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A review on photovoltaic/thermal hybrid solar technology

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ABSTRACT

A significant amount of research and development work on the photovoltaic/thermal (PVT) technology has been done since the 1970s. Many innovative systems and products have been put forward and their quality evaluated by academics and professionals. A range of theoretical models has been introduced and their appropriateness validated by experimental data. Important design parameters are identified. Collaborations have been underway amongst institutions or countries, helping to sort out the suitable products and systems with the best marketing potential. This article gives a review of the trend of development of the technology, in particular the advancements in recent years and the future work required.

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1. Introduction

A photovoltaic/thermal hybrid solar system (or PVT system for simplicity) is a combination of photovoltaic (PV) and solar thermal components/systems which produce both electricity and heat from one integrated component or system. In other words, PV is used as (part of) the thermal absorber [1]. Those PV and solar thermal panels operating side by side are therefore not exactly within this "combi-panel" terminology. There are alternative approaches in PVT integration. Among many others, there can be selections among air, water or evaporative collectors, monocrystalline/polycrystalline/amorphous silicon (c-Si/pc-Si/a-Si) or thin-film solar cells, flat-plate or concentrator types, glazed or unglazed panels, natural or forced fluid flow, stand-alone or building-integrated features, etc. Accordingly, available installations are ranging from PVT air and/or water pre-heating system to hot water supply through PV integrated heat pump, and to actively-cooled PV concentrator through the use of economical reflectors. Design decisions have to be made on the collector type, the thermal to electrical yield ratio, as well as the solar fraction for optimizing the overall benefits. These all have determining effects on the system operating mode, working temperature and efficiency.

Fig. 1 shows the main features of a flat-plate PVT collector. Fig. 2 shows the longitudinal cross-sections of some common air-type PVT collector configurations whereas the cross-sectional views of some examples of the water-type designs are in Fig. 3.

A significant amount of research and development work on the PVT technology has been conducted in the last 35 years with a gradual increase in the level of activities. There appears a wider scope of international participations after the turn of the century. Nevertheless, real project applications are still limited at this stage. This article gives a review of the trend of development of the technology, starting from the early groundwork and placing more emphasis on the developments after year 2000. A projection of the future work is also given.

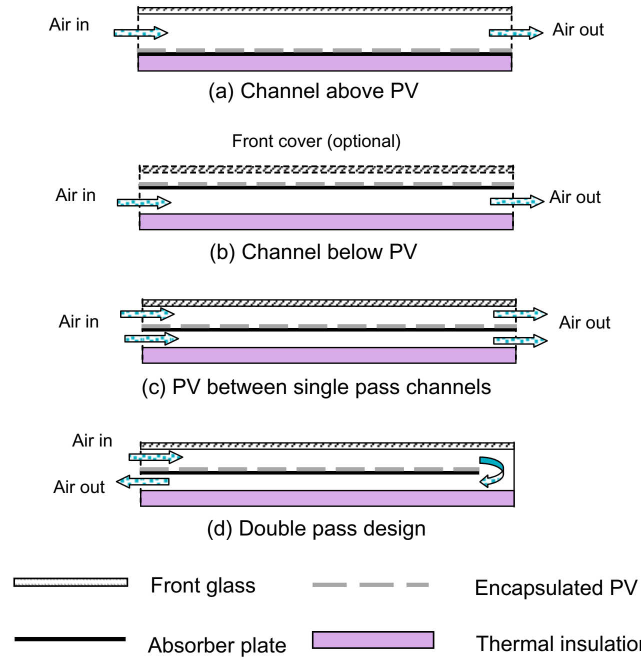

Fig. 2. Longitudinal cross-sections of some common PVT/a collector designs.

2. Groundwork and early developments

2.1. Basic concepts

A solar cell has its threshold photon energy corresponding to the particular energy band gap below which electricity conversion does not take place. Photons of longer wavelength do not generate electron–hole pairs but only dissipate their energy as heat in the cell. A common PV module converts 4–17% of the incoming solar radiation into electricity, depending on the type of solar cells in use and the working conditions. In other words, more than 50%

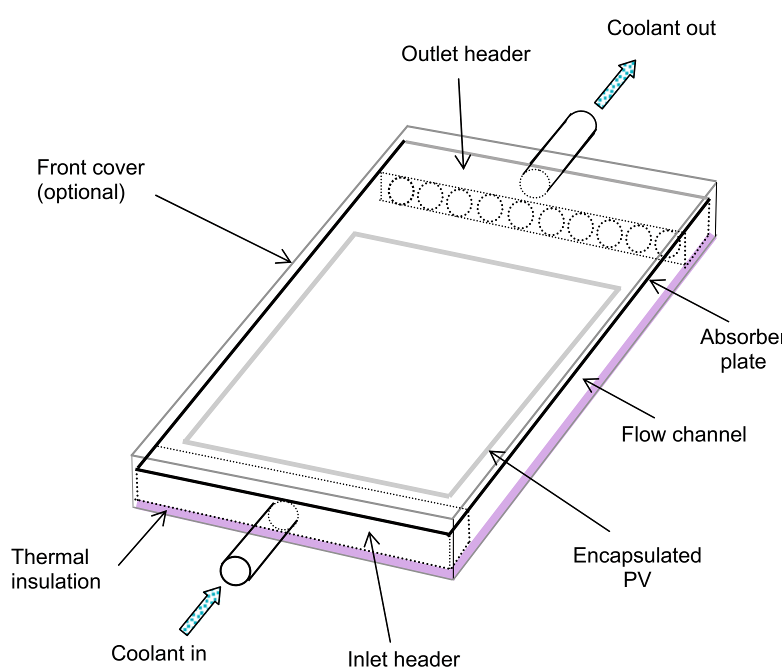

Fig. 1. Main features of a flat-plate PVT collector.

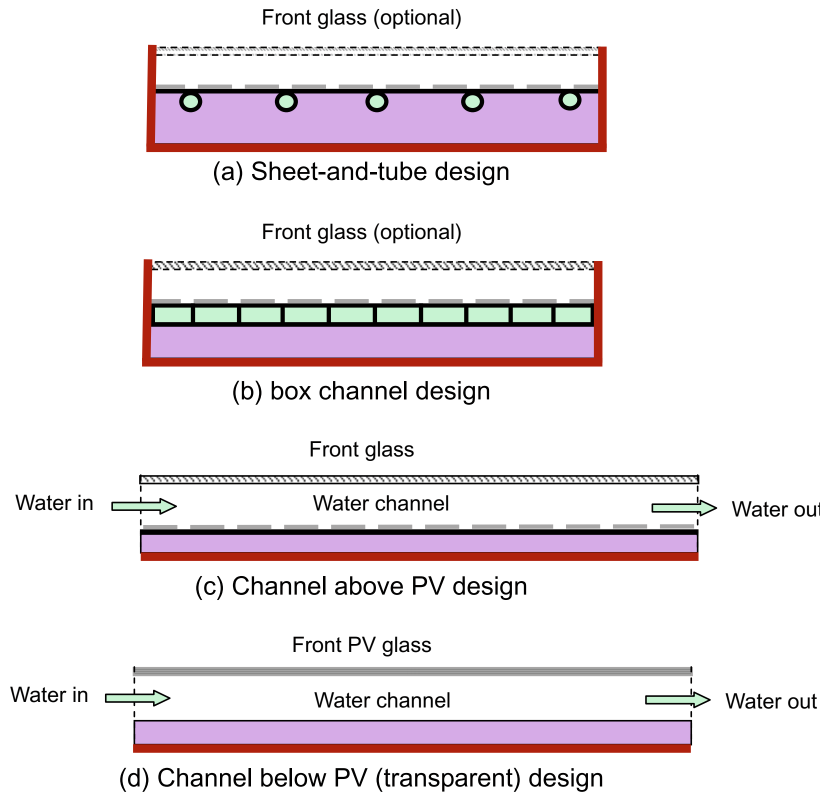

Fig. 3. Cross-sections of some common PVT/w collector designs.

of the incident solar energy is converted as heat (after deducting the reflected portion). This may lead to extreme cell working temperature as much as 50 °C above the ambient environment. There can be two undesirable consequences: (i) a drop in cell efficiency (typically 0.4% per °C rise for c-Si cells) and (ii) a permanent structural damage of the module if the thermal stress remains for prolonged period. Numerous correlations expressing cell temperature and efficiency as functions of the pertinent weather variables and cell working conditions are summarized by Skoplaki and Palyvos [2,3]. By cooling the solar cells with a fluid stream like air or water, the electricity yield can be improved. But conceptually the better design is to re-use the heat energy extracted by the coolant. Then the energy yield per unit area of panel (or facade in the case of building-integrated installation) can be improved. These are the incentives leading to the evolvement of PVT hybrid solar technology.

2.2. Early work

Theoretical and experimental studies of PVT were documented as early as in mid 1970s. Wolf [4], Florschuetz [5,6], Kern and Russell [7] and Hendrie [8] on different occasions presented the key concept and the data with the use of either water or air as the coolant (i.e. the PVT/a and PVT/w systems in abbreviation). The technical validity was soon concluded. The research works that followed were mainly on flat-plate collectors, like the contributions from Raghuraman and Cox [9,10], Braunstein and Kornfeld [11] and Lalovic [12] in the 1980s. The works of O'leary and Clements [13], Mbewe et al. [14], Al-Baali [15] and Hamdy et al. [16] included performance analysis on light concentrating PVT systems.

Garg and his co-workers carried out detailed analytical and experimental studies on hybrid PVT air and liquid heating systems from late 1980s for about 10 years [17–25]. Working with a steady state PVT/a model, they pointed out that the increased transmission losses due to the addition of a second front cover do not justify the heat loss reduction – beyond the critical point the single-glass cover collects more heat than double-glass [21]. Based on the weather of New Delhi, their transient simulation analysis [23] found that in terms of overall energy performance, the double-glass configuration is better than the single-glass option for conventional PVT/a collectors. For mechanical operated system, Bhargava et al. found that the PVT/a system can be self-supported within a certain range of design parameters like packing factor and air flow rate [17]. They also developed a steady state model to analyze the system performance of a PVT/a collector with integrated compound parabolic concentrator (CPC) troughs [22,25]. The parametric study showed that the thermal and electrical outputs increase with increased absorber length, air mass flow rate and packing factor, but decrease with increased duct depth. The final design is then subject to the cost-performance analysis.

Sopian et al. [26] developed a steady–state model for comparing the performance of single- and double-pass PVT/a collectors; the better performance of the double-pass design was found attributed to the productive cooling of the solar cells and the reduction in front cover temperature. An experimental unit was introduced accordingly [27]. Prakash [28] carried out transient analysis on a conventional PVT collector designed for air- and water-heating, respectively. Compared with water heating, the lower thermal efficiency of the air-heating design as a result of poor heat transfer between the absorber plate and the flowing air was concluded.

Bergene and Lovvik [29] proposed a detailed physical model of a flat-plate PVT/w collector system for performance evaluation. The fin-width to tube–diameter ratio was investigated and the total efficiency was found in the range of 60–80%. As for thermosyphon systems, Agarwal and Garg showed that the thermal efficiency depends on the packing factor, but this is not the case for cell efficiency [18]; the quantity of water in the storage tank also has an effect. Their study was extended to acquire experimental data on a flat-plate PVT/w collector system equipped with simple parabolic reflectors [19].

With the use of modified Hottel–Whillier model, de Vries [30] investigated the steady–state long-term performance of various PVT collector designs in Netherland. The single-covered design was found better than the uncovered design (of which the thermal efficiency is unfavorable) or the double covered design (of which the cell efficiency is unfavorable). Nevertheless, the exergy analysis performed by Fujisawa and Tani [31] indicated that the exergy output density of the uncovered design is slightly higher than the single-covered design, taking the fact that the thermal energy contains much unavailable energy. For some low-temperature water-heating systems, like swimming pool applications, the low-cost unglazed PVT/w system is recommended. During some severe cold days in winter, anti-freeze liquid can be used but then the drawback would be a slight drop in summer performance [32].

Experimental tests on PVT/w systems in Riyadh (at 24.6°N), Saudi Arabia [33] showed that the high ambient temperature in summer could lead to 30% drop in PV efficiency, though the thermal efficiency remains good. In winter time the PV modules show improved performance yet the thermal side performance deteriorates.

On the other hand, Rockendorf et al. [34] constructed prototypes of thermoelectric collector (first generating heat and subsequently electricity) and PVT/w collector (with solar cells on aluminum-absorber and copper-tubing combination); the TRNSYS simulation results showed that the electrical output of the PVT/w collector is significantly higher than that of the thermoelectric collector.

In the above studies of flat-plate collectors, the calculated thermal efficiency of PVT/liquid systems are generally in the range of 45–70% for unglazed to glazed panel designs. For PVT/a systems, the thermal efficiencies can be up to 55% for optimized collector design.

2.3. Technological developments in the 1990s

The increase in PVT research in the 1990s apparently had been a response to the global environmental deterioration and the growing interest of the construction industry towards the building-integrated-photovoltaic (BiPV) options. PVT collectors provide architectural uniformity at the building facade and are aesthetically better than the two separated arrays of PV and solar thermal collectors being placed side by side. Alternative cooling features of the BiPV systems have been examined by different research teams, such as Clarke et al. [35,36], Moshfegh and Sandberg [37], and Brinkworth et al. [38]. Hollick [39] reported the improved overall efficiency when solar cells were added onto the solar thermal metallic cladding panels.

As for concentrator-type (c-PVT) systems, Akbarzadeh and Wadowski [40] made suggestions on a heat-pipe-based coolant design which is a linear, trough-like system. Each cell is mounted vertically at the end of a flattened copper pipe with a finned condenser area. The system is designed for 20× concentration, and the cell temperature was reported not exceeding 46 °C on a sunny day, as opposed to 84 °C in the same conditions but without coolant flow. Luque et al. [41] successfully developed the EUCLIDES prototype – a concentrating array using reflecting optics and one-axis tracking. They also [42] discussed the temperature distribution at a solar cell under concentration with inhomogeneous illumination, when the cell is electrically isolated from the heat sink.

On the other hand, combining PVT and solar-assisted heat pump (SAHP) technology has been seen as an alternative approach for achieving higher hot water supply temperature and better PV cooling. This involves the direct coupling of a PVT panel (designed for direct expansion of refrigerant) to a heat pump system. In this arrangement, liquid refrigerant vaporizes at the tubing underneath the flat-plate collector, which is now the PVT evaporator. By means of the Rankine refrigeration cycle operation, solar energy is absorbed at the PVT evaporator that operates at a lower temperature than the ambient environment, and later on released at the water-cooled condenser at a higher temperature. Cell efficiency is then higher than the standard operating efficiency. The coefficient of performance (COP) of the heat pump is also improved because of the higher evaporating temperature than the air-source heat pump. Based on this working principle, Ito et al. [43,44] constructed a PVT–SAHP system with pc-Si aluminum roll-bond panels. The experimental results indicated that the COP of the heat pump is able to reach 6.0, and with hot water supplying to the condenser at 40 °C. It was also found that the presence of solar cells affects little the thermal performance of the SAHP. But the complication in control can be a concern.

Generally speaking, the R&D efforts on the PVT collector systems in the first 25 years or so had been on improving the cost-performance ratio as compared to the solar thermal and PV systems working side by side. For real-building project applications, the PVT/a systems were more readily adopted in the European and North American markets though the higher efficiency of the PVT/w system has been confirmed. Notwithstanding this advantage, solar houses that carried PVT/w panels were once sold commercially in Japan in late 1990s but the construction work was soon stopped because of the lack of market demand to support its profit making [45]. The contemporary issues related to the PVT technology, including the marketing potentials, were summarized in the expert reports of the working teams commissioned by the Swiss Federal Office [46,47] and the IEA (International Energy Agency) [48]. An overview of the applications and development directions was also presented in Bazilian et al. [49].

2.4. Performance assessment

To assess the electrical performance of a PVT system is straightforward since the use of electricity can be immediate and the provision of storage is optional. The situation is different for thermal performance. The PVT collector is only one part of a complete heat-supply system that is made up of many sub-systems (or the balance of system), like thermal storage, auxiliary heater, mechanical device and flow conduits, to name some examples. The system designer has to determine the appropriate solar fraction and other design parameters in achieving the best overall benefits.

The thermal efficiency and electrical efficiency of a PVT collector are, respectively, given by:

$$\eta_t = \frac{\dot{m}C(T_{out} - T_{in})}{GA} \tag{1}$$

$$\eta_e = \frac{V_{mpp}I_{mpp}}{GA} \tag{2}$$

where $\dot{m}$ and C are, respectively, the mass flow rate and specific heat capacity of the coolant, A the collector aperture area, T_{in} and T_{out} the coolant temperatures at the inlet and outlet, G the incident solar irradiance normal to surface, V_{mpp} and I_{mpp} are the voltage and electric current at maximum power point operation.

The electrical efficiency is related to the cell efficiency η_{cell} by the ratio of the cell surface area A_{cell} to the aperture area (which is known as the packing factor β), in that

$$\eta_e = \frac{A_{cell}\eta_{cell}}{A} = \beta\eta_{cell} \tag{3}$$

The thermal efficiency is conventionally shown as a function of the reduced temperature, which is defined as

$$T^* \equiv \frac{T_{in} - T_a}{G} \tag{4}$$

where T_a is the ambient temperature. The Hottel–Whillier–Bliss model [50] modified by Florschuetz [6] can be expressed as

$$\eta_t = F_R\left[(\tau\alpha)_e(1-\eta_e) - U_L\left(\frac{T_{in}-T_a}{G}\right)\right] \tag{5}$$

where F_R and U_L are the modified heat removal factor and overall heat loss coefficient, $(\tau\alpha)_e$ is the effective transmittance, and η_e is the electrical efficiency evaluated at ambient temperature. F_R represents the ratio of the actual useful heat gain to the maximum possible useful heat gain. Alternatively if T_m is the mean fluid temperature at the collector and F' the collector efficiency factor, then

$$\eta_t = F'\left[(\tau\alpha)_e(1-\eta_e) - U_L\left(\frac{T_m-T_a}{G}\right)\right] \tag{6}$$

A linear expression of Eq. (6) gives

$$\eta_t = \eta_{to} - aT^* \tag{7}$$

where the ordinate intercept η_{to} is the collector thermal efficiency at zero reduced temperature and the slope a relates to the collector heat loss factor.

To evaluate the overall system performance, some researchers (such as Bhargava et al. [17]; Bergene and Lovvik [29]; Fujisawa and Tani [31]) use the concept of total system efficiency η_o, which is the direct sum of the thermal efficiency η_t and the electrical efficiency η_e, i.e.

$$\eta_o = \eta_e + \eta_t \tag{8}$$

Other researchers consider that electricity is in a higher grade form since it is converted from thermal energy. The energy saving efficiency is then introduced (as in the work of Huang et al. [51]; Tiwari et al. [52]; Chow et al. [53]), in that

$$\eta_{saving} = \frac{\eta_e}{\eta_{power}} + \eta_t \tag{9}$$

where η_{power} is the electric power generation efficiency of conventional power plant.

As a complimentary approach, the exergy analysis is often performed. Exergy represents the maximum quantity of work that can be produced in some given environment. By definition, exergetic efficiency (ε) is the ratio of total exergy output to total exergy input. In a PVT system, the exergetic efficiency within the time period t_1 to t_2 can be expressed as

$$\varepsilon_{pvt} = \frac{\int_{t_1}^{t_2}(A\dot{E}x_t + A_{cell}\dot{E}x_{pv})dt}{A\int_{t_1}^{t_2}\dot{E}x_{sun}dt} = \varepsilon_t + \beta\varepsilon_{pv} \tag{10}$$

where $\dot{E}x_t$ is the thermal exergy output per unit collector area, $\dot{E}x_{pv}$ the photovoltaic exergy output per unit cell area, $\dot{E}x_{sun}$ the exergy input of solar radiation, ε_t the exergetic efficiency of the thermal collector and ε_{pv} is the exergetic efficiency of the solar cells. The exergy outputs are related to the energy outputs as follows [54]:

$$\dot{E}x_{pv} = \dot{E}_{pv} \tag{11}$$

$$\dot{E}x_t = \dot{E}_t\left(1 - \frac{293}{293+(T_2-T_a)}\right) \tag{12}$$

where $\dot{E}_t$ is the thermal output power per unit collector area, $\dot{E}_{pv}$ the photovoltaic output power per unit cell area, and T_2 is the final temperature of the coolant.

On economical evaluation, the life cycle cost analysis can be performed [55]. The life cycle cost for a PVT system is its total cost of investment and operation over its entire service life. Most of these costs occur beyond the acquisition date and must be evaluated using the time value of money, including inflation, tax and/or company discount rates. A simplified approach is to ignore the time element so the cost payback time (CPBT) can be used. This is by adding together the cash inflows from successive years until the cumulative cash inflow is the same as the required investment.

In analogy to the economical evaluation, two environmental cost-benefit parameters, the energy payback time (EPBT) and greenhouse gas payback time (GPBT), can be used to evaluate the time period after which the real environmental benefit starts. EPBT is the ratio of embodied energy to annual energy output. Embodied energy refers to the quantity of energy required to produce the material in its product form. For a BiPVT system for example,

$$\mathrm{EPBT} = \frac{\Sigma_{pvt} + \Sigma_{bos} - \Sigma_{mtl}}{E_{pv} + E_t + E_{ac}} \tag{13}$$

where Σ_{pvt}, Σ_{bos} and Σ_{mtl} are, respectively, the embodied energy of the PVT system, of the balance of system, and of the replaced building materials; E_{pv} is the annual useful electricity output, E_t is the annual useful heat gain (equivalent), and E_{ac} is the annual electricity saving of the HVAC system due to the thermal load reduction.

Similarly in terms of greenhouse gas (GHG) emission,

$$\mathrm{GPBT} = \frac{\Omega_{pvt} + \Omega_{bos} - \Omega_{mtl}}{Z_{pv} + Z_t + Z_{ac}} \tag{14}$$

where Ω stands for the embodied GHG (or carbon dioxide equivalent) and Z the reduction of annual GHG emission from the local power plant owing to the BiPVT operation.

Coventry and Lovergrove pointed out that the exergy analysis may not be most appropriate in assessing PVT designed for low-temperature water heating, taking the fact that electricity or mechanical work is not the only desired system outputs [56]. Besides the efficiency, economical and environmental payback time evaluations, there are in fact other methods to evaluate the overall PVT performance by combining the outputs of electricity and heat in different ways, such as to determine the cost saving from the tariffs for heating energy and electrical energy. This is a market-based approach to assess the energy cost savings and sounds good for energy management. But this is affected by the political environment and is never universally valid [54]. On the other hand, it should be aware that the energy performance of a given PVT product or system design varies with the local environment, in particular the latitude. Parameters derived for different places may not be compared directly.

3. Developments of flat-plate PVT collector systems reported in the last decade

3.1. Air-type collector systems

3.1.1. Collector design and performance

The air-type product design provides a simple and economical solution to PV cooling, and the air can be heated to different temperature levels through forced or natural flow. Forced circulation is more efficient than natural circulation owing to better convective and conductive heat transfer, but the required fan power reduces the net electricity gain.

Hegazy [57] performed an extensive investigation of the thermal, electrical, hydraulic and overall performance of four types of flat-plate PVT/a collectors. As in Fig. 2, these included: channel-above PV as Mode 1, channel-below PV as Mode 2, PV between single-pass channels as Mode 3, and finally the double-pass design as Mode 4. The numerical analysis showed that while Mode 1 has the lowest performance, the other three have comparable energy yields. In addition, Mode 3 consumes the least fan power.

Tripanagnostopoulos et al. [58] conducted outdoors tests on PVT/a and PVT/w collectors of different design configurations for horizontal-mounted applications. They found that PVT/a collectors are around 5% higher in production costs than the PV modules. This would be around 8% for PVT/w collectors with pc-Si cells, and around 10% when the entire system costs were considered. It was suggested that when the collectors are placed in parallel rows and keeping a distance between rows to avoid shading, low-cost booster diffuse reflectors can be placed between the adjacent rows to increase the radiation received at collector surfaces. Their experimental tests gave a range of thermal efficiency from 38% to 75% for PVT/a collectors and 55% to 80% for PVT/w designs, based on the steady state noon-hour measurements in the University of Patra (at 38.2°N) in Greece. The high side values were obtained when the reflectors were in place.

By the use of validated theoretical models, Tonui and Tripanagnostopoulos [59] studied the degree of improvement by adding suspended metal sheet at the middle of the air channel and the finned arrangements at the opposite wall of the air channel. It was found that these low-cost improvements are more effective at small collector length (<6 m for instance), and can be readily applied to BiPVT/a installations. On the other hand, the effect of channel depth, mass flow rate or system length on fan power consumption was found small. The works of Othman et al. [60] also stressed on the importance of fins through their experimental and mathematical analysis; their double-pass PVT/a hybrid system consisted of c-Si cells pasted to the absorber plate with fins attached at the other side of the absorber surface.

Tiwari et al. [52] evaluated the overall efficiency performance of an unglazed PVT/a collector in India. The results gave the optimal air flow rate, duct length and duct depth. Energy matrices were derived considering the embodied energy at different processing stages [61]. As a continuation, Raman and Tiwari [62,63] studied the annual thermal and exergy efficiency of the PVT/a collector for five different Indian climate conditions. It was observed that the exergy efficiency is 40–45% lower than the thermal efficiency under strong solar radiation. Also the double-pass design shows better performance than the single-pass option, as an echo to the findings of Sopian et al. [26] and Hegazy [57]. Furthermore, the life cycle analysis showed that the EPBT is about 2 years. On the other hand, Joshi and Tiwari [64] carried out exergy analysis of an unglazed PVT/a collector for the cold climate region of India. The instantaneous energy and exergy efficiencies were found in the ranges of 55–65% and 12–15%, respectively. The effect of fill factor was also evaluated [65].

Dubey et al. [66] studied different configurations of glass-to-glass and glass-to-tedlar PV modules. Analytical expressions for electrical efficiency with and without airflow were developed as a function of climatic and collector design parameters. Experiments at the Indian Institute of Technology, Delhi found that the glass-to-glass type is able to achieve higher supply air temperature and electrical efficiency. This is because the radiation that falls on the non-packing area of the glass-to-glass module is transmitted through the front cover. Its annual average PV efficiencies with and without duct were determined 10.4% and 9.75%, respectively, hence a difference of about 0.7%. The percentage differences between the PV efficiency of the glass-to-glass to the glass-to-tedlar type were respectively, 0.24% with duct and 0.086% without duct. Their study extended to derive the analytical expressions for multiple PVT/a collectors connected in series, including the testing procedure [67,68].

Tripanagnostopoulos [69] further introduced a PVT/bi-fluid collector with the input of improvement features from their previous studies. Three alternative modes of placing the water heat exchanger inside the air channel were tested and the results showed that the water heat exchanger positioned at the PV rear surface gives the best results for combined water and air heat extraction. The integrative design is able to cut down the CPBT from 25 years of a standard PV module to 10–15 years for low-temperature water system operation.

Assoa et al. [70] developed a PVT/bi-fluid collector that combines the functionality of air pre-heating and domestic hot water generation. The design includes alternate positioning of the thermal solar collector section and the PV section. The higher fluid temperatures as a result allow the coupling of components such as solar cooling devices during summer, and facilitate a direct domestic hot water system without the need for additional auxiliary heating device. Parametric studies were carried out both numerically and experimentally. Under favorable collector length and mass flow conditions, the thermal efficiency could reach 80%.

3.1.2. The building-integrated installations (BiPVT/a)

From a holistic viewpoint, Bazilian et al. [71] summarized the potential applications of PVT cogeneration in the built environment. The multi-functional external façade/roof was identified good for PVT installation that produces heat, light and electricity simultaneously. Other than the use of airflow behind the PV modules, a PVT system designed for light transmission requires no additional system cost except for ambient light sensors to optimize the gain from daylighting.

In Denmark, two EU financed BiPVT/a projects in retrofit housing were taken place in Lundebjert and in Sundevedsgade/Tondergade in 2000–2001 [72,73]. These involved the testing of different applications of PV-powered ventilation systems, such as the assessment of different ways of architectural integration, air-to-air heat exchanger performance and direct coupling of DC fans with PV outputs. The results showed that the actual benefit of fresh-air pre-heating is low – only about one-third of the direct pre-heating by the sun was utilized. There could be high heat loss from the building to the solar wall rather than the utilization of solar radiation. It was suggested that the PV panels should be cooled on the backside by natural ventilation during summer in order to save fan power.

In UK, the Brockstill Environment Centre in Leicester (at 52.7°N) opened in 2001 was installed with a roof-mounted PVT/a system together with solar air collectors [74]. To assess the performance of various operational and control modes, a combined simulation approach was adopted incorporating both ESP-r and TRNSYS transient simulation tools. Monitored actual energy use data of the building shows very positive results.

In the subtropical area, Ji et al. [75] studied numerically the energy performance of a BiPV façade with a ventilating air gap behind the PV modules in a high-rise building of Hong Kong. It was found that the provision of the free airflow gap affects little the electrical performance, but is able to reduce the heat transmission through the PV façade. Yang et al. [76] carried out a similar study based on the weather conditions of three cities in China: Hong Kong (at 22.3°N), Shanghai (at 31.2°N) and Beijing (at 39.9°N). It was found that the ratio of space cooling load reduction owing to the airflow behind the PV modules is ranged from 33% to 52% on typical days.

Chow et al. [77] investigated the BiPVT/a options of a hotel building in Macau (at 22.2°N). The PVT facade was attached to a 24-h air-conditioned services room. The effectiveness of PV cooling by means of natural flow of air behind the PV modules was investigated with two options: free openings at all sides of the air gap as Case 1, and in Case 2 the enclosed air gap that behaves as a solar chimney for air pre-heating. These were compared with the conventional BiPV case. The ESP-r simulation results showed insignificant difference in electricity output from the three PV options. This outcome was caused by a reverse flow at the air gap in night-time, owing to the 24-h room cooling effect. It was concluded that both the climate condition and system operating mode affect significantly the PV productivity.

The main difficulty in analyzing BiPVT/a performance lies in the estimation of its thermal behavior. Once the temperature profile and the sun shading situation has been deduced, the electrical performance is then readily determined. But the thermal computation can be problematic. For instance, the estimation of the convective heat transfer coefficients is far from straightforward, because the actual processes involve a mix of forced and natural convection, laminar and turbulent flow, and simultaneously, the developing flow at the air entrance. The external wind load on the panels further complicates the situation. For a semi-transparent facade, thermal energy enters and transmits through the air cavity both directly (for glazing) and indirectly (through convection and radiation exchange). The heat transfer to the ventilating stream is probably most complex, particularly when the buoyant flow is being utilized exclusively.

By assuming bulk airflow in the vertical duct behind the PV panels, Sandberg and Moshfegh [78] derived analytical expressions for the coolant flow rate, velocity and temperature rise along the duct length. Experiments were conducted and found well matching with the theoretical predictions for constrained flow, but less accurate for ducts with opened ends. For the latter, Mittelman et al. [79] developed a generalized correlation for the average channel Nusselt number for the combined convective–radiative cooling. Their solution of the governing conservation equations and boundary conditions was carried out by means of CFD technique. Also using CFD, Gan analyzed the effect of air gap size on the PV performance in terms of cell temperature for a range of roof pitches and PV panel lengths at different solar heat gain levels [80,81]. To reduce possible overheating or hot spot formation, a minimum air gap of 0.12–0.15 m for multiple-module and 0.14–0.16 m for single-module installations are recommended.

Mei et al. [82] carried out dynamic thermal simulation of a BiPVT/a collector system with TRNSYS. Validation was executed against experimental data from a pc-Si PV facade constructed in the 1990s (of 15% overall transparency) at the Mataro Library in Spain. The heating and cooling loads for various European buildings with and without such a ventilated facade were determined. The impact of climatic variations on the energy was evaluated. The results showed that 12% of winter heating energy can be saved for the use of the pre-heated ventilation in a building located in Barcelona (at 41.3°N), but only 2% for Stuttgart (at 48.8°N) in Germany and Loughborough (at 52.8°N) in UK. The higher latitude locations need higher percentage of solar air collectors in the combined system. Further, Infield et al. [83] explored different approaches to estimate the thermal performance of BiPVT/a facades, including a design methodology based on an extension of the familiar heat loss and radiation gain factors. Through this, the energy yield of the semi-transparent PV facade of the Mataro library was well explained.

Fig. 4 shows a ventilated PV glazing assembly that consists of a PV glazing at the outside and a clear glazing at the inside. The different combinations of vent openings allow different ventilating flow provisions, which can be either buoyant-induced or mechanical-driven. The heating mode belongs to the BiPVT/a category. Other than the opaque c-Si solar cells on glass, the see-through a-Si solar cell may be used and could offer a better scenery view from the indoor space. Chow et al. [84] analyzed numerically the overall energy performance of its application in the Hong Kong office environment. The surface transmission (i.e. thermal radiative and convective heat transfer) through the glazing assembly was found dominated by the material properties of the inner glass, but the overall heat transfer is affected by both the outer and inner glass properties, like their extinction coefficients. Experimental measurements at the City University of Hong Kong were also reported [85]. Comparisons were made between two similar window glazing configurations: one with PV glass and the other with absorptive glass. The comparative study on single, double and double-ventilated cases showed that the ventilated PV glazing arrangement is able to reduce direct solar gain and glare effectively. The savings on air-conditioning electricity consumption can be at 26% for the single-pane installation, and at 82% for the double-pane ventilated case. Further, via a validated ESP-r simulation model [86], the natural-ventilated PV double-glazing technology as applying to typical office environment of Hong Kong was found cutting down significantly the air-conditioning power consumption by 28%, as compared to the conventional single absorptive glazing system. With daylight control, Chow et al. [87] found that the PV ventilated glazing systems can improve significantly the electricity consumption in office buildings. The simulation results showed that for the range of climate regions from tropical to temperate, the PV natural-ventilated glazing system has advantages over the natural-ventilated absorptive glazing option, as well as the single-pane glazing systems.

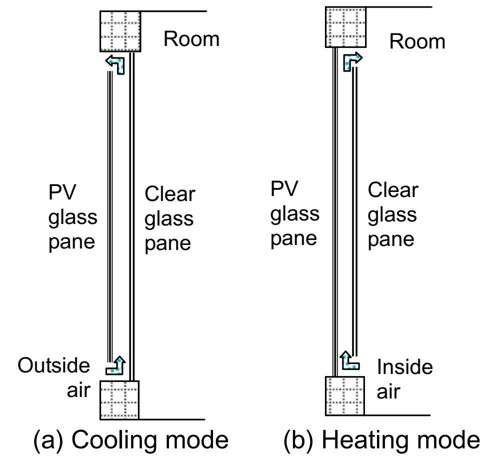

Fig. 4. Different modes of ventilated PV glazing operation.

While the ventilated designs are found better than the heat recovery PVT designs for the warm climate applications, Crawford et al. [88] compared the EPBT of a conventional c-Si BiPV system with two BiPV systems (i.e. c-Si and a-Si) incorporated with heat recovery unit. They found that the EPBT of the three installations in Sydney (at 33.5°S) of Australia are in the range of 12–16.5 years, 4–9 years, and 6–14 years, respectively. Hence with the heat recovery unit integration, the EPBT can be almost cut by one half.

In Hefei (at 31.9°N), Ji et al. [89] investigated theoretically and experimentally the performance of a photovoltaic-trombe wall which was constructed at a roof-top environmental chamber at the University of Science and Technology of China. This south-facing facade was composed of a PV glazing at the outside, an insulation wall at the inside with top and bottom vent openings, leaving an air duct in between for space heating through natural circulation. The results confirmed the dual benefits of the system: improving the room thermal condition and generating electricity. The indoor temperature can be raised by 5–7 °C in winter. On the other hand, the cooling effect contributed by the ducted flow is able to maintain the working efficiency of the pc-Si cells at 10.4% on average.

3.2. Liquid-type PVT system

3.2.1. PVT/w collector design and performance

3.2.1.1. Design configuration and applications. Zondag et al. developed a range of steady–state and dynamic simulation models for PVT/w energy performance analysis [90,91]. These included 1-D, 2-D and 3-D models of a serpentine PVT/w collector and their accuracy was verified by experimental data. It was found that all these computational models are agreeable to the experimental results of the Eindhoven University of Technology within 5%, but the use of 2-D and 3-D models is possible to generate detailed performance data for design improvement. Through additional computer modeling and analysis, they obtained the efficiency curves of nine different PVT/w collector configurations for performance evaluation. At zero reduced temperature, the thermal efficiencies of the uncovered and single covered sheet-and-tube collectors were found 52% and 58%, respectively, that of the channel-above-PV design is 65%. Also compared were the annual yields when these collectors were considered serving a solar water-heating system of a Dutch residence. The channel-below-PV (transparent) configuration appears to be the best option from the efficiency point of view, while the more economical single-cover sheet-and-tube design is a good alternative since its efficiency is only 2% less. The single cover sheet-and-tube design is introduced as one most promising for domestic hot water production. For low-temperature water-heating, the uncovered PVT/w collector is recommended, since the reflection losses at the cover are virtually eliminated, while the front heat loss is small because of the low working temperature level.

Sandnes and Rekstad [92] investigated the energy performance of a PVT/w collector with c-Si solar cells (either with or without front cover) pasted on polymer thermal absorber. The opposite surface was in black color (absorption coefficient = 0.94 for normal incidence) which allows its serving as a solar thermal collector when turned up-side-down. Square-shape box-type absorber channels were filled with ceramic granulates. This improves heat transfer to flowing water. The analysis showed that the presence of solar cells reduces the heat absorption by about 10% of the incident radiation, and the glass cover (if exists) reduces the optical efficiency by around 5%. Its application to low-temperature water-heating system is promising.

Chow [93] introduced an explicit dynamic model for analyzing single-glazed sheet-and-tube collector performance. Through the multi-nodal finite different scheme, the exact influences of fluctuating irradiance and dynamic auto-control device operation can be readily analyzed. The appropriateness of the nodal scheme was evaluated through sensitivity tests. The steady–state energy flow analysis also reveals the importance of having good thermal contact between the encapsulated solar cells and the absorber plate, as well as between the absorber plate and the water tubing.

The work of Zakherchenko et al. [94] also pin-pointed the importance of having good thermal contact between the solar cells and thermal absorber and so, commercial PV module should not be directly used in PVT design. They introduced a substrate material with 2 mm aluminum plate covered by 2 μm insulating film, of which the thermal conductivity was only 15% less than that of aluminum. They also pointed out that the solar cell area should be smaller than the size of the absorber, and should be at the portion of the collector where the coolant enters. As an echo to this last point, Dubey and Tiwari [95] examined the performance of a self-sustained single-glazed PVT/w collector system with a partial coverage of PV module (packing factor = 0.25) in New Delhi. The electricity generated from the PV module positioned at the water inlet end was used to drive a DC circulation pump. The analytical model developed based on a partially covered PVT/w collector connected in series with an identical solar thermal collector (without PV) confirmed that better system thermal efficiency and cell efficiency can be achieved.

Using the TRNSYS program, Kalogirou [96] modeled a pump-operated domestic PVT/w system complete with water tank, power storage and conversion, and temperature differential control. Later on, Kalogirou and Tripanagnostopoulos [97] further examined domestic PVT/w applications working with either thermosyphon or pump circulation modes. Their simulation study covered 12 cases with two types of PV modules (pc-Si and a-Si) in three cities: Nicosia (at 35°N) in Cyprus, Athens (at 38°N) in Greece, and Madison (at 43°N) in USA. The results showed that while the electricity generations are higher for pc-Si cells, the thermal contributions are slightly higher for a-Si cells. The a-Si modules also have better cost/benefit ratios owing to their lower initial costs. The economical advantage is more obvious for Nicosia and Athens where the availability of solar radiation is higher. Similar conclusions are reached when considering comparable applications at industrial scale [98]. Also in Cyprus, Erdil et al. [99] carried out experimental measurements on an open-loop PVT/w domestic water pre-heating system. Water flowed by gravity into a channel-above-PV type collector. The CPBT was estimated about 1.7 years, considering the required modification costs on a PV module.

Based on the analytical works of de Vries [30], Vokas et al. [100] performed a theoretical analysis of PVT/w application in domestic heating and cooling systems in three cities with different climate: Athens (at 37.9°N), Heraklion (at 35.5°N) and Thessaloniki (at 40.5°N). The thermal efficiency of their PVT collector system was found around 9% lower than the conventional solar thermal collector. Hence the interpolation of the PV laminate affects very little the thermal efficiency. The difference between the mentioned two systems in the percentage of domestic heating and cooling load coverage is only around 7%. Nevertheless, the actual performance, like the percentage of solar coverage, is confirmed geographical dependent.

Saitoh et al. [101] in Japan studied experimentally the performance of a single-glazed sheet-and-tube PVT collector with brine (propylene glycol) solution as the coolant. At constant coolant supply temperature and flow rate, the cell efficiency was found in the range of 10–13%, and collector efficiency 40–50%. The total efficiency is roughly equivalent to that of the solar thermal collector, and the total exergy efficiency is higher than the individual PV and solar thermal systems. Field measurements at a low-energy house in Hokkaido were also observed. With a solar fraction of 46.3%, the system electrical efficiency was 8–9% and thermal efficiency 25–28%. Compared with the conventional system, the payback periods are, respectively, 2.1 years for energy, 0.9 year for GHG emission, and 35.2 years for cash flow.

In Hong Kong, Chow et al. [102] carried out outdoor measurements on two identical sheet-and-tube thermosyphon PVT/w collector systems, in which one was glazed and the other unglazed. Together with a validated numerical model, the appropriateness of having front glazing was evaluated. The first law of thermodynamic evaluation indicates that the glazed design is always suitable if either the thermal or the overall energy output is to be maximized, but the exergy analysis supports the use of unglazed design if the increase of PV cell efficiency, packing factor, ratio of water mass to collector area and wind velocity are seen as the desirable factors.

Based on a theoretical model, Dubey and Tiwari [103] in India analyzed the thermal energy, exergy and electrical energy yield of PVT/w sheet-and-tube collectors by varying the number of collectors in use, their series/parallel connection patterns, and the weather conditions. It was concluded that with the same water flow rate, the collectors partially covered by PV cells is beneficial for those users with priority on hot water production, and those fully covered are beneficial for users with priority on electricity generation. For enhancing economical/environmental benefits, the optimum hot water withdrawal rate was evaluated [104].

3.2.1.2. Absorber materials. While metallic sheet-and-tube absorber has been most commonly adopted in flat-plate collectors, the use of copolymer absorber was also examined extensively. This alternative offers several advantages:

(i) the reduction in weight leads to less material utilization and easier installation;
(ii) the manufacturing process is simplified because of the fewer components involved and

(iii) the investment can be lowered as a result of the reduced material and installation costs.

Yet there are disadvantages like low thermal conductivity, large thermal expansion and limited service temperature. The copolymer in use has to be good in physical strength, UV-light protected and chemically stable.

In Taiwan, Huang et al. [51] studied a PVT/w collector system complete with DC circulating pump and storage tank. The collector was constructed with commercial PV modules attached on a corrugated polycarbonate absorber plate with square-shaped box channels. The results showed that the characteristic daily thermal efficiency could reach 38%, the primary-energy saving efficiency exceeds 60% and PV efficiency 9%. The overall efficiency is better than those experienced in either conventional solar water-heating collectors or PV modules.

In view of the limitations on the fin performance of a sheet-and-tube PVT/w collector [93], an aluminum-alloy channel-type PVT/w collector was developed through the collaborative efforts of the City University of Hong Kong and the University of Science and Technology of China. Several generations of the modular collector feature were produced and tested under the climatic conditions of Hong Kong [105,106] and Hefei [107]. The thermosyphon system was found working well both under the subtropical and temperate climate conditions. Measurements showed that the temperature difference between the front and back surfaces of the absorber is only around 1 °C under normal operation. Dynamic simulations showed that better convective heat transfer between the coolant and the channel wall can be achieved by reduced channel height and increased number of channels per unit width [108]. Sensitivity tests in Hefei showed that the daily cell efficiency reaches 10.2%, daily primary-energy saving efficiency reaches 65% with a packing factor of 0.63 and front cover transmissivity 0.83 [109]. With the use of typical weather year data of Hong Kong, the CPBT was found 12 years which is comparable to the more bulky side-by-side system, and much better than the 52 years for plain PV modules [110].

According to Affolter et al. [111], the typical solar performances of PVT/liquid collectors are similar to those of non-selective-type solar thermal absorbers. They also presented the general results concerning the stagnation temperature, i.e. the elevated panel temperature in the absence of water flow. Observations showed that the absorber of a solar thermal collector with a state-of-the-art spectrally selective coating may reach 220 °C. Since a PVT absorber generally has higher solar reflectance and higher infrared emission than a solar thermal absorber, the stagnation temperature may be lowered to 150 °C. But this is still higher than 135 °C, i.e. the temperature that the common encapsulation materials like EVA (ethylene vinyl acetate) resin may withstand [112]. At above 135 °C, EVA oxidizes rapidly.

In France, Cristofari et al. [113] developed a finite difference model to study the performance of a PVT/w collector with polycarbonate absorber and pc-Si PV modules. Water in forced-flow passed through parallel square channels at very low flow rate (and therefore with negligible pumping power). The system design capacity was based on the hot water demands for the inhabitants at Ajaccio (at 41.9°N), a seaside Mediterranean site. Yearly-average efficiencies of 55.5% for thermal, 12.7% for PV, 68.2% for total system, and 88.8% for energy saving were obtained. The maximum stagnation temperature reached at the absorber was found 116.2 °C, which is acceptable.

Fraisse et al. [114] pointed out that the low operating temperature requirement (35 °C) of Direct Solar Floor (DSF) system is very suitable for the application of PVT/liquid system. Using the TRNSYS simulation program, they studied such an application for a glazed collector system located at the Macon area (at 46°N) in France. Propylene glycol was used as the coolant. The annual c-Si cell efficiency was found only 6.8%, which represents a decrease of 28% as compared to a conventional non-integrated PV module typically at 9.4% annual efficiency. Without the glass cover, the cell efficiency is 10% due to the better cooling effect, and so is 0.6% better than a standard PV module. Moreover, in the case of a glazed collector with a conventional control system for DSF, the maximum temperature reached at the PV modules is higher than 100 °C. The fact is the heating needs are null during summer so the collectors become oversized. This temperature level does not allow the use of EVA in PV modules due to strong risks of degradation. The use of either a-Si cells (in the absence of EVA and improved solar absorption) or uncovered collector (with more effective cooling) was suggested.

3.2.1.3. PV module design. One way to improve the system efficiency is to employ a bifacial PV module having two active surfaces and so generating more electric energy than the traditional one-surface module with the same areas. Water, due to its optical properties, absorbs light mainly in the infrared region and thus is compatible with PV modules using shorter wavelengths in the solar radiation spectra for its conversion to electricity. The water absorption only slightly affects the working region of a-Si PV cell (decrease of water transparency at around 950 nm), but it strongly absorbs the light with wavelengths above 1100 nm (the 'thermal part" of the solar spectrum). Therefore, the combination of a water-filled solar collector with Si bifacial solar PV module in a PVT/w system can be advantageous. In Mexico, Robles-Ocampo et al. [115] carried out experimental test on a PVT/w system with c-Si bifacial PV module in Queretaro (at 20.6°N). The transparent plane collector was fabricated with a 15 mm channel underneath a glass cover, which was found better than the plastic cover in terms of longer service life. Stainless steel mirror reflectors (to prevent oxidation in the outdoor environment) were used for illuminating the rear face of the solar cells. Measurements found that the glass water-filled plane collector placed above the PV module reduces the front face efficiency by 10%. When considering the radiation flux incident directly onto the active elements of the hybrid system, the system is able to achieve a thermal efficiency of around 50% and an equivalent electrical efficiency of 16.4%.

3.2.2. Building-integration installations (BiPVT/w)

Compared to the development of BiPVT/a systems, the research works on BiPVT/w systems have been less popular. Ji et al. [116] studied numerically the annual performance of a BiPVT/w collector system for use in residential buildings of Hong Kong. Pump energy was regarded negligible. Assuming isotropic sky conditions as well as perfect bonding of PV encapsulation and copper tubing onto absorber, the annual thermal efficiencies of the above systems on west-facing facade were found 47.6% and 43.2% for film cells and c-Si cells, respectively, and the corresponding cell efficiencies 4.3% and 10.3%. The reductions in space heat gain were estimated 53.0% and 59.2%, respectively.

Using the Hottel–Whillier PVT/w collector model available in TRNSYS, Chow et al. [117] studied a BiPVT/w system applicable to multistory apartment building in Hong Kong for water pre-heating purpose. The a-Si PVT collector arrays covered two-third of the west- and south-facing external facades, giving a solar fraction of 34%. A portion of the electricity generation was used to support the two independent sets of circulating pumps which are operating at optimized flow rate. The net thermal efficiency was found around 30% and cell efficiency around 5.4%. Later on, Chow et al. [118] constructed an experimental BiPVT/w system at a roof-top environmental chamber. The modular box-structure PVT/w collectors were mounted on a SW-facing facade. The energy efficiencies of thermosyphon and pump circulation modes were compared across the subtropical summer and winter periods. The results show the better energy performance of the thermosyphon operation, with thermal efficiency reaches 39% at zero reduced temperature and the corresponding cell efficiency 8.6%. Compared with the bare facade, the interior surface temperature of the PVT/w wall fluctuates with much smaller amplitude. The space cooling load is reduced by 50% in peak summer. Ji et al. [119] further carried out an optimization study on this type of installation specifically on the appropriate water flow rate, packing factor and connecting pipe diameter.

With the above measured data, Chow et al. [120] developed an explicit dynamic thermal model of the above BiPVT/w collector system. As confirmed by extensive model validation exercises, the finite difference model was found able to give high quality results. Its use in evaluating the annual system performance in Hong Kong re-confirmed the better performance of the natural circulation mode because of the elimination of the circulation pump sets and hence the better cost saving [121]. The cost payback time was estimated around 14 years, which is comparable to the stand-alone box channel PVT/w collector system case. This BiPVT/w application is able to shorten the CPBT to one-third of the plain BiPV application.

In Australia, the design of a roof-mounted BiPVT/w system was theoretically analyzed by Anderson et al. [122]. Their prototype BiPVT/w collector was integrated to the standing seam or toughed sheet roof, on which passageways were added to the trough for liquid coolant flow. Their modified Hottel–Whillier model was validated by a steady–state outdoor thermal test rig. The results showed that the key design parameters like fin efficiency, lamination requirements, as well as thermal conductivity between the PV module and the supporting structure, affect significantly the electrical and thermal efficiencies. They also suggested that a lower cost material like pre-coated steel can replace copper or aluminum for thermal absorption since this does not significantly reduce the efficiencies. Another suggestion was that the system should be integrated "into" (rather than "onto") the roof structure, as the rear air space in the attic can provide a level of insulation equivalent to a highly insulating material.

3.3. PVT integrated heat pump (PVT/heat pump)

Bakker et al. [123] described a space and tap-water-heating system with the use of roof-sized PVT/w array combined with a ground coupled heat pump. The system performance, as applied to one-family Dutch dwelling, was evaluation through the TRNSYS simulation program. It was found that the system is able to satisfy all the heating demand, while meeting nearly all of its electricity consumption and keeping the long-term average ground temperature constant. The required investment is comparable to those of the conventional provisions but the PVT system requires less roof space and offers architectural uniformity.

More recently, extensive analysis of the PVT/heat pump system with variable pump speed operation has been performed in China. Experimental investigation on unglazed PVT evaporator system prototype with R-22 as the refrigerant was done in Hefei (at 31.9°N). The winter-day test shows a peak COP at 10.4 and an average value of 5.4, at 20 °C condenser water supply temperature [124,125]. Mathematical models based on the distributed parameters approach were developed [126,127]. The simulation results, which are in good agreement with the measured data, show that at fixed compressor speed and refrigerant flow, and with 30 °C condenser water supply temperature, the PVT evaporator arrays had an overall efficiency in the range of 0.64–0.87, thermal efficiency 0.53–0.64 and PV efficiency 0.124–0.135. Accordingly, the COP of the PV–SAHP reaches 8.4 (peak) and 6.5 (average), and the cell efficiency at 13.4% (average). These were better than the conventional SAHP performance.

Though front cover may not be a necessity for PVT evaporator working in the warm seasons, in cold winter however, the ambient temperature can be much lower than the evaporating temperature. Then the heat loss at the PV evaporator is no longer negligible. The front cover in position is able to improve both the photothermic efficiency and the system COP. Pei et al. [128] conducted a comparative study on the merit of this front cover. The result analysis indicates that the single-glass cover on one hand is able to raise the photothermic exergy efficiency, but on the other hand, has an adverse effect on the photovoltaic exergy efficiency. On the whole for winter operation, the overall PVT exergy efficiency as well as the COP can be improved in the presence of the glass cover. This is beneficial considering the higher space heating demand in winter.

4. Developments of concentrator-type PVT design reported in the last decade

The use of concentrator-type PVT (or c-PVT) instead of flat-plate type is able to increase the radiation intensity on the solar cells. This approach is promising due to the significantly lower cost of the reflectors relative to the solar cells. Higher efficiency solar cells that handle higher current can be used though they are more expensive than the flat-plate module cells. Additional costs may also go to the complex sun tracking driving mechanism [129]. Cell efficiency decreases when non-uniform temperature across the cell exists. Series connections of cells increase the output voltage and decrease the current at a given power output, thus reducing the ohmic losses. But the cell at the highest temperature will limit the efficiency of the whole string. This is known as the 'current matching problem' [130]. The coolant circuit should be designed to keep the cell temperature low and uniform, be simple and reliable, and keep parasitic power consumption to a minimum.

Concentrators with the use of lenses or reflectors can be generally grouped into three categories: single cells, linear geometry, and densely packed modules. For highly concentrating systems, more concentrator material per unit cell/absorber area is needed. The use of lenses is then more appropriate than reflectors owing to their lower weight and material costs. However, concentrator systems that utilize lenses are unable to focus scattered light, and this limits their usage at places largely with clear weather. On the other hand, using "liquid" as the coolant is more effective than using "air" to obtain better electrical output. For these reasons, reflector-type c-PVT systems are common for medium- to high-temperature hot water systems applicable for cooling, desalination, or other industrial processes. At lower operating temperatures, a flat-plate solar collector may give a higher efficiency than the concentrator-type collector when both are directly facing the sun. But the performance gap will diminish when the working temperature gradually increases. This is because at higher temperature differential, the large exposed surface of a flat-plate collector incurs more thermal loss.

In Lieida (at 41.7°N) of Spain, Rosell et al. [131] constructed a low-concentrating PVT prototype with the combination of flat-plate channel-below-PV (opaque) collector and linear Fresnel concentrator that worked on two-axis tracking system. The total efficiency was found above 60% when the concentration ratio was above 6×. Their theoretical analysis re-confirms the importance of the cell-absorber thermal conduction.

A combined heat and power solar (CHAPS) collector system designed for single tracking was developed in Australia. This is a linear trough system in which the row of cells is cooled by water with anti-freeze and anti-corrosive additives flowing in internally finned aluminum pipe. Through glass-on-metal parabolic reflectors of 92% reflectance and with a concentration ratio of 37×, light is focused onto c-Si solar cells (at about 20% conversion efficiency under standard conditions) bonded to an aluminum receiver [132]. Measured results under typical operating conditions gave a thermal efficiency around 58%, electrical efficiency around 11%, and together a combined efficiency of 69%.

Considering heat cannot be transported over large distances, Kribus et al. [133] developed a miniature concentrating PV system that can be installed on any rooftop. By concentrating sunlight about 500 times, the solar cell area is greatly reduced. The design is based on a small parabolic dish which is similar to a satellite dish and is relatively easy to deliver and handle without the use of special tools.

Cost reduction can be realized by laminating thin aluminum foil on steel substrate, thus the concentrator is benefitted by the good mechanical properties of steel and the high solar reflectance of aluminum. Accordingly, stainless steel parabolic reflector can be made with less mechanical support than aluminum reflector. This leads to more even light distribution over the cells and hence better cell efficiency. In high latitude countries like Sweden, the solar radiation is asymmetric over the year because of the high cloud coverage during the winter months, and thus concentrated to a small angular interval of high irradiation. This makes the use of economical stationary reflectors or concentrators attractive. Nilsson et al. [134] at the Lund University (at 55.7°N) carried out tests on an asymmetric compound parabolic reflector system with two truncated parabolic reflectors which were made of anodized aluminum and aluminum laminated steel, respectively. Their measurements nevertheless found that changing the back reflector from anodized aluminum to aluminum laminated steel does not change the energy output. They also found that the optimal cell position is to face the front reflector. This will result in the lowest cost for electricity generation, assuming no space restriction. For limited roof space as in residential buildings, their recommendation is to place the solar cells on both sides of the absorber, since the cost of adding cells to the other side of the absorber is relatively low once a trough with cells on one side of the absorber is constructed.

Vorobiev et al. [135,136] presented a theoretical study on a two-stage hybrid device that involves solar cell working with an energy flux concentrator and a heat-to-electric/mechanic energy converter. Two options were explored:

(i) System with separation of "thermal solar radiation" and
(ii) System without solar spectrum division and solar cell operating at high temperature.

The first option allows the solar cell to operate at low (ambient) temperature, but then requires the production of a new kind of solar cell which does not absorb or dissipate solar radiation at infrared level. Calculation shows that with a concentration up to 1500, the total conversion efficiency could be around 35–40%. The solar cell in the second option is subject to concentrated sunlight; with the use of GaAs-based single-junction cell having room temperature efficiency at 24% and a concentrator at 50×, the total conversion efficiency is around 25–30%, and can be even higher if a higher concentration is used.

5. Miscellaneous and commercial developments in the last decade

5.1. Improved longwave absorption

Since long wavelength irradiance with photon energies below the bandgap energy is hardly absorbed at all, the solar absorptance of the solar cells is significantly lower than of a black absorber (with absorptance = 0.95). Santbergen et al. [137] suggested two methods to increase long wavelength absorption: (i) to use semi-transparent solar cells followed by a second absorber and (ii) to increase the amount of long wavelength irradiance that is absorbed in the back contact of the solar cell. Computer analysis showed that the first and second methods are able to achieve an overall absorption of 0.87 and 0.85, respectively.

5.2. High temperature applications

Water/lithium bromide chillers are currently one of the most promising and used technologies in the field of air-conditioning by absorption machines. Mottelman et al. studied the application of c-PVT system in a single effect absorption chiller with desorber inlet temperature set in the range of 65–120 °C and without thermal storage [138]. The PV module was based on triple junction (III–V) cells with a nominal conversion efficiency of 37%. Such cells are commercially available today. A typical optical efficiency of 0.85 for dish concentrator was used in the theoretical analysis. The results showed that the loss in cell efficiency owing to increased operation temperature was not significant. Under a reasonably wide range of economic conditions, the c-PVT cooling system can be comparable to (and sometimes even better than) a conventional cooling system. The findings were subject to further field measurements and reliability test.

Mittelman et al. [139] also proposed a c-PVT water desalination system, in which a c-PVT collector field is to couple to a large-scale multiple-effect-evaporation thermal desalination system. Small dish concentrator type was used in the numerical analysis. The vapor formed in each evaporator condenses in the next (lower temperature) effect and thus provides the heat source for further evaporation. Additional feed pre-heating is provided by vapor process bleeding from each effect. The top brine temperature is varied in the range of 60–80 °C. The simulation results indicate that this approach can be competitive relative to other solar-driven desalination systems, and even relative to the conventional reverse-osmosis desalination. The high concentration option with the use of advanced III–V solar cells appears to be advantageous, because of its higher ratio of electricity to heat generation.

5.3. Autonomous applications

Solar distillation of brackish water is another good option to obtain fresh water in view of its simple technology and low-energy need. The concept can be readily accepted by rural people. A proposed self-sustainable design of PVT-integrated-active solar still was tested in India [140,141]. Compared with a passive solar still, the daily distillate yield was found 3.5 times higher, and 43% of the power used to run the pump can be saved. Based on 0.05 m water depth, the range of economical payback period can be shortened from 1.1–6.2 years to 3.3–23.9 years (depending on the selling price of distilled water), and the energy payback time from 4.7 years to 2.9 years.

Crop drying has been another application area being investigated. This is the process of removing excess moisture from crop produced through evaporation, either by natural or forced convection mode. A PVT mixed mode dryer was designed and an analytical expression for the characteristic equation was derived by Tiwari et al. [142]. Experimental tests were executed for the forced mode under no load conditions. The detailed analysis of annual gains for different Indian cities shows that Jodhpur (at 26.3°N) is the best place for the installation of this type of PVT dryer.

5.4. Commercial applications

Although there are plenty reported literatures on the theoretical and experimental findings of PVT collector systems, those reporting actual full-scale testing and long-term monitoring of the PVT systems have been scarce [143]. The number of commercial systems in service remains small. The majority involves flat-plate collectors but with limited service life. The operating experiences are scattered. In the inventory of IEA SHC Task 35, over 50 PVT projects have been identified in the past two decades. Less than 20 of these were belong to the PVT/w category. While most of these were in Europe such as UK and Netherlands, five projects were realized in Thailand recently, in which large-scale glazed a-Si PVT/w systems were installed at different hospital and government buildings [144]. What in need presently is the documentation of the long-term monitoring of the systems performance, including the operating experiences and problems encountered in real projects.

At present, a number of manufacturers participate in the development, production and marketing of a range of PVT products. To quote some examples, the Israeli manufacturer Millenium Electric has introduced an unglazed PVT collector with a combined energy output via air, water and electricity. The Dutch manufacturer PVTWINS has produced an unglazed PVT/w collector at different sizes and materials. The Menova Energy of Ottawa in Canada has developed a novel c-PVT system called Power-Spar.

The performance of PVT commercial products can be tested either outdoor or indoor. The outdoor test needs to be executed in steady conditions of fine weather, which should be around noon hours and preferably with clear sky and no wind. This can be infrequent, say for Northern Europe, it may take six months to acquire the efficiency curve [145]. Indoor test can be quicker and provides repeatable results. But so far the indoor facility requirements for standardized testing procedure of PVT collectors do not exist. To make available an internationally accepted testing method is one important step for promoting the PVT products in the commercial market and making them competitive with the individual solar thermal and PV panels. An important issue is that the sun simulator should be able to give an accurate representation of the terrestrial spectrum (AM1.5).

5.5. The market potential

Benefited by the government policy and public awareness, the current market for both solar thermal and photovoltaic are growing rapidly. PVT has the potential to experience a similar growth and in future, the market share might be even larger than that for solar thermal collectors.

According to the Roadmap [1] published through the PVT Forum of the European PV Catapult project, the largest market potential of PVT lies in the domestic sector (about 90% of the current market). In short term the customers can be from the single-family houses for the domestic hot water systems; this sooner or later will be extended to the multifamily buildings where the hot water demand will be more stable. The investment can be incorporated in the mortgage of the buildings. For the intermediate future, the possible niche markets are then collective tap water systems, direct space heating, swimming pool heating, autonomous applications, and heat pump integration. Applications in the commercial, agricultural and industrial fields will then take shape. The c-PVT collectors may have the market when tracking become economically viable. Solutions will come out to make PVT an integral part of the building design. In longer term, applying PVT in solar cooling may turn out to be promising.

As a matter of facts, PVT products suit a wide range of applications and market sectors. They can be attractive to those who are fond of advanced technology. Customers may include not only homeowners (for small-scale family applications), but also for larger scale, the property developers, housing authorities, energy companies, owners of recreation and sports centers, public swimming pools, camping sites, hospitals and hotels. Differences are expected across the climate, terrestrial and cultural boundaries. In a market survey carried out by IEA SHC Task 35, it has been found that the markets in different countries have their own characteristics, and that in European countries the installers and the architects have different perspective on combined production of heat and electricity [143]. The high energy output per unit collector area is definitely an advantage coming to low-energy building design in which the sun-facing areas should be fully made use of.

At this point in time, the main bottlenecks for the commercialization of PVT products are the lack of economic viability, public awareness, product standardization, warranties and performance certification, installation training and experiences. It is important for the reliability of the technology to be thoroughly assessed. This then requires further research and development works on new products, recognized testing procedures and standards, as well as well-monitored demonstration projects.

6. Summary

The performance of various PVT collector types had been studied theoretically, numerically and experimentally for more than three decades. A range of PVT systems and products has been put forward and evaluated by researchers and professionals on various occasions. Their endeavor has been reviewed in this article. Generally speaking, in the early work, the research efforts were on the fundamental theories, the consolidation of the conceptual ideas and the feasibility study on basic PVT collector design configurations. In the 1990s, the PVT studies were more related to the collector design improvement and cost-performance evaluation. There were more rigorous analyses of the energy and mass transfer phenomena on conventional collectors with experimental validation. The ideas of building-integrated design began to emerge and the demonstration projects made available for documentation.

In the last decade however, the focus has been generally shifting towards the development of complimentary products, innovative systems, testing procedures, and design optimization. Also explored was the marketing potential of multi-functional devices via user feedback, life cycle cost and/or embodied energy evaluations. The numerical analyses become more comprehensive with the use of powerful analytical tools. There have been increased uses of explicit dynamic modeling approach, as well as CFD techniques. The evaluation has been extended to geographical comparison of year round performance based on typical weather data on one hand, and the second-law thermodynamic assessment on the other. There have been attentions on monitoring product robustness, system reliability, and environmental implications.

After all, there exist no perfect rules in the correct use of PVT collector and/or system; all depend on the geographical location and actual application case by case. At locations with low levels of solar radiation and ambient temperatures, space heating is almost required all the year and PVT/a can be useful and cost effective. At locations with high solar input as well as ambient temperature, PVT/w can be useful for providing year round water pre-heating services, and on top with intermittent air heat extraction to provide space heating in winter and natural ventilation in summer. There are good opportunities for extension to solar cooling and heat pump integrations. Concentrator type can be used for elevating fluid service temperature from medium to high level.

At the present level of activities globally, the numbers of commercially available collectors and systems are still very limited. Major barriers like product reliability and costs remain to breakthrough. Collaborations have been underway among institutions or countries, helping to identify the suitable product materials, manufacturing techniques, analytical tools, testing and training requirements, potential customers, market strength, and so on. Since a PVT product has a much shorter economic payback period than the PV counterpart, PVT as a renewable energy technology (rather than PV) is expected to first become competitive with the conventional power generation. At this stage, the research and development work should be carried on, including thermal absorber design and fabrication, material and coating selection, energy conversion and effectiveness, performance testing, system optimization, control and reliability. Product quality and ease of delivery and installation are important, so are the aesthetics, green image and business concerns. PVT is expected to have significant market expansion potential in the near future.

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