In the proposed work, consider the solar irradiance, ambient temperature, system cost, and discount rates as input sensitive parameters of PTS configurations.

The solar irradiance and ambient temperature causing a direct impact on the energy yield of the PTS configurations. The increase in energy yield leads to a decrease in the cost of energy generation [69]. The increment in PTS system cost leads to an increase in the LCOE of the system. The rate of discount varies country wise. The rate of discount is having a directly proportional relationship with the LCOE of PTS configuration. Fig. 13 shows the tornado analysis of all PTS configuration by considering the minimum and maximum values of each input response.

Recommendations

The PTS, as mentioned above configurations, are having the feasibility of commercialization concerning different applications. Some of the recommendations of PTS configuration are as follows

- The Liquid type PTS configurations are more apt for the tropical countries to generate ample hot water for domestic needs along with electrical energy. Some of the liquid type configurations are present in commercial markets.
- The air type PTS configurations have the feasibility in industrial applications. Still, it is obligatory to consider the industrial thermal safety standards and precautions to come up as a commercial product. As far as without storage, air type configuration is concerned – the design of the application should be in such a way that the utilization of hot air available is direct. The storage air type PTS configurations possess more advantages than the ’without a storage system. Nevertheless, the single-pass air type configuration (storage type) is more convenient to come up as a commercial product for space heating applications and industrial drying applications.
- The PCM based PTS configurations are more harmonious in the industrial heat management systems. The different materials of PCM engender a wide range of applications in various sectors. The demeanor and energy reversibility process plays a vital role in the selection of PCM for congruous use.
- The Nanofluid PTS configurations are confronting challenges in commercialization – concerned with economic aspects, maintenance, and safety standards.
- The TEG integrated PTS configuration has more energy and economic feasibility as compared to all other arrangements, which are apt for rooftop power generations in all the locations. Hence, the TEG material cost and its integration concepts are the current research area of thermoelectrics.
- In the process of commercialization, government policies play a vital role. The renewable energy policymakers present all over the world have to encourage the PTS configurations for the domestic and industrial applications by providing subsidies.

Conclusion and future scope

This article discusses different configurations of photovoltaic thermal systems. In that, active contours (configurations) have a high heat abstraction rate of 12% than the passive arrangements. In the overall designs discussed, TEG integrated with the PV system is a more feasible configuration for domestic rooftop power generation. In any case, more research is needed in the field of TEG materials to produce electrical energy for low heat sources with maximum conversion efficiency. This article discusses the economics involved in all the PTS configurations. As can be seen, the LCOE of the PTS configurations is increased by 8.7% to 90% LCOE of stand-alone PV. To point out, the energy gain by the PTS configurations comprises 10% to 50% higher than the stand-alone PV.

The all-out life pattern of PTS arrangement varies from 25 to 30 years relying upon its designs. Nonetheless, the economic payback period for the PTS configuration is 20–25 years, which is less than the stand-alone PV system due to additional equipment for the thermal extraction. Nevertheless, the energy payback is 15–20 years for various PTS configurations due to the thermal gain, heat energy made available to be utilized for multiple heating applications.

In the future, focus on the research works on the control of liquid/airflow, integration of PCM/TEG with more thermally conductive substances, and the materials of Nanofluid/PCM/TEG need to increase their energy density for low-grade heat sources is significant.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

Authors thank VIT for providing ‘VIT SEED GRANT’ for carrying out this research work.

Appendix A

Table A1

References

[1] Grubišić-Čabo, Filip, Sandro Nižetić, Tina Giuseppe Marco. Photovoltaic panels: a review of the cooling techniques. Trans. FAMENA 40.SI-1 (2016): 63–74.

[2] Shukla A, Kant K, Sharma A, Biwole PH. Cooling methodologies of photovoltaic module for enhancing electrical efficiency: a review. Sol Energy Mater Sol Cells 2017;160:275–86. https://doi.org/10.1016/j.solmat.2016.10.047.

[3] Ibrahim A, Othman MY, Ruslan MH, Mat S, Sopian K. Recent advances in flat plate photovoltaic/thermal (PV/T) solar collectors. Renew Sustain Energy Rev 2011;15: 352–65. https://doi.org/10.1016/j.rser.2010.09.024.

[4] Khelifa A, Touafek K, Ben Moussa H, Tabet I. Modeling and detailed study of hybrid photovoltaic thermal (PV/T) solar collector. Sol Energy 2016;135:169–76. https://doi.org/10.1016/j.solener.2016.05.048.

[5] Data sheet from solimpeks n.d. http://www.solimpeks.com/product/volther-powertherm/.

[6] Data sheet DualSun n.d. https://www.news.dualsun.com/wp-content/uploads/DualSun-EN-Datasheet.pdf.

[7] Datasheet Powerhybrid 240 n.d. https://www.energy-xprt.com/products/model-powerhybrid-240-electrically-biased-module-524379.

[8] Sathe TM, Dhoble AS. A review on recent advancements in photovoltaic thermal techniques. Renew Sustain Energy Rev 2017;76:645–72. https://doi.org/10.1016/j.rser.2017.03.075.

[9] Sargunanathan S, Elango A, Mohideen ST. Performance enhancement of solar photovoltaic cells using effective cooling methods: a review. Renew Sustain Energy Rev 2016;64:382–93. https://doi.org/10.1016/j.rser.2016.06.024.

[10] Chow TT, Pei G, Fong KF, Lin Z, Chan ALS, Ji J. Energy and exergy analysis of photovoltaic-thermal collector with and without glass cover. Appl Energy 2009;86: 310–6. https://doi.org/10.1016/j.apenergy.2008.04.016.

[11] Kostić LT, Pavlović TM, Pavlović ZT. Optimal design of orientation of PV/T collector with reflectors. Appl Energy 2010;87:3023–9. https://doi.org/10.1016/j.apenergy.2010.02.015.

[12] Tselepis S, Tripanagnostopoulos Y. Ecomomic analysis of Hybrid Photovoltaic/Thermal solar systems and comparison with Standard PV modules. PV Eur – From PV Technol to Energy Solut 2002:9–12.

[13] Ibrahim A, Othman MY, Ruslan MH, Alghoul MA, Yahya M, Zaharim A, et al. Performance of photovoltaic thermal collector (PVT) with different absorbers design. WSEAS Trans Environ Dev 2009;5:321–30.

[14] Guo J, Lin S, Bilbao JI, White SD, Sproul AB. A review of photovoltaic thermal (PV/T) heat utilisation with low temperature desiccant cooling and dehumidification. Renew Sustain Energy Rev 2017;67:1–14. https://doi.org/10.1016/j.rser.2016.08.056.

[15] Vivek R, Tiwari GN. A comparison study of energy and exergy performance of a hybrid photovoltaic double-pass and single-pass air collector. Int J Energy Res 2009;33:605–17.

[16] Zhang X, Zhao X, Smith S, Xu J, Yu X. Review of R&D progress and practical application of the solar photovoltaic/thermal (PV/T) technologies. Renew Sustain Energy Rev 2012;16:599–617. https://doi.org/10.1016/j.rser.2011.08.026.

[17] Chauhan A, Tyagi VV, Anand S. Futuristic approach for thermal management in solar PV/thermal systems with possible applications. Energy Convers Manag 2018; 163:314–54. https://doi.org/10.1016/j.enconman.2018.02.008.

[18] Hernández-Moro J, Martínez-Duart JM. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renew Sustain Energy Rev 2013;20:119–32. https://doi.org/10.1016/j.rser.2012.11.082.

[19] Athukorala CD, Jayasuriya A, Ragulageethan S, Sirimanna M, Attalage RA, Perera A. A techno-economic analysis for an integrated solar PV/T system with thermal and electrical storage – case study. IEEE Trans Energy Convers 2015; 182–7. https://doi.org/10.1109/MERCon.2015.7112342.

[20] Buonomano A, De Luca G, Figaj RD, Vanoli L. Dynamic simulation and thermo-economic analysis of a PhotoVoltaic/Thermal collector heating system for an indoor-outdoor swimming pool. Energy Convers Manag 2015;99:176–92. https://doi.org/10.1016/j.enconman.2015.04.022.

[21] Parrado C, Girard A, Simon F, Fuentealba E. 2050 LCOE (Levelized Cost of Energy) projection for a hybrid PV (photovoltaic)-CSP (concentrated solar power) plant in the Atacama Desert, Chile. Energy 2016;94:422–30. https://doi.org/10.1016/j.energy.2015.11.015.

[22] Li G, Zhao X, Ji J. Conceptual development of a novel photovoltaic-thermoelectric system and preliminary economic analysis. Energy Convers Manag 2016;126: 935–43. https://doi.org/10.1016/j.enconman.2016.08.074.

[23] Bianchini A, Gambuti M, Pellegrini M, Saccani C. Performance analysis and economic assessment of different photovoltaic technologies based on experimental measurements. Renew Energy 2016;85:1–11. https://doi.org/10.1016/j.renene.2015.06.017.

[24] Bai A, Popp J, Balogh P, Gabnai Z, Pályi B, Farkas I, et al. Technical and economic effects of cooling of monocrystalline photovoltaic modules under Hungarian conditions. Renew Sustain Energy Rev 2016;60:1086–99. https://doi.org/10.1016/j.rser.2016.02.003.

[25] Tse K-K, Chow T-T, Su Y. Performance evaluation and economic analysis of a full scale water-based photovoltaic/thermal (PV/T) system in an office building. Energy Build 2016;122:42–52. https://doi.org/10.1016/j.enbuild.2016.04.014.

[26] Flora Anne NN, Lee H, Wee D. Technical and economic analysis of thermoelectric modules with macroporous thermoelectric elements. Energy Convers Manag 2017; 135:327–35. https://doi.org/10.1016/j.enconman.2016.12.077.

[27] Bianchini A, Guzzini A, Pellegrini M, Saccani C. Photovoltaic/thermal (PV/T) solar system: Experimental measurements, performance analysis and economic assessment. Renew Energy 2017;111:543–55. https://doi.org/10.1016/j.renene.2017.04.051.

[28] Thinsurat K, Bao H, Ma Z, Roskilly AP. Performance study of solar photovoltaic-thermal collector for domestic hot water use and thermochemical sorption seasonal storage. Energy Convers Manag 2019;180:1068–84. https://doi.org/10.1016/j.enconman.2018.11.049.

[29] Yu Bendong, Zhong Dan, Liu Jinxiang, Niu Xiaofeng. A novel solar PV/T driven air purification system based on heterogeneous photocatalytic reaction principles: a short review and preliminary investigation. Energy Convers Manag 2020;210: 112697. https://doi.org/10.1016/j.enconman.2020.112697.

[30] Al-Waeli AH, Kazem HA, Yousif JH, Chaichan MT, Sopian K. Mathematical and neural network modeling for predicting and analyzing of nanofluid-nano PCM photovoltaic thermal systems performance. Renew Energy 2020;2020(145): 963–80. https://doi.org/10.1016/j.renene.2019.06.099.

[31] Alghoul MA, Shahahmadi SA, Yeganeh B, Asim N, Elbreki AM, Sopian K, et al. A review of thermoelectric power generation systems: Roles of existing test rigs/prototypes and their associated cooling units on output performance. Energy Convers Manag 2018;174:138–56. https://doi.org/10.1016/j.enconman.2018.08.019.

[32] Balaska A, Tahri A, Tahri F, Stambouli AB. Performance assessment of five different photovoltaic module technologies under outdoor conditions in Algeria. Renew Energy 2017;107:53–60. https://doi.org/10.1016/j.renene.2017.01.057.

[33] Michael JJ, Iniyan S, Goic R. Flat plate solar photovoltaic-thermal (PV/T) systems: A reference guide. Renew Sustain Energy Rev 2015;51:62–88. https://doi.org/10.1016/j.rser.2015.06.022.

[34] Luque A, Hegedus S. Handbook of Photovoltaic Science and Engineering. 2011. doi:10.1002/9780470974704.

[35] Muzathik AM. Photovoltaic modules operating temperature estimation using a simple correlation. Int J Energy Eng 2014;4:151–8.

[36] Alonso Garcia MC, Balenzategui JL. Estimation of photovoltaic module yearly temperature and performance based on Nominal Operation Cell Temperature calculations. Renew Energy 2004;29:1997–2010. https://doi.org/10.1016/j.renene.2004.03.010.

[37] Pounraj P, Prince Winston D, Kabeel AE, Praveen Kumar B, Manokar AM, Sathyamurthy R, et al. Experimental investigation on Peltier based hybrid PV/T active solar still for enhancing the overall performance. Energy Convers Manag 2018;168:371–81. https://doi.org/10.1016/j.enconman.2018.05.011.

[38] Nižetić S, Čoko D, Yadav A, Grubišić-Čabo F. Water spray cooling technique applied on a photovoltaic panel: the performance response. Energy Convers Manag 2016;108:287–96. https://doi.org/10.1016/j.enconman.2015.10.079.

[39] Bahaidarah HMS, Baloch AAB, Gandhidasan P. Uniform cooling of photovoltaic panels: a review. Renew Sustain Energy Rev 2016;57:1520–44. https://doi.org/10.1016/j.rser.2015.12.064.

[40] Bahaidarah H, Subhan A, Gandhidasan P, Rehman S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 2013;59:445–53. https://doi.org/10.1016/j.energy.2013.07.050.

[41] Moharram KA, Abd-Elhady MS, Kandil HA, El-Sherif H. Enhancing the performance of photovoltaic panels by water cooling. Ain Shams Eng J 2013;4:869–77. https://doi.org/10.1016/j.asej.2013.03.005.

[42] Odeh SD, Abu-mulaweh HI. Design and development of experimental setup of Hybrid PV / Thermal collector. Glob J Eng Educ 2012;14:170–6.

[43] Mazón-Hernández R, García-Cascales JR, Vera-García F, Káiser AS, Zamora B. Improving the electrical parameters of a photovoltaic panel by means of an induced or forced air stream. Int J Photoenergy 2013;2013. https://doi.org/10.1155/2013/830968.

[44] Kumar R, Rosen MA. Performance evaluation of a double pass PV/T solar air heater with and without fins. Appl Therm Eng 2011;31:1402–10. https://doi.org/10.1016/j.applthermaleng.2010.12.037.

[45] Abreu SL, Colle S. An experimental study of two-phase closed thermosyphons for compact solar domestic hot-water systems. Sol Energy 2004;76:141–5. https://doi.org/10.1016/j.solener.2003.02.001.

[46] Chandrasekar M, Senthilkumar T. Experimental demonstration of enhanced solar energy utilization in flat PV (photovoltaic) modules cooled by heat spreaders in conjunction with cotton wick structures. Energy 2015;90:1401–10. https://doi.org/10.1016/j.energy.2015.06.074.

[47] Alami AH. Effects of evaporative cooling on efficiency of photovoltaic modules. Energy Convers Manag 2014;77:668–79. https://doi.org/10.1016/j.enconman.2013.10.019.

[48] Chandrasekar M, Suresh S, Senthilkumar T, Ganesh Karthikeyan M. Passive cooling of standalone flat PV module with cotton wick structures. Energy Convers Manag 2013;71:43–50. https://doi.org/10.1016/j.enconman.2013.03.012.

[49] Zhu L, Raman A, Wang KX, Anoma MA, Fan S. Radiative cooling of solar cells. Optica 2014;1:32–8. https://doi.org/10.1364/OPTICA.1.000032.

[50] Riggs Brian C, Biedenharn Richard, Dougher Christopher, Ji Yaping Vera, Qi Xu, Romanin Vince, et al. Techno-economic analysis of hybrid PV/T systems for process heat using electricity to subsidize the cost of heat. Appl Energy 2017;208: 1370–8. https://doi.org/10.1016/j.apenergy.2017.09.018.

[51] Gifford, Jason S., and Robert C. Grace. CREST Cost of Renewable Energy Spreadsheet Tool: A Model for Developing Cost-Based Incentives in the United States; User Manual Version 4, August 2009-March 2011 (Updated July 2013). No.

NREL/SR-6A20-50374. National Renewable Energy Lab.(NREL), Golden, CO (United States), 2013.
[52] NREL data base n.d. https://www.nrel.gov/pv/lcoe-calculator/documentation.html.
[53] IEA data base n.d. https://www.iea.org/data-and-statistics/charts/levelised-cost-of-electricity-lcoe-for-solar-pv-and-coal-fired-power-plants-in-india-in-the-new-policies-scenario-2020-2040.
[54] IRENA data base n.d. https://www.irena.org/publications/2020/Jun/Renewable-Power-Costs-in-2019.
[55] Daghigh R, Ruslan MH, Sopian K. Advances in liquid based photovoltaic/thermal (PV/T) collectors. Renew Sustain Energy Rev 2011;15:4156–70. https://doi.org/10.1016/j.rser.2011.07.028.
[56] Hazami M, Mehdaoui F, Naili N, Noro M, Lazzarin R, Guizani A. Energetic, exergetic and economic analysis of an innovative Solar CombiSystem (SCS) producing thermal and electric energies: application in residential and tertiary households. Energy Convers Manag 2017;140:36–50. https://doi.org/10.1016/j.enconman.2017.02.040.
[57] Sopian K, Liu HT, Kakac S, Veziroglu TN. Performance of a double pass photovoltaic thermal solar collector suitable for solar drying systems. Energy Convers Manag 2000;41:353–65. https://doi.org/10.1016/S0196-8904(99)00115-6.
[58] Sopian K, Yigit KS, Liu HT, Kakaç S, Veziroglu TN. Performance analysis of photovoltaic thermal air heaters. Energy Convers Manag 1996;37:1657–70. https://doi.org/10.1016/0196-8904(96)00010-6.
[59] Aste N, Chiesa G, Verri F. Design, development and performance monitoring of a photovoltaic-thermal (PVT) air collector. Renew Energy 2008;33:914–27. https://doi.org/10.1016/j.renene.2007.06.022.
[60] Elsheikh AH, Sharshir SW, Mostafa ME, Essa FA, Ahmed Ali MK. Applications of nanofluids in solar energy: a review of recent advances. Renew Sustain Energy Rev 2018;82:3483–502. https://doi.org/10.1016/j.rser.2017.10.108.
[61] Al-Waeli AHA, Sopian K, Chaichan MT, Kazem HA, Hasan HA, Al-Shamani AN. An experimental investigation of SiC nanofluid as a base-fluid for a photovoltaic thermal PV/T system. Energy Convers Manag 2017;142:547–58. https://doi.org/10.1016/j.enconman.2017.03.076.
[62] Kylili Angeliki, Fokaides Paris A. Life cycle assessment (LCA) of phase change materials (PCMs) for building applications: a review. J Build Eng 2016;6:133–43. https://doi.org/10.1016/j.jobe.2016.02.008.
[63] Gao, Elizabeth, Bao Zhang, L. D. Stephenson, B. Boddu, and Jonathan Trovillion. Prediction of phase change material (PCM) degradation. Proceedings of the Thermal Performance of the Exterior Envelopes of Whole Buildings XII, Clearwater, FL, USA (2013): 1–5.
[64] Babu C, Ponnambalam P. The role of thermoelectric generators in the hybrid PV/T systems: a review. Energy Convers Manag 2017;151:368–85. https://doi.org/10.1016/j.enconman.2017.08.060.
[65] Babu C, Ponnambalam P. The theoretical performance evaluation of hybrid PV-TEG system. Energy Convers Manag 2018;173:450–60. https://doi.org/10.1016/j.enconman.2018.07.104.
[66] Mundada AS, Shah KK, Pearce JM. Levelized cost of electricity for solar photovoltaic, battery and cogen hybrid systems. Renew Sustain Energy Rev 2016;57:692–703. https://doi.org/10.1016/j.rser.2015.12.084.
[67] Tomar V, Tiwari GN, Bhatti TS. Performance of different photovoltaic-thermal (PVT) configurations integrated on prototype test cells: an experimental approach. Energy Convers Manag 2017;154:394–419. https://doi.org/10.1016/j.enconman.2017.11.033.
[68] Short, Walter, Daniel J. Packey, Thomas Holt. A manual for the economic evaluation of energy efficiency and renewable energy technologies. No. NREL/TP-462-5173. National Renewable Energy Lab., Golden, CO (United States), 1995.
[69] Fu, Ran, David J. Feldman, Robert M. Margolis. US solar photovoltaic system cost benchmark: Q1 2018. No. NREL/TP-6A20-72399. National Renewable Energy Lab. (NREL), Golden, CO (United States), 2018.