

Original Research Paper

# Hybrid Photovoltaic/Thermal (HPV/T) Systems: From Theory to Applications

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**Abstract:** Hybrid photovoltaic/ thermal systems are very promising clean energy harvesting devices where they can be used either standalone system or can be incorporated with other systems. In this study, historical developments leading to current Hybrid Photovoltaic/Thermal (HPV/T) systems as it is used today and global findings to enhance the performance of HPV/T system through state-of-the-art analyses are presented in a thematic way. The findings from initial studies on the HPV/T systems is revealed in an historical way and rest of sections are formed based on selected criteria. The paper covers basic and advanced type collectors, working fluids, analyzing methods to assess performance, thermodynamic approaches, optimization of design parameters and mass flow rates, techniques to enhance performance and comparative studies. Especially, various parametric studies to optimize performance of the HPV/T with respect to selected parameters including different types of absorbers, packing factor, cooling schemes, working fluid types, modifications at different sections of the system are comprehensively investigated. Based on the conclusions, the variation in electrical and thermal efficiencies are mainly in the scope of this study. It is observed from the literature that solar HPV/T system has a great potential to be one of the up and coming clean energy technology.

**Keywords:** HPV/T Systems, Thermal and Electrical Efficiency, Performance Enhancement, PV Systems, COP, Photovoltaics

## Introduction

### Renewable Sources

The structure of the modern society has been built based on the technological developments where energy is one of the vital demands of this system. Without using available energy in the world, the comfort and convenience provided by the growing technology would not be realized. Thus, vast amount of research has been done and money have been spent to resolve energy problems (Sahin *et al.*, 2007; IEA, 2016a). Total energy requirement to maintain today's modern life have been primarily met by the use of fossil fuels but this leads to serious environmental problems (IEA, 2016b). World attention was turned to renewable energy resources over the years due to high oil prices and increase in pollution. Recently, governments agree that renewable sources should be utilized at maximum level. Today, these sources can approximately meet 14% of the world's total energy demand, however, their future potential is

gradually increase (IEA, 2017; Hasan and Sumathy, 2010). Solar power has the greatest potential among other renewable energy sources since it can be easily and continuously harvested to provide unlimited energy in an environment friendly way (Lamnatou and Chemisana, 2017; Cuce and Bali, 2009a; 2010; 2009b). Accordingly, the potential of global use of solar energy is much higher than other renewable energy sources. The Earth is irradiated with solar energy approximately total value of 3.8 million EJ by sun annually (Johansson *et al.*, 1993). Since they can be manufactured in compact design and be used in remote areas of the world, Hybrid Photovoltaic/Thermal (HPV/T) units are fascinating power generators by harvesting useful solar energy at any specific location. A main advantage of a particular HPV/T collector is that it can produce both electricity and heat simultaneously since it is consisted of thermal device (T) which is coupled with Photovoltaic (PV) cells. As a natural consequence, a particular HPV/T module have more potential to produce more output (thermal and

electrical energy) than single PV or simple thermal collector (Zondag *et al.*, 1999; Zondag, 2008). Moreover, these systems can be efficiently used in applications where the surface area is limited. Also, waste heat produced by PV cells can be efficiently delivered to the thermal collector module instead of releasing it to the surroundings. So, system cooling is automatically ensured. A particular study is proved that by using HPV/T systems, the collector area can be squeezed up to 40% instead of using separate thermal and PV modules (IEA, 2007). HPV/T systems have long-lasting structures and can work in silent locations (Ibrahim *et al.*, 2011). Accordingly, the lifespan of a particular HPV/T system varies between 20 and 30 years and maintenance requirements are negligible. The HPV/T technology has grown so much over the years due to many advantages emerged from the use of these systems and they are expected to be dominate renewable market in near future (Hoffmann, 2006). A significant amount of effort has been dedicated to advance HPV/T technology since it was first discovered. In the next section, a vast history of HPV/T systems is reviewed in terms of available literature. Throughout the paper, HPV/T systems will be investigated and classified in detail. The potential use of HPV/T systems in the future is discussed along with appropriate recommendations.

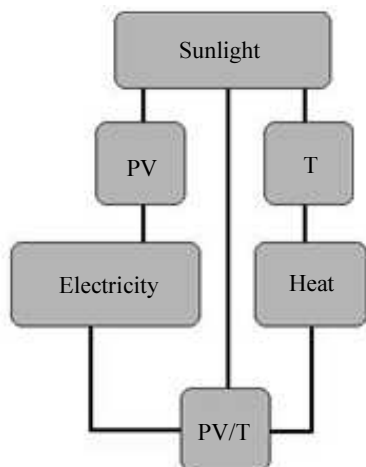
## Development of Solar Photovoltaics and Solar Photovoltaic/Thermal Systems

The historical evolution of photovoltaic phenomenon is launched during the nineteenth century. Becquerel, a famous French physicist, is the one who initially demonstrates the photogalvanic effect by using liquid electrolytes where the experiment revealed light-electricity conversion in 1839 (Luque and Hegedus, 2003). Later, Smith discovered photoconductivity of solid selenium in 1873. Accordingly, the current generation in selenium tubes initiated by the photon impingement is shown by Adams and Day in 1876. After Planck presents the quantum nature of light in 1900, the quantum theory for solids is put forward by Wilson in 1930. Several years later, Mott and Schottky demonstrate the basic theoretical expressions for solid-state rectifier (Joshi *et al.*, 2009a). In 1941, Ohl demonstrates the first silicon cells by using melt grown junctions (Green, 2009). The phenomenon is successfully proved but the efficiency is seen to be less than 1%. Later, Kingsbury and Ohl develop cell with junctions processed based on helium ion bombardment which enables material to has reasonable spectral properties. In 1954, Chapin *et al.* build the first high-power silicon based PV cell with 6% overall efficiency while he is performing experiments on silicon semiconductors (Peter, 2007). PV cells are initially deployed to be used at the Vanguard I space satellite equipped with power radios. The first PV unit with high efficiency made from silicon PV cells is introduced by

Sharp Corporation in 1963. Governments lead researchers to focus on renewable energy sources and photovoltaics by initiating new grants after the oil embargo declared by OPEC in 1973 which is resulted with high oil prices (Zondag, 2008). Due to the massive effort has been put into PV technology, potential energy applications with PV modules start to spread all over the world in the 1970s. At the same time, the idea of using thermal collectors together with PV modules has triggered the research on Hybrid Photovoltaic/Thermal (HPV/T) collectors. Boer introduces the first HPV/T collector which is using air as a heat transfer fluid, in 1973 and he calls it as Solar One House (Boer and Tamm, 2003). This unit is the first attempt which can harvest solar energy and convert it to both electricity and heat energy for domestic use. Accordingly, Wolf (1976) studies water-circulated system where water is used as a heat transfer fluid instead of air. Annual performance of hybrid solar photovoltaic and heating system that is designed for a single-family dwelling is monitored in his study. Later, the interest is directed to ventilated PV façades in the early 1990s as a result of several projects become a current issue in Switzerland concerning about Building-Integrated Photovoltaics (BIPV) (Posnansky *et al.*, 1994; 1992). Today, HPV/T technology has found itself a huge place in the energy market and massive research has been dedicated to improve its efficiency and reduce its maintenance and installation cost. Due to the investments on HPV/T technology, the gap between renewable and traditional power sources is getting narrower.

## General Overview of HPV/T Collectors

The dual operation of PV module and the heat extraction module have resulted in very promising efficiencies since during photovoltaic operation, the low-grade heat originated from the PV cells can be utilized as thermal energy without rejecting it to the surroundings. Basically, a HPV/T collector is a solar harvesting device that can produce electricity due to light-electricity conversion processes at the PV cells and can produce thermal energy due to specific type of collector (Tripanagnostopoulos *et al.*, 2002). Sunlight cannot be fully converted directly into electricity by the PV module, instead most of the absorbed energy is transferred into the remaining material as lost heat. But, the heat extraction unit that is firmly in contact with PV modules can collect the waste heat and can convert it to a thermal energy (Tonui and Tripanagnostopoulos, 2007a). HPV/T systems has wide range of design types. A basic design of HPV/T system can be seen from Fig. 1. The classification of HPV/T modules can be done in several ways such as flat-plate or concentrating which is based on the design or can be based on the type of fluid used as heat transfer agent.



**Fig. 1:** Components of Photovoltaic/Thermal (PV/T) systems. Solar Photovoltaic (PV) unit produces electricity and solar thermal (T) unit produces useful heat, simultaneously (Riffat and Cuce, 2011)

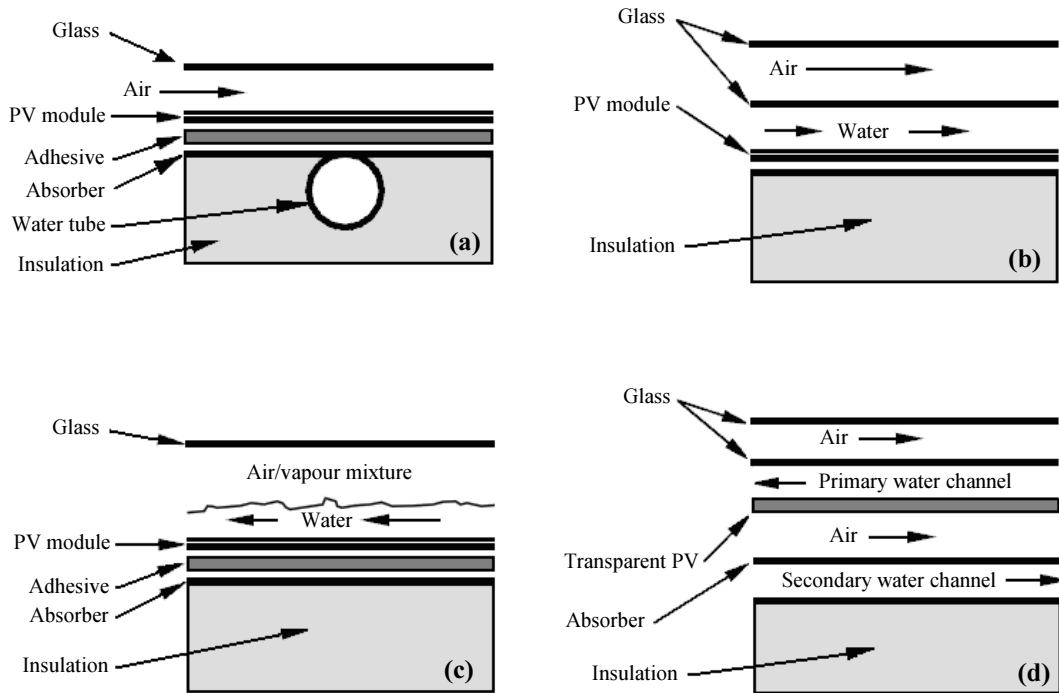
### HPV/T Collectors: Flat-Plate Types

In late 1970s, the fundamentals of flat-plate type HPV/T collectors are initially explained by Russell and Kern (Russell *et al.*, 1981). The fundamental theoretical model of HPV/T collectors are initially introduced by Hendrie by using basic solar thermal collector techniques (Hendrie, 1979). Then well-known Hottel-Whillier model is modified and adapted to the thermal analyses for flat-plate HPV/T collectors (Florschuetz, 1979). In the new model, an assumption is made that local electrical conversion efficiency is a linear function of local absorber temperature. Based on this assumption, steady state energy balance for conventional flat-plate collectors is simply modified based on existing relations and the supporting information can still be kept available in the new model.

The classification of flat-plate HPV/T collectors can be made based on working fluids such as water, air, bifluid (water and air) and nanofluids. Zondag *et al.* (2003) studies sheet-and-tube, channel, free flow and two-absorber flat-plate HPV/T designs where all designs are illustrated in Fig. 2. The basic design of the water type flat-plate HPV/T collector can be seen from Fig. 2a which consists of conventional PV array integrated onto a thermal collector module. It is observed that these designs have different drawbacks such as conventional flat-plate sheet-and-tube HPV/T scheme should be modified to reach higher efficiencies for commercial uses and the heat transfer fluid for channel type flat-plate HPV/T collector should be selected carefully to maintain sufficient irradiation energy. Moreover, free flow HPV/T collector is shown to lose available heat due to evaporation. According to results, the best efficiency is obtained at the channel-below-transparent-PV scheme due to being lack of disadvantages of previous designs.

Liquid based HPV/T collectors are found to operate with higher efficiencies compared to air based ones. Even if air based HPV/T collectors have cheaper installation costs, they are rarely preferred in domestic applications (Aste *et al.*, 2008). Flat-plate HPV/T units may be used as stand-alone or grid-connected system. Talavera *et al.* (2007) showed that grid connected systems are more profitable than standalone systems based on the economical turnover of the HPV/T systems provided that specific economic conditions are successfully ensured.

The power of using HPV/T system instead of using separate PV and thermal unit has been validated. Detailed time-dependent mathematical models are built for flat-plate HPV/T units for building applications and results are validated with experiments in order to show the superiority of using hybrid system (Huide *et al.*, 2017). It is observed that time-dependent mathematical model successfully predicted efficiencies of three units. Results confirm that HPV/T systems show best performance in urban areas. Even if single thermal system has competitive thermal efficiencies, HPV/T system still have the best performance due to the electric generation. Accordingly, variation in daily solar irradiation level is shown to play an important role on the total system efficiency. Singh *et al.* (2016) model Dual Channel Semitransparent Hybrid Photovoltaic Thermal (DCSHPV/T) collector where air flow passage above the cells is named as upper channel and air flow passage beneath the cells is named as lower channel. According to results, overall exergy efficiency and overall thermal efficiency are found to be 5.78% and 35.41%, respectively. Vats and Tiwari (2012) estimate thermal and exergy efficiency of a crystalline silicon (c-Si) cell HPV/T collector for a room contained a volume of 21 m<sup>3</sup>. It is concluded that only 33% of the thermal energy can be effectively used. Yazdanpanahi *et al.* (2015) install an experimental rig consisted of a conventional HPV/T collector. The test results are used to validate one-dimensional steady thermal model and four-parameter PV current model. A good agreement is observed between mathematical model and experimental test results. Additionally, they add the effects of several different exergy losses into equations by introducing extra parameters. Khelifa *et al.* (2016) experimentally and theoretically analyze sheet-and-tube type HPV/T collector by modelling heat transfer mechanism on every node which are selected on different layers. Tiwari and Tiwari (2016) evaluate the advantages of potential use of HPV/T collector as a solar greenhouse dryer where the environmental conditions of India is used for the study. Payback period of the drier system is estimated between 1.2 and 10 years with respect to efficiency demand level. Kazanci *et al.* (2014) evaluate the performance of using HPV/T collector at the concept green energy house at the Technical University of Denmark. In this house, ground is utilized as heat sink.



**Fig. 2:** Cross sectional view of different types of PV/T collectors. (a) sheet and tube, (b) channel, (c) free flow and (d) dual absorber (Ibrahim *et al.*, 2011; Zondag *et al.*, 2003; Riffat and Cuce, 2011; Charalambous *et al.*, 2007)

### Solar Concentrating HPV/T Collectors

PV technology is still growing remarkably, but the total amount of money spent for the unit electricity production by PV modules should still needed to be reduced (Kribus *et al.*, 2006). This problem can be overcome by concentrating more light on existing PV modules by using imaging or non-imaging optical concentrator so that more radiation energy can be converted to an electric energy. The research on concentrating PV technology is started in the 1980s (Kalogirou, 2014). Concentrating PV systems are very cost effective. By concentrating more photons to the PV unit, either much smaller PV areas can be attained to reach same energy level or more energy can be harvested by using the similar system. These may lead to reduction in installation cost or payback period. However, concentration results in higher module temperatures compared to non-concentrating ones (Othman *et al.*, 2005). The functional relations between the temperature of PV module and electrical efficiency are presented in literature in detail (Gupta *et al.*, 2002; Katz *et al.*, 2001; Radziemska, 2003; Radziemska and Klugmann, 2002; Singh *et al.*, 2008).

In general, the classification between concentrating solar photovoltaic and/or hybrid photovoltaic/thermal systems are implemented based on the Concentration Ratio (CR). Accordingly, Winston develops a method that determines solar tracking characteristics of concentrating systems based on CR values (Winston,

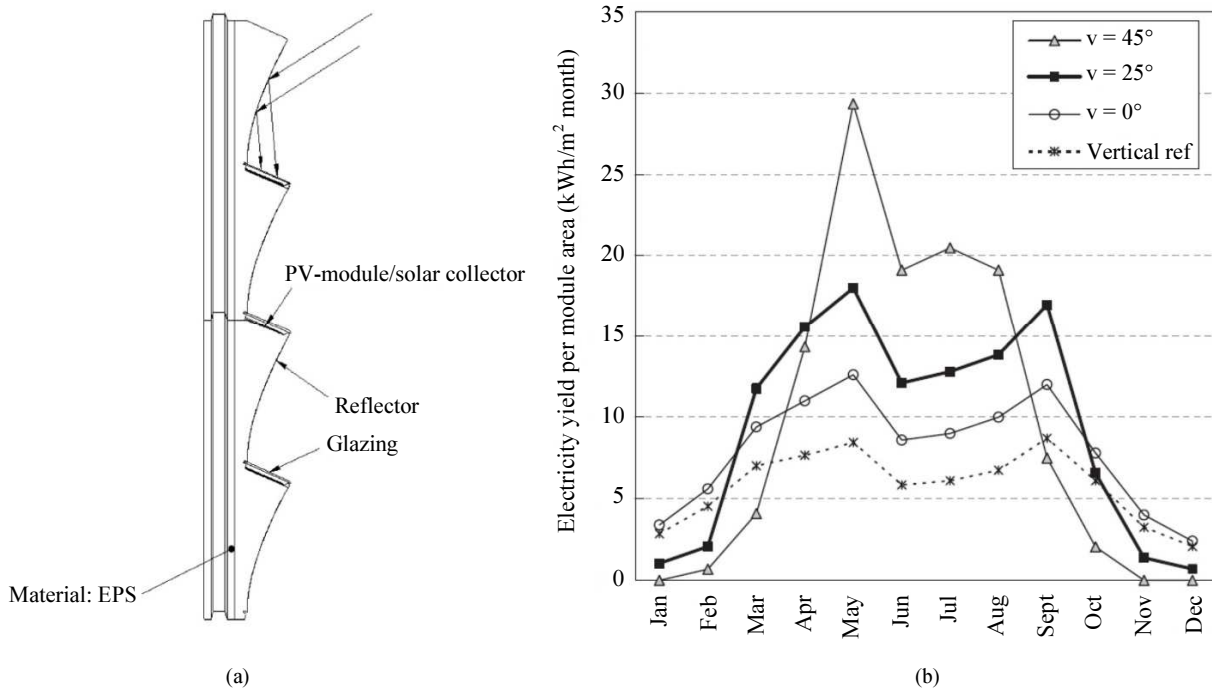
1974). He proposes that solar tracking system is required for a concentrating system with CR higher than 2.5 whereas no tracking is required for a concentrating system with CR lower than 2.5. Sharan *et al.* (1985) reveal the economic benefits of using Concentrating Hybrid Photovoltaic/Thermal (CHPV/T) systems integrated with active and passive cooling systems. The results show that increasing CR value is beneficial for the system performance providing that the outputs are fully utilized. Moreover, an optimum CR value is found to be around 10. The performance of the solar cell is shown to be highly dependent on the temperature profile of the solar module. The change in illumination intensity changes the temperature of the solar cells, so the performance changes accordingly. The functional dependency between illumination intensity and performance of solar cell is investigated by Al-Baali (1986). Three identical solar panels are installed in order to reveal the effects of the concentration and cooling by monitoring their performances. A plane reflecting mirror is used to concentrate the light onto solar panels. According to the results, solar cell temperatures between 35 and 40 degrees are found to be best operating temperatures. Thus, panel with reflecting mirror and cooling system is found to be the design by giving the best results. Garg *et al.* (1991) study the advantages of using various types of plane reflectors to enhance the performance of an air based HPV/T system based on the

results obtained by using their theoretical model. They demonstrate that the decrease in installation expenses can be ensured by replacing expensive PV cells with cheaper concentration plate structures.

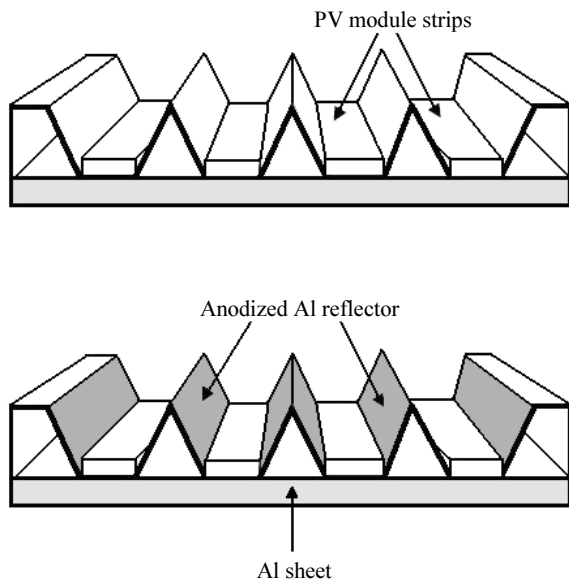
Compound Parabolic Concentrators (CPCs) are solar radiation traps which are designed to efficiently collect and concentrate light from distant sources. Garg and Adhikari (1999a) use CPC to investigate the change in the overall performance of an air based HPV/T system while, Brogren *et al.* (2000) study the effects of using CPC on the overall performance of water based HPV/T system. Both studies agree that using CPC is advantageous. The value of the optical efficiency of the water based system is estimated to be 0.71 numerically which is shown to be good agreement with the experiment results. Brogren and Karlsson (2001) demonstrate that the unit price of PV electricity of the concentrating system with low concentration can be further reduced by using low-cost aluminum reflectors. Coventry (2005) designs an enhanced concentrating water based HPV/T system, that is named as Combined Heat and Power Solar (CHAPS) unit, with a high CR value of 37. The device is a type of linear concentrator and be able to track the sun on a single axis during operation. Combined efficiency of the unit is shown to be 69% which is a combination of thermal and electrical efficiencies that are estimated around 58% and 11%, respectively. Various types of concentrators are tested for CHPV/T systems. The performance of water based HPV/T system equipped with a linear Fresnel concentrator which can be able to track the sun on a dual axis is studied by Rosell *et al.* (2005). While the CR value is set above the value of 6, combined efficiency of the unit is monitored to be over 60%. Additionally, theoretical studies confirm that thermal resistance between the absorber plate and PV cells plays an important role on the system performance. CHPV/T systems can be designed with low concentrating ratios for specific applications (Reis *et al.*, 2010). On the other hand, Kostic *et al.* (2010a; 2010b) aim to concentrate maximum energy on a specified PV area by finding optimal position for reflectors for the water based HPV/T collector and he also studies the results of reflectance from flat-plate concentrators made of Al foil and Al sheet on combined system efficiency. When concentrators are operated in optimal positions, the combined efficiency of the system equipped with Al foil made flat-plate concentrators is found to be 55% which is seen better than unconcentrated system in terms of overall daily thermal yield. Additionally, concentrated system yields 17.1% better electrical efficiency. Li *et al.* (2011) compare the performance characteristics of different schemes of trough CHPV/T systems integrated with crystal silicon or GaAs PV cell arrays irradiated at a specific energy flux ratio. System equipped with GaAs cell array shows better electrical performance over

system with silicon cell array. Gajbert *et al.* (2007) conduct a parametric study to optimize module and reflector geometries in order to achieve better efficiencies for the stationary, low-concentrating façade-integrated photovoltaic systems whereas (Gajbert *et al.*, 2007) similar systems which are available for the façade integration are discussed previously in detail (Mallick *et al.*, 2004; 2006; Zacharopoulos *et al.*, 2000). The schematic view of stationary façade integrated PV system can be seen from Fig. 3. The geometry and inclination of the reflectors are parametrically analyzed to achieve maximum electrical yield. As seen from Fig. 3b, the electricity production is always higher for concentrated PV system with zero tilt angle. Nevertheless, the output of the system remarkably increases in summer and slightly decreases in winter for other tilt angles. The results obtained from the MINSUN simulation software and measurement data are found in good agreement showing that annual electricity production has a maximum limit of 120 kWh per m<sup>2</sup> PV cell area at the CR value of 4.65, a module tilt angle value of -15° and optical axis of 35° for the climatic conditions of Stockholm, Sweden. The annual electricity production is estimated 72% better than the production of vertical reference module without reflector.

The performance characteristics of an asymmetric Compound Parabolic Concentrating Hybrid PV/T (CPC HPV/T) system developed for high altitudes constructed with reflectors made of aluminum laminated steel and anodized aluminum are evaluated by Nilsson *et al.* (2007) System is designed to be able to be used at the high-altitude countries such as Sweden. Thermal and I-V characteristic curves of the system are plotted based on the data obtained from the MINSUN. According to results, no significant difference in annual yield of selected reflectors is observed. The electrical yield of the system with reflectors are estimated to be around 168 kWh per m<sup>2</sup> cell area which is higher than the value of 136 kWh per m<sup>2</sup> cell area for the reference design without reflectors. The thermal energy yield of the system is observed to be around 145 kW h/per m<sup>2</sup> glazed area at 50°C. Hatwaambo *et al.* (2008) compare the advantages of using rolled aluminum foil, anodized aluminum and miro reflector materials in order to enhance fill factor for low concentrating PV systems. The CR value of the reflector is set to 3.6 during experiments. The performance of the rolled aluminum reflector is not meet with the expectations and in all schemes and fill factors show decreasing trends. On the other hand, it is highlighted that the usage of aluminum reflector is resulted in decrease in installation costs, that is, the cost of the setup with rolled aluminum is estimated to be almost three times less than the cost of the setup with anodized aluminum and five to six times less than the cost of the setup with the miro reflector per meters square.



**Fig. 3:** Schematic view of façade-integrated concentrating PV system with CR value of 3 and monthly performance values with respect to different tilt angles (Gajbert *et al.*, 2007)



**Fig. 4:** Structure of the V-trough concentrating PV module (Solanki *et al.*, 2008; Chen and Riffat, 2011; Riffat and Cuce, 2011)

Solanki *et al.* (2008) construct a system with V-trough channels made of thin Al metal sheets embedded with PV modules in order to concentrate more incoming solar radiation on PV cells and provide better heat dissipation as shown in Fig. 4. In design, six mono-crystalline Si PV

cells are embedded into 6 V-trough channels in single line to increase concentration ratio. Test results indicate that the temperature of PV cells into troughs are similar to the ones in a flat-plate PV module in spite of concentration. The value of the conversion efficiency is found to be 17.1% for the V-trough PV module which was estimated to be 62% higher than the reference flat-plate PV module. Tripathi and Tiwari (2017) build fully covered CHPV/T system and experimentally study to monitor its performance by evaluating two schemes. In the first scheme, system is not moving and in the second scheme, system is tracking the sun between three main positions with the help of Manual Maximum Power Point Tracking technique (M-MPPT). According to results last scheme is much efficient in terms of overall energy and exergy yield. Karathanassis *et al.* (2017) build parabolic-trough CHPV/T collector with a rotating axis. System is observed to reach approximately 50% overall energy. Cooling system for the PV units is placed at the focal axis consisted of elongated plate-fin heat sinks made of microchannels having either constant or stepwise-varying width along three consecutive sections, respectively. Widyolar *et al.* (2017) test a novel custom built parabolic trough HPV/T collector equipped with two concentrator sections. The schematic view of the system can be seen from Fig. 5. The efficiency value predicted by the model is 47%. But due to the losses and imperfections at the experiment setup, this value cannot be obtained as seen from Fig. 5b. At the maximum

exergy efficiency, the cell temperature reaches up to 200°C. Additionally, wavelength selection is applied in order to use high energetic photons for electric production and lower ones for thermal gain. The exergy efficiency is obtained up to 37%. The output temperature of the CHPV/T collector varies while the mass flow rate of the coolant water kept constant. However, the mass flow rate should be controlled in order to get constant output temperature, especially for industrial use. Atheaya *et al.* (2016) build analytical model of CPC HPV/T collector with constant outlet temperature in order to estimate its performance characteristics as well as exergy efficiency. Partially covered and fully covered schemes are compared. It is found that the targeted temperatures can be obtained with lower efficiencies at constant mass flow rate. The system with concentration ratio of 5 is shown to have ability to reach higher

temperatures. Daneshazarian *et al.* (2018) reviewed CHPV/T systems in terms of industrial and domestic applications. The performance of HPV/T collector with high concentrator module consisted of Fresnel lens and optical prism is studied by Xu *et al.* (2016). The system allows the light to highly concentrate on a small area where the optical path can be seen from Fig. 6. As seen from the Fig. 6, there is a good agreement between experimental and simulation data. They also note that electrical efficiency can increase with increasing irradiance level and decrease with increasing cell temperature. 2D steady state thermal model and diode model are used for the numerical investigation. Very promising electrical and thermal efficiencies are observed which are estimated to be 28% and 60%, respectively. The performance of using HPV/T unit with Fresnel lens and nanofluid layer is studied by An *et al.* (2016).

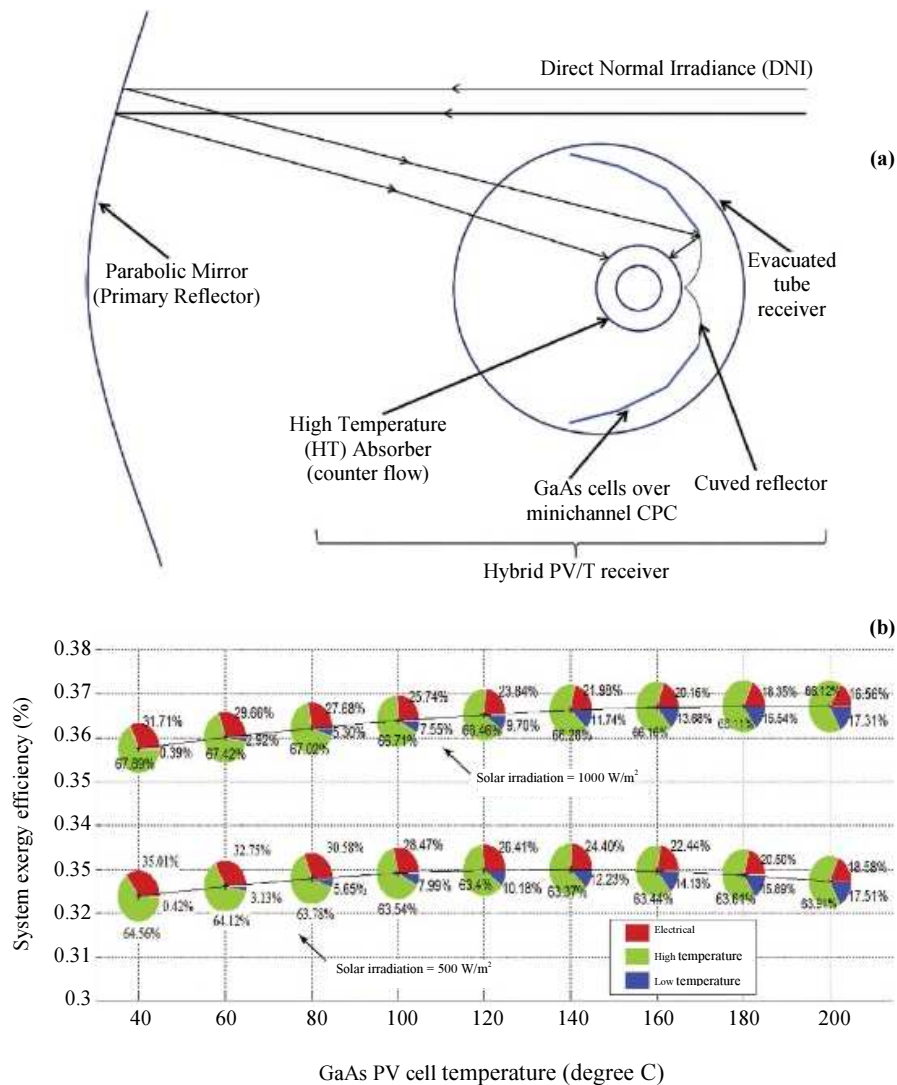


Fig. 5: Schematic view of PV/T unit with double-stage concentrators and performance characteristics with respect to different cell temperatures (Widyolar *et al.*, 2017)

**Table 1:** Selected studies of concentrating PV and hybrid PV/T systems

Type of solar cell	Absorption unit	Specifications	Type of analysis	Enhancement method/ Investigation	Performance values at optimum conditions	Change in Performance	Cost analysis	Error analysis	Literature	Remarks
N/A	Finned air channel, double pass. Collector dimensions are 0.85x1.22 m (WXL).	CR=1.85	Theoretical and experimental	Light concentration by using series of Compound Parabolic Concentrators (CPC) and use of fins for a double pass system.	Combined efficiency is obtained up to a value slightly above 70%. Electrical efficiency is below 10%.	N/A	N/A	Almost 10% difference is observed between experimental and theoretical results.	41	Steady-state theoretical model is built based on energy balance within layers of PV/T. Good reference for experimental system design.
N/A	Metallic plate absorber with passive and active cooling.	Variable CR up to 120 selected for model.	Theoretical	Passive and active cooling comparison. Using cost model to seek optimum CR value for minimum unit cost.	The value of the optimum CR is around 10.	N/A	Unit cost graphs are plotted with respect to selected parameters and CR ratio.	N/A	48	There is an optimum CR ratio where the cost of unit of electrical energy reaches minimum. Unit cost decreases with increasing CR when overall efficiency is considered.
Triple-junction	Small-scale metallic cooling plate with coolant tubes.	CR=500, solar tracking, dual axes.	Theoretical and experimental	Miniature design with high concentration. Parabolic dish is used.	Thermal efficiency is obtained around 60% and electrical efficiency is around 18%.	N/A	Electricity cost is estimated to be \$2.5 per peak electric Watt.	N/A	39	Payback time of the system is less than 10 years. The heat can be constantly provided in low-temperature applications.
N/A	Metallic black Painted absorber	CR=2.88 and 1.0.	Theoretical	System with compound parabolic concentrator (CPC) troughs.	Thermal efficiency is obtained around 50%.	N/A	N/A	N/A	51	Model is presented based on thermal resistances. Study presents fundamentals of concentrating solar units.
Monocrystalline silicon	Finned extruded aluminum spine receiver.	CR=37, sun tracking, single axis.	Experimental	Concentration is provided by using glass-on-metal mirrors. Solar cells are embedded on aluminum spine receiver.	Thermal efficiency is obtained to be 58% and electrical efficiency is 11%.	N/A	N/A	N/A	54	Combined system. Gaps between mirrors and shading are significant parameters.
Monocrystalline silicon	V-trough system	Solar tracking, dual axes.	Theoretical	V-trough low Concentration system.	N/A	The annual yield is increased by 86% compared to the that of conventional modules.	N/A	Good agreement is observed with data presented in literature.	56	Theoretical model is shown to successfully predict system performance.
Opaque silicon	Aluminum plate absorber with wide single water channel.	CR=11, sun tracking, dual axes.	Theoretical and Experimental	Using Fresnel lens to concentrate light.	Thermal efficiency is obtained up to 60%.	N/A	N/A	Model can predict within 9% accuracy.	55	The structure of the system can be installed easily. Very compact.
Single-crystalline silicon	Sheet-and-tube design made of aluminum.	Two Al sheet flat solar reflectors with dimensions of 1.37x0.72 m.	Theoretical and experimental	Light concentration is ensured by two flat sheet aluminum reflectors	Thermal efficiency is obtained to be 36.9% and electrical efficiency is 3.69%.	The energy gain level is estimated between 20.5 to 35.7% compared to conventional solar collectors.	Flat reflectors bring additional cost which is around 10%.	Good agreement is observed between experimental and numerical results.	57	The modification offers reduction in the payback time. Optimum position angle has seasonal dependence.
Single crystalline silicon, polycrystalline silicon, super cell and a GaAs cell arrays	Finned water pipe.	CR = 16.92, sun tracking, single axis.	Experimental	Trough concentrating system.	Instantaneous thermal efficiency is seen to be 49.84% and electrical efficiency is 9.88%.	Electrical efficiency is 2% and thermal efficiency is 7.4% higher than these of low-cost system.	The cost of the electricity \$2.37 per watt which is almost same price as flat-plate collector.	N/A	59	Study compares different cell types. System with GaAs cells shows better electrical performance.
Thin film Copper-indium-gallium-diselenide	No absorber	CR=4.65, façade integrated system.	Simulation and experimental	Optimization of module and reflector geometries by parametrically investigating parameters such as tilt angle and concentration ratio.	120 kWh/m <sup>2</sup> cell area electricity production is obtained.	72% higher electricity is produced per cell area compared to vertical system without reflector.	N/A	Good agreement is observed between numerical and experimental results. Data is broadly-distributed.	60	The installation cost can be reduced by spending more on reflector material than cell material. System geometry is optimized.
Semitransparent PV	Absorber with aluminum channel.	Fully covered system with sun tracking on single axis.	Theoretical and experimental	Efficiently sun tracking by applying manual maximum power point tracking technique (M-MPPT).	Thermal efficiency is obtained up to 37% and electrical efficiency is up to 10%.	System with sun tracking yields 1.25 times more thermal energy compared to stable system.	N/A	The value of the root mean square percent deviation is less than 2.71.	67	System is positioned at three different angles during daytime.
Monocrystalline silicon	Two plate absorber with elongated plate-fin heat sinks prepared in two different configurations.	Sun tracking, double axes. Anodized aluminum sheets are used as reflectors. CR= 1090 suns.	Experimental And numerical	Custom made cells and efficient cooling	Thermal efficiency is seen to be 44% and electrical efficiency is 6%.	N/A	1.75 Euro/W is estimated per meter square active area.	Uncertainty for each parameter is lower than 2%. Experimental and numerical results are in good agreement.	68	Reliable system. System may be tested under sun with tracking.
InGaP/GaAs/Ge triple-junction solar cells	Heat sink with axial grooved tube water channel	CR= 1090 suns.	Experimental And numerical	High concentration is provided by Fresnel lens and optical prism.	Thermal and electrical efficiency can be obtained up to 60% and 28%, respectively.	N/A	N/A	RMSD values are 2.6% and 21.4% for electrical and thermal efficiencies, respectively. Results are in really good agreement.	72	Two dimensional steady-state thermal model is used.
Polysilicon	Two square tubes made of aluminum connected in series.	CR=10.2, three square linear concentrating Fresnel lenses, sun tracking.	Theoretical and experimental	Spectral filtering by using nanofluid and using Fresnel lens.	Overall system efficiency is 25.2%	System with nanofluid filter shows 13.3% better performance compared to the system without filter.	N/A	N/A	73	Experiments are conducted in limited conditions.
GaAs	Absorber with Aluminum Minichannel struts covered with glass tube	CR = 60, sun tracking, dual axes.	Theoretical and Experimental	Double concentrator (parabolic through and CPC), allowing PV and thermal units have independent working characteristics.	Thermal efficiency is seen to be 37% and electrical efficiency is 8%.	N/A	System cost is \$283.1/m <sup>2</sup> (per unit of parabolic trough aperture area)	Fair agreement is observed between experimental and theoretical results.	74	Compact and promising system. Outdoor testing is available. High outlet temperatures can be reached (up to 365°C)

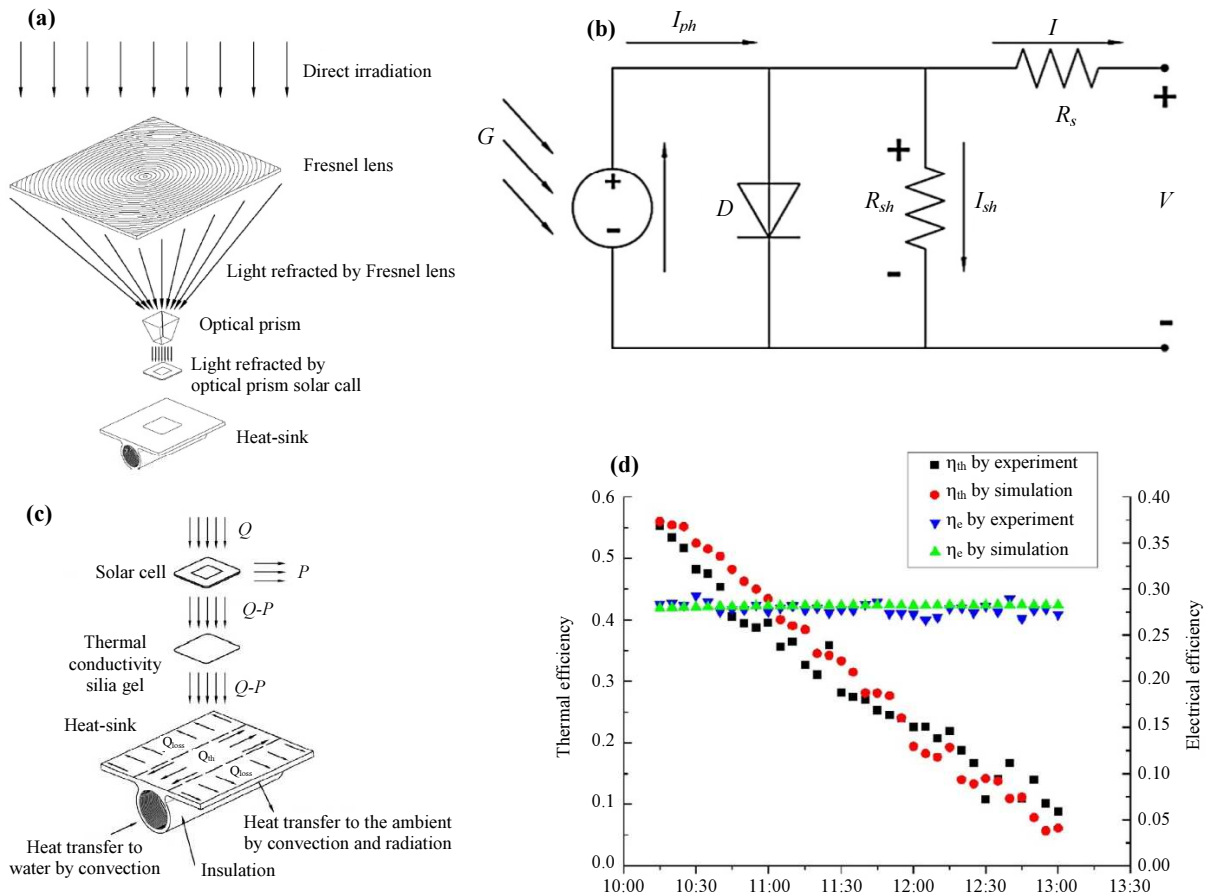
The mechanism of spectral splitting is presented in Fig. 7. The electrical power tends to decrease with increasing particle size, but more importantly the electrical efficiency

is still increasing. Thermal power increases with increasing particle size since the fluid temperature can be risen. On the other hand, thermal efficiency is decreasing due to poor

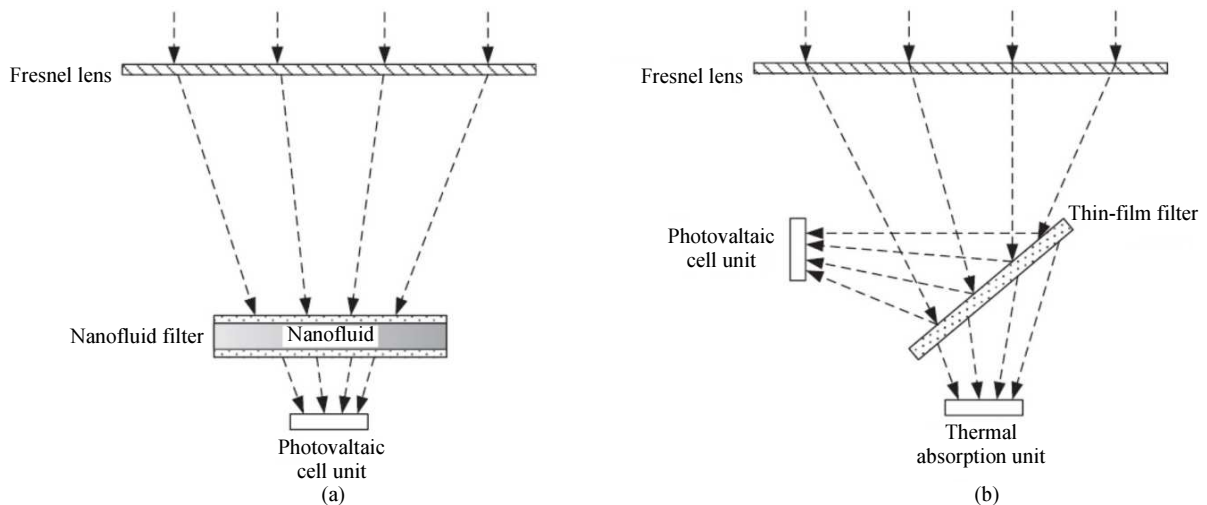


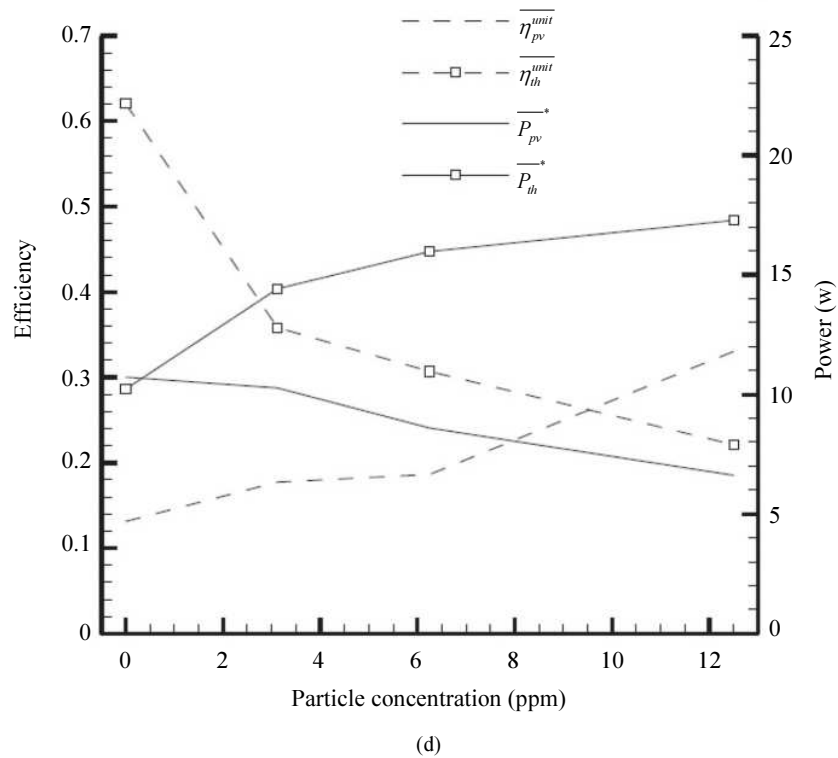
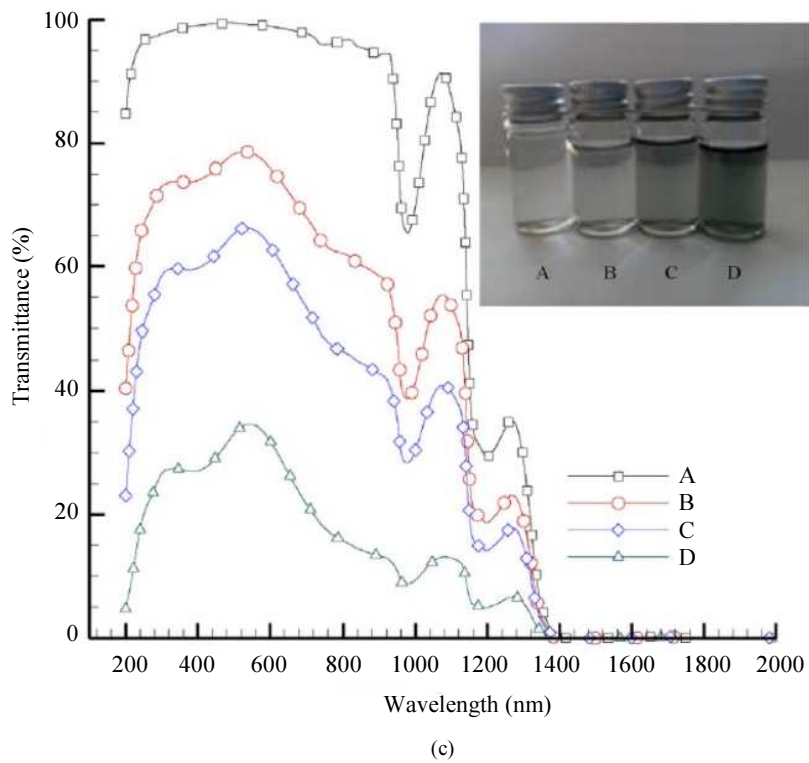
heat dissipation as a result of bigger particle sizes. Polypyrrole nanofluid layer is used for the spectral filtering of incoming concentrated light. Maximum overall efficiency of the system is observed to be 25.2%. Abdelhamid *et al.* (2016) demonstrate a HPV/T collector with 60x concentration consisted of non-imaging optics and

GaAs cells. Electrical efficiency up to 25% is observed. As seen from this section, concentration technique can result in significant increase in both thermal and electrical efficiency. But for these systems, very efficient cooling system is required. Summary of this section formed by selected studies can be seen from Table 1.



**Fig. 6:** High concentrating PV/T unit with Fresnel lens. (a) Schematic view of the system, (b) equivalent circuit model of solar cells, (c) heat fluxes on the system, (d) performance characteristics during operation period (Xu *et al.*, 2016)





**Fig. 7:** Concentrating PV/T system with spectral splitter. (a) spectral splitting method by using nanofluid filter, (b) spectral splitting method by using thin film filter, (c) optical performances of solutions of pure water and polypyrrole nanofluid with different particle concentration, (d) normalized performance characteristics with respect to type of the solution (An *et al.*, 2016)

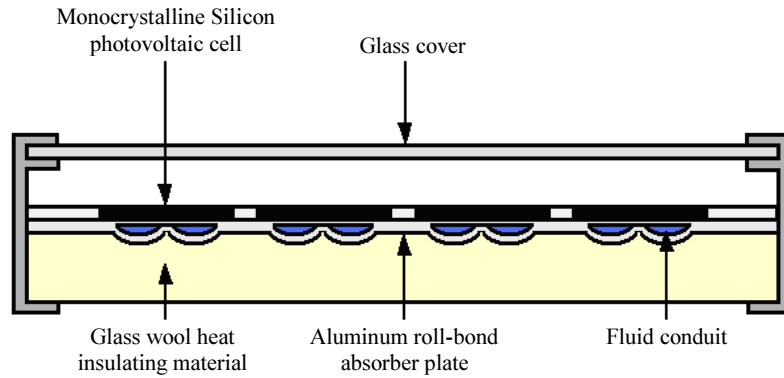
## HPV/T Collectors Using Water as Heat Transfer Fluid

Wolf (1976) builds a new module made of solar arrays, a thermal collector and a battery for residential use. The idea of cooling the system by using water as a heat transfer fluid immediately takes the attention of other scientists. Preliminary studies relating to water based HPV/T collectors are initially performed by Kern and Russell (1978a; 1978b; Chen and Riffat, 2011). Performance of five types of hybrid solar heating and cooling system configurations including baseline solar heating system, parallel heat pump system, series heat pump system, absorption-cycle chiller and high-performance series advanced heat pump are tested for four different climatic regions (Miami, Boston, Ft. Worth and Phoenix) in the USA. According to results, among these locations advanced heat pump system can be able to supply the most energy demand. The use of hybrid systems is shown to be more effective in northern region since heat demand from that region is higher than southern regions. The parametrical field experiments are carried out to test the performance characteristics of a HPV/T collector by Hendrie (1979) and Hendrie and Raghuraman (1980) by gradually changing fluid temperatures and climatic characteristics. Heat loss coefficient, efficiency and maximum thermal efficiency are observed to be 6.77 W/m<sup>2</sup>K, 0.62, 42.6%, respectively. Lalović *et al.* (1986) construct HPV/T collector by combining an array of amorphous Silicon (a-Si) PV cell module and solar thermal collector module. The datasets are obtained under test conditions at the module temperature of 40°C and the solar irradiation value of 700 W per meter square. Solar cells with a total area of 0.9 m<sup>2</sup> are operating at approximately 4% efficiency. System is shown to be able to heat water up to 65°C. Moreover, electrical performance of the system is not yield a significant change where all results eventually lead that system should be used at broader regions.

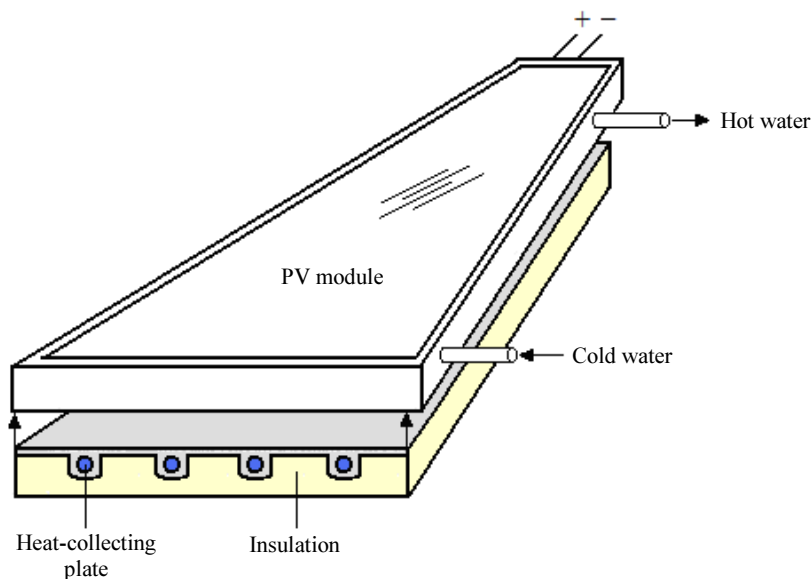
Over the years, the attention given to the HPV/T systems is grown. In the early 1990s, the number of studies on water based HPV/T collectors is escalated by many researchers (Bergene and Bjerke, 1993; Bergene and Lovvik, 1995; Garg *et al.*, 1989; Hayakashi *et al.*, 1989; Huang, 1993; Huang and Du, 1991; Duffie and Beckman, 1991). A detailed theoretical model of water based HPV/T collector is developed in order to monitor its performance by Bergene and Lovvik (1995). The model is able to predict the thermal performance of the system and the heat transfer amount within the cooler and absorber layers as well as considering radiation heat transfer. Overall system efficiency is estimated in the range of 60-80% scale. They proposed that the system might be useful if used as electricity generator and pre-heater for domestic use. The possible applications of HPV/T solar water heaters are

studied at Indian Institute of Technology by several researchers (Garg *et al.*, 1989; Agarwal and Garg, 1994; Garg and Agarwal, 1995; Garg *et al.*, 1994). Studies reveal that system performance is significantly affected by the water level in the storage tank and mass flow rate of circulating water. Moreover, they propose that the HPV/T solar water heaters can be really useful when used in rural areas due to their compactness and effectiveness in daily use. For example, HPV/T collector of about 2 m<sup>2</sup> is shown to be able to produce sufficient electricity which can be able to run 2 tube lights of 20 W each for 5 h and 1 television of 30 W for 4 h. Fujisawa and Tani build and test water based flat-plate HPV/T collector with mono-crystalline Si PV cells placed onto a non-selective aluminum absorber plate and liquid conduit section to provide heat transfer as seen in Fig. 8 (Fujisawa and Tani, 1997). To be able to predict more realistic results, exergy approach is also added into analyses. The coverless HPV/T collector is seen to show best performance. And the significance of the HPV/T collectors is supported with annual conversion performance data. Results show that the total energy yield of the single covered HPV/T collector is comparable to that of the conventional PV module.

A flat-plate water based HPV/T system is tested for the Saudi Arabian climate by Al Harbi *et al.* (1998). Results indicate that PV modules are not able to operate with sufficient effectiveness during summer so the overall system efficiency is not meet expected values due to high temperatures, but system is promising to be able to be used during winter Huang (1999; Huang *et al.*, 2001). develop and test an unglazed water based HPV/T collector with a 60W standard PV module placed on a collector plate as shown in Fig. 9. Initially, tube-in-sheet collector plates with W/D ratios of 6.2 and 10 are tested. Results show that the performance of HPV/T collector is not meet with expected values. So, new collecting plate with polycarbonate multi-channel structure with W/D ratio of 1 are implemented. This corrugated polycarbonate panel scheme is found to be successful by meeting expected thermal performance. 4°C temperature difference is observed between the water in the storage tank and the PV module. A mathematical model of water based HPV/T system is developed by Kalogirou (2001) and for the analyses, climatic data for the Cyprus is used. Transient simulation program TRNSYS is used for analyses. The thermal system of the model consist of a pump, a hot water storage tank and a differential thermostat whereas the electricity side of the model consist of a battery bank, an inverter and series of PV panels. The payback time of the system is estimated to be around four and a half years by increasing the overall annual efficiency of the PV unit from 2.8% to 7.7% and supplying 49% of the hot water demand of a particular house. Norton *et al.* (2001) propose novel approaches to characterize and to obtain the performance characteristics of the thermosyphon solar water heaters.



**Fig. 8:** Components of the glass covered water based hybrid PV/T collector (Ibrahim *et al.*, 2011; Fujisawa and Tani, 1997; Riffat and Cuce, 2011)



**Fig. 9:** Structure of the hybrid water based PV/T collector with sheet and tube absorber plate (Ibrahim *et al.*, 2011; Huang *et al.*, 2001; Riffat and Cuce, 2011)

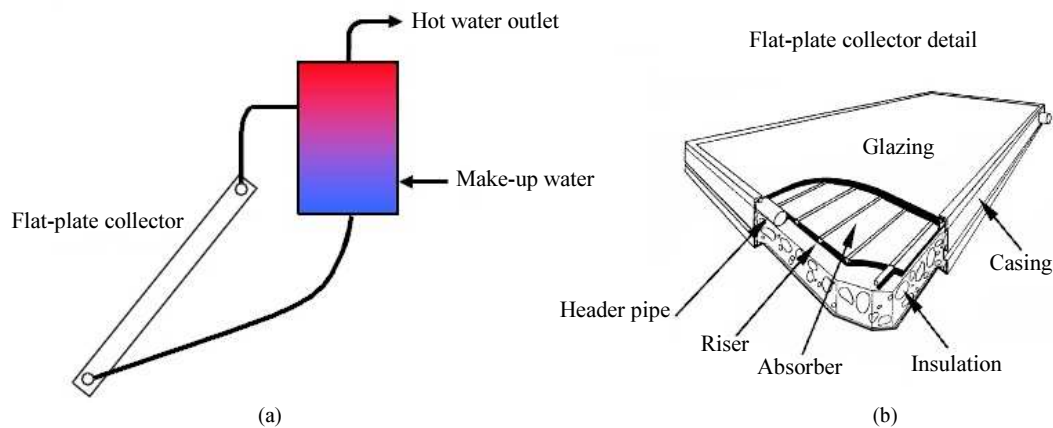
Sandnes and Rekstad (2000; 2002) evaluate the performance of using a water based HPV/T collector constructed by placing of single-crystal silicon made PV cells on a polymer thermal collector. The inner surface of the channels of the absorber plate are coated with the ceramic granulates to improve heat transfer within the surface and fluid. They recommend that the design is suitable for the low temperature applications in order to get better electrical efficiency from the PV system. Zondag *et al.* (2002) derive steady-state and transient simulation models to analyze performance characteristics of water based HPV/T collectors which are able to predict experimental results within 5% accuracy for daily output. It is observed that the predictions obtained from simplest 1D steady-state model are approximately as good as predictions obtained from more complex 3D dynamical model. However, 2D and 3D models are

needed to analyze HPV/T design in detail, since more info can be dig by using complex models. Chow (2003) analyzes a single-glazed flat-plate water based HPV/T collector by constructing an explicit dynamic model by implementing control-volume finite-difference approach. The model is able to successfully evaluate the performance of the HPV/T collector even is able to calculate instantaneous energy outputs. Kalogirou and Tripanagnostopoulos (2005) evaluate the performance of a glazed flat-plate water based HPV/T collector consisted of a total surface area of 4 m<sup>2</sup> and a 160 L hot water storage tank for the climates of Madison (Wisconsin), Nicosia (Cyprus) and Athens (Greece). The system can be seen from Fig. 10. Amorphous and polycrystalline silicon PV cells are used at the system construction. The results indicate that the electrical output of the system with polycrystalline silicon PV

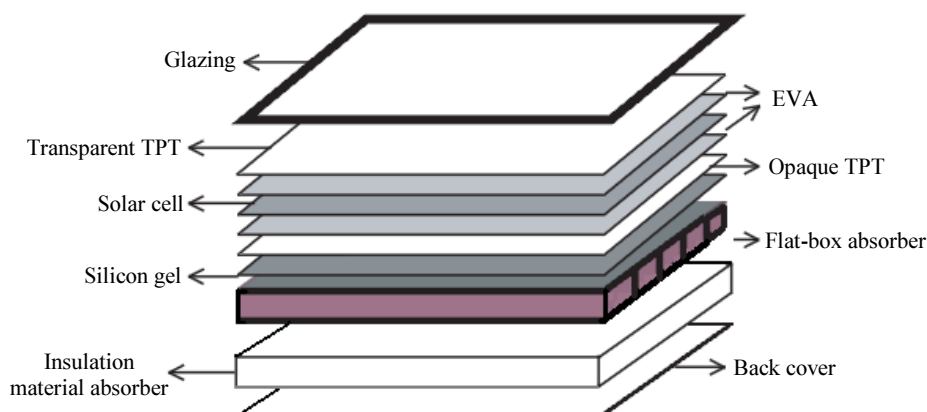
cells are observed to be 499 kWh, 532 kWh and 515 kWh with respect to three locations. Accordingly, electrical outputs of the system with amorphous silicon PV cells are observed to be 224 kWh, 260 kWh and 251 kWh, respectively. They highlight that single PV system can be able to generate 30% more electrical energy than HPV/T but still using hybrid system is better due to production of significant amount of hot water for a house demand.

Tiwari and Sodha (2006a; 2006b) conduct several parametric studies to monitor performance characteristics and compare a water and an air based HPV/T collectors constructed in different designs by improving their initial models of Integrated Photovoltaic and Thermal Solar (IPVTS) system. Theoretical expressions are derived for calculating the overall thermal efficiency of IPVTS system and obtain temperature profile of PV module as well as water as a function of climatic and design parameters. Four different design schemes, namely glazed with tedlar

(GT), unglazed with tedlar (UGT), Glazed Without Tedlar (GWT) and Unglazed Without Tedlar (UGWT) are considered for their study. According to results, the daily characteristic efficiency of water based IPVTS system is better than rest of the air based design schemes except GWT. IPVTS system's overall thermal efficiency is estimated 65% for summer and 77% for winter. Chow *et al.* (2006; 2005; 2007a) design a thermosyphon HPV/T system and evaluate its performance for domestic use. Absorber plate design consist of several extruded aluminum alloy box-structure models. The schematic view of different layers of the HPV/T collector as well as the absorber can be seen in Fig. 11. According to the results, the new design has more potential for domestic use. He *et al.* (2006) construct and analyze the performance of thermosyphon HPV/T system with aluminum-alloy flat-box absorber design. The system is able to yield 40% daily thermal efficiency while initial water temperature in the system is equal to daily mean ambient temperature.



**Fig. 10:** A hybrid PV/T thermosyphon system. (a) system layout and (b) components of the collector module (Ibrahim *et al.*, 2011; Kalogirou and Tripanagnostopoulos, 2005; Riffat and Cuce, 2011)



**Fig. 11:** Structural elements of water based hybrid PV/T thermosyphon system (Ibrahim *et al.*, 2011; Chow *et al.*, 2006; Riffat and Cuce, 2011)

Zakharchenko *et al.* (2004) study water based HPV/T system with different panel materials such as  $\text{CuInSe}_2$ , crystalline Silicon (c-Si) and amorphous Silicon ( $\alpha$ -Si) manufactured with very low packing factor. He also conducts a parametric study by using several additional materials and with different construction schemes in order to decrease thermal resistance between the PV panel and the collector. Results show that due to selection of poor quality substrate materials at commercial PV panels, desired thermal resistance cannot be reached. Thus, custom PV panel is constructed with metallic substrate and insulating layer. This design is help to increase the power output by 10%. Kalogirou and Tripanagnostopoulos (2006) show that a HPV/T system can meet with domestic hot water demand sufficiently based on the results obtained through several simulations. They use amorphous Silicon ( $\alpha$ -Si) and polycrystalline Silicon (pc-Si) PV modules coupled with water extraction structure to evaluate electrical and thermal efficiencies. The results are obtained from three locations namely, Nicosia, Madison and Athens which are indicated that pc-Si PV cells produces more electric power than amorphous ones on the other hand, their contribution to thermal output is low. Even if simple PV system can produce 38% more electrical energy, however HPV/T are found to be still successful if thermal output is under consideration. Another flat-box aluminum-alloy water based HPV/T system is designed and tested for moderate climates by Ji *et al.* (2007). Parametric studies are carried out by using different initial temperatures and water mass flow rates. Emissivity of the front-glazed layer and packing factor are adjusted to be 0.83 and 0.63, respectively. According to results, the specific daily values namely, electrical, thermal and total efficiencies and specific primary-energy savings are found to be around 10.15, 45, 52 and 65%, respectively. Saitoh *et al.* (2003) study on brine cooled sheet-and-tube HPV/T collector at their field

experiments and compare its performance those of single PV and solar thermal collectors. Exergy analyses reveal that combined HPV/T has the best output. Vokas *et al.* (2006) derive theoretical model of HPV/T system in order to parametrically analyze its performance for domestic cooling and heating applications with respect to different ambient conditions and total surface area. According to results, HPV/T system is able to provide 21.4 and 11.9% of total domestic cooling and heating load, respectively. It is also highlighted that regional difference plays significant role on the overall system performance.

Theoretical approaches have been very useful to investigate changes in water flow characteristics such as flow regime (Yazdanifard *et al.*, 2016; Bhattarai *et al.*, 2012). Also, these theoretical approaches let researchers to investigate other design effects on the system performance in detail (Fudholi *et al.*, 2014; Riffat and Cuce, 2011). Ji *et al.* (2006a) show that the height and number of the water-flow channel have a significant effect on the overall system performance of a box-frame HPV/T collector based on the data obtained through time-dependent simulations. Chow *et al.* (2007b) perform dynamic simulations on a HPV/T thermosyphon system in order to estimate its overall energy yield and payback period for subtropical climates. It is found that the payback time of the HPV/T system is much shorter than single PV system. Conventional HPV/T system is installed and tested for the New Delhi environmental conditions by Dubey and Tiwari (2008). An analytical expression is derived and validated with experiments in order to reflect the characteristics of the flat-plate HPV/T system designed in several different schemes. Two identical flat-plate collectors with a total area of  $4.32 \text{ m}^2$  are implemented in series and a PV module with an effective area of  $0.66 \text{ m}^2$  is placed at the bottom of one of collectors. The schematic view of cross sectional system design can be seen from Fig. 12.

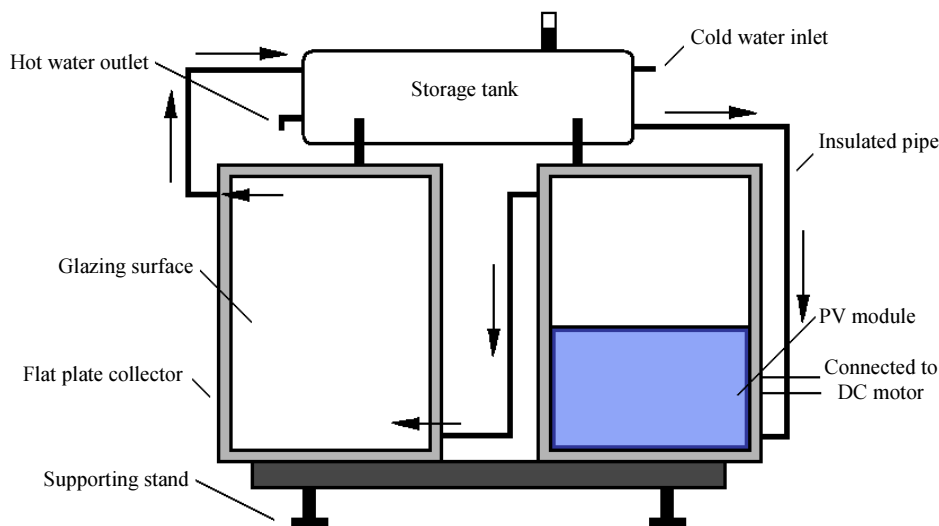


Fig. 12: Components of the solar hybrid PV/T water heating system (Riffat and Cuce, 2011; Dubey and Tiwari, 2008)

The overall system performance of two designs are compared for three months period. The flat-plate HPV/T collector which is partially covered with PV cells is observed to perform better than the uncovered one in terms of mean cell and thermal efficiency. Accordingly, Dubey and Tiwari (2009) compare the performance of uncovered and partially covered flat-plate HPV/T collectors which are connected in series through several simulations by using their own theoretical model. Analytical expressions are constructed based on computer based thermal models and basic energy equations and they are evaluated for four different climates in India namely, Bangalore, New Delhi, Mumbai, Srinagar and Jodhpur. The performance characteristics of four different schemes consisted of HPV/T collectors connected in series and parallel are evaluated in terms of their annual electrical and thermal outputs. Results show that partially covered PV modules are the best option for producing electricity and hot water simultaneously when hot water production is considered primary demand. On the other hand, fully covered PV module is recommended to be used while electricity production is the primary demand.

Fraisse *et al.* (2007) study on combined system consisted of Direct Solar Floor (DSF) and a water based HPV/T collector where DSF provides efficient heat storage, regulation and space heating, simultaneously. The approach is to use DSF a system which is operating at low temperature level to cool PV modules. And the low-grade heat is used in order to further increase thermal efficiency. They conclude that the PV efficiency is lowered 28% due to glass cover and using EVA and glass cover significantly degrade hybrid system performance. Nevertheless, DSF system is shown to be sufficiently effective for water based HPV/T cooling (Chow, 2010). The advantages of placing glass covers on the thermosyphon water based HPV/T system is investigated by Chow *et al.* (2009a) from the thermodynamics aspects. Effects of the several factors on the overall system efficiency are parametrically investigated. For example, it is seen that using glazed covers always beneficial for the hybrid system. Moreover, the increase of PV cell efficiency, wind velocity and packing factor is found to be always favorable for an unglazed system on the other hand, the increase of ambient temperature and illumination intensity is found to be always favorable for a glazed system according to exergy and energy analyses. Tiwari *et al.* (2009) derive analytical expression to obtain temperature distribution of an IPVTS water heater while water is extracted at a constant rate. At the analyses, energy balance is implemented to a system consisted of a storage tank and a flat-plate collector. Dubey and Tiwari (2010) study on overall system exergy and energy characteristics of thermosyphon HPV/T system with and without water extractions constructed in different schemes. Environmental conditions of New Delhi, Srinagar, Mumbai, Bangalore and Jodhpur are considered in the study. According to study,

Srinagar and Jodhpur are the two cities where the system yield minimum and maximum excess energies and efficiency values, respectively. Additionally, considered HPV/T system is shown to be very useful when used at the remote and urban areas.

Huang *et al.* (2001) perform several studies on the overall thermal efficiency of IPVTS system with respect to different design schemes and climatic parameters through numerical approaches. They show that there is an optimum withdrawal flow rate. It is observed that daily overall thermal efficiency of IPVTS system is directly proportional to flow rate level and inversely proportional to outlet flow temperature. Optimum outlet water collection rate is shown to be 0.006 kg/s. Chow *et al.* (2009b) show that hybrid systems are more advantageous than non-hybrid systems in terms of economic arguments. They perform their studies by using a water based BIHPV/T system by using Hong Kong's climate data. Moreover, they conclude that the overall system performance is much better when water is circulated naturally instead of circulation is provided by the pump. The payback period of the system is estimated to be up to 14 years. Daghigh *et al.* (2011) observe that the thermal, electrical and overall system efficiencies of the building-integrated HPV/T system with amorphous silicon cells are 72, 4.9 and 77%, respectively at a flow rate of 0.02 kg/s, illumination intensity value between 700 and 900 W/m<sup>2</sup> and ambient temperature value between 22 and 32°C. On the other hand, at the same conditions same efficiencies for the HPV/T system with crystalline silicon cells are observed to be 51, 11.6 and 63%, respectively. Touafek *et al.* (2011) demonstrate a novel HPV/T system which is built by using low cost materials. These modifications result in an increase in overall efficiency of the system by advancing electrical and thermal conversion. For the new design, the functional relationship between absorber thickness and temperature distribution is studied. Galvanized iron is selected as an absorber material. A good agreement between theoretical and experimental results is observed, where the results agreed that the novel design have great potential to increase overall system performance with low cost materials. This enhancement on the performance of the system allows novel design to be an alternative to conventional solar thermal collectors and side by side PV module.

Even if recent studies discuss mostly about high tech fluids such as nanofluids, water types are still preferred for domestic applications. The annual performances of hybrid PV system, photovoltaic and Solar Thermal (ST) system are compared for uses at the rural houses of China by Huide *et al.* (2017). Time dependent heat balance equations are established at different layers of flat-plate system including glass cover, inner glass layer, PV layer, copper tube and water layer. System of equations are built for photovoltaic system. And all these equations are used to observe performance characteristics of the HPV/T system.

**Table 2:** Selected studies of water based PV and hybrid PV/T systems

Type of solar cell	Absorption unit	Type of analysis	Study aim	Performance values at optimum conditions	Change in Performance	Cost analysis	Error analysis	Literature	Remarks
Amorphous silicon	Copper tube with aluminum heat-exchange plate	Experimental	Testing a-Si cells and installation of initial water type design.	Electrical efficiency is 4%, thermal efficiency is around 40%.	Double-glazed system shows up to 20% better Performance compared to single-glazed system while output temperature is increased.	Cost of the electricity production is below \$2 per peak Watt.	N/A	79	Fundamental study. One of initial designs of water based system. System is capable of producing hot water up to 65°C.
N/A	Tube (copper) and sheet absorber	Theoretical	Optimizing the design parameters for high efficiency.	Overall system efficiency is obtained between 60-80%.	N/A	N/A	N/A	81	Study presents fundamental steady-state model with fairly good predictions.
N/A	Tube and sheet absorber	Theoretical and numerical	Optimizing water mass flow rate and packing factor.	Mean daily thermal efficiency can be obtained up to 55%. Electrical efficiency is in the range of 7 to 8%.	Thermal efficiency increases around 5% when no solar cell is used.	N/A	N/A	88	Study shows that there is an optimum mass flow rate for highest efficiency. Pump system is controlled with differential temperature controller.
Monocrystalline silicon	Aluminum-alloy absorber plate with EVA	Theoretical and experimental	Comparing the performances of PV, PV/T and solar thermal system	Thermal efficiency is around 51% and electrical efficiency is around 11%.	Thermal efficiency is seen to be 16% lower in PV/T system compared to solar thermal system.	N/A	Good agreement is observed. The value of the RMSD is 0.6% between ST and PV/T.	32	Comparison study. Transient two-dimensional model is used. The selection of the any considered system depends on the application.
C-Si solar	Sheet and tube absorber	Theoretical	Building dynamic model and investigation of effects of several parameters, number of glass covers and glazing.	Thermal efficiency is seen up to 50% and electrical efficiency is seen up to 12.6% for single glazed system.	Thermal efficiency is 20 % higher for double glazed scheme compared to that of unglazed scheme, electrical efficiency is around 3 % higher in unglazed scheme compared to double glazed scheme. Thermal efficiency is increased by 10% due to use of glazing.	N/A	Good agreement is observed based on the published data	128	Dynamic analyses may provide more detailed info about the system. Glazing has a positive effect on thermal performance but negative effect on electrical performance. Temperature distribution on solar panel is considered.
Multi-crystalline silicone	Glass covered sheet and tube collector.	Theoretical	Optimizing water replenishment rate in storage tank. Sizing the system based on optimum condition.	N/A	10% reduction in collector area and 66% reduction in storage volume for residential use can be achieved. 7% reduction in collector area and 23% reduction in storage volume for industrial use can be achieved.	N/A	N/A	129	The collector area and the volume storage tank can be further reduced which will eventually affect the cost of the system. The system is proposed for low-temperature applications.
Polycrystalline silicon	Flat-box-type thermal absorber	Numerical and experimental	Developing building integrated system producing electricity and heating domestic water simultaneously.	Thermal efficiency is obtained around 37.5% and electrical efficiency is around 9.39%.	N/A	Payback period is estimated to be around 14 years with annual saving value of 256\$	Good agreement is observed between experimental and numerical results.	125	The proposed building integrated system is capable of producing more output per unit compared to conventional solar system.
N/A	Sheet and tube absorber	Theoretical	Investigation of the effects of the flow regime on the system performance.	Thermal efficiency is seen around 65% and electrical efficiency is around 10%.	Turbulent flow increases thermal efficiency around 5%.	N/A	Good agreement is observed based on the published data.	112	Turbulent effect may increase system efficiency around 10% if glazing is applied.
Polycrystalline silicon	Sheet and tube (copper) absorber	Theoretical and experimental	Comparison study between PV/T and solar collectors based on transient analyses.	Thermal efficiency is seen around 58.7% and electrical efficiency is around 13.7%.	The value of the thermal efficiency is around 13% lower for PV/T system compared to conventional solar collector.	N/A	Good agreement is observed between experimental and numerical results.	113	Thermal efficiency of the PV/T system is lower however primary energy saving efficiency is 16% higher compared to solar collector.
Polycrystalline silicon	Sheet and tube absorber with glazing.	Theoretical and experimental	Web flow tube design, direct flow tube design and spiral flow tube design.	Thermal efficiency is obtained around 54.6% and electrical efficiency is around 13.8%.	Primary energy saving efficiency increases by 10% while mass flow rate increases in given range.	N/A	N/A	114	System performance is monitored for given mass flow rates. Absorber with spiral flow design shows the best performance.
Monocrystalline silicon	Copper thermal tray absorber	Experimental	Designing novel copper wide flow channel and reducing thermal resistance by 9.93%.	Overall system efficiency is up to 87.52%	Thermal efficiency is 4% higher than conventional ones.	N/A	N/A	194	Simple design modification brings more advantages in terms of efficiency.
Monocrystalline silicon	Sheet and heat pipe absorber	Experimental	Parametrically investigating the effect of inclination angle and using heat pipe to have better heat transfer mechanism.	Thermal efficiency is observed up to 52.8%.	Max variation in thermal efficiency is around 10% for optimum system.	N/A	N/A	279	Study shows the effectiveness of using heat pipes in absorber design and their optimum angle.
Monocrystalline silicon	Aluminum absorber plate with micro heat pipe array	Experimental	Testing new absorber design with high conductive pipes.	Maximum electrical efficiency is observed up to 14.65% and maximum thermal efficiency is observed up to 45.38%.	The seasonal variation in electrical efficiency is around 3% and the seasonal variation in thermal efficiency is around 14%.	N/A	N/A	280	Heat transfer has increased significantly.



All results are validated with experimental results. The three different systems, namely, PV, ST and HPV/T are simultaneously tested. ST system is found to have maximum thermal output as expected, but still HPV/T system have the most total useful equivalent thermal energy. Guarracino *et al.* (2016) construct time-dependent electrical and thermal model of sheet-and-tube PVT collector where non-homogeneous temperature distribution is considered on the surface of the solar module. The simulation show that thermal performance of the HPV/T collector is highly responsive to selected parameters of HPV/T module and variations in weather. Thakare *et al.* (2016) optimize water replenishment rate for the storage tanks in order to higher thermal performance. The use of the theory result in reduced system sizes. Summary of this section formed by selected studies can be seen from Table 2.

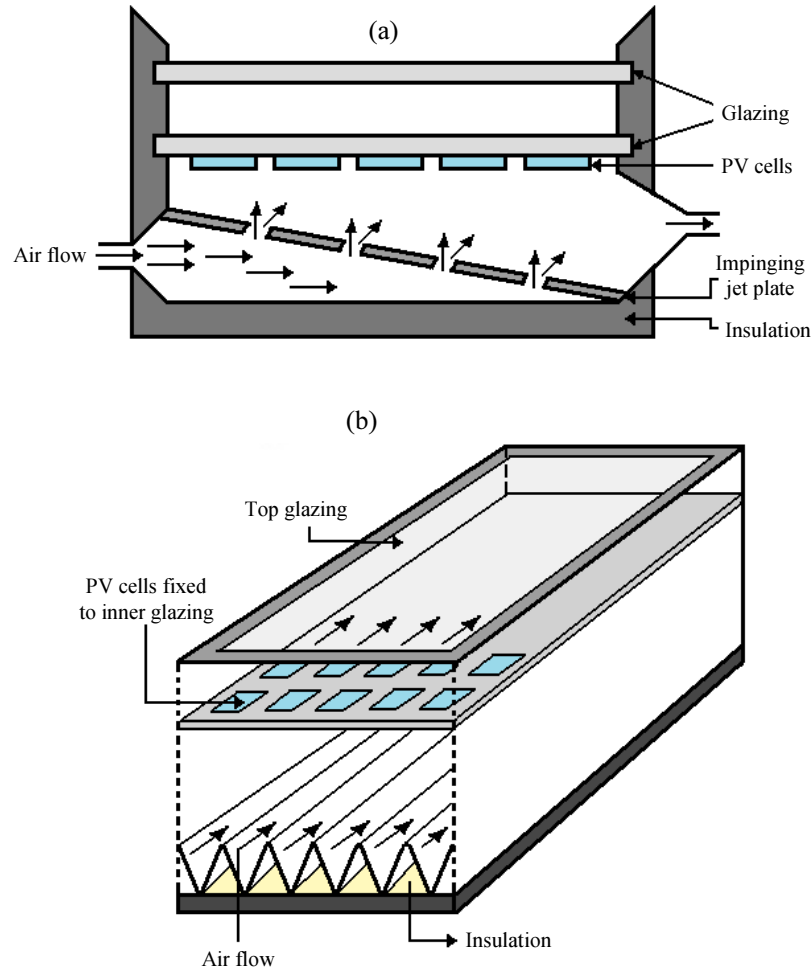
### HPV/T Collectors Using Air as Heat Transfer Fluid

As mentioned earlier, initial studies on air based HPV/T collectors which are conducted at the experimental structure called as Solar One House at the University of Delaware which are performed by Boer (Zondag, 2008; Boer and Tamm, 2003). Later, Florschuetz (1979; 1975; 1976) investigate using air and water at the absorber module of a HPV/T collector as a heat transfer fluid, accordingly observed the effects on the performance of the system in mid 1970s. Hendrie (1982) install air based HPV/T collector with two different design schemes as seen from Fig. 13. At the first scheme, air enters from the inlet of the secondary absorber, then passes through 0.25 cm holes and hits onto the primary absorber, on the other hand, air flows through V-corrugated secondary absorber plate where the tips of the V shapes are in contact with the primary absorber plate at the second scheme. Electrical and thermal efficiencies are calculated to be 8.9% and 42% for the first scheme and 7.8% and 40% for the second scheme, respectively. Younger *et al.* (1981) build and test the performance of HPV/T system consisted of PV-laminate at the air channel where the backside is coated with Teflon material with a porosity of 60  $\mu\text{m}$ . Raghuraman (1981) demonstrate air based HPV/T system where PV cells are adhered directly onto the absorber plate. An extra layer with the thickness value of 0.5 cm and the thermal conductivity value of 0.2 W/mK in between PV cells and absorber plate is added to avoid short-circuiting the PV-laminate. Thermal performance is estimated to be 42% and it is added that significant difference is exist between absorber plate and PV cells. An air based HPV/T system made of 20 air based HPV/T collectors with the total area of 36  $\text{m}^2$  is installed at the Brown University in order to supply the electrical and thermal energy demand of a specific building (Russell *et al.*, 1981; Loferski, 1982). The system is found to be able to supply 65% of the total energy demand of the building. Performance of a glazed

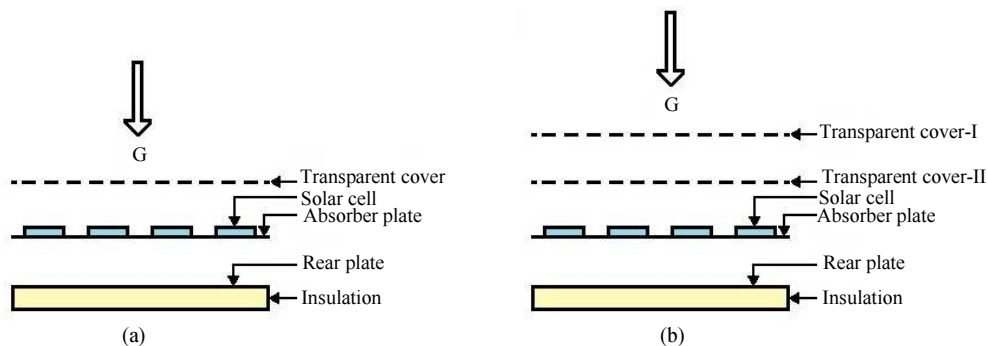
air based HPV/T system is investigated for the remote residence by Komp and Reeser (1987). The best conditions are met by allowing heat dissipates to surroundings via natural convection in summer and using a fan to circulate hot air in winter. Cox and Raghuraman (1985) analyze the performance of an air based HPV/T collectors embedded with single crystal silicon PV cells through several simulations. According to results, the thermal efficiencies of the systems start to decrease when the area covered by PV cells occupies approximately more than 60% of the total collector area. The optimum scheme is reached when the system is installed by using a nonselective secondary absorber, gridded-back PV cells and a cover with high transmissivity/low emissivity above the PV cells. In the early 1990s, several solar drying applications by using HPV/T units are carried out at the Indian Institute of Technology (Garg *et al.*, 1991; Bhargava *et al.*, 1991). Posnansky *et al.* (1992) test air based Building-Integrated Hybrid PV/T (BIHPV/T) system in order to partially supply the heating demand of the building where the system is able to yield total thermal energy of 12 kW. An air based HPV/T system is tested at the environmental conditions of Switzerland (Posnansky and Eckmanns, 1995). The system is operating based on the principle that the excessive energy is stored in an underground storage where this energy is intentionally released in winter to supply the heating demand of the structure. The variation in thermal energy is estimated in between 32-45% for that specific HPV/T system. An air based BIHPV/T system consisted of amorphous silicon PV modules is tested in Italy to evaluate its overall performance (Bloem and Ossenbrink, 1995; Clarke, 1995; Moshfegh, 1995; Ossenbrink, 1994). The proper height for air based HPV/T collector is studied by Shaw (1995) by considering enhanced buoyancy effect for better performance. Sopian *et al.* (1996) compare the overall outputs of single-pass and double-pass air based HPV/T collectors by using steady-state models. Since lower front cover temperature is observed, the double-pass scheme is selected to be better option. Garg and Adhikari (1997) conduct a parametric study on two schemes of air based HPV/T collectors namely single and double glass, as presented in Fig. 14. According to results, several system parameters such as mass flow rate, collector length and cell density is found to be directly proportional to system efficiency, whereas duct depth is found to be inversely proportional to system efficiency for both schemes. It is added that the efficiency of the single-glass scheme is more prone to changes in duct depth. Moshfegh and Sandberg (1998) study on the buoyancy-driven air convection behind the PV panels by analyzing the flow regime and heat transfer mechanisms via numerical and experimental results. Experiments are performed in a channel with height of 7.0 m where the width between the channel walls is set to 0.23 m. Results reveal that total amount of heat input is about 200  $\text{W}/\text{m}^2$  and approximately 30% of the heat is

transferred via radiation to the unheated wall and rest of it released to the air through convection. A dynamic simulation to compare the time dependent performances of an air based HPV/T collector with single and double glass designs by using the New Delhi's climatic data is performed by Garg and Adhikari (1998). Double-glass scheme yield significantly better results than single-glass

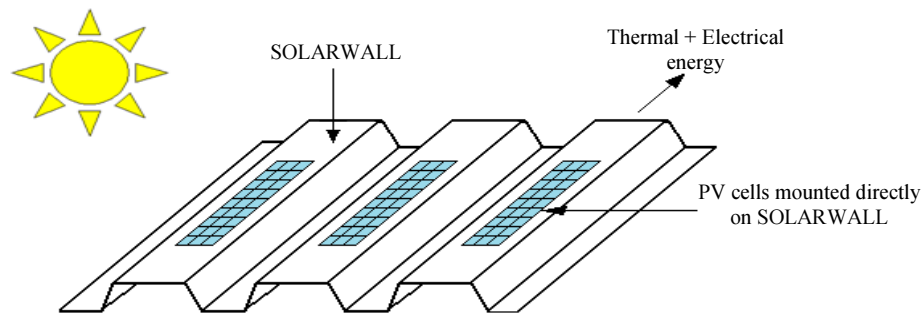
scheme. Hollick (1998) install and test the performance of a solar cogeneration system consisted of PV cells and SOLARWALL panels as seen in Fig. 15. The results showed that the addition of SOLARWALL panels greatly enhanced the PV cell efficiency and accordingly, total efficiency. The payback time of solar cogeneration system is estimated to be relatively shorter.



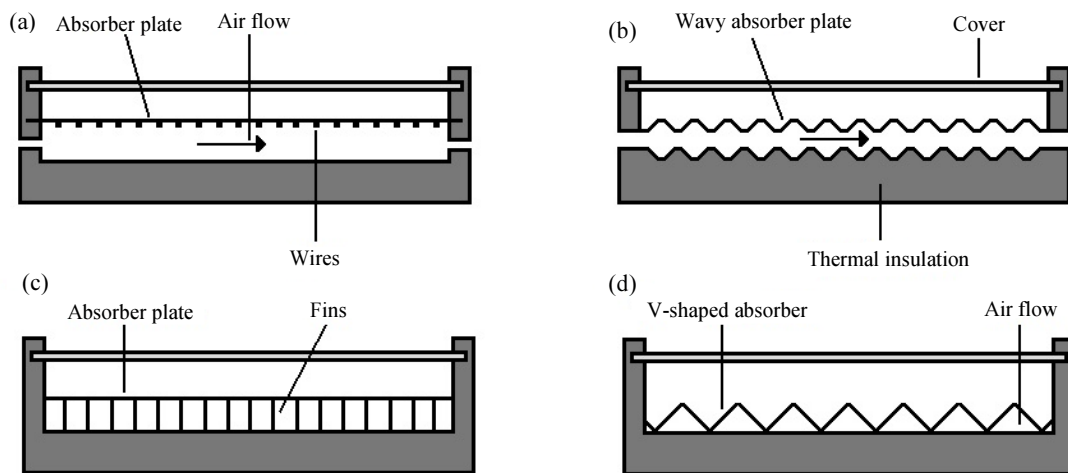
**Fig. 13:** Different types of an air based hybrid PV/T system. (a) impinging jet flow channel design and (b) V-corrugated flow channel design (Zondag, 2008; Riffat and Cuce, 2011; Hendrie, 1982)



**Fig. 14:** Cross sectional view of air based hybrid PV/T collector with different number of covers. (a) single-glass cover and (b) double-glass cover configuration (Ibrahim *et al.*, 2011; Riffat and Cuce, 2011; Garg and Adhikari, 1997)



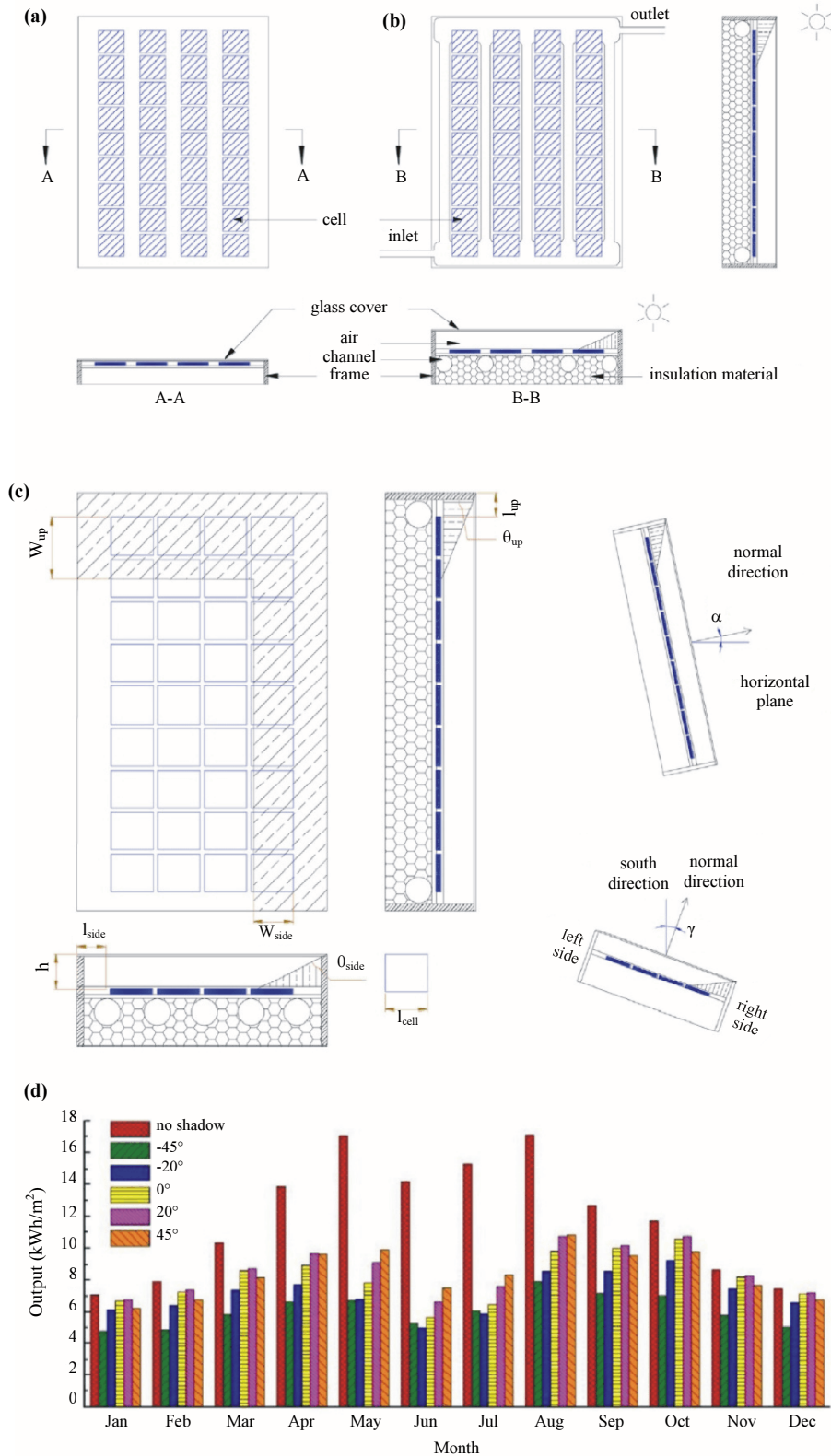
**Fig. 15:** Structure of SOLARWALL integrated PV panels (Riffat and Cuce, 2011; Hollick, 1998)



**Fig. 16:** Cross sectional view of air based hybrid PV/T collectors with different duct configurations. (a) absorber plate augmented with wires (b) wavy absorber plate (c) absorber plate integrated with rectangular fins and (d) V-corrugated absorber plat

PV-roofs are extensively studied by the researchers at the University of Gävle (Dunlop, 1998; Sandberg and Moshfegh, 1998; Sandberg *et al.*, 1998; Strobach *et al.*, 1998). Several numerical and experimental studies are conducted on the roof integrated air based HPV/T collectors to investigate flow characteristics and heat transfer mechanisms. Garg and Adhikari (1999b) perform several parametric studies on the air based HPV/T collectors and plot thermal efficiency curves for different absorber plates based on simulation results. The performance of the HPV/T system with selective coated absorber is elected to be the best case even showing better results than the black painted absorber. Additionally, thermal performance of the system is shown to be higher when absorber is not fully covered with PV cells. Pottler *et al.* (1999) study to enhance the performance of air based HPV/T collector by comparing four different schemes as seen in Fig. 16 where absorber plates are modified differently for each scheme. All four configurations have unique absorber designs namely, absorber with wires used as surface extensions, wavy absorber plate design, absorber plate with fins and V-shaped absorber. The design with single pane cover and absorber with fin wire are elected to be best scheme

which can yield much higher efficiencies if the wires are closely spaced each other. The optimal spacing between these fins is found to be 5 to 10 mm. It is added that the optimal flow regime should be laminar with low Nusselt numbers. A double-pass air based HPV/T collector is analyzed for solar drying applications based on steady-state differential equation system by Sopian *et al.* (2000). The increase in PV panel temperature is estimated to be around 18°C and the overall efficiency of the combined unit is 60% at the conditions including the illumination intensity level 800 W/m<sup>2</sup> and mass flow rate of 0.036 kg/s. Hegazy (2000) conducts an extensive study on air based HPV/T collector designed in different schemes. The parametric observation is presented with respect to different mass flow rates and absorber types. All designs show comparable performances and it is seen that the air which flows over or beneath the absorber plate result in impairment in performance. Wang *et al.* (2014) investigate the effects of frame shadows on electrical performance. The performance characteristics with respect to different positions of the unit as well as the model details can be seen from Fig. 17. It can be concluded that frame shadow between the glass cover and PV cells have undeniable effect of the system performance.

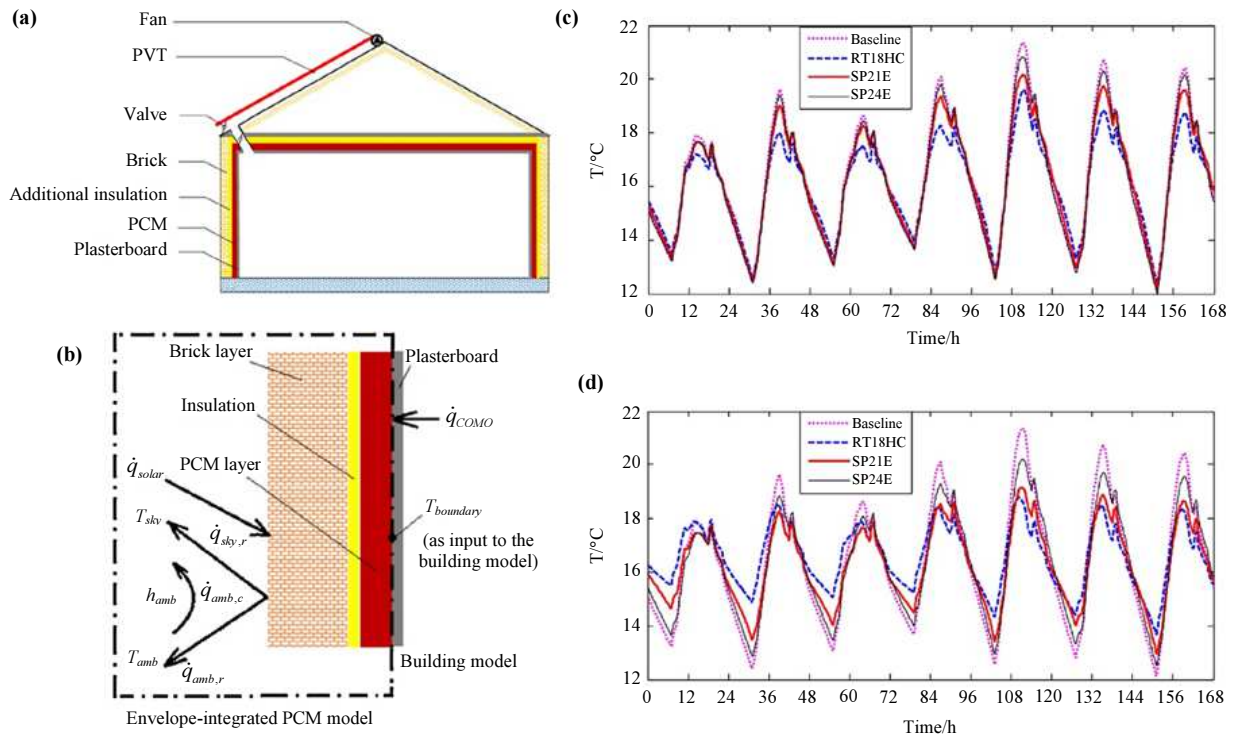


**Fig. 17:** Effects of frame shadow on hybrid PV/T system performance. (a) structure of BIPV system (b) structure of BIPV/T system (c) representation of frame shadow on the unit (d) monthly performance values of the hybrid BIPV/T system with respect to different azimuth angles (Wang *et al.*, 2014)

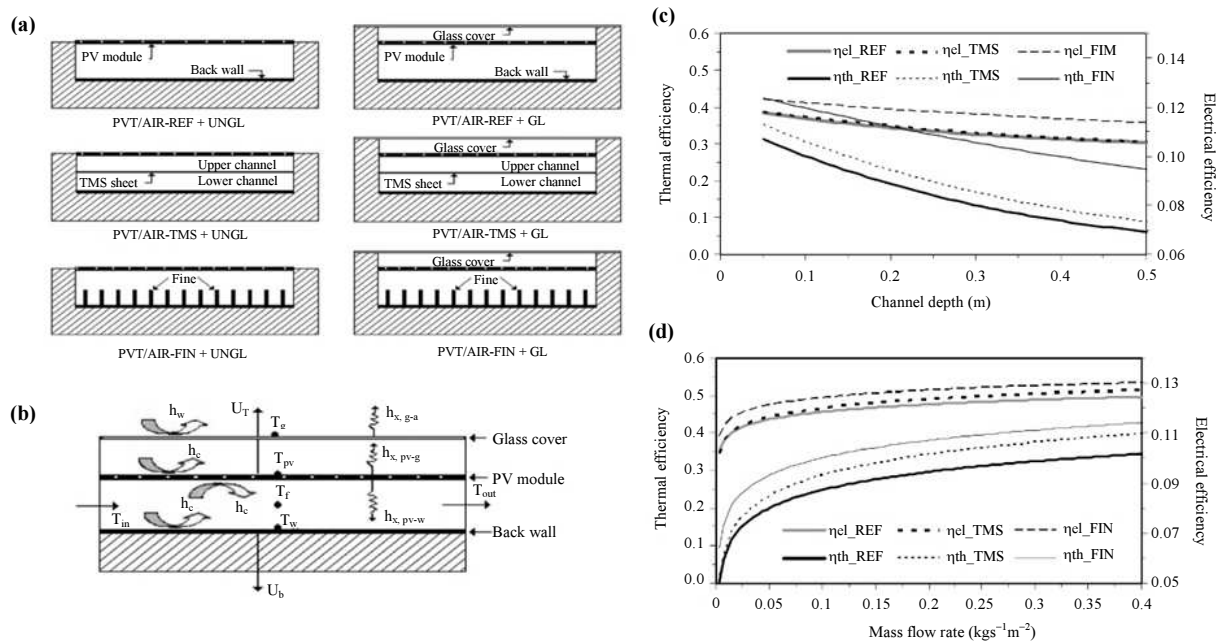
Tripanagnostopoulos *et al.* (2000) attempt to enhance system performance by partially using blackened metal sheet surface, namely at the half of the total surface area of the air channel. Brinkworth (2000) investigate heat and flow characteristics in an cooling duct inclined at a specific angle which is designed for building integrated PV cells by comparing the heat transfer coefficients observed through calculations. Bazilian *et al.* (2001) compare the potential use of PV and HPV/T units for domestic use. They conclude that HPV/T systems have great potential in renewable energy market especially at the low temperature applications. Bazilian and Prasad (2002) investigate the advantages of using a cogeneration system for a typical residential building by conducting numerical analyses. The predictions on output temperature of the air and the temperature of PV module are found to be in good agreement with the experimental results. Jie *et al.* (2002) analyze the difference in annual power yield and heat gain for a PV-wall structure with enabling/disabling ventilation. The observation reveal that the ventilation had a negligible effect on the power yield. However, ventilation significantly decrease heat gain compared to that of without ventilation. Mei *et al.* (2003) analyze the performance of a BIHPV/T collector based on TRNSYS results by estimating heating and cooling loads of several structures in different locations in Europe. Results show that HPV/T façade can be able to supply 12% of heating load demand in Barcelona and on the other hand only 2% of the heat load demand can be met in Loughborough and Stuttgart when the ventilation is used. Several researches are conducted to monitor BIHPV/T performance in different environments and in different operating conditions (Rounis *et al.*, 2016; Wang *et al.*, 2017; Lin *et al.*, 2016; Koyunbaba *et al.*, 2013; Kim *et al.*, 2014). Lin *et al.* (2016) investigate the performance of BIHPV/T with phase change materials and ventilation. The system and effects of adding different materials on temperature profiles are presented in Fig. 18. Temperature profile differs based on type of PCM and ventilation.

Cartmell *et al.* (2004) perform simulation and experimental test for six months period on multi-operational, roof mounted HPV/T collector with ventilation made of a PV cell having total area of 37 m<sup>2</sup> and a thermal collector having total area of 12.5 m<sup>2</sup>. The results indicate that system mentioned in the study can be able to provide significant amount heat load annually. A potential use of an air based HPV/T collector as a solar dryer is studied to dry herbs and species by Janjai and Tung (2005). It is observed that

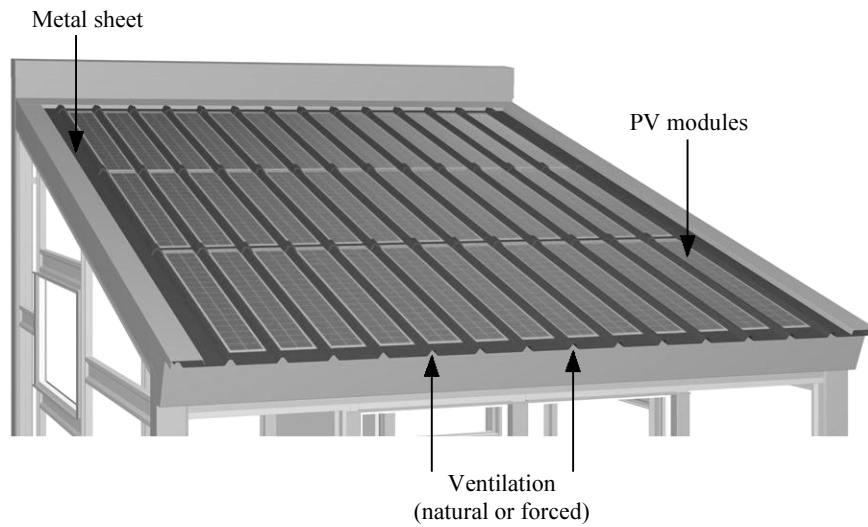
mixture of lemon-grasses and rosella flowers with total mass of 200 kg can be dried within 3 and 4 days, respectively by using a HPV/T collector with total collector area of 72 m<sup>2</sup>. Naphon (2005) conduct a parametric study on a double-pass HPV/T collector with longitudinal fins in order to reveal flow and heat transfer characteristics and exergy performance. The functional dependence with respect to the height and the number of fins versus entropy generation and performance are acquired. Efficiency is seen to be positively affected with increasing height and number of fins and while entropy generation is negatively affected with increasing height and number of fins. An air based BIHPV/T collector consisted of multi-crystalline silicon PV cells is analyzed at the environmental conditions of Nice and Paris by Guiavarch and Peuportier (2006). System is placed onto a roof of a domestic house in Paris and the efficiency is observed to be 14% for the unventilated scheme. It is estimated that if the ventilation air was preheated by PV cells the efficiency would reach the value of 20%. Tonui and Tripanagnostopoulos (2007b) modify an air based HPV/T system by using two cheap heat extraction modules in order to monitor the change in the heat transfer characteristics. The use of thin metal sheet and finned wall are the two options considered for the system modification. Different modified designs mentioned in the study can be seen from Fig. 19. The channel depth has a negative effect on the system performance, but increase in mass flow rate is favorable for the system performance in a limited section. Moreover, the prementioned heat extraction mechanism can be easily coupled with building façades and roofs. A novel air based HPV/T system consisted of ribbed sheet steel absorber embedded with PV cells and a layer of tedlar is demonstrated and analyzed by Assoa *et al.* (2007). The system can be easily incorporated with façades and roofs. The schematic view of the system can be seen from Fig. 20. It is highlighted that when using proper collector length and mass flow rate, the collector efficiency can reach up to 80%. Absorber is a vital part HPV/T structure which can affect the system performance and cost. Thus, design is studied by many researchers and occasionally it is built by using cheaper materials to decrease the installation cost (El Hocine *et al.*, 2016; Slimani *et al.*, 2016). Slimani *et al.* (2016) study HPV/T collector in detail which is suitable for an indirect solar dryer. System overview and performance characteristics can be seen from Fig. 21. The glazing of HPV/T collector result in decrease in electrical efficiency whereas increase in thermal efficiency as expected.



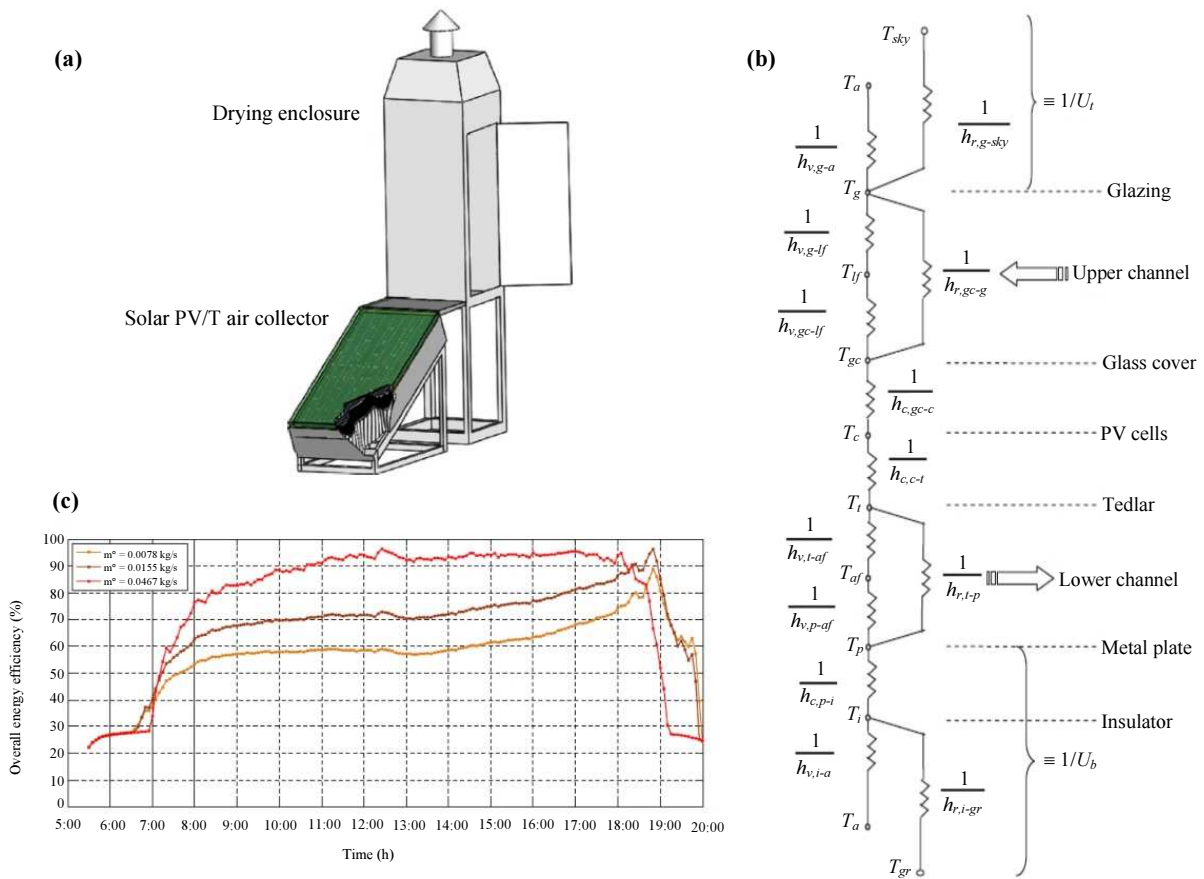
**Fig. 18:** Thermal characteristics of building with integrated phase change materials and solar PV/T. (a) schematic view of the building features (b) overview of the model of building envelope integrated with PCM (c) ambient temperature of the house with PCM layer thickness of 5 mm (d) ambient temperature of the house with PCM layer thickness of 30 mm (Lin *et al.*, 2016)



**Fig. 19:** Air based hybrid PV/T collector. (a) schematic view of different designs, (b) heat transfer model with nodes, (c) performance of PV/T collector versus channel depth, (d) performance of PV/T collector versus mass flow rate (Tonui and Tripanagnostopoulos, 2007b)



**Fig. 20:** Roof integrated air based hybrid PV/T collector with ribbed sheet steel absorber (Riffat and Cuce, 2011; Assoa *et al.*, 2007)



**Fig. 21:** An air based hybrid PV/T drier. (a) structure of the unit (b) thermal circuit resistance model (c) hourly overall energy efficiency with respect to different mass flow rates (Slimani *et al.*, 2016)

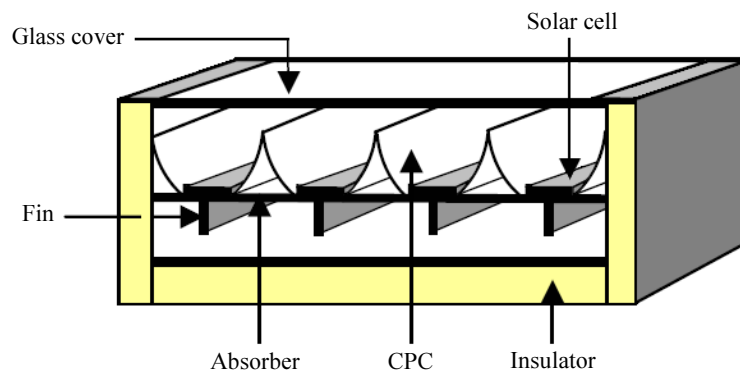
Joshi and Tiwari (2007) investigate the heat characteristics of an air based HPV/T system at the environmental conditions of Srinagar, India. The

environmental data is obtained from Indian Metrological Department. The value of the energy efficiency is seen to fluctuate between 55-65% and the value of exergy

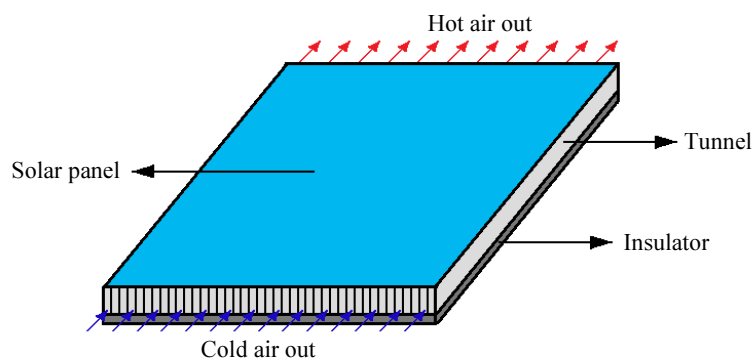
efficiency is observed between 12-15%. Alfegi *et al.* (2007) construct a theoretical model for a single-pass air based HPV/T collector consisted of CPC and fins installed both sides of the absorber. The schematic view of the system can be seen from the Fig. 22. Air is circulating around the absorber plate by making two passing. The functional relations between air temperature versus absorber distance is investigated. The increase in overall efficiency is observed while mass flow rate ranges from 0.0316 to 0.09 kg/s at the illumination intensity of 400 W/m<sup>2</sup>. Raman and Tiwari (2008) study to determine best environmental conditions for an air based HPV/T system based on thermal and exergy yields. Jodhpur is found to be the most economical region among five selected cities, namely Mumbai, Jodhpur, Srinagar, Bangalore and New Delhi. Ji *et al.* (2008) demonstrate the advantages of using PV-trombe wall by using custom made system showing an increase in indoor temperature by 5-7°C in winter with the electrical efficiency value of 10.4%.

Dubey *et al.* (2009) obtain electrical characteristics of a PV module acquired from four different schemes, namely glass to glass PV unit with duct and without duct, glass to tedlar PV unit with duct and without duct by using developed analytical expressions. The glass to

glass PV unit with duct scheme is found to have the best electrical efficiency and highest outlet air temperature among other schemes. The annual mean efficiency of the glass to glass PV unit with duct is found to be better than that of 9.75% without duct. Solanki *et al.* (2009) develop analytical expressions based on energy balance within module layers for new air based HPV/T collector. The new system is installed and tested for parametric studies. The thermal efficiency of the system is obtained to be 42% and electrical efficiency of the system are obtained to be 8.4%. Mittelman *et al.* (2009) analyze passive air cooling within PV panels by calculating heat transfer coefficient of combined regime based on numerical approach. Gan (2009a; 2009b) investigate the flow and heat transfer characteristics within the air gap beneath the PV modules with respect to different lengths of PV modules and various roof pitches at constant illumination intensity levels. Fudholi *et al.* (2010) review solar dryers for applications including agricultural and marine products. The performance of single-pass air based HPV/T system consisted of a rectangle tunnel absorber is analyzed by Jin *et al.* (2010). The rectangle tunnel is installed at the back side of the PV panel which is acting as an absorber that can be seen from Fig. 23.



**Fig. 22:** Cross sectional view of air based hybrid PV/T collector with double pass flow channel, fins and CPC (Ibrahim *et al.*, 2011; Riffat and Cuce, 2011; Alfegi *et al.*, 2007)



**Fig. 23:** Structure of air based hybrid PV/T collector with single pass flow channel and rectangle tunnel absorber (Ibrahim *et al.*, 2011; Riffat and Cuce, 2011; Jin *et al.*, 2010)



The values of thermal, electrical and the total efficiencies of the HPV/T collector are determined to be 10.02%, 54.70% and 64.72%, respectively at the illumination intensity level of 817.4 W/m<sup>2</sup>, the ambient temperature of 25°C and mass flow rate of 0.0287 kg/s. Sohel *et al.* (2014) derive time-dependent mathematical model for a BIHPV/T collector and test the results by comparing data collected from two unit integrated to different buildings in order to assess the performance behavior of the system when operating under changing conditions. The two buildings are a net-zero energy Solar Decathlon (SD) house and Sustainable Buildings Research Centre (SBRC) building which is also a net-zero energy unit. The HPV/T system is used to generate electricity for the house and for air conditioning. Thermal output of the system is stored inside the PCM storage part of the design. It is observed that both thermal and first law efficiencies are increased with increase of air inlet temperature, whereas electrical efficiency and second law efficiency are decreased with the increase of ambient temperature.

HPV/T systems are tested under different ambient conditions and optimized with different algorithms (Nahar *et al.*, 2017; Singh *et al.*, 2015a; Singh and Agrawal, 2015; Lin and Ma, 2016; Michael *et al.*, 2016). Kumar and Rosen (2011a) perform a parametric study on the double-pass HPV/T collector with vertical fins to investigate effects of several variables, namely design, ambient and operating conditions, cell temperature on the overall performance of the system. According to results, it is possible to decrease the value of PV cell temperature

from 82°C to 66°C if fin area is expanded. Alta *et al.* (2010) compare three different types of air based HPV/T systems with respect to three different tilt angles (0°, 15° and 30°) and mass flow rates (25, 50 and 100 m<sup>3</sup>/m<sup>2</sup>h). According to results, the systems made of finned absorber plates yield the best efficiencies among others. It is added that the increase in transparency of cover and the increase in the number of fins results in more temperature difference. Zhao *et al.* (2011a) compare a novel PV/e roof module with conventional systems. The new PV/e roof system functions as the electricity generator, roof element and the evaporator of a heat pump system. PV/e system shows significantly better performance than conventional PV, HPV/T and PV-heat pump systems. Slimani *et al.* (2017) compare the performances of three types of HPV/T schemes and a single PV system for the environmental conditions of Algiers, Algeria. The three schemes are consisted of conventional flat-plate HPV/T system prepared in different designs such as one without any modification, one with glazing and one with double pass heat transfer layer. The mathematical models are numerically solved and validated with experimental findings. According to the results, for an air flow of 0.023 kg/s the hybrid air based system with double pass layer have the best overall energy efficiency which is approximately 14% more than glazed design and 44% more than single PV system. These types of performance studies are performed to analyze new developments for BIHPV/T systems (Shukla *et al.*, 2016; Kane and Verma, 2013; Gaur and Tiwari, 2015).

**Table 3:** Selected studies of building integrated PV and building integrated hybrid PV/T systems

System Description	Specifications	Analyses Type	Mass Flow rate (kg/s)	Performance	Literature	Remarks
PV Trombewall	Façade integration. The setup consists of semi-transparent a-Si solar cell with an air gap of 0.50 m.	Numerical and experimental	air(0.013 - 0.033)	Daily mean thermal efficiency is 27.2% and daily mean electrical efficiency is 4.52%.	168	No forced ventilation. Air is naturally circulated. The results of the experiments are compared with 2D model. CFD analyses are included.
BIPV/T water heating system	Unglazed system with aluminum collector. 50 mm of glass wool plate is used to isolate collector. Water is used as coolant which is connected to storage tank.	Experimental	water(0.165)	Average electrical efficiency is 17% and average thermal efficiency is 30%. Maximum reported electrical efficiency is 18.9%.	169	Experimental setup is integrated into the roof. Maximum temperature in the storage tank is reported as 40 degrees.
PV system with three-layer ETFE cushion	ETFE (Ethylene Tetrafluoroethylene) cushion is used to enhance heat regulation. Solar panels are made of amorphous silicon material.	Experimental and simulation	N/A	Overall system efficiency is more than 25.5%.	204	Experimental setup is integrated into the roof. The air temperature inside the volume insulated by the ETFE cushion is 16.8–31.0°C higher than outside temperature.
Building integrated Semitransparent Photovoltaic (BISPV) modules	75W BISPV modules. No inclination.	Experimental	N/A	Efficiency is in the range of 11-18% for roof integration and it is in the range of 13-18% for façade integration.	199	Experimental setup is integrated into the roof and facade. No forced ventilation. Air is naturally circulated.
BIPV with Thermoelectric cooler.	One diode, two-resistance model.	Theoretical	N/A	The value of the electrical Efficiency is almost constant around 10% at ambient temperature.	200	BIPV system can be cooled up to 10°C without losing any power. The results obtained from simulations can be used as reference values for similar studies.
Building Integrated Opaque Photovoltaic Thermal (BIOPVT) systems	System consists of amorphous silicon and CIGS thin film Photovoltaic (PV) modules.	Theoretical	air(0.004-0.85)	Mean electrical efficiency is 7.25% for a-Si based system without air duct and same is 7.57% for system with air duct.	201	Experimental setup is integrated into the roof with specified inclination. Air mass flow rate has a significant effect on system performance.
Building Integrated Semi-Transparent Photovoltaic Thermal (BISPV/T) systems	Solar panels with monocrystalline silicon (c-Si) PV cells	Numerical and experimental	air(0.004-0.85)	The value of the electrical efficiency is 12% for the system without air duct and same value is 13.11% for the system with air duct	202	Experimental setup is integrated into the roof with and without duct. The system without air duct can supply conditions in comfort zone.

**Table 4.** Selected studies of air based PV and hybrid PV/T systems

Type of solar cell	Absorption unit	Type of analysis	Study aim	Performance values at optimum conditions	Change in Performance	Cost Analysis	Error analysis	Literature	Remarks
N/A	Glass covered system with rectangular channel	Theoretical	Analyzing PV/T systems for air heating applications and comparison of single and double pass designs.	Thermal efficiency is seen to be 33 %.	Thermal efficiency of double pass system is 10% higher than single pass system.	N/A	N/A	145	Steady-state models are used for thermal analyses. Average daily thermal efficiency increases with increasing mass flow rate.
N/A	Channel modified with non-absorbent porous packing material.	Theoretical	Using packing at the flow channel to enhance efficiency.	Thermal efficiency is obtained up to 64 %.	The change in thermal efficiency is around 10% compared to nonmodified channel.	N/A	N/A	249	The change in performance is parametrically investigated. Study reveals the advantage of having turbulence in flow passage. But this increases the cost and pumping power.
N/A	Rectangular channel	Numerical and experimental	Parametric analyses on the flow and heat transfer characteristics of naturally circulated air in the gap behind the panel.	N/A	30% of the heat is transferred due to radiation.	N/A	Good agreement is observed with the experimental data.	147	Radiation within the channel walls plays an important role in the heat transfer. CFD analyses are added.
N/A	Continuous, wavy and V-shape aluminum absorber	Numerical and experimental	Optimizing air mass flow and testing absorber geometries.	Thermal efficiency can be obtained up to 77%.	Optimized design can show up to 8% better efficiency.	N/A	Maximum error in experimental results is less than 10%.	155	Efficient heat transfer mechanism is provided by using extended surfaces. Optimum fin geometry is sought for minimum pressure loss.
N/A	Building wall structure	Numerical	Optimizing the system to decrease panel temperature for a system with and without ventilation.	The value of the electrical efficiency can be obtained up to 5% depending on the facing position.	System with ventilation has 0.04% better efficiency than system without ventilation.	N/A	N/A	163	The model presented in the study can be used to optimize PV-wall structures to reach better efficiencies.
N/A	Channel sheet type	Theoretical and experimental	Building dynamic model to investigate environmental effects.	The value of the thermal efficiency is observed around 50% at ambient conditions.	The change in thermal efficiency is around 15% with respect to air temperature.	N/A	The maximum RMS value is 4.2%.	189	Developed dynamic model can be able to predict operating performance in real conditions.
Monocrystalline silicon	Absorbent black plate with single and double pass design.	Numerical and experimental	Testing double pass and glazing effects by using a detailed thermal and electrical model. And comparing PV/T performance with PV unit.	Maximum overall efficiency is observed to be 74% for glazed HPVT with double pass channel.	The overall efficiency of the optimum design is 13% higher than reference PV/T system.	N/A	Good agreement is observed with the experimental data.	198	A detailed model is built to compare different solar systems. The effects of glazing and double pass are evaluated based on conventional systems.
Monocrystalline silicon	Roof with duct and without duct	Theoretical and experimental	Investigating the effect of a duct for building integrated PV/T.	The value of the electrical efficiency is obtained to be 13.1%.	The design without duct has 1% lower electrical efficiency.	N/A	Good agreement is observed with the experimental data. Max RMS error is 4.77%.	202	Model is developed for building integrated panel with semitransparent cells and it is shown that model can correctly predict performance characteristics of this unit.
Polycrystalline silicon	Anodized aluminum alloy rectangle channel	Numerical and experimental	Comparing the performances of different designs under real operating conditions.	The value of the thermal efficiency is seen around 18% at the field.	Max difference in electrical efficiency between selected designs can reach up to 50%.	N/A	Good agreement is observed with the experimental data. The RMS error is 3.22%.	203	The study reveals realistic results for a system operating under real conditions.
Amorphous silicon	Roof with three layers of ETFE cushion	Experimental	Enhancing the performance of roof integrated PV/T by using ETFE (ethylene tetrafluoroethylene) cushion	Overall efficiency is observed up to 25.5%.	Measured air temperature inside ETFE cushion roof is 16.8 to 31°C higher than ambient air temperature.	N/A	N/A	204	ETFE is considered as viable structure for roof use. Apart from solar utilization, ETFE cushion plays an important role for the thermal comfort by creating thermal resistance between indoor and outdoor environments.
N/A	Insulated back wall	Numerical	Analyzing the performance of BIPV/T system with multiple inlet and ventilation for a large-scale building.	Max electrical efficiency can reach up to 16% whereas max thermal efficiency can reach up to 45%.	Multiple inlet system can have 1% higher electrical efficiency and 14-24% higher thermal efficiency with respect to weather conditions.	N/A	N/A	165	Study investigating BIPV/T with multiple inlets for possible retrofitting applications.
N/A	Channel sheet type	Theoretical	Investigating the effect of the shadow due to existence of the frame that supports the glass cover.	The value of the electrical efficiency is observed to be 13%.	The presence of frame shadow reduces the electrical efficiency by 2.6%.	N/A	N/A	166	Study reveals the importance of design parameters. The effects of the thickness of the air layer between glass cover and cells are parametrically analyzed.
N/A	Roof integration with and without ventilation.	Theoretical	Optimizing PCM material dimensions.	N/A	The thermal performance is seen to be 48% better than the reference house without using the PV/T ventilation.	N/A	Good agreement is observed with the experimental data. The RMS error is 3.22%.	167	The use of PCM material increases the thermal performance.
Polycrystalline silicon	Parallel plate thermal collector without absorber plate.	Numerical and experimental	Testing new design without absorber plate.	Overall efficiency is seen up to 80%.	Maximum 5% difference is observed between systems with and without absorber plate.	N/A	Good agreement is observed with the experimental data. 4.4% difference exists between experimental and numerical results for overall efficiency.	190	Direct attachment of parallel plate collector to overcome problems in heat extraction from PV unit to working fluid.
N/A	Plate with single channel	Theoretical	Optimizing single channel PV/T array with Evolutionary Algorithm (EA).	Overall energy efficiency is observed to be around 10.6%.	The value of the overall energy gain of the optimized system is 87.86% higher than unoptimized system.	N/A	N/A	191	Study shows the application of Evolutionary Algorithm (EA) to optimize PV/T performance.
N/A	Roof integration with and without ventilation.	Theoretical	Optimizing PCM material for PV roof Taguchi-Fibonacci search method.	The maximum value of the Coefficient of Thermal Performance Enhancement is 72.22%.	Coefficient of Thermal Performance Enhancement value is changed from 45.54 to 72.22% after optimization.	N/A	N/A	193	Study shows the application of Taguchi-Fibonacci method to optimize building integrated units with PV panels and phase change materials.
Monocrystalline silicon	Absorber with parallel vertical tubes or with enclosure	Theoretical and experimental	Trying to acquire cheaper absorber design with sufficient efficiency.	The value of the thermal efficiency is seen around 36.32% and electrical efficiency is around 12.7%.	Maximum 50% difference is observed in thermal efficiency between models.	N/A	Sufficient agreement is observed with the experimental data. The RMS error is 31.36%.	176	Simple design has considerable efficiency, but requires more enhancement.

Gaur *et al.* (2016) numerically and experimentally analyze semitransparent BIHPV/T collector consisted of mono crystalline Silicon (c-Si) PV module with and without air duct. The efficiency of the two systems are around 12%. Amori and Abd-ALRaheem (2014) compare air based HPV/T collectors constructed in four types, namely single duct double pass, double duct, single pass, single duct single pass and no duct for the climate conditions of Iraq. Single duct single pass scheme is observed to yield best electrical efficiency. Hu *et al.* (2016a; 2014) study the possible advantages of using three layers of Ethylene Tetrafluoroethylene (ETFE) cushion integrated with 2-piece PV modules. It is expected that ETFE cushion can increase thermal efficiency. The temperature of the ETFE layer is found to be 16.8-31.0°C higher than ambient temperature which is very promising for their thermal advantage. Most of the studies mentioned in this section involve building integrated units. Table 3 shows the summary of the section covers building integrated units. Also, Table 4 covers whole section

related to air based HPV/T units. Table 3 and 4 are formed by selected studies.

### Bifluid Based HPV/T Collectors

The heat transfer mechanism of the HPV/T collector can be designed for both water and air circulation where in this case absorber module is made of both air duct and water tubes. By this way, hot air and water production can be provided simultaneously or heat extraction from unit surface can be increased. Moreover, HPV/T system can be operated for desired output. Abu Bakar *et al.* (2014) mathematically model 2D steady state bifluid based HPV/T collector and analyze its performance. At the design, the water is circulating in a serpentine tubes and air is flowing beneath the tubes inside the air duct. Satisfactory thermal and electrical efficiencies are observed for selected air and water mass flow rates. Ji *et al.* (2014) design HPV/T collector where either water or air can be selectively used as coolants so that freezing and seasonal problems can be eliminated.

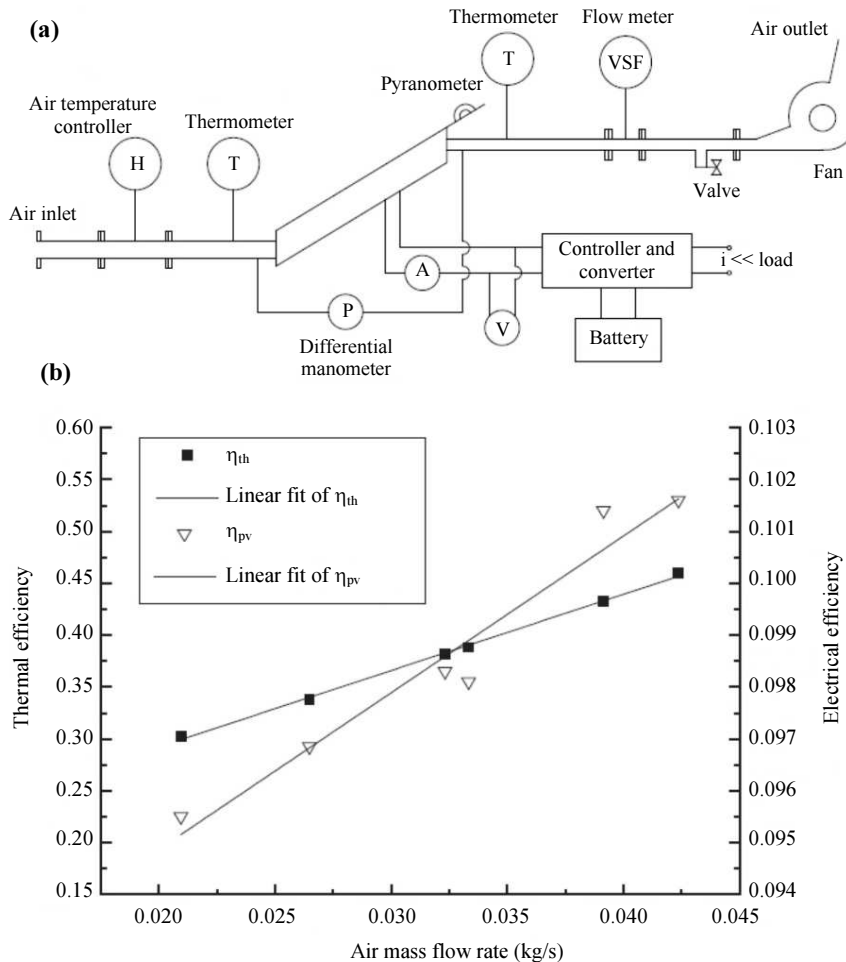
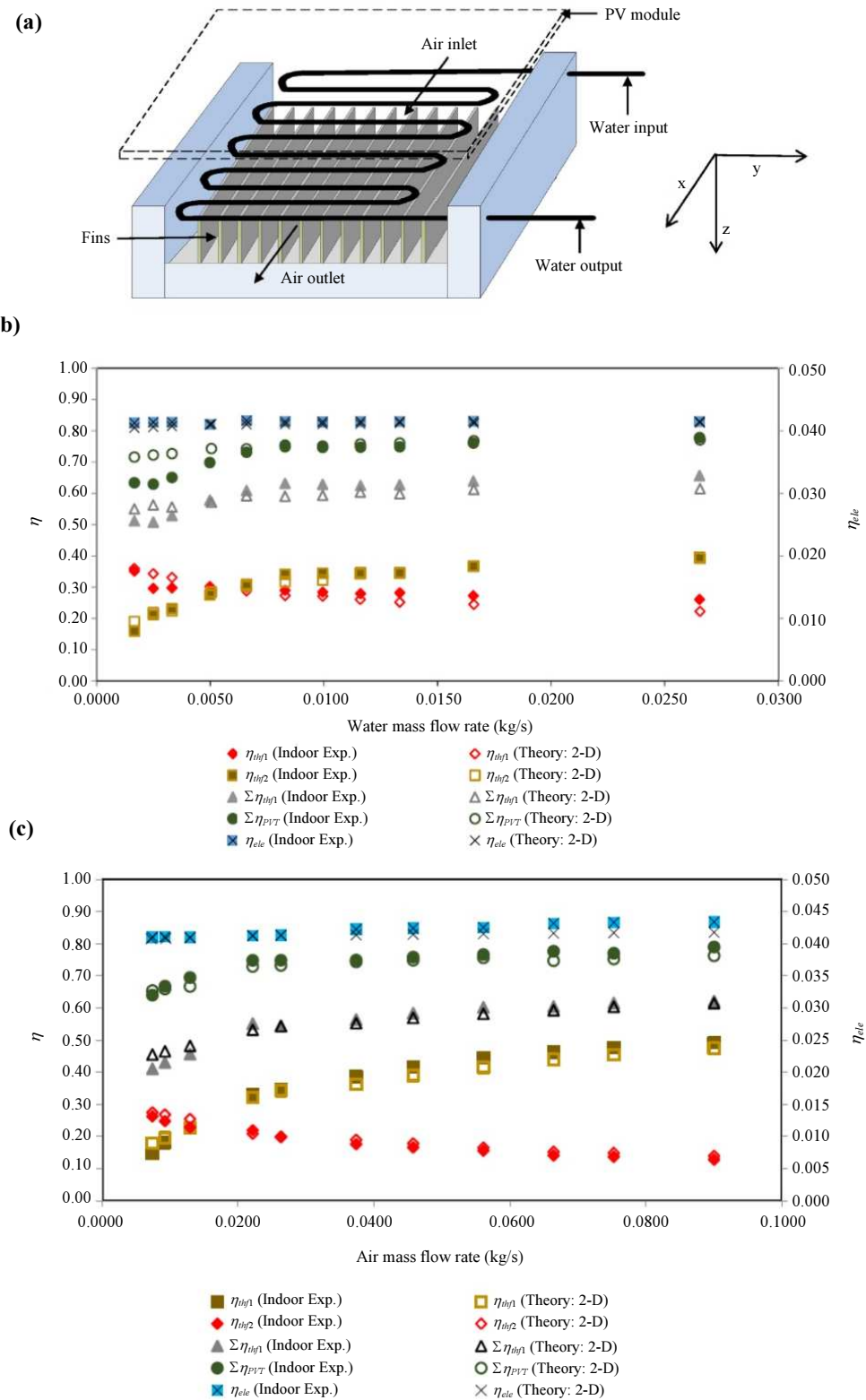


Fig. 24: Tri-functional hybrid PV/T system. (a) schematic view of PV/T air heating system, (b) performance characteristics versus air mass flow rate (Ji *et al.*, 2014)



**Fig. 25:** Bifluid hybrid PV/T collector (a) components of the unit (b) performance characteristics versus water mass flow rate at fixed air flow rate of 0.0262 kg/s (c) performance characteristics versus air mass flow rate at fixed water flow rate of 0.0066 kg/s (Jarimi *et al.*, 2016)

Experimental setup and performance parameters can be seen from Fig. 24. Fluid flow rates and ambient conditions are found to have significant effect on system performance. The bifluid system is observed to be able to operate different weather conditions with overall thermal efficiency of 36%. Jarimi *et al.* (2016) compare the performances of HPV/T solar collector operated in three modes where air, water and bifluid are used to cool the unit under operation. The water and air flow channels of the system can be seen from Fig. 25. As seen from the Fig. 25, optimum flow rates are parametrically sought by changing air and water mass flow rates with respect to efficiencies. When air mass flow rate is fixed at 0.0262 kg/s, the water flow rate is varying between 0.0017 to 0.0265 kg/s. Solar simulator is used for indoor experimental studies and 2D model is developed for further investigation. Experimental tests for bifluid operation are conducted based on either constant water flow rate or constant air flow rate. The solar irradiation rate is set to 700 W/m<sup>2</sup> for experiments. They conclude that the system can be used under three modes selectively and bifluid system can produce more output providing that it is optimized for operation. Assoa *et al.* (2007) perform parametric study on a bifluid based HPV/T collector by

using steady-state 2D theoretical model. Parameters such as collector length and water mass flow rate are investigated. They observe that mass flow rate has slight effect on the air temperature. Hot water or air can be produced by using HPV/T based on the demand of the application (Michael *et al.*, 2016). Guo *et al.* (2015) present HPV/T collector which has two operation modes namely, water heating mode and air heating mode.

### Solar Photovoltaic Units with Ventilation

Building integration of PV modules can be implemented with PV façades or PV roofs where during installation, an air gap is usually left between the PV module and wall. This enables air to flow through the gap and cool PV cells via natural convection. If the low-grade heat carried by the air flowing through this gap is recovered without directly releasing it to the atmosphere overall system efficiency can be increased. This is called ventilated PV with heat recovery. Using PV façades has two-way advantages, namely undesired thermal losses can be prevented during winter or excessive solar irradiation can be reflected from the system surface in summer.

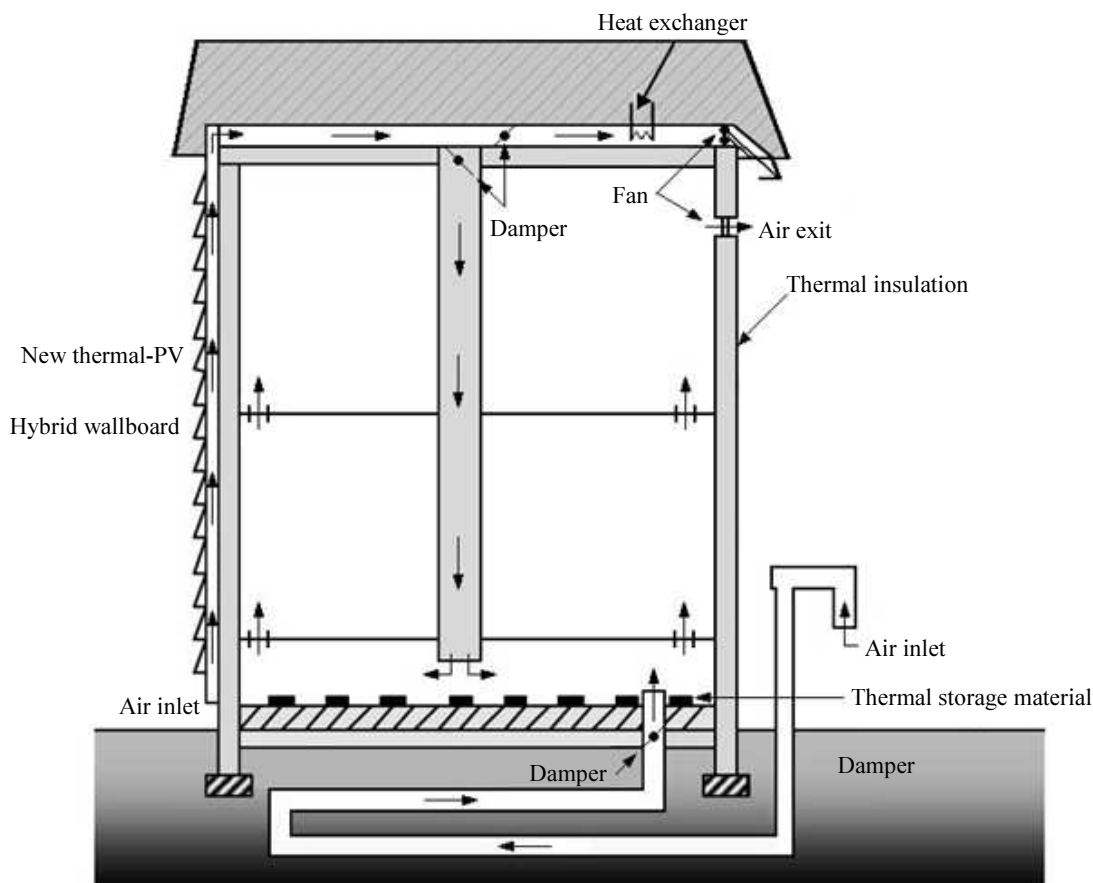


Fig. 26: Structure of the new hybrid wallboard (Riffat and Cuce, 2011; Nagano *et al.*, 2003)

PV façades became popular in the early 1990s (Zondag, 2008). Ricaud and Roubeau (1994,) test the performance of air based HPV/T collector consisted of square aluminum channels and glass cover which is called 'Capthel'. The system efficiency is seen to be relatively high. Amorphous silicon PV are elected to be best components for the solar based cogeneration systems. PV façades and PV roofs are analyzed by several researchers at the University of Cardiff (Brinkworth, 2000; Brinkworth *et al.*, 1997; 2000; Yang *et al.*, 1994; 1996). Krauter *et al.* (1999) study the effects of using HPV/T systems as the building envelope and their façade integrations. 18°C decrease in PV cell temperature is observed if the ventilation is enabled. It is also added that when the ventilation speed reached to 2 m/s, the increase of 8% in electrical efficiency is obtained. Cross (1994) test the performance of integrated solar roof system by using a solar simulator. Takashima *et al.* (1994) study the performance of a PV roof cooled via natural convection based on theoretical expressions.

Nagano *et al.* (2003; 2001) conduct several studies on solar exterior wallboards where the schematic view of the design can be seen from Fig. 26. Six different schemes of HPV/T collectors are compared where all differ based on cell types, protections and back of cells used as wallboards. Due to their performance in winter, wall mounted HPV/T systems are observed to be more successful than PV roofs. Thermal efficiency of unglazed system is in between 20-22% whereas thermal efficiency of the glazed system is in between 29-37% at the inclination angle of 80 degrees. Ji *et al.* (2003) investigate the performance of façade-integrated HPV/T system consisted of either thin film or single crystalline silicon PV cells based on analytical model outputs. According to results, annual thermal efficiencies of the systems consisted of thin film or single crystalline silicon PV cells are obtained to be 47.6% and 43.2%, respectively. It is added that cooling load can be reduced if façade-integrated system is used. Omer *et al.* (2003) compare the performances of two different schemes of Building-Integrated PV systems (BIPV) where first design consisted of PV façade with thin film cells used at the educational building whereas the second design consisted of crystalline PV roof slates used at the detached house. It is observed that the difficulties at the design step, installation, commissioning and operation periods can alter the PV performance and can increase the cost.

Benemann *et al.* (2001) touch upon several key factors from several the projects concerning BIPV systems. Yoo and Lee (2002) install PV modules on the surface of a building to provide shading to reject excessive sun light and to test the performance. Data collected from a year period show that efficiency of the sunshade solar panel is 9.2%. Mei *et al.* (2006)

develop a HPV/T powered desiccant cooling system. The system have two advantages, namely excess heat from the ventilated PV façade is used to drive the desiccant cooling system and shading is provided simultaneously to reduce the cooling load of the building. A desiccant cooling unit with an extra solar air collector is integrated to the PV sheds and ventilated PV façade. COP of the cooler is estimated to be 0.518. They propose that 75% solar fraction can be reached by using this innovatory design. Matuska and Sourek (2006) perform a study to compare performances of façade collectors and conventional roof-located collectors. The schematic view of the façade solar system can be seen from Fig. 27. According to results, 30% increase in façade solar collector area is shown to be necessary to reach usual 60% solar fraction compared with conventional roof solar collectors installed with a 45° slope. It is also added that with proper insulation façade collectors did not significantly affect the building behavior.

Ji *et al.* (2007) test the effects of using DC fan assisted air circulation at the PV-trombe wall system. They perform several simulations to obtain heat transfer characteristics of the PV-trombe wall by enabling and disabling DC fan. The maximum increase in the indoor temperature is 14.42°C for a room with PV-trombe wall ventilated with DC fan compared to a reference room. The overall electrical efficiency of the system is observed up to 10-11% with glass cover addition. Ventilation with DC fan is very helpful to improve the conditioning the room temperature and cooling of PV cells. Agrawal and Tiwari (2010) study to optimize BIHPV/T system and estimate its thermal performances for cold climates based on time-dependent theoretical model. According to results, connection of BIHPV/T systems in series results in the highest outlet air temperature. The thermal and electrical yield of a system with an effective area of 65 m<sup>2</sup> for one-year period are observed to be 1531 kWh and 16,209 kWh, respectively. Additionally, overall thermal efficiency is calculated to be 53.7% for same period. Chow *et al.* (2008) analyze a system consisted of a building-integrated PV and a water heater unit by using transient numerical model which built based on finite difference method. Experimental data is compared with numerical outputs for validation. The model is found to be very useful for obtaining system performance over long periods. Chow *et al.* (2007c) conduct a parametric study to investigate performance of the façade-integrated PV water heating system with respect to different seasons and different operating modes. They propose that natural water circulation is more effective than forced water circulation. The electrical and the thermal efficiencies of the system is estimated to be 8.56% and 38.9%, respectively.

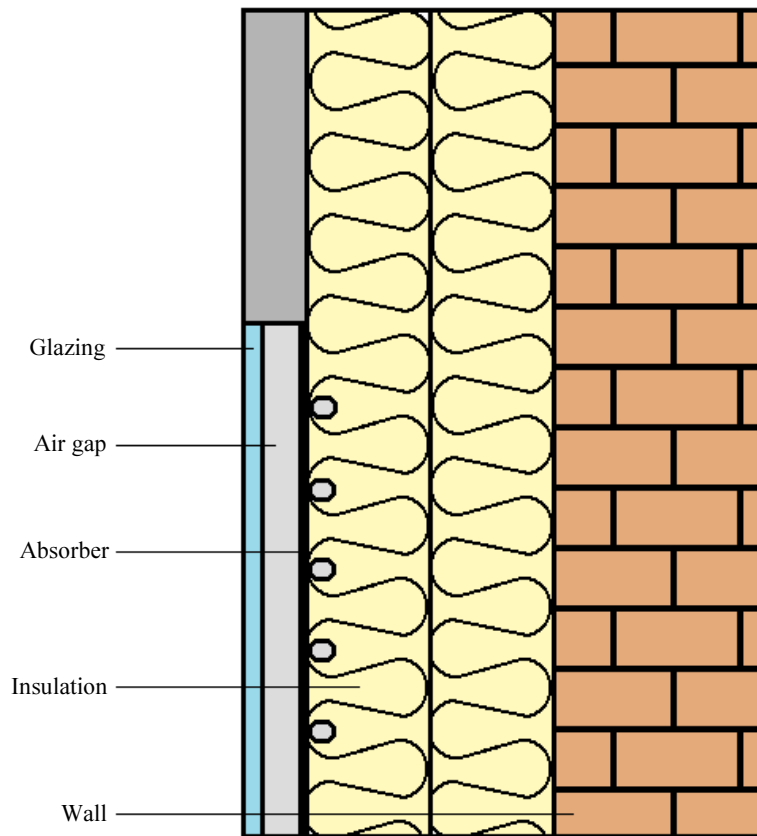


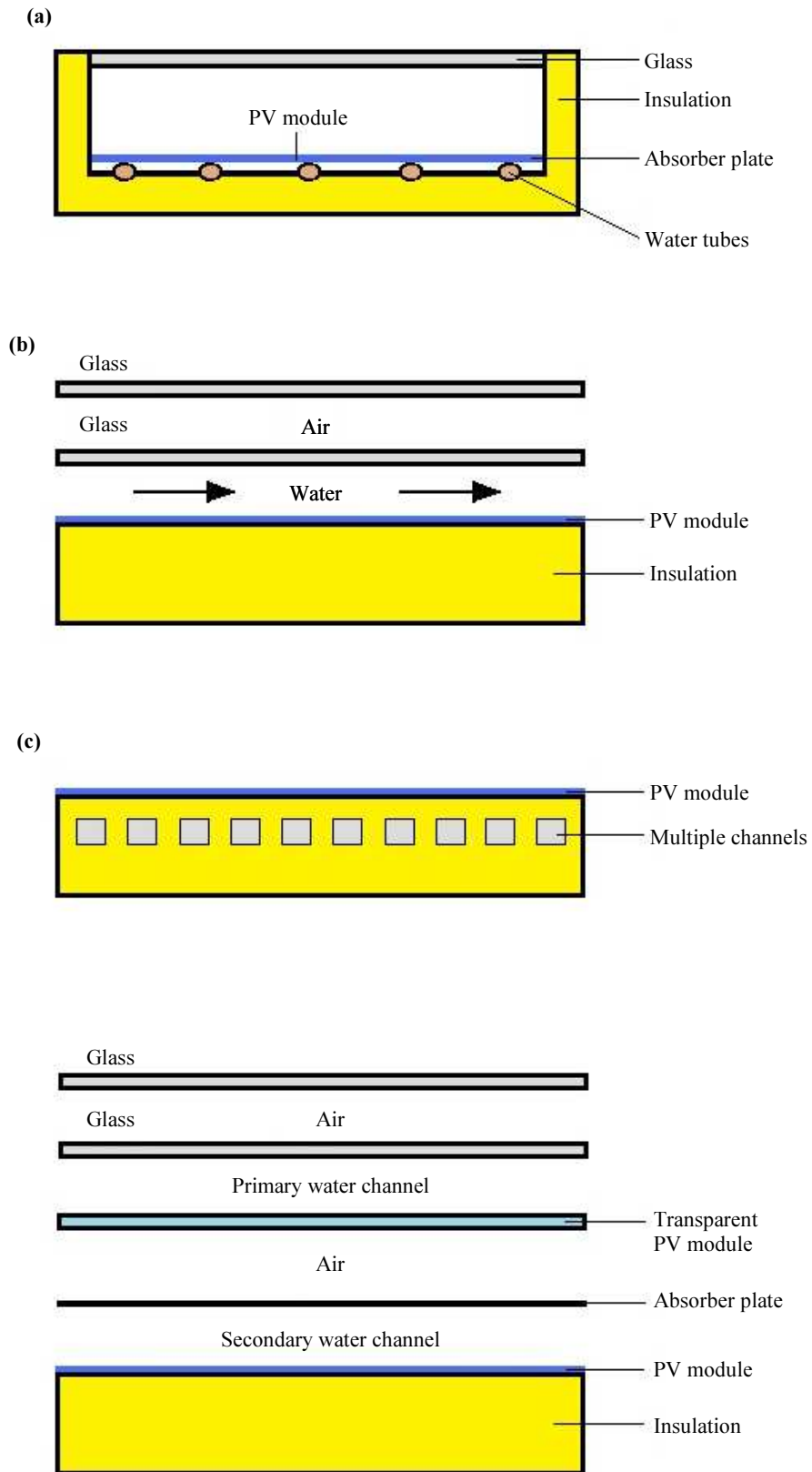
Fig. 27: Cross sectional view of façade solar collector (Riffat and Cuce, 2011; Matuska and Sourek, 2006)

Tian *et al.* (2007) analyze the effects of building-integrated photovoltaics such as PV façades and the PV roofs on the building thermal characteristics. It is obtained from the results that ventilated PV façade and the PV roof have considerable effect on the surface temperature of the building and sensible heat flux density. Anderson *et al.* (2009) show that the overall performance of a BIHPV/T system is a function of several factors such as lamination method, fin efficiency and thermal resistance between PV cells and supporting structure. Hottel-Whillier model is expanded and modified for theoretical analyses. Anderson *et al.* (2010) study to investigate possible advantages of using colored absorbers where the color scale is ranging from black to white. Colored schemes are observed to have a significant influence on system performance. Lu and Yang (2010) show that payback period of the roof-mounted BIHPV/T system can be affected from the installation angle and location by using their 22 kW system. Strong relation between long-term behavior of the PV system versus its installation, orientation and location are observed. Kim *et al.* (2016) use HPV/T system to pre-heat outdoor air flow and attempt to increase the efficiency of the heat recovery ventilator system in winter. Experimental studies are performed on

a small-scale house. 10% improvement in heating performance was observed.

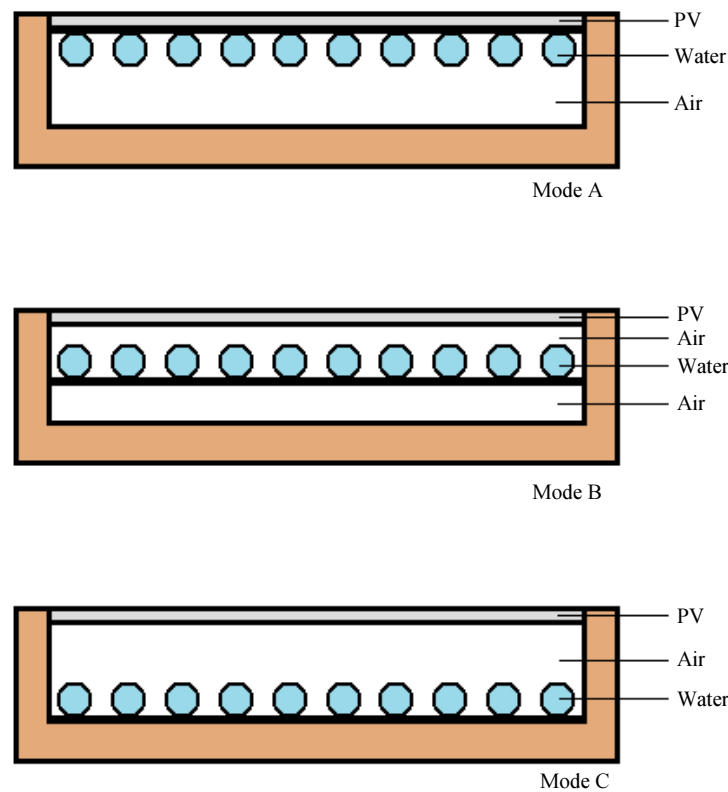
### Alternative Schemes of HPV/T Collectors

So far, different schemes of water and/or air based HPV/T collectors are extensively explored and presented from the literature. Schematic view of common construction types for HPV/T systems can be seen from Fig. 28a to 28d. The simplest scheme can be seen from Fig. 28a where PV module is placed onto an absorber collector plate with water tubes crossing beneath the PV layer. In the second scheme, different types of heat transfer fluids flow over the PV module in different layers which is illustrated in Fig. 28b. In the third scheme, multiple channels are placed beneath the PV module without any cover plate which can be seen from Fig. 28c. In the last scheme, transparent PV modules are sandwiched within the layers consisted of heat transfer fluids as seen from Fig. 28d. The last design is more attractive due to lower PV cell temperatures during operation however, complexity of the system makes the module difficult to manufacture (Hasan and Sumathy, 2010; van Helden *et al.*, 2004).



**Fig. 28:** Several common structures of hybrid PV/T collector (Hasan and Sumathy, 2010; Riffat and Cuce, 2011)





**Fig. 29:** Three different design schemes of an unglazed PV/T collector (Hasan and Sumathy, 2010; Riffat and Cuce, 2011; Tripanagnostopoulos *et al.*, 2001a)

Tripanagnostopoulos *et al.* (2001a) test a HPV/T system that can allow water or air circulate as working fluids during operation. The system consists of polycrystalline silicon PV module which can be attached to either air flow channel or water flow pipes. Three different of HPV/T system schemes are considered for the comparison that are illustrated in Fig. 29. Mode A, where the water flow pipes closely attached to the PV cells, is shown to yield best results. Tripanagnostopoulos *et al.* (2001b) compare two different designs of the HPV/T system, namely first design consists of black tedlar and polycrystalline silicon PV cells and the second design consists of PV module placed within glass and transparent tedlar. Both systems are vertically installed and analyzed under natural or forced air circulation. According to results, the second scheme yields 6°C lower PV cell temperature which increases the electrical efficiency of the system. Tiwari and Sodha (2007) conduct a study to investigate the performance of air heaters consisted of glazed and unglazed HPV/T collectors, with and without tedlar layers. Different combinations are tested numerically for the climatic conditions of New Delhi, India. According to results, glazed HPV/T system without tedlar yields the best results. The overall performance is inversely related with the increase of PV module length

due to accumulation of losses. Joshi *et al.* (2009b) perform tests to compare the performances of glass-to-glass HPV/T unit and glass-to-tedlar HPV/T unit by using the New Delhi's climatic data. Best overall efficiency is observed at the glass-to-glass HPV/T unit.

Erdil *et al.* (2008) build and investigate the performance of a water based HPV/T system used as preheater. The fluid is working between the glazing and the PV module. The payback period of the system is estimated less than 2 years thus, the design is attractive in terms of the economic perspective. Kamthania *et al.* (2011) test a façade integrated double-pass air based HPV/T system at the environmental conditions of New Delhi. The annual overall electrical energy yield is obtained to be 469.87 kWh and thermal energy yield is estimated to be 480.81 kWh. Additionally, the room temperature can be kept 5-6°C higher than air temperature in winter if the system is utilized. Kumar and Rosen (2011b) propose that more advancements are needed for the air HPV/T collectors. Fan *et al.* (2016) builds HPV/T system coupled with Solar Air Heater system (HPV/T SAH). The model is built and validated experimentally in order to reach outlet temperature values up to 90°C. Temperatures above 90°C is achieved at specific times in a typical day.

## Evaluation of Performance Characteristics of Solar Units

A typical HPV/T system is a compact unit that unites PV module and thermal collector in a single system which allows this unit to produce thermal power and electrical power, simultaneously. As a result, theoretical background to model thermal collectors and PV modules will be presented in different sections.

### Theoretical Background of the Flat-Plate Thermal Collectors

Mathematical expression for the available heat produced by the flat-plate thermal collector can be presented from the literature as follows (Charalambous *et al.*, 2007):

$$Q_u = \dot{m}C_p(T_{fo} - T_{fi}) \quad (1)$$

where,  $T_{fo}$  and  $T_{fi}$  are defined as the fluid temperature circulated inside the collector at the outlet and inlet, respectively. Accordingly, thermal collector's steady-state thermal efficiency can be estimated as follows:

$$\eta_{th} = \frac{Q_u}{G} \quad (2)$$

where,  $G$  is the total irradiation level. Equation 1 can be re-expressed by considering the temperature of the absorber plate by the following equation:

$$Q_u = A_c [S - U(T_{ap} - T_{amb})] \quad (3)$$

where,  $T_{amb}$ ,  $T_{ap}$ ,  $S$ ,  $A_c$  and  $U$  are defined as the temperature of the ambient and the absorber plate, absorbed solar energy, area of the HPV/T collector and overall heat loss coefficient, respectively. Equation 3 is

simplified into new form by Hottel and Willier (1958) as follows:

$$Q_u = A_c F_r [S - U(T_{fi} - T_{amb})] \quad (4)$$

where,  $F_r$  is referred as the heat removal factor of the HPV/T collector.  $F_r$  can be estimated as follows:

$$F_r = \frac{\dot{m}C_p}{A_c U} \left\{ 1 - \exp\left(-\frac{A_c U F_e}{\dot{m}C_p}\right) \right\} \quad (5)$$

where,  $F_e$  is defined as the collector efficiency factor and can be presented by:

$$F_e = \frac{\frac{1}{U}}{W \left[ \frac{1}{U[D_o + (W - D_o)F_{fe}]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}} \right]} \quad (6)$$

In Equation 6,  $F_{fe}$ ,  $D_i$ ,  $D_o$ ,  $C_b$ ,  $W$  and  $h_{fi}$  are defined as fin efficiency factor, inside and outside tube diameter, thermal conductivity of the bond between the fin and tube, tube spacing and heat transfer coefficient of fluid, respectively. The first parameter can be calculated as follows:

$$F_{fe} = \frac{\tanh(x)}{x} \quad (7)$$

where:

$$x = \sqrt{\frac{U}{k\delta} \left( \frac{W - D_o}{2} \right)} \quad (8)$$

where,  $\delta$  is referred as the thickness of the fin. The schematic view of a fundamental solar thermal collector can be seen from a Fig. 30.

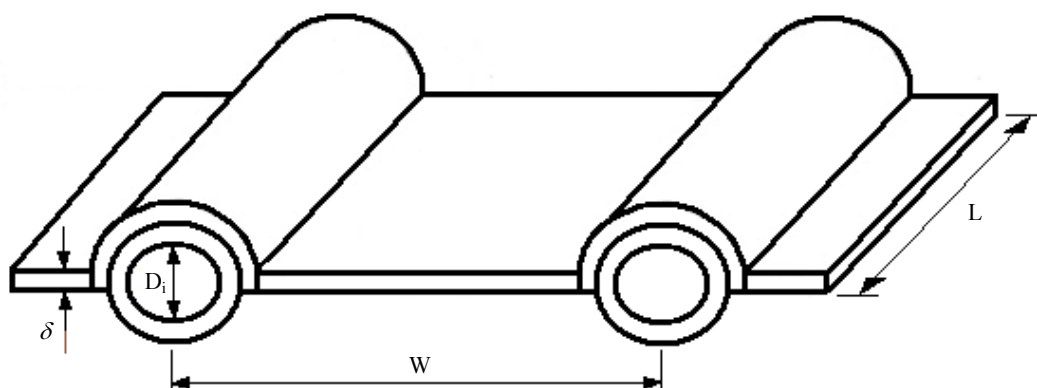


Fig. 30: Basic structure of solar thermal collector with identified dimensions (Riffat and Cuce, 2011; Charalambous *et al.*, 2007)

## Theoretical Background of Photovoltaic Units

Maximum Power Point (MPP) is defined as the specific operating condition where maximum possible power generated by a PV module is reached for a given illumination intensity level ( $G$ ). The electrical efficiency of a PV module operating at MPP is estimated as follows:

$$\eta_{el} = \frac{I_m V_m}{G A_c} \quad (9)$$

PV modules are able to harness only a small percent of the incident solar radiation. Rest of the absorbed photons is dumped as a waste heat; thus, PV module temperature does increase. However, there is an inverse relation between module temperature and the efficiency of a PV module. This relation can be expressed by the following equation:

$$\eta_{el} = \eta_{ref} (1 - \zeta [T - 25]) \quad (10)$$

where,  $\eta_{ref}$  is the defined as the PV module's reference efficiency which is generally given for the standard test conditions ( $G = 1000 \text{ W/m}^2$  and  $T = 25^\circ\text{C}$ ).  $\zeta$  is the temperature coefficient of the PV module efficiency. In short, PV module produces simultaneous electrical energy and waste thermal energy. Increasing the electrical efficiency of a PV module by reducing the temperature of the PV module and recovering this waste heat is the main idea behind the HPV/T system technology.

## HPV/T Studies Based on Analytical Models

Florschuetz (1976) and Raghuraman (1981) initially develop specific models by modifying common relations in order to explain thermal and electrical characteristics of HPV/T systems. Florschuetz (1976) brings up an expression showing the relation between cell temperature and system efficiency based on linear approach. He modifies fundamental Hottel-Whillier model which is consisted of fundamental relations for the analyses of flat-plate collector earlier (Hottel and Willier, 1958). He assumes that cell array efficiency and local thermal losses vary linearly with respect to an absorber temperature. He shows that electrical conversion efficiency is type of a function that linearly decreases with increasing absorber temperature within operation limits. Raghuraman (1981) analyzes water and air based HPV/T systems where PV cells are directly stuck to the absorber by using a thermal model. Thermal efficiency of the system is estimated to be 42%. Schott (1985) and Evans (1981) also derive a

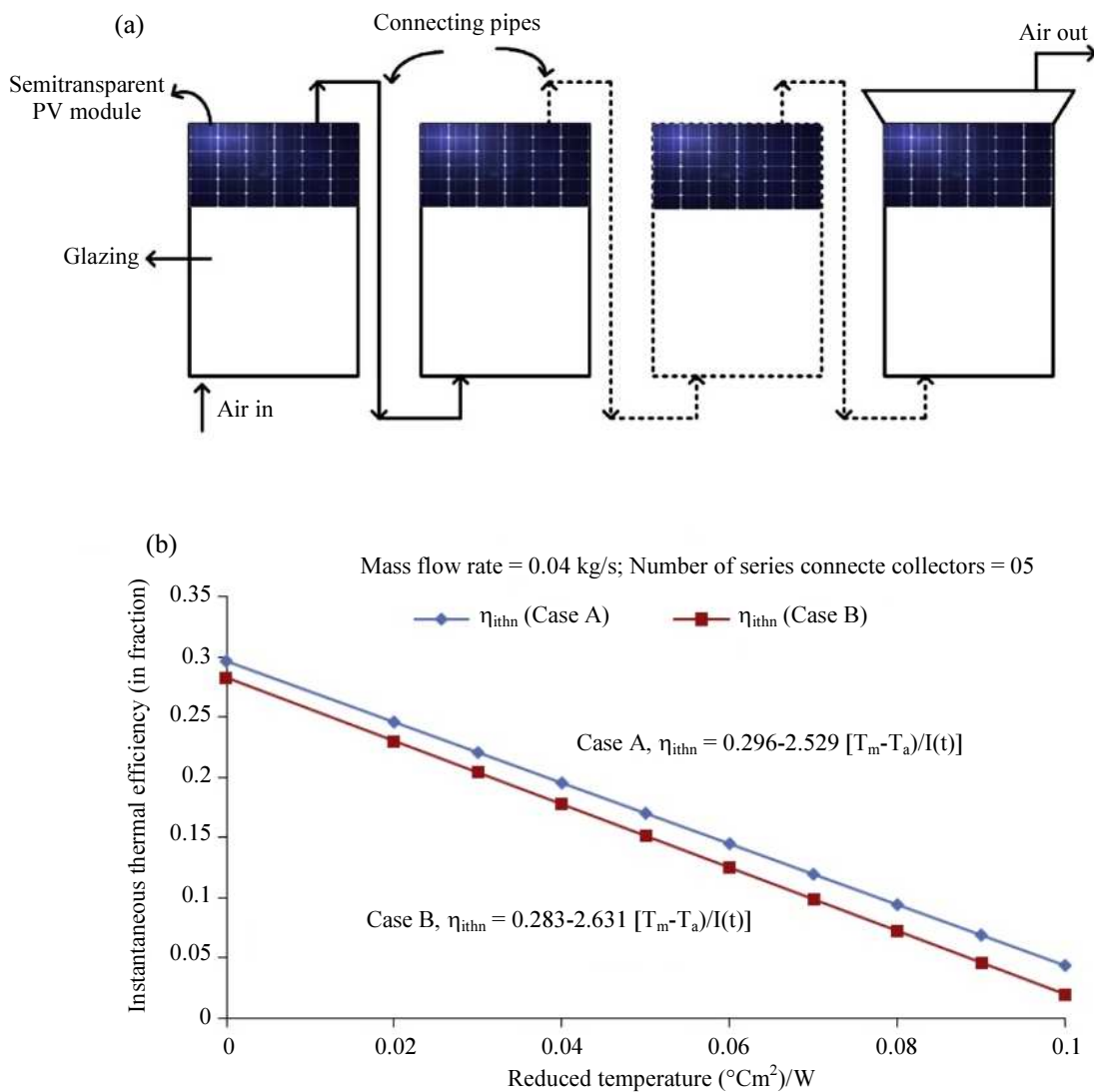
function that relates electrical efficiency of a PV module to cell temperature. Lovvik and Bergene (1995) present a comprehensive analytical model based on energy transfer within module layers to predict the energy output of a water based HPV/T system. The model is able to calculate thermal efficiency by calculating the net thermal output. The overall efficiency of the systems is estimated to be between 60 and 80% for a given conditions. The comparison between the performances of single-pass and double-pass air based HPV/T system are performed analytically by Sopian *et al.* (1996). Since the front cover temperature tends to be lower in double-pass design, it is shown to have a better thermal performance. Ito *et al.* (1999) perform theoretical and experimental studies to investigate the performance of heat pump consisted of a flat-plate collector deployed as an evaporator in the thermodynamic cycle.

Choudhury and Garg (1993) evaluate the advantage of using packing above the back plate in the flow passage for the air based HPV/T systems by comparing their overall yields. Hegazy (2000) performs a parametric study by using analytical model to compare the efficiencies of four different types of air based HPV/T systems with respect to different flow rates and absorber plates. It is seen that air flow under or above the absorber plate results in the lowest performance, besides, other HPV/T designs are observed to have comparable electric and thermal yields. Chow (2003) analyzes the transient energy characteristics of flat-plate water based HPV/T collector with glazing by using explicit dynamic model. Tiwari *et al.* (2006) develop an analytical model consisted of energy balance equations applied within different layers of HPV/T module to estimate system performance of air based collector. Analytical results are validated with experimental data. Overall efficiency is increased 18% due to better heat recovery in the enhanced system. Joshi and Tiwari (2007) obtain outputs of a parallel plate air based HPV/T collector through analytical model where the ambient data is taken from Indian Metrological Department. The exergy efficiency of the system is calculated in the range of 55-65% whereas, energy efficiency of the system is calculated within 12-15%. The results are verified and shown to be in good agreement with the data presented by Bosanac *et al.* (2003). The electrical performance characteristics of PV modules can be predicted based on valid models (Cuce *et al.*, 2017; Cuce and Cuce, 2015).

Dubey and Tiwari (2009) theoretically analyze serial systems made of partially covered flat-plate water based HPV/T collectors. It is shown that up to  $28^\circ\text{C}$  increase in outlet water temperature can be obtained if number of collectors connected in series is increased from 4 to 10. Joshi *et al.* (2009c) compare

the energy and exergy efficiencies of PV and HPV/T systems. According to results, the variation in exergy efficiency of the HPV/T system is observed within 11.3-16% while the variation in exergy efficiency of the PV system is observed within 7.8-13.8%. Dev and Tiwari (2010) compare the validity of linear and non-linear mathematical models which can reveal the characteristics of a HPV/T system. Non-linear equation is found to yield more reliable results than linear one. Sarhaddi *et al.* (2010) develop electrical and thermal model of an air based HPV/T system and verify the output results. The overall efficiency of considered HPV/T system is determined to be 45%. Rajoria *et al.* (2016) compare the performance of Solar Cell Tiles (SCT) array which is analyzed for the

first time as well as semi-transparent HPV/T array. Additionally, expressions are derived to obtain room temperature of a building where BIHPV/T system is installed at the roof. The performance of producing useful thermal energy gain is found to be significantly higher for semi-transparent HPV/T roof. Analytical expressions are developed for a novel HPV/T system equipped with a Micro Heat Pipe Array (MHPA) structure by Hou *et al.* (2016). MHPA is developed to increase solar heat transfer. Additionally, mathematical model is developed based on heat transfer processes. Experimental and simulation studies are conducted to validate mathematical model. The model shows several significant disagreements in thermal efficiency due to sessional difference.



**Fig. 31:** Partially covered air based hybrid PV/T collector connected in series. (a) structure of the overall system, (b) fitted performance values for case A (PV modules are placed at the inlet of each collector) and case B (PV modules are placed at the outlet of each collector) (Shyam and Tiwari, 2016)

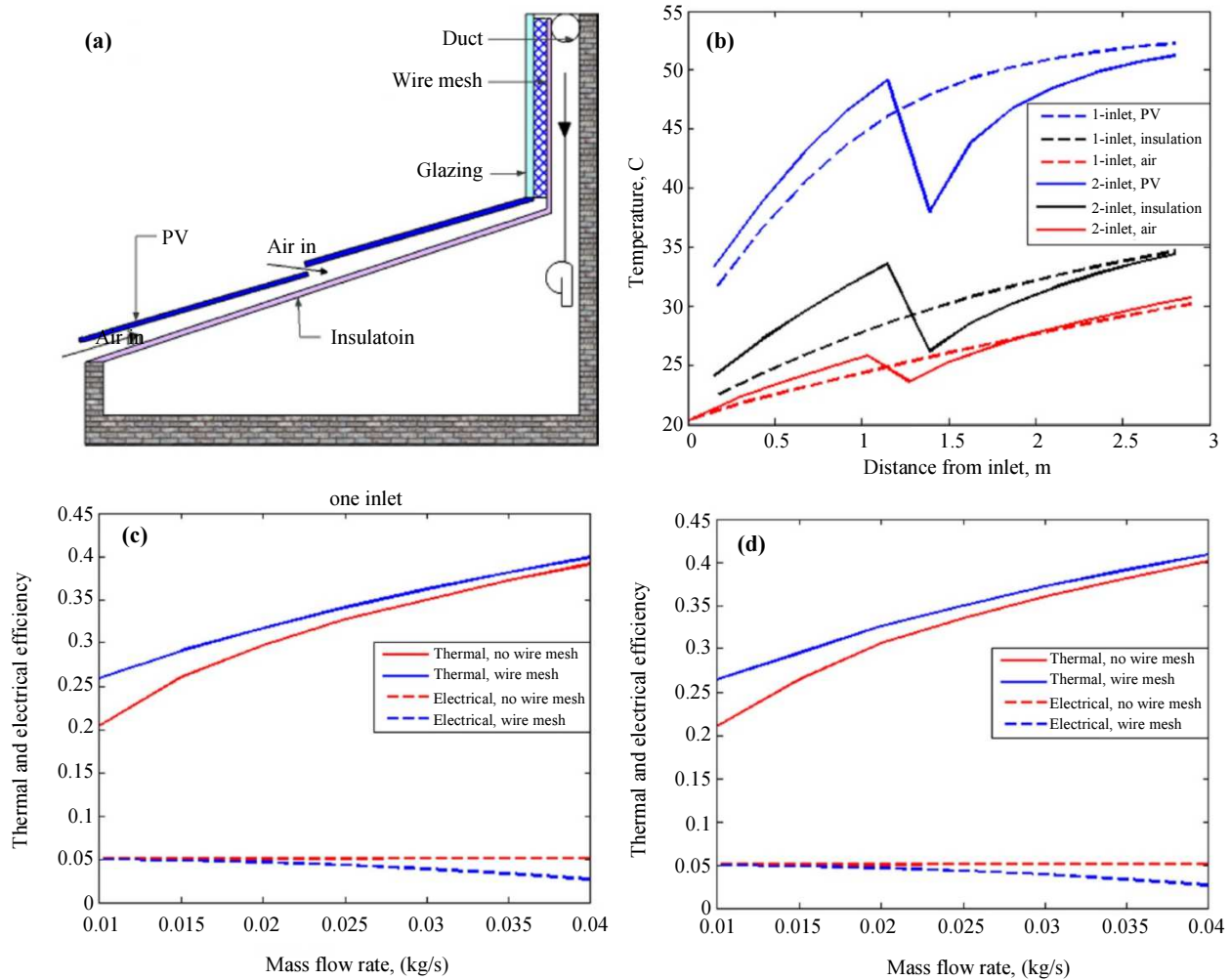
Singh *et al.* (2015b) optimize a flat-plate HPV/T system by using technique called Generic Algorithm (GA). Several parameters are selected as variables including dimensions of the channel, velocity of air flow through the channel, thickness of the tedlar and glass and temperature of inlet fluid. According to results 4.6% and 13.14% improvement can be achieved in overall exergy efficiency and overall thermal efficiency when overall thermal efficiency is optimized. Shyam and Tiwari (2016) derive several expressions for a HPV/T cluster connected in series and partially covered with semi-transparent PV units. Semi-transparent PV modules are placed at the outlet and inlet sections of collectors. The schematic view of panel connection is presented in Fig. 31. An increase in mass flow rate causes a decrease in the solar cell temperature and maximum outlet temperature. Accordingly, cell efficiency starts to increase. On the other hand, electrical efficiency tends to increase regardless of the number of units connected in series. Results show that the case where solar cells placed at the inlet sections is better in terms of energy output and payback time which is estimated to be 1.12 years. Jarimi *et al.* (2016) derive several equations and build 2D theoretical model to analyze bifluid based HPV/T collector. They validate results by using experimental design under solar simulator and they observe good agreement between experimental and theoretical results. Shan *et al.* (2014) investigate characteristics of BIHPV/T units with respect to time by using dynamic model. It is shown that meteorological parameters and the evaporating temperature have significant effect on thermal performance of the system.

### HPV/T Studies Based on Numerical Approach

Cox and Raghuraman (1985) conduct numerical simulations on flat-plate air based HPV/T collectors embedded with single crystal silicon PV cells in order to reduce the infrared emittance and to increase solar absorptance. Garg and Adhikari (1999b) study thermal characteristics of an air based HPV/T system with respect to different types of absorbers and packing factor. According to the results, selected absorber for the study shows better performance than conventional black painted absorber and the collector with no PV cells is seen to have better thermal performance than that of with fully covered PV cells. Several studies are also performed on PV roofs based on numerical approaches at the University of Gävle, in the late 1990s (Dunlop, 1998; Sandberg and Moshfegh, 1998; Sandberg *et al.*, 1998; Strobach *et al.*, 1998). Zondag *et al.* (2002) perform several estimations on the performance of the water based HPV/T collector based on four different numerical models where all results are validated with

test results within acceptable accuracy range. 1D simple steady-state model is shown to be sufficient enough to predict daily thermal output. However, 2D and 3D models are shown to be required for deeper analyses such as for design enhancements. According to results, 54.2% of the total solar irradiation can be converted to useful heat. Moshfegh and Sandberg (1996) perform parametric study to investigate heat and flow characteristics in a vertical duct heated by one side based on the data obtained through numerical analyses. Results are obtained for a duct with a specific height dimension of 6.5 m and variable width dimensions. Temperature profiles for the walls and outlet air as well as velocity profile for the air flow are presented with respect to different heat fluxes. Zhu *et al.* (2002) demonstrate a numerical model to investigate indoor performance of PV module and heat characteristics of the structure. According to numerical findings, thermal resistances across contact surfaces have significant effect on the temperature profile. But the transparent glass cover's extinction coefficient shows no prominent effect on the temperature profile.

Huang *et al.* (2004) perform a study to reveal heat characteristics of a BIHPV/T integrated with phase change material. Temperature profiles are numerically obtained with respect to various ambient temperatures and irradiation intensity values. The performance of PV façade is shown to be able to be significantly increased if the system operates at moderate temperatures. Ji *et al.* (2006b) numerically investigate the performance of the water heating system driven by a HPV/T unit by modifying Hottel-Whillier model. Parametric study is performed with respect to various mass flow rates and different packing factors to reveal changes in the overall system performance. Results show that HPV/T can supply clean electrical and thermal demands of a building, so that, the energy consumption can be significantly reduced for domestic use. Gaur and Tiwari (2010) numerically study on the performance of the active solar still integrated HPV/T collector. The number of HPV/T collectors are optimized with respect to water with different heat capacities based on exergy and energy analyses. Kim *et al.* (2011) perform numerical analyses on a 125 W PV module to reveal heat characteristics. It is observed that, while ambient temperature increases, short circuit current ( $I_{sc}$ ) increases and open circuit voltage ( $V_{oc}$ ) significantly decreases. BIHPV/T system with multiple inlets is simulated in order to observe the performance enhancement due to addition of more inlets to the system (Yang and Athienitis, 2014). The schematic view of the system with multiple inlets is presented in Fig. 32. It can be seen from Fig. 32 that PV unit temperature in two-inlet is lower than that in one-inlet system. But still 5% enhancement in thermal efficiency is observed for two-inlet system.



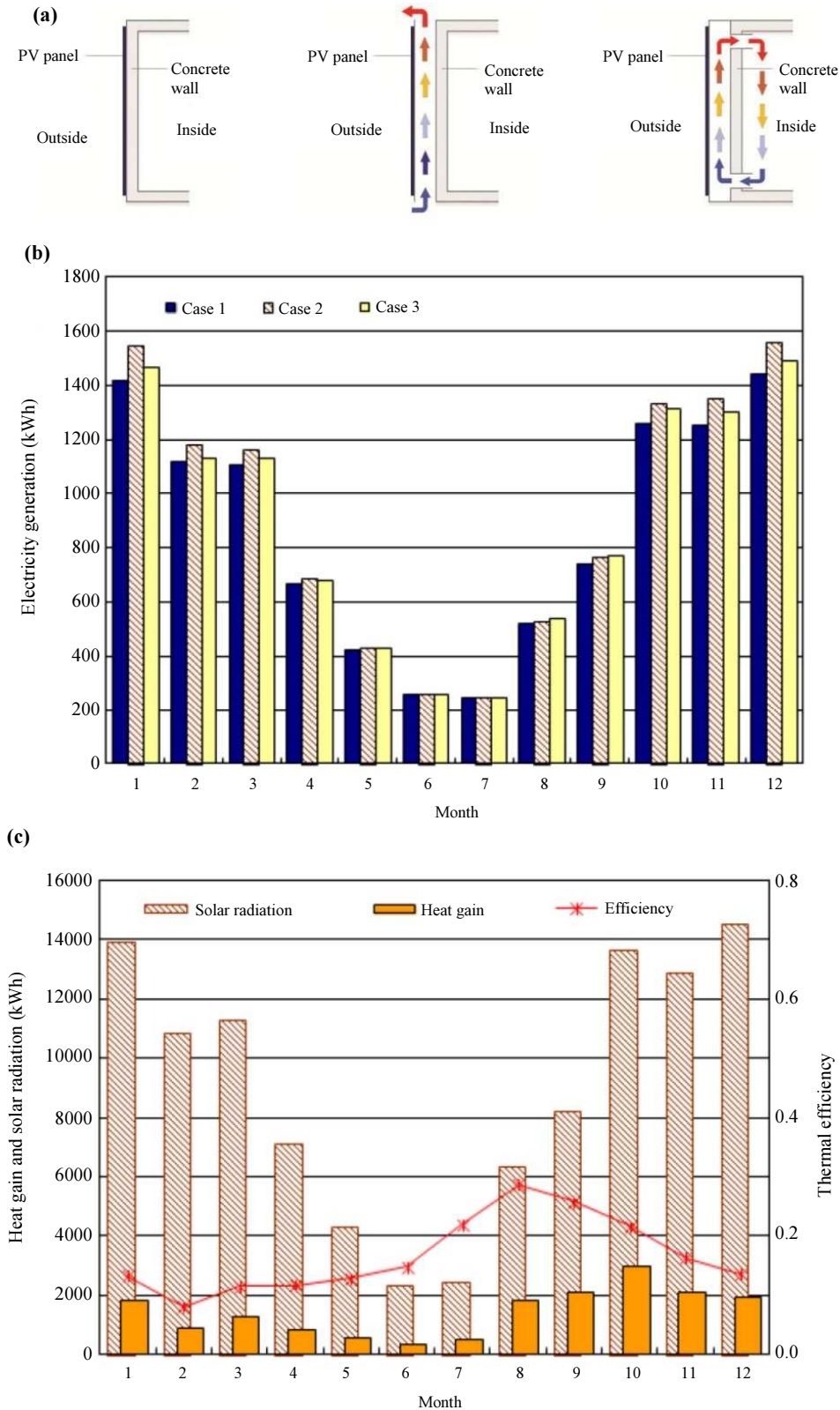
**Fig. 32:** Building integrated hybrid PV/T system with multiple inlets. (a) Construction of the system, (b) temperature distribution of one and two inlet design, (c) performance characteristics of one inlet glazed unit, (d) performance characteristics of two inlet glazed unit (Yang and Athienitis, 2014)

In order to validate numerical models, full scale experiments are conducted on BIHPV/T system with single inlet. After the results are compared between experimental studies and numerical ones, results are also obtained for the system with two inlets. 5% increase in thermal performance is observed for two-inlet scheme. Additionally, it is observed that addition of vertical glazed solar collector to the single inlet system increases thermal performance in winter.

### HPV/T Studies Based on Models and Simulations

Kalogirou (2001) presents a model of a HPV/T collector and simulates its operation by using Transient System simulation program (TRNSYS) for the climatic conditions of Cyprus. Optimum flow rate is parametrically investigated with respect to the overall

yield where optimum output is seen at the flow rate of 25 L/h. Additionally, using HPV/T system is shown to increase the overall annual efficiency of the single PV unit from 2.8% to 7.7% and be able to supply 49% of the hot water demand of a domestic house. Ji *et al.* (2008) estimate thermal and electrical performance of a photovoltaic heat pump based on mathematical model results. Mentioned values are estimated to be above 50% and 12%, respectively. In another study, Ji *et al.* (2009) conduct a study to reveal spatial heat characteristics of a refrigerant of a HPV/T driven heat pump system by using time-dependent mathematical model. The model successfully predicts the time-dependent spatial distributions of pressure, temperature, enthalpy and vapor quality of the refrigeration unit. Keliang *et al.* (2009) simulate the performance of a HPV/T driven heat pump with a compressor operating at variable frequencies by using mathematical models.



**Fig. 33:** A building integrated hybrid PV/T system. (a) Different integration types (b) monthly electricity generation of all cases (c) heat gain and efficiency of last two design (Kim and Kim, 2012)

According to the simulation results, the overall daily electrical efficiency, thermal efficiency and overall efficiency of the system are observed to be 13.5%, 47.9%, 62.5%, respectively. COP of the system is 6.01. da Silva and Fernandes (2010) perform simulations on a HPV/T collector by using Simulink/Matlab. They propose that the selection of specific novel gas or vacuum at relatively low pressure can help to reduce the emittance from PV modules by increasing optical thermal efficiency by 8% and preventing thermal losses. Zhao *et al.* (2011b) perform parametric study to optimize HPV/T system consisted of direct thermal absorber and silicon solar cells with and without solar concentration. According to the results, system can operate in optimum condition if Infrared (IR) section of the solar irradiation and visible section of the solar irradiation can be utilized in an effective way. Approximately 89% of the IR light can be converted into a thermal energy and 84% of the visible light can be converted into an electrical energy. It is additionally seen that while irradiation level is changed from 800 to 8000 W/m<sup>2</sup> the thermal efficiency is reaching a constant value of 40% and the outlet temperature of the working fluid is raised up to 196°C. Shahsavari and Ameri (2010) conduct several experiments and build theoretical model of a direct-coupled air based HPV/T system. Theoretical and experimental results reveal that placing glass cover on PV panels results in an enhancement in a thermal efficiency reversely, impairment in electrical efficiency due to the increasing cell temperature. Moreover, it is underlined that there is an optimum number for the circulation fans to achieve maximum electrical efficiency. The addition of air based BIHPV/T to a building as an envelope can significantly affect the thermal characteristics of the building. Kim and Kim (2012) simulate building environment with and without BIHPV/T systems by using TRNSYS. Also, BIPV is added to the study. Air gap does not exist when BIPV is attached to the wall while air gap does exist when BIHPV/T is attached to the building walls. The schemes which are compared in simulation study as well as comparative data can be seen from Fig. 33. The maximum PV temperatures are observed for the reference case with no ventilation. The annual electricity yield is highest for Case 2. Thermal gain is also higher for Case 2. Results show a difference in thermal characteristics of buildings with and without air based BIHPV/T installations. This difference changes as a function of total amount of energy produced by BIHPV/T system. Oyieke and Inambao (2016) simulate a HPV/T system with vacuum insulation for subtropical climate conditions. TRNSYS analyses are validated with experimental

studies. Thermal efficiency is about 16.8% for prementioned environment.

## HPV/T Studies Based on Experiments

Experimental studies have always been the vital part of the performance evaluation of HPV/T systems since 1970s. Experimental studies are performed in order to establish an optimum design for a system which can expose better electrical and thermal efficiencies and also check the validity of the newly designed analytical models. Tripanagnostopoulos *et al.* (2000) conduct experimental studies and parametrically analyze several factors on the air based HPV/T system with respect to different modifications made in the air channel. All configurations considered in the study can be seen from Fig. 34. Air flow channel depth is gradually changed for the performance analyses at the first configuration. At the second step, fins and tubes are added to a HPV/T system in order to enhance the heat transfer. At the end, air channel is divided into two sections by attaching metallic sheet in the middle. According to the results, overall thermal yield of the system is tended to decrease for longer air channel depth. It is added that the use of tubes and fins positively affect the electrical and thermal efficiencies of the system with bringing some additional drawbacks such as pressure drop and additional manufacture cost. In overall, metallic sheet is found to heal the electrical and thermal yield of the considered system. Tonui and Tripanagnostopoulos (2007a) test the advantage of either using fins at the back wall or placing thin flat metallic sheet in the middle at the air flow channel to increase overall performance of an air based HPV/T system. They propose that these enhancements for the HPV/T systems can lead an increase in PV applications to harvest clean energy.

Different absorber designs are also tested by several researchers (Michael and Selvarasan, 2017; Hu *et al.*, 2016a; Deng *et al.*, 2015). Cuce *et al.* (2013) experimentally analyzed performance characteristics of photovoltaics based on selected parameters from thermodynamics perspectives (Cuce and Cuce, 2014; 2012; Cuce *et al.*, 2011). He *et al.* (2011) experimentally investigate a system consisted of amorphous silicon PV cells and double-glazed window for the climatic conditions of Hefei, China. The use of double-glazed window is found to result in decrease in the indoor heat gain. However, the system is proposed to be useful for the office buildings. Sun *et al.* (2011) analyze the performance of PV trombe wall with respect to different south façade designs. Results reveal that the increase in PV allocation on the glazing could cause 17% reduction in the overall thermal efficiency

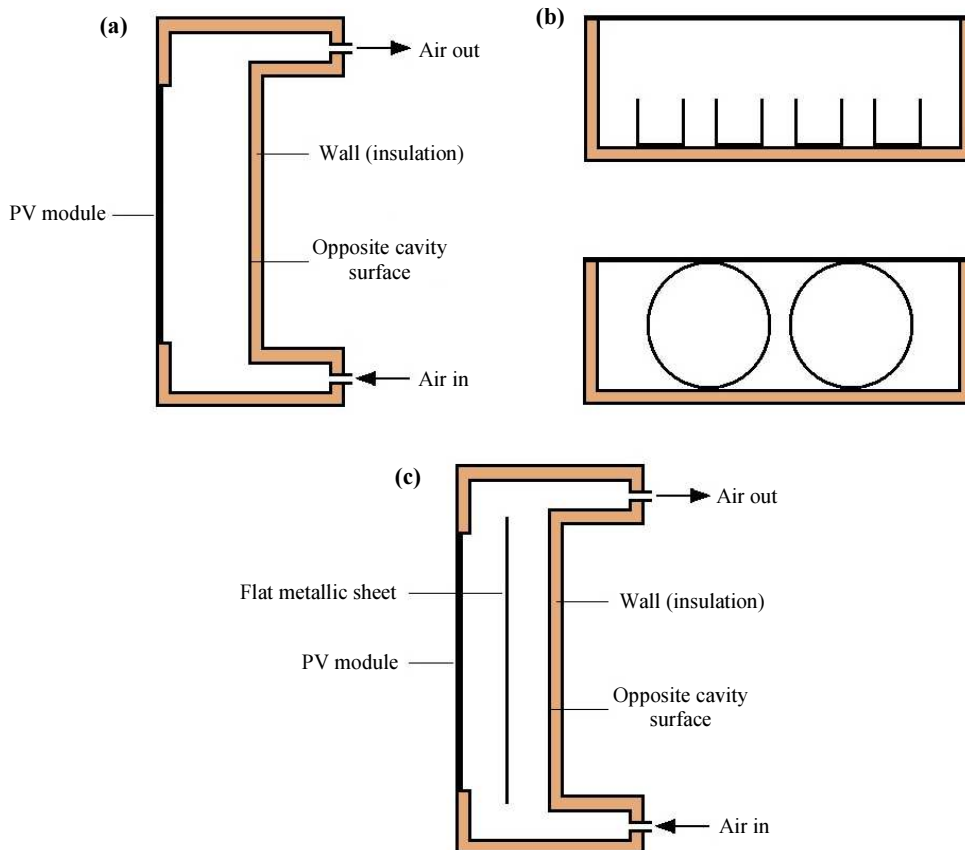


of the PV-trombe wall. On the other hand, maximum 5% reduction is observed in electrical efficiency if PV cells are fully covered glazing. Li *et al.* (2011) experimentally compare the performance of trough type CHPV/T collector with a total surface area of 2 m<sup>2</sup> embedded with different types of PV cells such as GaAs, a single crystalline silicon, a polycrystalline silicon and a super PV cell arrays. The maximum electrical yield is observed for the system with GaAs PV cell whereas silicon types are seen to have better thermal performance. Pei *et al.* (2013) combine HPV/T system and heat pipe technology in order to solve freezing problem at high altitudes. Heat pipe system can provide heat transfer without consuming any excess power. In the experiments four HPV/T thermal collectors are used each equipped with nine heat pipes. Water temperature is observed to reach about 45°C for glass covered system. The thermal efficiency of the unglazed scheme is found to be 37.1% which is almost 4 percent lower than the thermal efficiency of glazed scheme. Performance materials including effective glass structures for building integrated PV applications

are experimentally studied to regulate heat for the energy saving buildings (Cuce and Riffat, 2016; Cuce, 2016; Cuce *et al.*, 2016). Moradgholi *et al.* (2014) experimentally analyze the performance of HPV/T system cooled with thermosyphon type heat pipe system. The system allows heat to be extracted from the PV units at constant temperature. System is placed at different angles in summer and winter. System produced up to 7% more electric power than single PV system. Yang and Athienitis (2015) compare single and double inlet BIHPV/T systems under full-scale simulator. Results show that double inlet type could increase the thermal efficiency by 5 %.

### Parameters Significantly Contribute to the HPV/T Performance

The thermal and electrical characteristics of any type HPV/T system is a function of several parameters such as inlet temperature and mass flow rate of the working fluid, number of covers and absorber design types including tube diameter, tube spacing and fin thickness.



**Fig. 34:** Three different design schemes of air based hybridPV/T collector (Riffat and Cuce, 2011; Tripanagnostopoulos *et al.*, 2000)

## The Effect of Glazing

Fujisawa and Tani (1997) investigate the performance of a HPV/T system consisted of mono-crystalline Si PV cells and aluminum absorber plate as liquid heater. Realistic thermal and electrical energy production is estimated by applying exergy analyses. Results reveal that the non-glazed scheme yielded slightly more useful energy than the single-glazed scheme. Sandnes and Rekstad (2000) test a water based HPV/T system consisted of a polymer absorber plate. They propose that the heat losses can be compensated by employing an additional glass cover, however, the reflective losses are still on increase if glazing had applied. Zondag *et al.* (2003) study to compare the performances several different schemes of HPV/T systems. Among all designs, single cover sheet-and-tube scheme is seen to be the most suitable scheme for the hot water production for domestic use. Since uncovered schemes are lack of reflection losses, they are shown to be better to be used for low temperature applications. Tiwari and Sodha (2006b) study to reveal advantages of four different HPV/T water/air heating system design schemes, namely, unglazed with Tedlar (UGT), Glazed with Tedlar (GT), Glazed Without Tedlar (GWT) and Unglazed Without Tedlar (UGWT). It is highlighted that GT scheme is more suitable to be operated at high temperatures, whereas, UGWT scheme is more suitable to be operated at low temperatures.

Fraisse *et al.* (2007) investigate the energy characteristics of a system consisted of a water based HPV/T system and a Direct Solar Floor (DSF). Different configurations are built and tested with respect to selection of glazed and unglazed covers. According to results, glass covered HPV/T system shows 6.8% annual electrical efficiency, which means 28% decrease when compared with a conventional non-integrated PV module with 9.4% annual efficiency. Chow *et al.* (2009a) study thermodynamic aspects of using glass cover on a water based HPV/T system based to enhance the overall system efficiency. It is concluded that glazing always results in an increase in thermal and overall efficiency. According to exergy analyses, increase in wind velocity, packing factor and PV cell efficiency are always beneficial for the system without glazing, increase in illumination intensity and ambient temperature were always beneficial for the glazed system. They underline that exergy analyses should be done for determination of design criteria based on electrical or thermal energy demand. The energy yields of three different open cycle air heating BIHPV/T systems are compared by Pantic *et al.* (2010). Glazing is shown to impair electrical performance significantly due to significant rise in PV module temperature.

## The Effect of Mass Flow Rate

The mass flow rate of working fluid is considered significantly important parameter on system performance. It should be optimized so that optimum operating conditions can be met by providing effective heat transfer. Garg and Adhikari (1997) perform simulations on an air based HPV/T systems with different configurations. According to results, the increase in mass flow rate cause increase in system efficiency, inversely an increase in duct depth caused a decrease in system efficiency. Bergene and Lovvik (1995) develop an extensive model to investigate the performance of water based HPV/T system. They report that slight increase in the thermal efficiency occurs while the mass flow rate was changing from 0.001 to 0.075 kg/s. Accordingly, they conclude that the demonstrated system can be used to pre-heat water for domestic use with almost constant efficiency. Sopian *et al.* (2000) evaluate the feasibility of double-pass air based HPV/T collector as a solar drier and seek optimum mass flow rate. The optimum operating condition is established for an illumination intensity level of 800 W/m<sup>2</sup> and a mass flow rate of 0.036 kg/s. At this condition, the collector efficiency is observed to be 60% with temperature rise of 18°C. Lower PV panel temperature is obtained as well as heat transfer is augmented while mass flow rate is increased. Kalogirou (2001) seek optimum conditions for a HPV/T system by using Transient System simulation program (TRNSYS) and Cyprus' climatic data. According to results, 0.007 kg/s mass flow rate is obtained to be optimum value for a 5.7 m<sup>2</sup> collector area. Two different designs of HPV/T collectors, namely, single glass covered and uncovered HPV/T collectors are studied Morita *et al.* (2000) based on thermodynamic laws. The values of 0.0014 kg/s and 0.0049 kg/s are found to be optimum mass flow rates for a single glass covered and uncovered HPV/T collectors, respectively. Abu Bakar *et al.* (2014) sought electrical and thermal efficiencies for different air and water mass flow rates for their bifluid cooled HPV/T system. The mathematical model is validated with published results for given mass flow rates. The parametric investigation is conducted in the range of 0.098 and 0.11 for air and water, respectively. When flow rate of water is kept constant around 0.0079 kg/s and air flow is kept at 0.013, 0.034 and 0.051 kg/s values, maximum predicted thermal, electrical and total equivalent thermal efficiencies are observed at the value of 43.7%, 11.1% and 76.3%, respectively. Kasaeian *et al.* (2017) investigate the effect of channel depth and air mass flow rate on HPV/T performance. It is observed that thermal efficiency is not a strong function of channel depth and electric performance is not significantly affected by the

change in depth and mass flow rate. However, for 5 cm channel depth while air mass flow rate changes from 0.018 to 0.06 kg/s, the thermal efficiency changes from 15% to 31%. Fudholi *et al.* (2014) show that the value of 0.041 kg/s is the optimum mass flow rate for a HPV/T collector with solar irradiation level of 800 W/m<sup>2</sup> and spiral flow absorber.

### The Effect of Absorber Module Parameters

There are specific design parameters that can significantly affect absorption and heat transfer characteristics of a HPV/T collector. Bergene and Lovvik (1995) observe the effects of ratios of two design parameters such as, tube Diameter (D) and tube spacing (W). Results reveal that, while W/D ratio is gradually changed from 1 to 10, outlet fluid temperature decreases. Charalambous *et al.* (2007) show that the thermal efficiency of the system significantly depends on the fin size, whereas electrical efficiency stays constant. It is added that the change in W/D ratio is worthless for cooling applications since system cost increases. In another study, Charalambous *et al.* (2011) develop a theoretical model to reach optimum absorber plate design which demanded less material and less investment. They propose that optimum serpentine absorber plate can contain 40.5% less mass and accordingly material content. Huang (1999; Huang *et al.*, 2001) test two different schemes of unglazed HPV/T systems with tube-in-sheet collector plates constructed by W/D ratio of 6.2 and 10. Two different schemes of tube-in-sheet collector plates are constructed by changing W/D ratio from 6.2 to 10. After testing these designs, no satisfactory results are obtained in terms of thermal performance. Thus, they decide to develop new design by employing novel polycarbonate multi-channel structure with the W/D ratio of 1. The overall daily efficiency is observed to be 38%.

### Thermodynamic Approaches to the HPV/T System Characteristics

Some mathematical expressions, especially ratios, are systematically defined by researchers from the thermodynamics perspective. Researchers at the University of Ontario Institute of Technology are analyzed characteristics of PV and HPV/T systems during operation based on thermodynamic approaches (Sahin *et al.*, 2007; Joshi *et al.*, 2009a; 2009c). The exergy aspects of PV systems are extensively investigated (Fujisawa and Tani, 1997; Saitoh *et al.*, 2003; Hepbasli, 2008; Joshi *et al.*, 2008). Cuce and Bali (2009a; 2010) perform parametric studies on two different types of PV modules with monocrystalline and polycrystalline cells by gradually changing illumination intensities as well as cell temperatures.

### Definitions for Photovoltaic Systems

Efficiency is a ratio which shows how much radiative energy is converted into electrical energy. In the literature, three main efficiency expressions are defined depends on what kind of losses are considered. Those reveal performance characteristics of photovoltaic cells. These are arranged as energy, exergy and power conversion efficiencies. The energy efficiency can be estimated by dividing theoretical electrical power output by total solar energy captured by the cell surface:

$$\eta_e = \frac{I_{sc} V_{oc}}{G A_c} \quad (11)$$

Accordingly, power conversion efficiency can be estimated by dividing the area under the photovoltaic cell's characteristic current-voltage curve by the input illumination intensity:

$$\eta_{pce} = \frac{\int_0^{V_{oc}} I(V) dV}{G A_c} \quad (12)$$

At last, exergy efficiency can be estimated by dividing the maximum useful energy produced by a photovoltaic cell by the input exergy of illumination intensity:

$$\eta_{ex} = \frac{I_m V_m}{G_{ex} A_c} \quad (13)$$

The exergy efficiency can also be expressed by using the Fill Factor (FF) as follows:

$$\eta_{ex} = \frac{I_{sc} V_{oc}}{G_{ex} A_c} FF \quad (14)$$

The functional relation between exergy value of the thermal radiation and total radiation was proposed by Petela (2003):

$$G_{ex} = \left[ 1 + \frac{1}{3} \left( \frac{T_{amb}}{T_{sun}} \right)^4 - \frac{4}{3} \left( \frac{T_{amb}}{T_{sun}} \right) \right] G \quad (15)$$

### Definitions for HPV/T Systems

HPV/T systems are combination of PV systems and thermal collectors. This enables these systems to provide thermal and electrical energy simultaneously. That corresponds to an exergy output which is a combination of useful thermal and electrical energies. Thus, the exergy efficiency of a HPV/T system ( $\eta_{ex-h}$ ) can be expressed by:

$$\eta_{ex-h} = \frac{E_{ex} + T_{ex}}{G_{ex} A_c} \quad (16)$$

In Equation 16,  $T_{ex}$  and  $E_{ex}$  are defined as the useful thermal and electrical energies of the considered system, respectively. Equation 16 can also be expressed as follows:

$$\eta_{ex-h} = \frac{V_m I_m + (1 - (T_{amb} / T_{cell})) Q}{\left[ 1 + \frac{1}{3} \left( \frac{T_{amb}}{T_{sun}} \right)^4 - \frac{4}{3} \left( \frac{T_{amb}}{T_{sun}} \right) \right] G A_c} \quad (17)$$

where,  $T_{cell}$ ,  $T_{sun}$  and  $Q$  can be called as the PV cell temperature, sun temperature and available thermal energy, respectively.

### Optimum Operating Conditions for HPV/T Collectors

From thermodynamics perspective, thermal and electrical energies are qualitatively classified into different sections. Charalambous *et al.* (2007) highlight that thermal energy cannot be produced unless a temperature gradient exists between energy sources. This means that thermal energy yield is strongly affected from ambient conditions. However, electrical energy can be produced regardless of the value of the ambient temperature. The ratio between electrical and thermal power can be determined based on the application. No optimum value can be proposed for all applications, instead it is a design preference depending on the energy demand. Coventry and Lovegrove (2003) seek an optimum value for ratio between thermal and electrical outputs for conventional HPV/T system for domestic use. The study is performed by considering 2001 US financial data prepared for flat-plate PV and domestic solar water heating systems. The value for optimum ratio is offered to be 4.24. They add that the ratio can be widely used, however may slightly deviate with respect to location and time. Sobhnamayan *et al.* (2014) try to optimize HPV/T system in order to maximize exergy efficiency of the system by using Genetic Algorithm (GA). For the analyses of the system, thermal and electrical models are built. Energy and exergy analyses are performed for each parametric study. Maximum exergy efficiency is estimated to be 11.36% for inlet water velocity and pipe diameter of 0.09 m/s and 4.8 mm, respectively. Pathak *et al.* (2014) perform optimization on different configurations, namely two panel HPV/T system, side by side HPV/T system, two module PV system and a two-panel solar thermal system where all have identical absorber areas

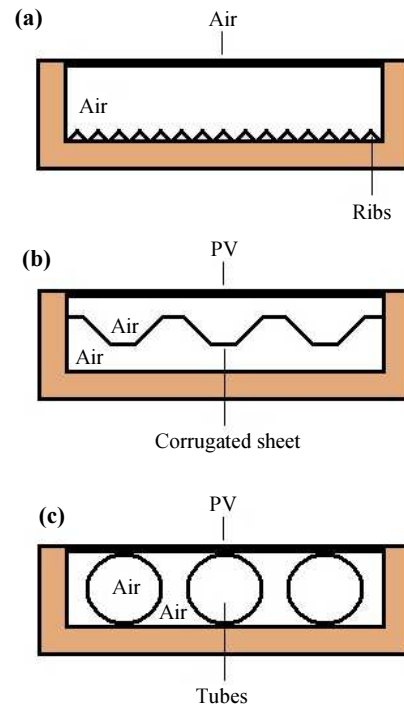
for limited areas for the climatic conditions of Detroit, Denver and Phoenix. According to results, HPV/T systems are still best choice, thermal system performed really good to produce low grade heat with low exergy. Krishna Priya *et al.* (2013) study to establish robust way to size a typical flat-plate HPV/T collector. It is concluded that the sizing is a strong function of electrical demand, thermal demand, outlet temperature and boiling point of the of the working fluid. Ooshaksaraei *et al.* (2017) compare four different HPV/T design with bifacial cells. They note that several optimum designs can be reached based on desired output. Optimization tools are available to seek optimum operating conditions (Kalani *et al.*, 2017; Singh *et al.*, 2015c). These tools can also be used to reach optimum conditions based on application requirements.

### Performance Enhancement Techniques for HPV/T Collectors

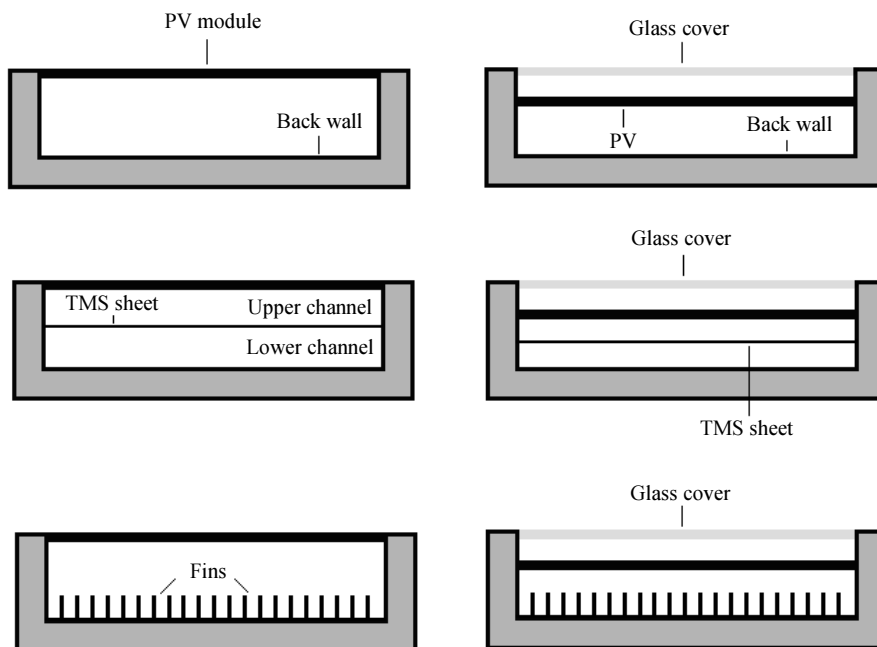
Many studies are dedicated to improve the efficiencies of HPV/T collectors by modifying design, using different working fluids, concentrating more light into PV cells, etc. These techniques consist of different viewpoints to augment the overall performance and increase useful energy output. Tripanagnostopoulos (2007) compare the advantages of performing several modifications on HPV/T collectors such as interposition of a corrugated sheet, placement of sheet combined with small ribs on the opposite air channel wall and placement of tubes inside air channel. All these modifications can be seen from Fig. 35. All these modifications result in fairly acceptable thermal efficiency values for heat extraction. Tonui and Tripanagnostopoulos (2007b) perform adjustments on the air channel of an air based HPV/T system by employing two cheap heat extraction apparatus in order to achieve higher overall output. The schematic views of the considered models are demonstrated in Fig. 36. It is observed that all modifications, namely placing Metal Sheet (TMS) in the middle of the air channel and fin installation on the opposite wall helped to heal overall performance of the system. The maximum thermal output is obtained for the design consisted of glazing and finned wall. Additionally, the design with thin metal sheet dividing the air channel also produces satisfactory results and it can be used for building protection. The proposed method is shown to be easily integrated with a building. Many other techniques are available in the literature related with the HPV/T design including absorbers, PV cells and cooling path (Ooshaksaraei *et al.*, 2017; Liang *et al.*, 2015; Joy *et al.*, 2016; Gholampour *et al.*, 2014). Reaching high efficient HPV/T collectors for the market is the key target (Haurant *et al.*, 2014).

The useful heat generated from the solar irradiation of PV cells is collected by thermal collectors. However, generally this heat is not enough to provide domestic demand. To overcome this problem different schemes are raised which consist of HPV/T units and other HPV/T driven systems. The new HPV/T scheme is proposed by Mohsenzadeh and Hosseini (2015) to cool solar panels efficiently and produce hot water at higher temperatures than single HPV/T systems. In the system HPV/T is operating as a pre- heater. Additional heating is provided with four vacuum tube solar water heaters placed both sides of the HPV/T unit. By this way, sufficient hot water is produced for domestic use and the output temperature of the water is reached to maximum value of 95.5°C. Phase Change Materials (PCM) plays an important role in PV and HPV/T cooling (Atkin and Farid, 2015; Gang *et al.*, 2011; Machniewicz *et al.*, 2015; Stropnik and Stritih, 2016). Su *et al.* (2017) attempt to improve the efficiency of the HPV/T collector by using phase change materials to regulate the temperature of the unit which has a big impact on system performance. The dynamic performance of the three systems where no PCM is attached, PCM is attached under the backplane and under the flow layer are compared. It is found that PCM have significant effect on system efficiency when placed under backplane which increases the overall efficiency approximately 10 percent. Elsafi and Gandhidasan (2015) build mathematical models of thermal and electrical systems in HPV/T system. They validate their models by using published data. Two cases are considered where fins are placed at the duct and no fins are placed at the duct.

Accordingly, several parameters are gradually changed for parametric research.



**Fig. 35:** Cross sectional view of an air based hybrid PV/T collector with three modifications in the flow channel to improve the heat transfer (Hasan and Sumathy, 2010; Riffat and Cuce, 2011; Tripanagnostopoulos, 2007)



**Fig. 36:** Cross sectional view of air based hybrid PV/T collector with different structures (Riffat and Cuce, 2011; Tonui and Tripanagnostopoulos, 2007b)

Results show that finned case yielded 1% higher annual thermal output and 3% higher electrical output. The use of PCM material can regulate heat transfer within the module. Browne *et al.* (2016) compare HPV/T collector with and without PCM where cooling water is circulating through thermosyphon flow. The use of PCM result 5.5°C increase in outlet temperature. Hangweirer *et al.* (2015) build CHPV/T collector equipped with a linear Fresnel concentrator mirror module where the module absorbs and reflect different wavelengths of incoming radiation. The useful wavelengths are concentrated into PV cells and the absorbed part of the light is used to heat thermal collectors. According to CFD results, electrical

efficiency is obtained up to 6.2% and thermal efficiency is obtained up to 61.2 percent. Kasaeian *et al.* (2017) simulate HPV/T collector cooled with pure water and Al<sub>2</sub>O<sub>3</sub>-water nanofluid. CFD environment is used to simulate heat transfer processes within different layers of the module. The usage of Al<sub>2</sub>O<sub>3</sub>-water nanofluid perform much better for transferring heat from the collector. Browne *et al.* (2015) review some phase change materials used as thermal regulators for HPV/T units. The use of Fresnel lens to increase HPV/T efficiency occupies large portion in HPV/T research (Feng *et al.*, 2016). An experimental setup used by Feng *et al.* is presented in Fig. 37. Performance of the system is evaluated in two different kinds of weather.

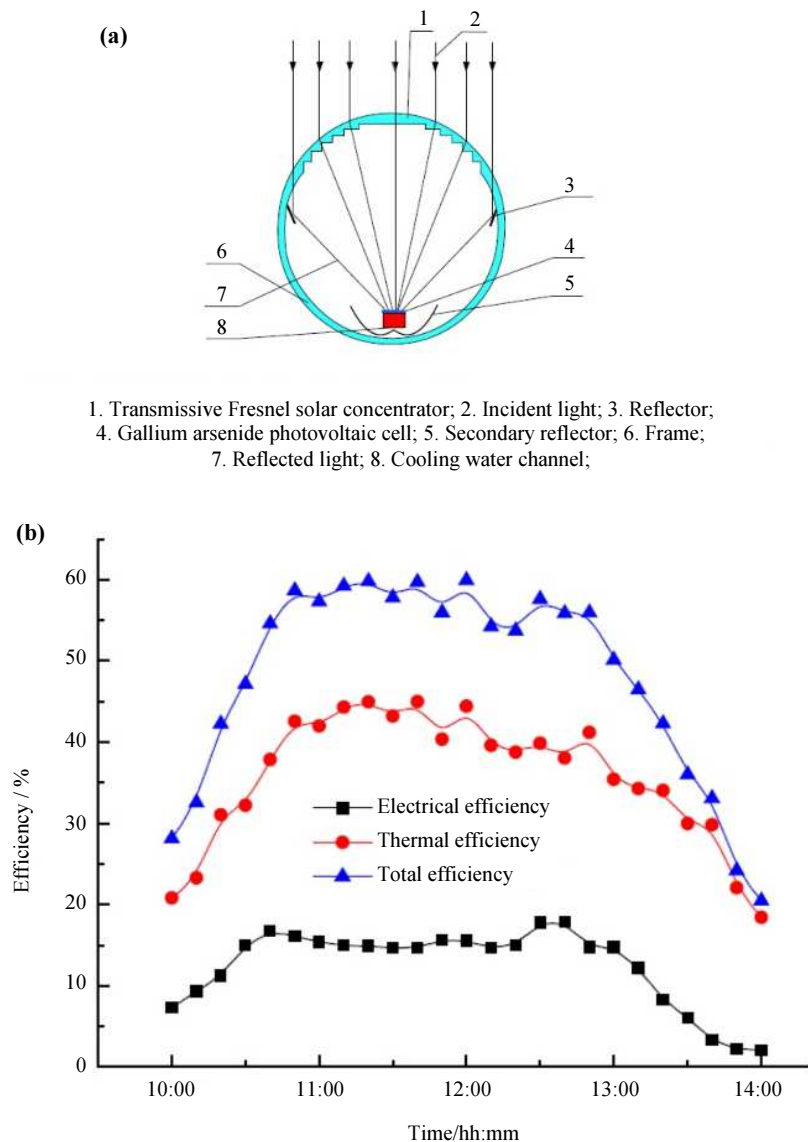
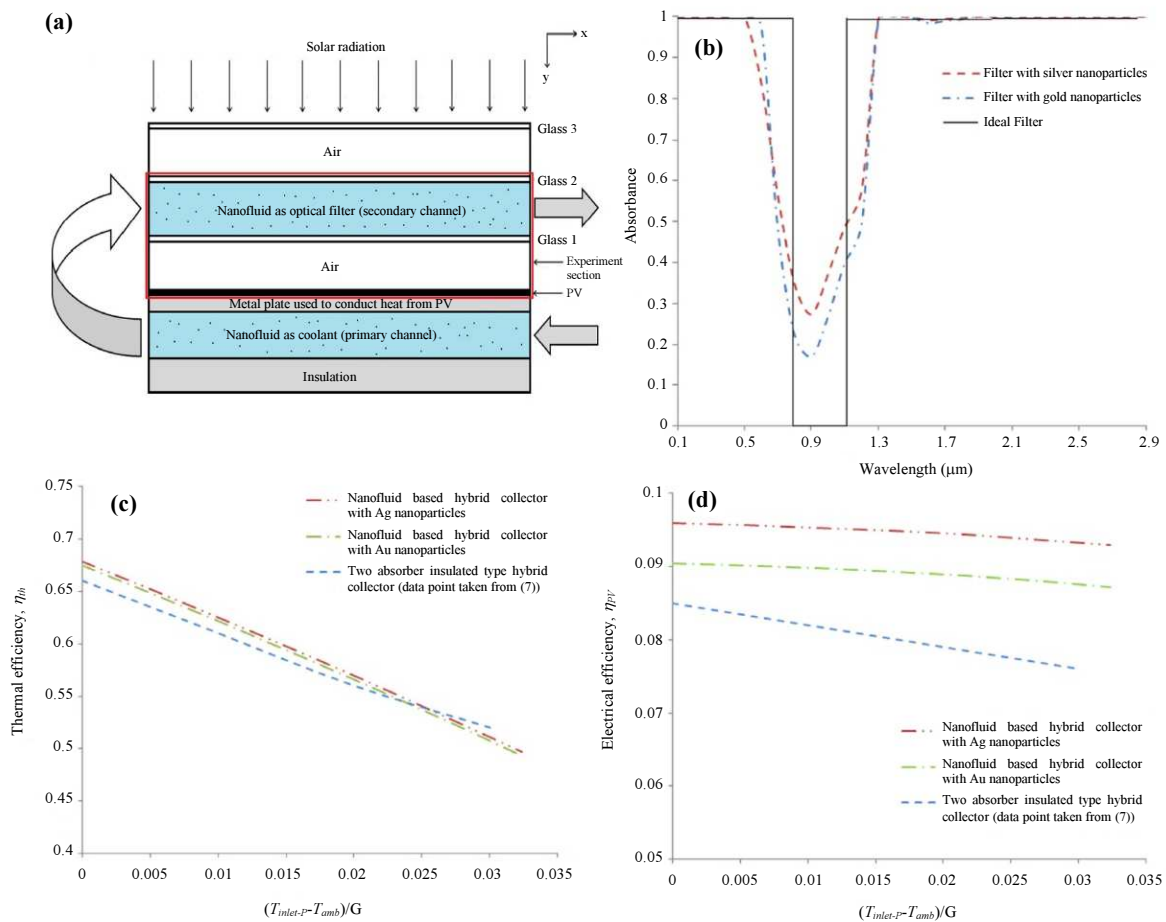


Fig. 37: A concentrating hybrid PV/T unit with transmissive Fresnel solar concentrator. (a) structure of the system, (b) hourly performance parameters in a clear sky (Feng *et al.*, 2016)



**Fig. 38:** Nanofluid based hybrid PV/T collector. (a) cross section of unit, (b) optical characteristic of selected nanofluids, (c) thermal efficiency versus reduced temperature, (d) electrical efficiency versus reduced temperature (Sarooha *et al.*, 2015)

The use of nanofluids for HPV/T systems have gained attention (Michael and Iniyar, 2015). They are generally used as filters in HPV/T applications (Sarooha *et al.*, 2015; Otanicar *et al.*, 2013). A structure of nanofluid based HPV/T collector and several results of the analyses can be seen from Fig. 38 obtained from the study of Sarooha *et al.* (2015). In this study nanofluid is used to filter unwanted part of the solar irradiation which has lower frequencies. Absorbance characteristics of the nanofluid and resulting efficiencies are presented in the Fig. 38. Al-Shohani *et al.* (2016) experimentally investigate the advantage of using water layer as a filter for HPV/T collectors. Water is used as solar ray wavelength splitter and as working fluid. The improvement is observed and it is found that the thickness of the water layer is important. Hasan *et al.* (2017) use three types of nanofluids, namely, SiC, TiO<sub>2</sub> and SiO<sub>2</sub> mixed with water to investigate how much they could improve the performance of the system. The sectional view of the system can be seen from Fig. 39. As seen from Fig. 39, PVT with SiC nanofluid shows the best thermal performance. The efficiency increases

almost linearly up to mass flow rate of 0.1666 kg/s. The nanofluids are sprayed to the back of the PV units as fluid jets. According to results, the use of SiC-water nanofluid system shows highest electrical and thermal efficiency. The electrical, thermal and overall efficiencies are observed to be 12.75%, 85% and 97.75%, respectively. Sardarabadi *et al.* (2017) compare the performances of HPV/T collectors with ZnO-water nanofluid and Phase Change Material (PCM). The system as well as the several performance results are given in Fig. 40. It is shown that the use of PCM resulted 13% increase in electrical efficiency whereas the use of nanofluid resulted 5% increase. Rosa-Clot *et al.* (2016) monitor the performance of HPV/T system modified with a novel technique called Thermal Electric Solar Panel Integration (TESPI) in Italy. The panel can be able to reject infrared light and fortify HPV/T module. Multifunctional glass structures are developed and experimentally tested for thermal regulations and to reach high PV efficiencies (Cuce *et al.*, 2015a; 2015b; 2014). Chen and Yin (2016) develop aluminum/High

Density Polyethylene (HDPE) Functionally Graded Material (FGM) panel which creates natural diffusion due to concentration gradient of aluminum molecules. Experimental results show promising improvement in electrical efficiency. Tabet *et al.* (2014) used Particle Swarm Optimization (PSO) technique to seek optimum inclination angle for HPV/T collectors for each monthly, seasonally and annually periods. Results yield several possible angles for each considered period to reach optimum operating condition. Different types of

fluids can be also used as beam splitters (Joshi *et al.*, 2016). Heat pipes are extensively used for HPV/T cooling applications (Chen *et al.*, 2017). The system integrated with heat pump can be seen from Fig. 41. The variation of efficiencies and COP are presented with respect to selected parameters. Table 5 covers several performance enhancement techniques implemented by researchers. Table 6 covers recently used cooling applications for HPV/T units to enhance heat extraction mechanisms.

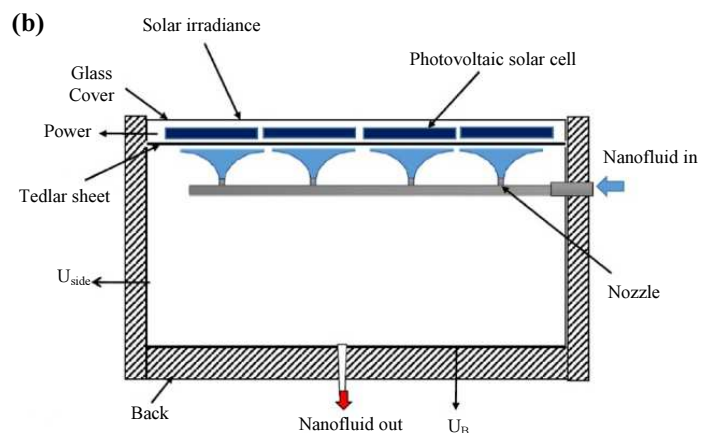
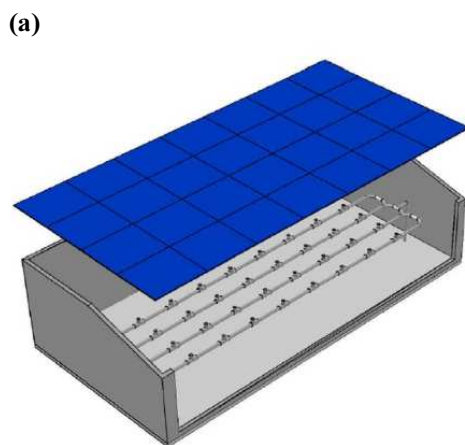
**Table 5:** Several specific performance enhancement methods for PV and hybrid PV/T systems

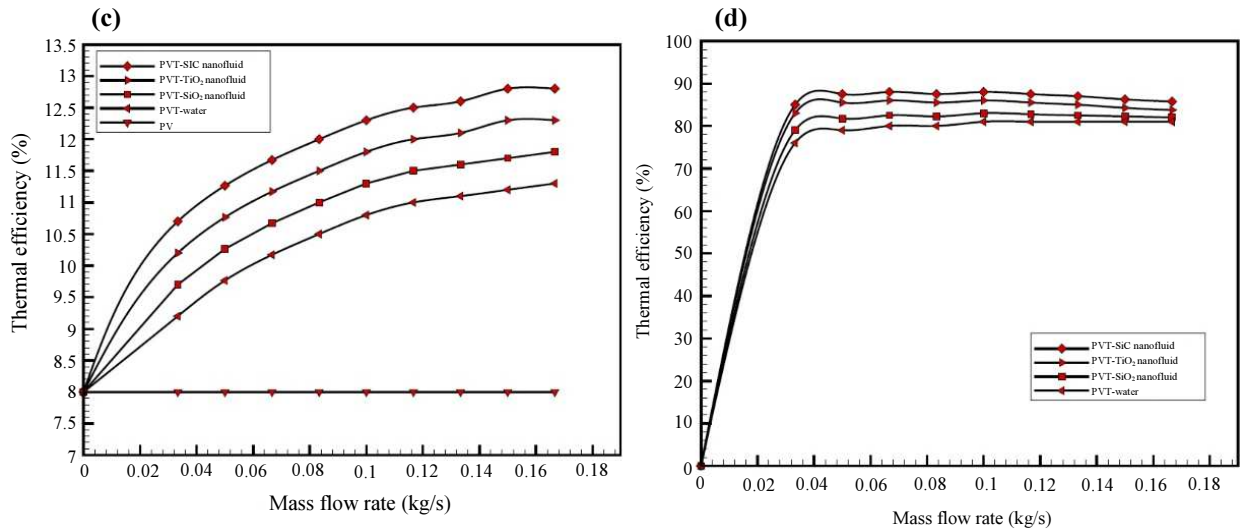
Type of System	Specifications	Enhancement method type	Description	Performance Parameters	Enhancement in performance	Literature	Remarks
Flat plate PV/T	Zinc-oxide/water nanofluid is employed as working fluid. System consists of Monocrystalline silicon PV cells.	Model	Using artificial neural network models and particle swarm optimization	N/A	N/A	305	Multi-layer perception and radial basis function artificial neural networks as well as adaptive neuro fuzzy inference system are used to optimize parameters of the PV/T system. The methods can be used for performance predictions during operation.
Flat plate PV/T	Single and double path design. Using bifacial PV cells	Modification	Systems have different packing factors and designs.	Overall energy efficiency is between 51%-67% for double path design.	Double path design has approximately 20% higher energy efficiency than single path design.	304	Steady-state analyses are performed. The optimum design can be determined based on desired output.
CPV/T	Systems consists of cycloidal transmissive Fresnel solar concentrator and Gallium arsenide PV cells with sun tracking.	Modification	Using transmissive Fresnel lens	The value of the maximum electrical efficiency is 18%. Overall system efficiency can be reached up to 55%.	Electrical efficiency is increased in the range of 5% to 8% with respect to the incidence angle.	323	Monte Carlo ray tracing method is used. System performance under different weather conditions is tested.
Flat plate PV/T	Open flow system with storage tank.	Modification	Solar PV/T system filled with graphite.	Maximum electrical efficiency is 7.2% for system filled with graphite.	Approximately 1.3% increase in electrical efficiency is observed.	308	The mass flow rate used for the analyses is 0.012 kg/s. PV modules and absorber tubes are used with specific filling which is a graphite layer. The layer is used to enhance heat transfer.
Solar cell thermal tile	System consists of PV system and single channel.	Model	Optimization of overall efficiency by using genetic algorithm (GA).	Overall energy efficiency is around 16.8%.	Approximately 10% increase in energy efficiency was observed.	306	Design parameters are determined for optimum condition.
Flat plate PV/T	System with single crystal silicon PV cells and water, ethylene glycol (EG) or their mixtures are selected as working fluids.	Modification	Copper tubes with serpentine design.	Electrical efficiency is observed up to 15%.	Overall efficiency enhancement of the system with water is 25%.	309	System with water coolant shows better efficiency than system with EG coolant due to high thermal conductivity.
PV system	Simple small-scale PV collector with c-Si solar cell.	Modification	Beam splitting by using different types of fluids.	N/A	Approximately 3% change in electrical efficiency is observed for coconut oil when the filter fluid temperature is set to 80°C.	336	Several different fluids are tested including Al <sub>2</sub> O <sub>3</sub> nanofluid, several organic oils and water.
PV system with advanced collector system	System with polycrystal silicon cells and perforated and mattblack dye coated steel collector.	Modification	PV modules are integrated to unglazed transpired collector (PV/UTC)	Overall system efficiency of the 2PV/UTC system is around 70% at optimum mass flow rate.	The overall efficiency of the 2PV/UTC system increases up to 20% at the optimum flow rate.	310	Higher mass flow rates result in higher efficiencies for UTC system.
Modified flat plate PV/T	Liquid cooled system with c-Si cells.	Modification	Infrared filtering effect is provided with a thin layer of water flowing in a polycarbonate (PC) box. System is called as thermal electric solar panel integration (TESPI) unit.	The values of mean electrical efficiencies are observed in the range of 8.77-13.19%.	Electrical efficiency of the TESPI panel is less than PV panel in the range of 0.9 to 1.9%, but daily thermal efficiency can rise up to 60%.	330	These PC box modules can be treated as retrofits to existing PV modules. The average cost of PC box is 2-3 €/kg.
Flat plate PV/T	System consists of mono crystalline silicon cells, copper tube and air channel.	Modification	Fan and pump are used to circulate fluid and operation modes are selective with optimum flow rate of 0.02 kg/(m <sup>2</sup> s) for air.	The value of the overall system efficiency is 48.6% for air heating mode and same value is 46.3% for water heating mode.	Thermal efficiency of the system operating at air heating mode is 2.9% higher compared to system operating at water heating mode	209	A tri-functional PV/T collector can operate in heating mode to heat either air or water. Steady-state and transient models are used.
BIPV/T	Water based PV/T collector.	Modification	Reaching high efficiencies by integrating PV/T collector to Solar Domestic Hot Water System (SDHWS).	Overall thermal efficiency is obtained up to 70%.	N/A	311	Solar energy is utilized at lower temperatures. Transient model is used for deeper investigation.
Flat plate PV/T	System with monocrystalline silicon photovoltaic module.	Modification	System is modified with vacuum tube and booster diffuse reflectors.	Overall electrical efficiency is 11.9% and overall thermal efficiency is 62.98%.	The maximum difference in overall efficiency is observed up to 25% with respect to mass flow rates and types of the working fluid.	312	Reflectors are increased the solar insolation on the PV module by 22% and they are increased the maximum temperature of the output water.
BIPV/T	A multifunctional roofing panel.	Modification	An aluminum/High Density Polyethylene (HDPE) functionally Graded Material (FGM) panel is associated with water tubes.	Overall system efficiency is observed up to 79.8%.	Electrical efficiency increases by 2.55% on the average when considered materials are used.	334	Panel creates natural diffusion due to concentration gradient of aluminum molecules. Heat is naturally transferred from insulated side to conductive side.



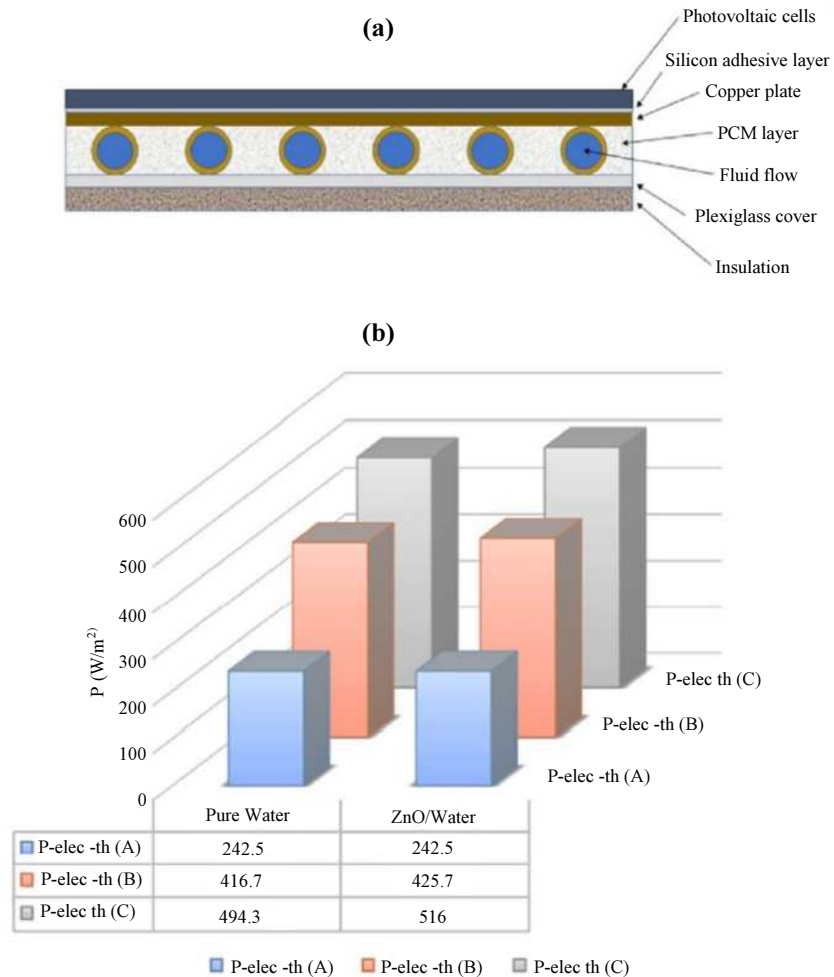
**Table 6:** Recent advanced cooling methods developed for PV and hybrid PV/T systems

Type of PV/T	Type of cell	Working Fluid	Method	Specifications	Type of Analyses	Output Performances	Change in Performance	Literature	Remarks
Flat plate	N/A	Air	PCM	Glass covered system with PCM layer thickness of 3cm.	Theoretical	Thermal efficiency is obtained around 30% and electrical efficiency is around 7.5%.	Efficiency increases by 10.7% if the PCM material placed at the upper layer of the air channel.	317	The place of the PCM material layer and its thickness are found to be important
Flat plate	N/A	Air	Nanofluid	Gold and silver nanofluid and silicon PV cells	Theoretical and experimental	The value of the overall efficiency is obtained around 65%.	%5 increase in overall efficiency is observed compared to two absorber insulated HPV/T system.	325	parameters for performance. Experiments are performed by using small-scale test rigs. Low energetic part of the incident light can be filtered. Mass flow rate of the nanofluid is 0.02kg/s.
Flat plate	Polycrystalline silicon	Water	Nanofluid	SiC, TiO <sub>2</sub> and SiO <sub>2</sub>	Experimental	Electrical efficiency is obtained up to 12.75% and thermal efficiency is obtained up to 85%.	Maximum power output of PVT with SiC nanofluid is increased by 62.5% compared to that of standard PV cell.	328	Nanofluids are used as coolants in this study and sprayed onto a collector surface as jet arrays.
Flat plate	Monocrystalline silicon	Water	Nanofluid and PCM	Zinc oxidenano particles and Paraffin wax PCM layer	Experimental	Overall energy efficiency is 13.42%.	Mean electrical output is increased by 13% compared to conventional PV system. Thermal output is increased by 9%.	329	Study uses both positive effects of using PCM and nanofluid.
Flat plate	Ge, Si, InGaAs, InGaP and CdTe	N/A	Nanofluid	Thin films of filters based on nanoparticle dispersion	Theoretical	The value of the overall efficiency of the system with CdTe nanoparticles is 29.03%.	The maximum increase in thermal efficiency is around 4%.	326	Model predictions are presented. Study can be used as reference for nanoparticle-based filter studies.
Flat plate	Monocrystalline silicon	Water	Heat pipe	System with PV panel (195W), heat pipes, aluminum sheet and manifold.	Theoretical and experimental	The value of the overall thermal efficiency is around 35% and electrical efficiency is observed around 10%.	The decrease in COP <sub>th</sub> and COP <sub>PVT</sub> is 0.02 and 0.04 when the value of the heat pipe pitch is increased by 5 mm.	337	System is used to drive heat pump. Study reveals how COP of the system and efficiencies of PV/T unit changes with considered parameters.
Flat plate	Silicon	Water	Nanofluid	Copper oxide – water mixture	Experimental	Overall system efficiency is obtained up to 35.84%.	The use of nanofluid is increased the thermal efficiency up to 45.76%.	324	Nano particles are added water to heal heat transfer characteristics.
PV panel	Monocrystalline silicon	Air	PCM	30 mm thickness	Theoretical and experimental	The value of the overall efficiency is obtained up to 14.54%.	The unit consists of PV panel, PCM infused graphite and finned heat sink has 12.97% better overall efficiency compared to single PV panel.	313	Study investigates the level of enhancement in performance of the system due to use of PCM infused graphite and surface extensions.
BIPV/T	N/A	Air	PCM	20 mm thickness., SP21E, SP24E and RT18HC are used.	Theoretical	N/A	The thermal performance is 48% better than the reference house without using the PV/T ventilation.	167	Coefficients of Thermal Performance Enhancement value can be obtained up to 70.2% when the air flow rate and thickness of the PCM layer is optimized.
Flat plate	Monocrystalline silicon	Water	Heat pipe	Nine heat pipes are used for both evaporating and condensing sections.	Experimental	The thermal efficiency of the wickless heat pipe PV/T system is 52.8%.	Thermal efficiency decreases up to 75% at the inclination angle below the value of 20°C for the system without wire mesh.	279	Optimum inclination angle is obtained for both system to optimize thermal performances.
Flat plate	Polycrystalline silicon	Water	Heat pipe	System with and without glass cover.	Experimental	The value of the overall efficiency is obtained up to 48.52%.	Overall efficiency of the system with glass cover is approximately 4% higher than the system without glass cover.	287	Novel system is used to enhance the performance and eliminate freezing issue.

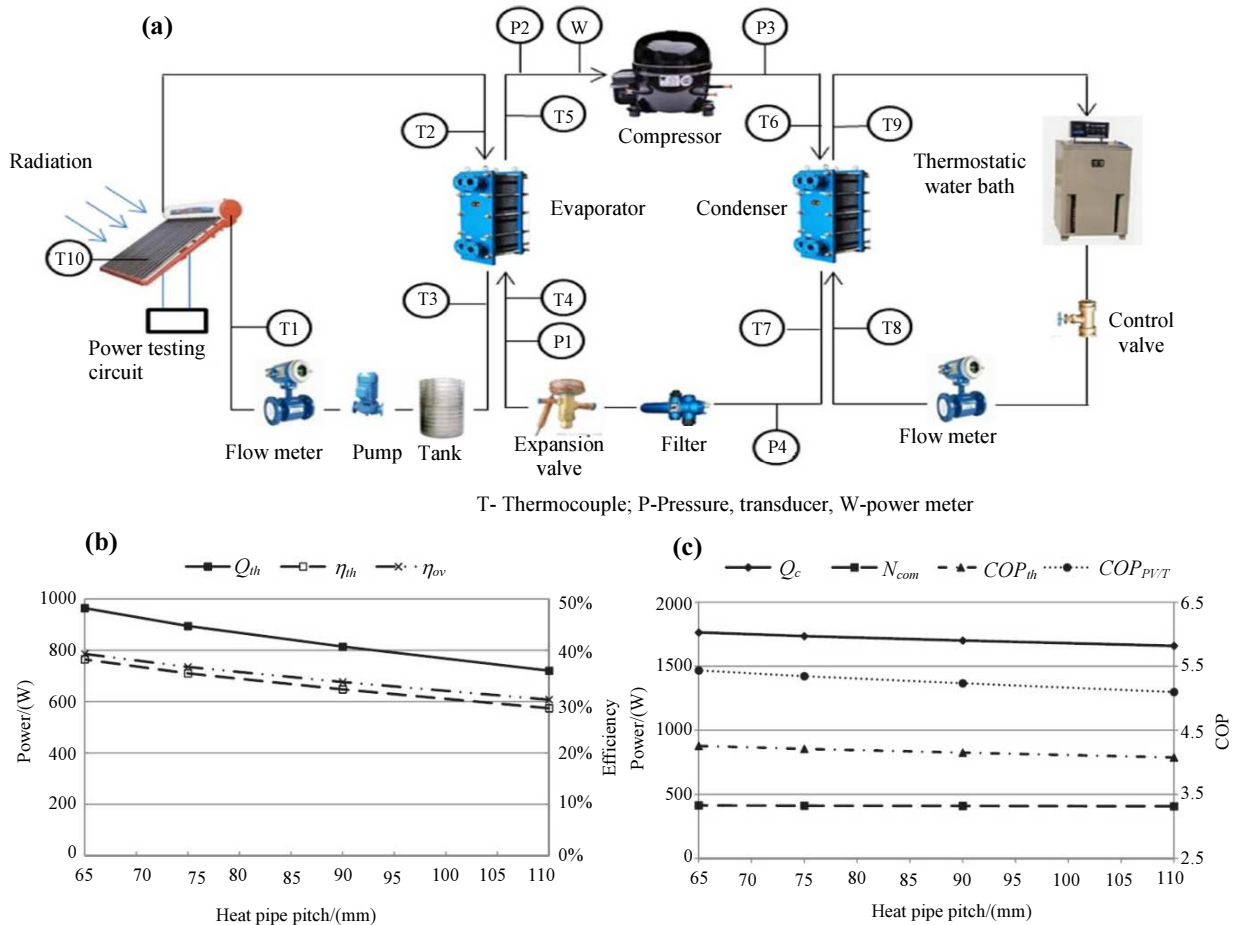




**Fig. 39:** A hybrid PV/T collector cooled with jet array nanofluid impingement. (a) general structure of the unit, (b) detailed schematic view of the unit, (c) electrical efficiency with respect to different nanofluids, (d) thermal efficiency with respect



**Fig. 40:** Enhancement of hybrid PV/T system performance with phase change material and nanofluid. (a) cross section of the system structure, (b) equivalent thermal-electrical power output for all designs (Sardarabadi *et al.*, 2017)

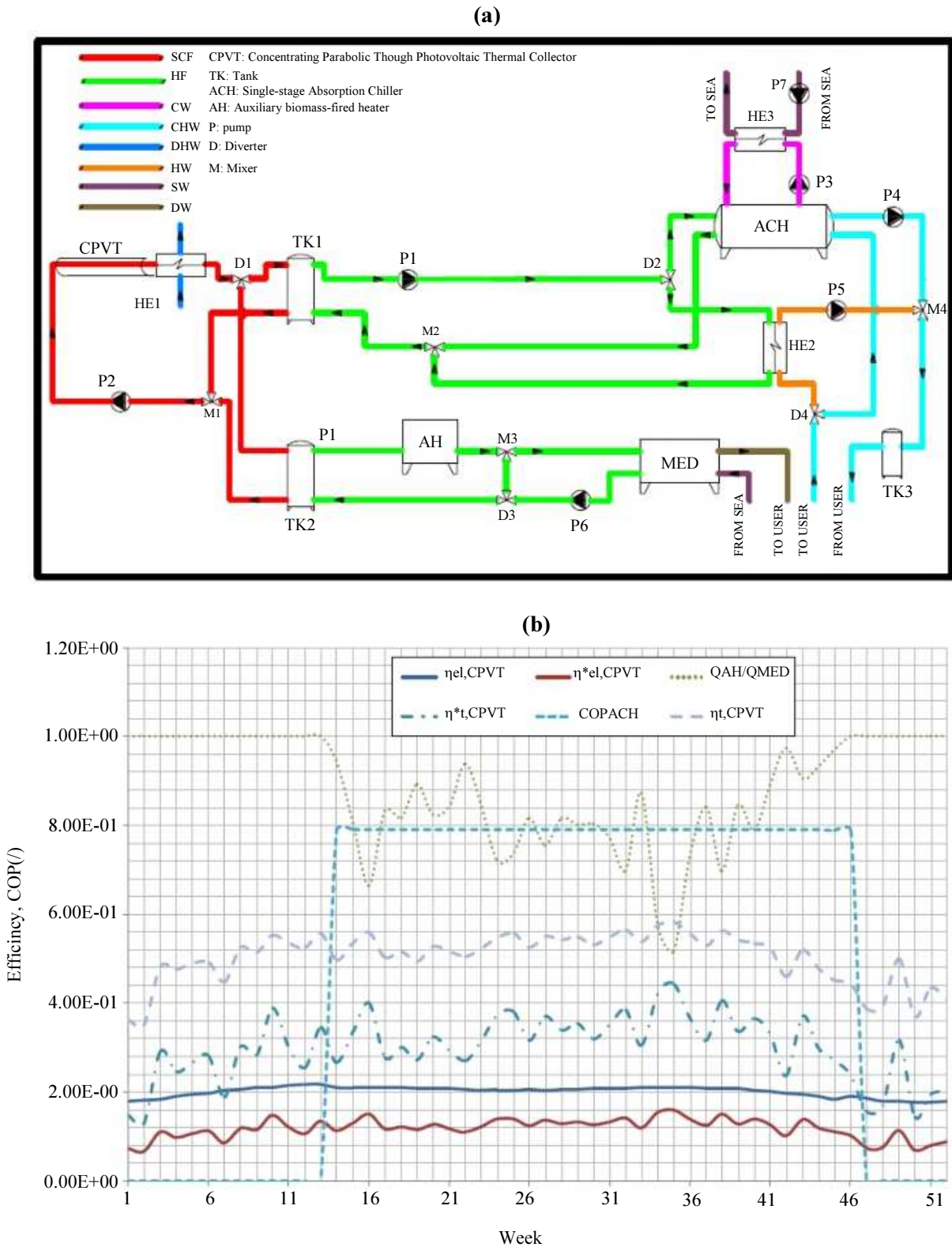


**Fig. 41:** A combined system consisted of heat pump and hybrid PV/T. (a) thermal efficiency versus heat pipe pitch, (b) COP of the heat pump versus heat pipe pitch (Chen *et al.*, 2017)

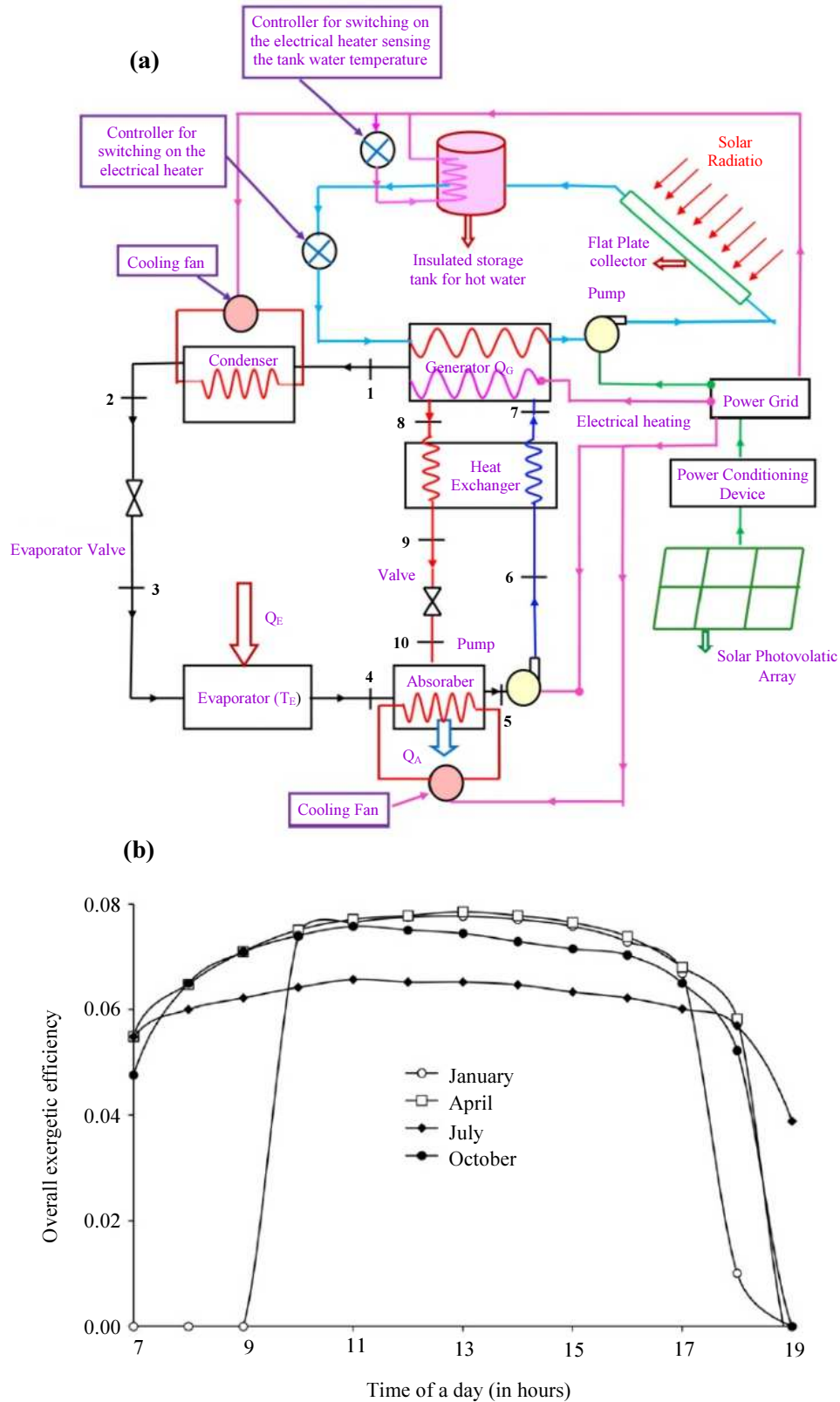
### Multifunctional Applications of HPV/T Collectors (HPV/T Driven Systems)

Recently, HPV/T driven multigeneration systems are started to be built by researchers. In these systems simultaneous production is obtained by utilizing clean energy source which is solar power in this case. Accordingly, more output can be provided by the complex system. Calise *et al.* (2014) build trigeneration system which is producing thermal and electrical energies and providing desalination. The system consists of CHPVT, solar heating and cooling and multiple-effect distillation technologies. The layout of polygeneration system which is discussed in the study can be seen from Fig. 42. The CHPV/T system can successfully meet the energy demand of the overall system. On the other hand, CHPV/T cannot supply enough energy to drive the system instead biomass energy is used to compensate energy deficit due to high fluctuations in environment conditions in winter. The performance of the system is simulated and economic benefits are investigated,

especially for European Mediterranean countries. The generated heat is used either for hot water production or for space cooling by using absorption chiller. Results show that maximum utilization of CPVT system can be accomplished by using tri-generation system with positive economic benefits. Calise *et al.* (2016) perform dynamic simulation on multigeneration system consisted of HPV/T driven heat pump and absorption chiller. It is observed that when energy efficiency of the PVT was 49%, the COP values are obtained to be 4 and 0.55 for heat pump and absorption chiller, respectively. Cooling applications of HPV/T driven systems has increased over the years (Buker *et al.*, 2015; Basu and Ganguly, 2016). Basu and Ganguly (2015) analyze a conceptual design where water–lithium bromide absorption system is powered by HPV/T collector. The layout of the combined system is presented in Fig. 43. They proposed that total number of 39 modules are required to meet energy demand of the system. The difference between total generation and consumption is seen for three months period.



**Fig. 42:** A novel PV/T driven system. (a) Schematic view of the system, (b) weekly performance characteristics of the components of the system (Calise *et al.*, 2014)



**Fig. 43:** A hybrid PV/T driven absorption refrigeration system. (a) System layout, (b) hourly performance characteristics of the system with respect to selected months (Basu and Ganguly, 2015)

**Table 7.** Selected hybrid PV/T driven multifunctional systems

Type of PV/T	Main system	Secondary system	Type of analyses	Application	Output Performances	Literature	Remarks
CPV/T	Multi-effect distillation (MED)	Chiller (ACH)	Theoretical	Domestic water, distillation, space heating and cooling	Thermal efficiency is around 50%, electrical efficiency is around 20%, COP of the ACH is 0.8.	338	Both MED and ACH systems can be driven in summer conditions. System has potential economic benefits and these benefits can be maximized if system is optimized to efficiently operate for specific application.
Flat plate PV/T	Solar assisted heat pump	Adsorption chiller	Theoretical	Domestic water, space heating and cooling.	Overall PV/T efficiency is observed up to 49.2%. COP of the heating	339	System can be economically beneficial under limited conditions. Heating and mode is 4.2 and COP of the chilling domestic water are provided by the system mode is 5.8 for the heat pump. in winter, whereas, cooling and domestic water are provided in summer.
BIPV/T	Indirect evaporative cooling system	N/A	Experimental	Power generation, space heating and cooling	System can produce multiple outputs including cooling power of 5.2kW, heating power of 3kW and power generation of 10.3 MW h/year.	340	System is a promising technology for green buildings.
Solar thermal and PV array	LiBr-H <sub>2</sub> O absorption system	N/A	Theoretical	Power generation, space cooling.	Mean value of the power generation is estimated around 17.4 kW h/day.	342	Optimization is required for given cooling load for better efficiency.
Flat plate Thermal collector and PV array	Organic Rankine Cycle	N/A	Theoretical	Power generation.	The value of the PV efficiency is obtained around 14% during operation and thermal efficiency of the ORC is observed up to 14.6%.	347	The selection of the working fluid is important. System may have a potential use in small cities. Five different schemes of ORC are considered.
Flat plate PV/T	Proton Exchange Membrane	N/A	Theoretical	Hydrogen production	Overall PV/T efficiency is 29% and 0.018 kg hydrogen production/day is obtained.	349	Study shows that more applications can be derived when PV/T system is associated with other systems.

Annual performance and economic benefits are investigated. System produces approximately 17 kWh cooling energy for domestic use annually. Payback period is estimated to be not more than 4 years. Tsai (2014) develop model in MATLAB/Simulink environment for HPV/T driven Heat Pump Water Heating (PVTA-HPWH) system. In the system, coolant of HPWH system increases HPV/T efficiency and improves COP. He *et al.* (2014) uses HPV/T collector to derive thermoelectric cooling and heating system. The thermal and electrical efficiencies of HPV/T collector are observed to be 23.5% and 16.7% and COP of the thermoelectric cooler is around 1.7. There are greenhouse applications in the literature where HPV/T systems are generally used to provide heat to condition environment temperature (Tiwari and Tiwari, 2016; Tiwari *et al.*, 2016). They can also be evaluated in this category because of possible multiple outputs. Tourkov and Schaefer (2015) use waste heat from the HPV/T collector to derive organic Rankine cycle. n-Butane is found to be optimum working fluid for that scheme. Ammous and Chaabene (2015) study to construct HPV/T driven desalination plant and to optimize the structure by using three optimization layers algorithm. The overall reduction in HPV/T surface and storage tank volume are estimated to be 12.5% and 27%, respectively. Many other applications areas can be found such as using waste heat to produce hydrogen (Cilogullari *et al.*, 2017). The summary of this section can be seen from Table 7, which is a combination of several selected recent studies.

### The Place of HPV/T Collectors in the Future

As highlighted by Hasan and Sumathy (2010), the expediency of the HPV/T systems is related to technical

qualities and economic advantages as comparison to alternatives. Energy production based on fossil fuel consumption still dominates the energy market but clean energy generation is expected to be more competitive in the future due to environmental problems. It has been experimentally and analytically shown that the demand for the HPV/T systems will be higher in the renewable market in the future, since they offer domestic electricity and thermal power production and they have a great potential to be used in remote areas. However, the research is still going on to further increase performance of the HPV/T systems and overcome drawbacks. The cost of renewable energy market sources will expected to fall in few years according to The International Renewable Energy Agency's report (IRENA, 2017). In these sources, the unit cost of the solar photovoltaic units per kWh shows the maximum fall. Accordingly, with the new technology and cheaper materials the renewable market has potential to drastically grow in a short time.

### Conclusion

It is obvious that a vast amount of research has been done to date on the hybrid photovoltaic/thermal systems. These efforts are divided into many branches where all are aiming to improve the overall efficiency of these systems from many aspects. HPV/T system is very promising energy producing device which can fulfill the energy gap realized due to excessive domestic and industrial demand. HPV/T systems can be easily used in remote areas and can be manufactured for wide range of applications. Their output can be optimized for specific need of the structure. Their building integration is not only providing annual electrical energy demand but also heal the building's

thermal comfort and life period with self-cleaning technologies. Various positive findings from the studies form a stronger driving force for future HPV/T studies. Some of these efforts focused on same target have already yielded satisfactory results but still more study opportunities are available, in fact they are required, for HPV/T systems. Even if a HPV/T system is a compact unit, it has quite unique and complex structure. That's the reason why researchers still put effort on HPV/T systems to prepare this technology for global use in near future. Summary of the finding are listed below:

- The overall performance of the HPV/T unit is always higher than that of the single PV or solar thermal unit. However, the differences in overall performances of these systems are strongly affected by the environmental conditions such as ambient temperature, humidity and altitude. In most cases, solar thermal unit produces more thermal energy than HPV/T system
- The electrical efficiency of the solar PV system or HPV/T system is observed in the range of 8-14% and it is not highly affected by the ambient conditions. But, for concentrating systems, the value of the instantaneous electrical efficiency can reach up to 30% level or even more. On the other hand, thermal efficiency is a function of ambient parameters and instantaneous values can show significantly fluctuations
- Different types of PV cells can also affect the electrical performance. GaAs cells show better efficiencies where their electrical efficiencies are observed to be better up to 2% compared to other silicon cells. Thin film and semi-transparent PV modules are under interest due to their advantages
- The payback period of the HPV/T system can be reduced by optimizing the system based on the characteristics of the application. The payback period of HPV/T system can be estimated up to 14 years. It can be further reduced by implementing appropriate modification. The typical payback period can be less than 4 years for HPV/T driven systems
- Some parameters such as mass flow rate of the working fluid significantly affects the performance of the HPV/T system. System should be operating at the optimum flow condition depending on the design and environment. Water based systems generally yield better performances than air based ones, but still air based ones are selected for most of the applications. Water is generally kept in a tank and constantly circulates in cooling lines. It was observed that withdrawal rate of the coolant is also important parameter for the system performance
- The energy output of the HPV/T unit needs to be optimized based on the type of the energy demand of the building. One of the ways to provide optimized output may be provided by partially placing PV cells on a total collector area instead of fully cover it with PV cells.
- At high altitudes, HPV/T systems suffer from freezing problems. And some research has already been presented for mountainous countries.
- PV systems are generally used as building envelopes and roof elements. They can be retrofitted to building as trombe wall, ventilated PV façade, etc. They can be incorporated with heat-insulation structures for building integration. These structures can have commercial or custom designs and they help thermal regulation for dwellings by keeping ambient and outside in different temperatures.
- Recently, HPV/T driven systems have drawn a great attention, since overall efficiency of the multifunctional systems can be further increased and multi outputs such as water desalination, crop drying or cooling can be obtained. In these systems, heat and electricity are partially or completely provided with HPV/T collectors. And they can be used as pre-heater or evaporator in the overall system. Mostly, heat pumps, absorption refrigeration systems and Rankine cycles are driven by HPV/T systems in studies
- Highest overall HPV/T efficiencies can be achieved by concentrating light on the surface area of the PV modules. Due to high temperatures, effective cooling is required for single PV systems. For this reason, enhancements on the cooling system have been made such as using fins at the flow channel. On the other hand, HPV/T system can be able to use this excessive heat as thermal energy. In order to concentrate incoming solar radiation onto solar cells, parabolic concentrators, low-cost aluminum plates, Fresnel lens and other optics are used. High thermal and electrical efficiencies up to 60% and 18% can be obtained by using CHPV/T systems, respectively
- Electric circuit models can be used to represent PV cells. Generally, one-diode five parameter model can sufficiently characterize I-V curve of a PV cell. It is achieved from the literature that series and shunt resistances are highly dependent on the operation conditions and they play a key role in maximum energy production by PV module.
- Simple steady-state models can sufficiently describe thermal characteristics of HPV/T units. The variation between thermal model predictions and experimental results are generally in good agreement with less than 5% difference. However, transient models are required during the design of HPV/T units. More details can be obtained from transient models about the operation mode of HPV/T systems
- Wavelength selection techniques are vital for HPV/T performance where in this technique

basically high energetic part of incident solar light is used to produce electricity and the less energetic part is used to produce thermal power. Beam splitters or filters are used for this purpose. Filter materials can be selected from liquid or solid materials. Nanofluid filters are taking attention recently, since they can easily provide cooling and carry waste heat during operation by convection. Different types are under research and their spectral characteristics are important for this purpose

- Optimum operation conditions for the HPV/T system can be sought by using Generic Algorithm (GA), Particle Swarm Optimization (PSO), Evolutionary Algorithm (EA) and Taguchi-Fibonacci search method techniques. Additionally, system modification can be realized by modifying collector module in several ways including making two turns for the working fluid by dividing the channel, using modified PV cells, using serpentine or multichannel flow tube design and using extended surfaces to enhance the overall performance. Novel materials can also be tested as well as thermal resistance between module layers can be reduced
- Recently, integration of phase change materials, heat pipes and nanofluids to the collectors are studied by the researchers to enhance heat transfer and accordingly the thermal efficiency of the HPV/T system. Electrical and thermal efficiencies can be improved up to 60% and 50% by implementing these techniques, respectively
- Glazing always increases the thermal efficiency, generally up to 10%, but it causes a decrease in electrical efficiency. Because PV cells suffer from high temperatures due to existence of glazing. Novel PV glazing systems integrated with multilayer and vacuum glazing concepts are in the centre of interest as these systems have a U-value below 1.0 W/m<sup>2</sup>K, which is promising
- Ventilation for building integrated PV units is required to gain waste heat instead of releasing it to the atmosphere. The necessity of the ventilation really depends on the application where in some cases it is not feasible such as in applications where PV panels used as building envelopes. And also, sometimes the electricity production from PV units are sufficient to meet the application demand. However, ventilation is really useful when the thermal comfort is the main objective
- Field testing of novel designs and improvements are really important to observe real performance characteristics of HPV/T units. That is, generally results obtained under real conditions are significantly different that the results obtained in laboratory conditions. Different loads can result in

different outputs. For example, a HPV/T system operating at the test conditions may yield overall efficiency value of 40%, but same system would yield 50% less overall efficiency value under real operating conditions

- The unit cost of the electricity is in the range of \$1.8 to \$2.5 per watt for the CHPV/T systems whereas unit electricity price is around \$2.3 per watt for flat plate collectors

## Author's Contributions

**Erdem Cuce:** Mentoring the research, revising/editing the body.

**Erman Kadir Oztekin:** Preparation of the main draft following the collecting data and evaluating the findings.

**Pinar Mert Cuce:** Preparation of the main draft following the collecting data and evaluating the findings.

## Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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