A review of solar photovoltaic systems cooling technologies

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Abstract. The global need for energy increases with mankind evolution and proliferation. The sharp decrease in fossil fuel sources and pollution increase, triggered research for renewable energy sources. The solar energy, available and sustainable, may be easily converted into both electricity and thermal energy. The photovoltaic paradox (need solar energy to function, but the electricity output decreases if temperature rises under the Sun’s heat) was controlled by using various cooling techniques for panels. A large number of papers published to date in literature on solar energy conversion applications are reviewed and classified. The emphasis is placed on methods employed to increase the solar-to-electricity energy conversion efficiency, i.e. thermal management of photovoltaic panels. The use of thermoelectric modules (in PV-T-TE devices, photovoltaic-thermal-thermoelectric) is highlighted.

1. Introduction
Even though only a small fraction of the energy dissipated by the Sun reaches the surface of the Earth, it still represents the most important source of energy available, when compared to fossil fuel reserves. If the humankind would be able to capture the entire incident solar heat flux, the annual global energy demand would represent only 0.01%, figure 1.

Figure 1. Available annual insolation vs. fossil fuel reserves and annual energy consumption.
This huge energy resource is not used to its proper potential. Following the first major oil crisis in the '70s, it became clear that search for energy sources, alternative to classic fossil fuel energy, has to be intensified. These energy sources, termed “renewable”, include solar, wind, geothermal, bio- and hydro-power, all being connected in one way or another to solar energy. Nevertheless, even if the interest on renewable energy sources increased in the recent decades, the share of solar energy in global energy (and electricity) production is still below 2%, figure 2.

The French physicist Alexandre Edmond Becquerel observed the photovoltaic (PV) effect in 1839, but the PV technologies started to be developed a century later, after 1940. In early '50s, the first high purity silicon crystals were produced and, in 1954, specialists at Bell Laboratories unveiled the first silicon PV cell with a conversion efficiency of 6%. Both the materials and technologies were too expensive at the time for mass production. During the following decades, researchers strived to improve fabrication technologies and to find materials with better properties and/or with lower prices.

The most recent data, show PV cells conversion efficiencies of up to 46%, but in special laboratory conditions (with concentrators, small surface, ultra-clean environment), figure 3, [2].

Figure 2. Renewable energy share of global electricity production, end-2017 [1].

Figure 3. The conversion efficiency of PV cells, in April 2018, [2].
The evolution of PV technologies.

By comparison, the industrially manufactured and commercially available solar panels exhibit solar energy conversion efficiencies of 11% - 20%, depending on material and production technologies, [3]. Regardless of material and manufacturing technology, figure 4, the solar PV cell may be modeled using an equivalent electrical circuit, figure 5, and mathematically described by the formula (1), [4]:

\[
I = I_L - I_o \left[ \exp \left( \frac{V + IR_o}{nkT/q} \right) - 1 \right] - \frac{V + IR}{Rs_h}
\]

where the output current, \( I \), is inversely proportional with absolute temperature, \( T \), ideality factor, \( n \), and Boltzmann constant, \( k \), and directly proportional with elementary charge, \( q \). Therefore, analytical and experimental studies, [4-9], demonstrate the same behavior of the PV cell output: the open circuit voltage decreases with increasing cell temperature, figure 6.

Intensive research has been performed in the area of cooling PV panels, in order to optimize and control the operational temperature. The first natural choices were related to use of fluid coolant, air and later, liquids, mainly water or glycols. The cooling methods evolved to more complex solutions, including heat pipes, microscale heat exchangers, phase-change materials (PCM), nano-fluids, thermo-electric generators (TEG), or combinations with other renewable energy systems, [10-20] and figure 7.

The main benefits sought from combining the PV panels with solar thermal collectors and/or other cooling solutions are:
- decrease/optimize/control the operational temperature of the PV panel;
- improve the system overall conversion efficiency (increase electrical and adding thermal);
- minimize the space required and possibly the cost of the system.

Figure 4. Evolution of PV technologies.

Figure 5. Equivalent electrical circuit for a PV cell.
2. Previous reviews

The early publications to review the photovoltaic/thermal (PVT) technologies were emphasizing the benefits of joining both solar conversion systems, thermal collectors and PV panels.

The concept of PVT (or PV/Th, [21]) technology is presented, along with description of different designs, evaluation models and potential benefits, especially in the building architecture, [22]. More detailed reviews on basic PVT include analytical and numerical modeling, numerical simulations, experimental work, as well as parameters affecting system performance (covered, uncovered, mass flow rate, absorber plate parameters, design types), and qualitative evaluation of thermal/electrical output, [23]. Also, in [24], manufacturing aspects, thermal and electrical module efficiency (losses) and reliability are presented. Another comprehensive review [25] details technological developments in air- and liquid-cooled PV modules, improvements proposed (high temperature applications, long wave absorption, autonomous applications, commercial applications), and market potential, especially in building integration.

The years that followed, witnessed the publication of several reviews [26-32] on PVT collectors, presenting the design, classification, performance, influence factors, theoretical and experimental analyses, for air and water-cooling agents. New PVT cooling technologies are described and reviewed, [33], such as refrigerant/heat pipe based hybrid collectors that provide higher conversion efficiencies. Opportunities for further works in development and optimization of feasible, economic and efficient system types and configurations adapted to real climatic conditions are also analyzed.

![Figure 6. The (I-V) curve for various operational temperature, [4].](image)

![Figure 7. PV cooling technologies.](image)
Mathematical models are reviewed [34] for simple thermal collectors or PV panels, as well as for various hybrid collector combinations and geometries. Technological solutions for both air and liquid cooled PV are presented [35-37].

The impact of various parameters (packing factor, mass flow rate, efficiency), of PV cell materials and manufacturing technologies (single crystalline silicon, polycrystalline silicon, amorphous silicon, GaAs, InP, thin film, dye sensitized) or the collector geometries and fluid agents, on the electrical and thermal performance of PVT collectors as well as improvement strategies are reviewed in [38]. Both non-concentrating and concentrating collectors are analyzed [39], along with thermal energy storage solutions (criteria for design, materials, heat transfer enhancement technologies) and a review of solar power stations.

For water flat plate PVT collectors, a review [40] included classification, discussions on thermal absorber (sheet-and-tube, roll bond, box channel, channels arrangement, pressure drop and connection system), performance comparison and thermal insulation. An extensive analysis [41] was performed to include the concentrating system, with the advantages and disadvantages of various combinations and technologies. Another overview of PVT technologies for both air and water-cooling fluids observed the improvements on overall solar conversion efficiency [42].

The large number of recent publications on PVT and combined cooling solutions triggered several extensive reviews. A reference guide, [43], included construction details of flat plate collectors (FPC), PV panels and PVT systems. Classifications and exhaustive presentations of cooling methods and flow geometries, along with tabulated data for experimental results, numerical models and software were included. Also, the guide indicates applications, limitations, advantages and future research directions in the PVT area. The structural/geometrical topologies of PVT panels for both liquid and air-based cooling solutions are presented in [44], detailing more than 30 distinct hybrid configurations. It also identifies the major factors that affect the typical PVT systems performance and effectively enhance the heat removal mechanisms thus improving the electrical and thermal solar conversion efficiencies.

An exhaustive review [45] compiles information on various factors that influences the conversion efficiency of PV panes: climatic parameters (solar irradiance, relative humidity, wind speed, ambient temperature, accumulated dust), design conditions (flow cannel geometry, tracking system geometry, glazing coating and thickness, material characteristics, fins, inlets) and operating parameters (mass flow rate, thermal resistance, fluid temperatures, packing factor, losses). The responses of the thermal, electrical and overall efficiencies of PVT system to various parameters and conditions are reviewed.

A comprehensive compilation and review [46] classifies the cooling solutions into two major categories, passive and active, with compatible methods already adopted and future trends. Even if it is focused on concentrating PV cooling solutions, [47] presents details for basic technologies for regular PV panels, including some recent advances in usage of heat pipes, microchannel heat sinks, phase change materials, thermoelectric materials, and indicates future areas of research.

A new approach [48] discussed and summarized the PV cooling technologies with emphasis on the thermal side (air cooled, water cooled, water and air, PCM, heat pipes, nano-fluids) more than on the electrical side. Both efficiencies (thermal and electrical) of PVT systems were compared for different heat transfer fluids, designs, advantages, limitations, applications, and scope.

Two of the most recent reviews [50,51] comprehensively present the now-classic air- and liquid-cooling technologies for PV panels, along with heat pipes, PCM, or TEG solutions, with emphasis on the works published in the last decade. The novel area reviewed in both publications is related to beam splitting (or spectrum filter) technology, that separates the wavelengths useful for PV cells from those used by thermal conversion part of the PVT system.

3. PV cooling solutions review

This chapter presents in a concise tabular format the current technologies employed for PV cooling. The solutions are included in table 1 in the same order as in figure 7, starting with hybrid PVT cooling with air and water, and continuing with newer hybrid designs. The emphasis of this review work is placed on the solution that includes thermo-electric devices, and therefore is presented at the end.
Table 1. Assessment of different PV cooling solutions.

| Technology                                      | Highlights                                                                 | Advantages                                                                 | Disadvantages                                                                 |
|------------------------------------------------|---------------------------------------------------------------------------|---------------------------------------------------------------------------|------------------------------------------------------------------------------|
| Photovoltaic/Thermal hybrid solar system        | Forced air circulation more efficient than natural (for building integration BIPVT) | Simple technology                                                        | Lower efficiency than water cooling                                          |
| (PVT air cooling)                               | More effective in cold climatic conditions                                | Air readily available                                                     | Lower mass flow rates and PV temperature reduction                           |
|                                                | Many designs possible (glazing, geometry etc.)                            | Increased overall efficiency                                              | Blowers required for forced air circulation                                    |
| Photovoltaic/Thermal hybrid solar system        | Effectively increases electrical efficiency                               | Higher conversion efficiency to electric energy                           | High initial cost                                                             |
| (PVT water cooling)                             | More efficient on bottom side than on top side                            | Hot water used for domestic applications                                  | Lower system life                                                            |
|                                                | Temperature control by mass flow rate variation                           | Lower space requirement for separate systems                              | Possible freezing in cold climatic conditions                                 |
|                                                | Other liquids may be used                                                 |                                                                           | Electricity consumption for pumping power                                    |
|                                                | Large scale integration                                                  |                                                                           | Possible leakage, fouling                                                    |
| PV/Phase-Change Materials                       | Heat from PV panel is stored during PCM melting                          | Store large heat amounts at small temperature change                      | Low thermal conductivity of PCM in its solid state                           |
| (PV-PCM cooling)                                | Absorptive capabilities of material degrade over time                     | System may operate during off-sunshine hours                              | Some PCMs are toxic and have fire safety issue                               |
|                                                | Compatibility, reliability, maintenance-free and high cooling capacity    | Phase-change occurs at a constant temperature                            | Disposal problem after end of life cycle                                     |
| PV/Heat Pipes (HP-PV cooling)                   | More complex design                                                      | Very high heat fluxes                                                     | Segregation reduces active volume for heat storage                            |
|                                                | Improved thermal output                                                  | Passive heat exchange                                                     |                                                                              |
|                                                | Corrosion issues influence the choice of pipe material                    | Heat transfer across long distances                                       |                                                                              |
|                                                |                                                                           | Easy to integrate                                                         |                                                                              |
| PV/Microchannel heat sink                       | Effective heat exchange                                                  | Removes large amounts of heat in a smaller area                           | Pressure drop limitations                                                    |
| (PV-MCHS cooling)                               | Low contact thermal resistance between the substrate and heatsink         | Low fluid inventory required                                              | Corrosion problem                                                            |
|                                                | Maintains isothermal conditions on the cell                              | Low power requirement                                                     | Undesirable uneven temperature distributions along the streamline             |
|                                                |                                                                           | Low thermal resistance                                                    | Manufacturing price                                                          |
| PV/Nano-fluids (PVT-NFs)                       | Improved thermal output                                                  | Nano-fluids are available                                                | Incipient technology                                                         |
|                                                | Enhance heat transfer / heat removal                                      | Higher thermal efficiency                                                 | Influences not determined                                                    |
|                                                | Sedimentation of nanoparticles may be a problem                          |                                                                           | (interaction with base fluids and characteristics)                           |
|                                                |                                                                           |                                                                           | Nano-particles high cost                                                     |
| PV/water spraying (jet impingement)             | Increased efficiency                                                    | Increased solar energy conversion                                         | Surface area of PV panel is partially cooled                                 |
|                                                | Higher heat transfer characteristics                                      | Higher heat capacity and thermal conductivity (low thermal resistance)     | Higher cost (maintenance, pumping power)                                     |
|                                                | Water (and heat absorbed) is wasted                                      |                                                                           | Heat waste                                                                    |
| PV/water immersion cooling                      | Temperature reduced and efficiency increased                             | Highly efficient                                                          | Submersion depth                                                             |
|                                                | Leak-proof design required                                               | Environmentally friendly                                                  | influences efficiency                                                        |
|                                                |                                                                           | Heat transfer from both front and back surfaces                          | Higher cost                                                                  |
|                                                |                                                                           |                                                                           | Complex system design                                                        |
Table 1. (continued from previous page).

| Technology                                      | Highlights                                                                 | Advantages                                      | Disadvantages                                                   |
|------------------------------------------------|---------------------------------------------------------------------------|-------------------------------------------------|-----------------------------------------------------------------|
| Floating, tracking, concentrating and cooling  | Uses reflectors and trackers Water sprays partially cool the surface      | Operates highly efficient                        | Evaporation causes water waste                                 |
| (FTCC)                                         | May be hybridized with OCR, space heating etc.                             | Avoid energy dispersion problems                 | Sprinklers cannot cover whole PV module surface                  |
| PV/Spectrum filter (Beam Split PVT)            | Minimize PV temperature by beam splitting Uses thin-film coatings,        | Lowered operational temperature                  | Not fully developed technology                                  |
|                                                | liquids, mirrors to separate solar radiation wavelength                    | Suitable for hybridization with concentrating or  | High cost (glass filters)                                       |
|                                                |                                                                          | other systems                                    |                                                                  |
| PV/Transparent coating (photonic crystal)      | Temperature problem is eliminated Enhances conversion efficiency Heat is  | Economic solution No space requirement necessary | Heat is wasted (reflected into space)                            |
|                                                | wasted                                                                    | Reduced PV temperature                           |                                                                  |
| PV/Thermoelectric hybrid system (PV-TE cooling)| Waste heat used to increase electrical efficiency Heat sink decreases    | Clean source of energy Electrical conversion     | Low conversion efficiency Heat conduction loss through           |
|                                                | surface temperature Low conversion efficiency rate                        | efficiency improved                              | thermoelectric device                                            |
|                                                |                                                                          | No direct contact PV - coolant                   | Higher price for low energy conversion gain                     |
|                                                |                                                                          | Alleviates hot spotting                          |                                                                  |
|                                                |                                                                          | Increasing life span of PV modules               |                                                                  |

4. Review of relevant publications
The large amount of publications in the literature on the topic of PV cooling technologies prevents any extensive review that may attempt to include all papers on theoretical, numerical or experimental work performed in this area. Therefore, the authors selected what seemed to be the most relevant of older and recent publications for each of the cooling technologies highlighted in table 1.

The number of reviewed publications depends largely on the extent of technology use in practice and in research. The research interest of the authors in the area of PV cooling using thermo-electrical elements is reflected in a larger number of publications reviewed on this particular topic, table 2.

Table 2. Review of relevant publications on PV cooling solutions.

| Technology                 | Reference | Relevant information                                                                 |
|----------------------------|-----------|--------------------------------------------------------------------------------------|
| PVT air cooling            | [52], 2002| Hybrid PVT solar collector cooled to evaluate PVT efficiency Outdoor tests show      |
|                            |           | improved electrical efficiency                                                      |
| PVT air cooling            | [53], 2004| PVT collector with blower, air passing to back side of PV Increased electrical     |
|                            |           | efficiency and reduced surface temperature                                          |
| PVT air cooling            | [16], 2006| PV module integrated with air duct to evaluate overall efficiency Results show      |
|                            |           | compatibility with model and increased efficiency                                   |
| PVT air cooling            | [17], 2007| Systems with fins and thin metal sheet (TMS), and glazing improves PVT performance  |
|                            | [19], 2008| Efficiency increased at 50-60% thermal and 11-12% electrical                         |
Table 2. (continued from previous page).

| Technology               | Reference | Relevant information                                                                                                                                 |
|-------------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| PVT air cooling         | [54], 2009| PV modules with glass-to-tedlar and glass-to-glass are evaluated for performance comparison. Better performance in overall thermal efficiency for the glass-to-glass hybrid PVT air collector. |
| PVT air cooling         | [55], 2010| Developed a computer simulation to calculate electrical and thermal parameters of a PVT air collector. Thermal, electrical and overall energy efficiencies are 17.18%, 10.01% and 45%, respectively. |
| PVT air cooling         | [56], 2012| A comparative analysis of different types of PVT air collectors. Unglazed, glazed and standard hybrid PVT air systems are analyzed in real climate conditions. |
| PVT air cooling         | [57], 2015| Most influencing parameters: solar radiation intensity, mass flow rate of air, optimum channel depth. Glazing improves thermal efficiency to 50-70%, but the electrical one remains at 10-12%. |
| PVT air cooling         | [58], 2016| PVT system is applied to air source heat pump (ASHP) in cold climatic conditions. TRNSYS transient simulation show outlet temperature at 76.6°C. |
| PVT air cooling         | [59], 2016| Model to determine PV module position effect on thermal and electrical performances. Maximum thermal and electrical performance for distance between PV module and cover of 3 cm and 5 cm, respectively. Analysis of variance demonstrates the superiority of hybrid PVT over standard PV system, comparing electrical efficiencies. |
| PVT air cooling         | [60], 2017| Extreme learning machine (ELM) applied to PVT air cooling. ELM model compared with genetic programming and artificial neural networks models, ELM being most accurate. |
| PVT water cooling       | [61], 1996| Hybrid PV/T system, water circulating through connecting pipes with fins attached to back side of PV module. Improved electrical performance. |
| PVT water cooling       | [62], 2003| Different designs of PVT systems have been discussed. 1-D steady state model is used for PVT analysis. |
| PVT water cooling       | [63], 2006| PVT models tested and electrical and thermal efficiencies evaluated. Increased electrical and thermal efficiency, and improved economic viability. |
| PVT water cooling       | [64], 2007| PV/T water heating system designed with natural circulation. Experiments performed outdoor with different water masses and initial water temperatures, validated the proposed model. The higher the covering factor and the glazing transmissivity, the better the overall performance. |
| PVT water cooling       | [65], 2007| Heat extraction system developed, cools PV panel either by air or water. Use of inserts, corrugated sheets and booster mirrors, that increases efficiency (30-70% thermal, 10-16% electric) and cost effectiveness. |
| PVT water cooling       | [18], 2008| PVT with partially covered FPC has better thermal (40-55%) and PV cell average efficiency (11-12%). |
Table 2. (continued from previous page).

| Technology                  | Reference   | Relevant information                                                                 |
|-----------------------------|-------------|---------------------------------------------------------------------------------------|
| PVT water cooling           | [66], 2009  | Glazing is favorable to photothermic process, but not to PV process.                   |
|                             |             | Increase of PV cell efficiency depends on packing factor, water mass to collector area ratio, and wind velocity (unglazed panel) and on ambient temperature and on-site solar radiation (glazed panel) |
| PVT water cooling           | [67], 2011  | PV panel cooled by thin film of water                                                  |
|                             |             | Results show improved electrical efficiency                                          |
| PVT water cooling           | [68], 2012  | Exhaustive review of technological advancement in PVT solar systems                   |
|                             |             | Useful applications: solar heating, water desalination, solar greenhouse, solar still, PVT-heat pump/air-conditioning system, building integrated PVT (BIPVT) and solar power co-generation |
| PVT water cooling           | [69], 2013  | PVT water collectors analyzed for constant collection temperature, and constant flow rate conditions, respectively |
| PVT water cooling           | [70], 2013  | Performance of two designs and flow configurations compared on annual overall thermal energy and exergy gain for four different real climatic conditions |
| PVT water cooling           | [71], 2014  | Second Law analysis of a water-cooled PVT collector                                  |
|                             |             | Simulations and optimization of operation                                             |
|                             |             | Electricity production from PV cells is better at low temperatures, but usability of thermal energy gets higher at high temperatures |
| PVT water cooling           | [72], 2014  | Seawater-proof PVT solar collector developed and applied to reverse osmosis (RO) desalination plant |
|                             |             | Results show increased electrical efficiency with seawater cooling                   |
| PVT water cooling           | [73], 2015  | Investigated the effect of dust deposition and of ambient air dry bulb temperature on the performance of the PVT module efficiency |
|                             |             | Dust deposition significantly affects the output current                               |
| PVT water cooling           | [74], 2015  | Water glazed PV/T system, with roll-bond flat plate aluminum absorber                 |
|                             |             | Model developed to evaluate performance of PV/T collectors show enhancements in electrical efficiency |
| PVT water cooling           | [43], 2015  | FPC used to increase PV module efficiency                                             |
|                             |             | Investigation on different solar flat plate collector PVT, efficiencies, advantages and disadvantages |
| PVT water cooling           | [75], 2016  | Model to maximize the energy conversion by optimizing flow rate                       |
|                             |             | Extracted energy increased by 7.82%, thermal efficiency decreased between 5.54% and 7.34% using connecting pipes |
| PVT water cooling           | [76], 2016  | Hybrid PVT solar collector for net zero energy buildings is proposed                  |
|                             |             | Results indicate higher yield in solar electricity                                    |
|                             |             | The output covers hot water, air conditioning, lighting and household appliances requirements |
| PVT water cooling           | [77], 2017  | Parallel plate thermal collector without absorber plate is proposed as pancake setup  |
|                             |             | Conversion efficiency is about 10% electrical and 50-60% thermal                      |
| PVT water cooling           | [78], 2017  | Multiple-channel heat sink for concentrated PV cells                                  |
|                             |             | Cell temperature rises to 91.4°C and flow rate at 0.6 m/s optimized conversion efficiency to 31.8% and net power to 4064 W |
Table 2. (continued from previous page).

| Technology          | Reference | Relevant information                                                                                                                                 |
|---------------------|-----------|------------------------------------------------------------------------------------------------------------------------------------------------------|
| PV-PCM cooling      | [79], 2004| Model for a 2D finite volume heat transfer in building-integrated PV-PCM. Both numerical simulation and experimental results indicate efficiency increase |
| PV-PCM cooling      | [80], 2006| Internal fins for bulk PCM thermal conductivity compared with datum single flat aluminum plate - system temperature by 30°C                                |
| PV-PCM cooling      | [81], 2015| Overall PV efficiency increased to around 13% Graphite infused PCM has increased thermal conductivity from 0.25 to 16.6 W/(mK)                           |
| PV-PCM cooling      | [82], 2016| Experiments on ZnO/water nanofluid (0.2 wt%) and paraffin wax PCM/Nanofluid increased PVT thermal energy output by 48%                                |
| PV-PCM cooling      | [83], 2016| PCM based thermal regulation of PV panel results in higher electricity production by 7.3% for a period of one year Surface temperature of PV module was found to be 35.6°C lower |
| PV-PCM cooling      | [84], 2016| Dynamic model for comparative performance analysis of PV/PCM Upper PCM ensured improved performance with 10.7%                                       |
| PV-PCM cooling      | [85], 2017| Proposed system yields about a maximum of 72% more thermal gains PV module operating temperature reduced by 17°C during peak hours                      |
| PV-PCM cooling      | [86], 2017| Pure and combined PCM enhances electrical performance of PV panel Transient energy balance presented to analyze thermal behavior Combined PCM increased electrical efficiency by an average of 5.8% |
| PV-PCM cooling      | [87], 2017| Maximum temperature reduction for simple water based and PCM-PVT arrangements were found to be around 47 and 53% respectively Gain of 2% in electrical efficiency achieved with paraffin (RT 30) |
| HP-PVT              | [88], 2010| Micro-heat pipe array with evaporator and condenser for heat transfer Experiments show increased electrical efficiency by 2.6% (air cooling) and by 3% (water cooling) |
| HP-PVT              | [89], 2011| Model to predict thermal-electrical performance of heat pipe Overall thermal, electrical and exergy efficiencies increased to 63.65%, 8.45% and 10.26% |
| HP-PVT              | [90], 2015| Annual average collector efficiency of 34.37% and thermal collection of 2328.16 MJ/year Tank volume is inversely proportional to the PV surface temperature |
| HP-PVT              | [91], 2016| Thermal efficiency from 20% in winter to 40% in summer, electrical efficiency constant at 13% MHAP-PVT more economic and efficient than conventional systems |
| HP-PVT              | [92], 2016| Wickless heat pipe compared with wire-meshed heat pipe Thermal efficiency on wickless heat pipe and wire-meshed heat pipe was 52.8% and 51.5%, respectively |
| HP-PVT              | [93], 2017| Advanced thermal management technique: nano-coated heat pipe plate Solar cell can be cooled down to below 40°C                                             |
| HP-PVT              | [94], 2017| Experiments on hybrid PV/T systems to analyze hot water to consumer Results show systems able to supply 60% of consumer's hot water needs on cloudy days and 100% on sunny days |
Table 2. (continued from previous page).

| Technology       | Reference   | Relevant information                                                                                                                                 |
|------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| PV-MCHS cooling  | [95], 2010  | Proposed microchannel cooling of solar panel heat pipes condenser Possible use for HP-PVT systems, high heat flux transfer                                |
| PV-MCHS cooling  | [96], 2011  | Novel design of flow channel configurations in liquid cooled heat sinks Flow field configurations exhibit appreciable benefits for application of heat sinks in PV cooling |
| PV-MCHS cooling  | [97], 2013  | Novel flat plate solar collector with micro-channel heat pipe array Maximum instantaneous efficiency of 80%, with the slope −4.72                          |
| PV-MCHS cooling  | [98], 2017  | Comprehensive, 3-D thermo-fluid model for PV layers, integrated with microchannel heat sink. Parallel flow more effective than counter flow                  |
| PV-MCHS cooling  | [99], 2018  | Maintains the solar cell temperature < 301 K Increase the Nusselt number between 1.8 and 1.6 times, respectively                                       |
| PV-MCHS cooling  | [100], 2018 | Active microchannel cooling to meet the escalating heat flux demands of CPV. Proposed novel heat sink structures and emerging technologies                   |
| PVT-NFs          | [101], 2017 | Use of nanofluid (water + Cu) more efficient than water in all cases Yearly enhancements of 4.35% thermal and 1.49% electrical                           |
| PVT-NFs          | [102], 2018 | Compared to no cooling and water cooling, by using 4 wt% nanofluid (with turbulent flow) the power output of the panel increased by ~35% and ~10% and exergy efficiency was higher by 50% and 30% |
| PVT-NFs          | [103], 2018 | Highest increase (of about 14%) in average Nu noticed for the Cu-MgO hybrid at 2% volume concentration Water based hybrid nanofluids with 2% Ag-MgO offers highest values in collector efficiency |
| Jet impingement  | [104], 2016 | With jet cooling, power output and conversion efficiency was enhanced by 51.6% and 66.6% for June and by 49.6% and 82.6% for December                      |
| Jet impingement  | [105], 2017 | With 36 nozzles on the back side of the PV panel, electrical, thermal, and combined PVT efficiencies were 12.75%, 85%, and 97.75%                       |
| Jet impingement  | [106], 2018 | An array of jets or a multiple jet are used to attain a steady elevated thermal performance on whole plane Water jets exhibit secondary peaks at low flow parameters of Re 10000 and a low distance between impingement plates to nozzle |
| Immersion cooling| [107], 2009 | Improved performance of PV cells immersed in liquids under simulated sunlight. Non-polar silicon oil showed best performance                           |
| Immersion cooling| [108], 2010 | PV panel submerged in water at different submersion depths Lower electrical efficiency when submerged in deeper water                                  |
| Immersion cooling| [109], 2011 | PV cells in two-axis dish concentrator tracking system immersed in de-ionized water CPV module cooled to 45°C at a 920 W/m² irradiance, 17°C ambient temperature and 30°C water inlet temperature |
| Immersion cooling| [110], 2012 | Two structural models were developed and tested under actual weather conditions at axial and lateral direction in agreement with simulations                |
| Immersion cooling| [111], 2013 | PV panel analyzed when submerged in water at various depths Surface temperature reduced effectively, enhances electrical efficiency                       |
| Technology                      | Reference   | Relevant information                                                                                                                                 |
|--------------------------------|-------------|-----------------------------------------------------------------------------------------------------------------------------------------------------|
| Immersion cooling              | [112], 2014 | Direct liquid-immersion cooling (dimethyl silicon oil) of CPV cells Temperature controllable from 20°C to 31°C at 920 W/m² irradiance                  |
| FTCC                           | [113], 1976 | Parabolic concentrators parameters are evaluated: sensitivity to mirror errors, average reflections, acceptance angle, reflector area Useful for high temperature thermal applications |
| FTCC                           | [114], 1995 | Performance evaluation of PV module with V-trough concentrator Showed increased efficiency in hot desert climate                                         |
| FTCC                           | [115], 2015 | Proposed high efficiency luminescent solar concentrator for flexible wave-guiding PV with optimal optical and power conversion efficiency Cost-effective and negligible heat losses or absorbed |
| FTCC                           | [116], 2015 | Model for angular distribution light escaping from luminescent solar concentrator (LSC) edge Enhances efficiency of PV modules                           |
| FTCC                           | [117], 2015 | Collection efficiency of LSC-PV elements with various shapes is studied. Overall values are slightly above 20% for optimized dye concentration, with a maximum of 30% |
| FTCC                           | [118], 2016 | Dynamic heating in solar dish concentrators was studied May provide thermal energy for high temperature applications                                    |
| FTCC                           | [119], 2016 | Investigation on improving optical efficiency of LSC Double-layer LSC assured optically efficiencies 10–14% greater than the maximum value of single-dye layer |
| FTCC                           | [120], 2016 | Smart solar concentrators lightweight, low cost and generate electricity 3-D tracing technique to analyze optimal optical performance                     |
| PV/Spectrum filter             | [121], 2004 | Analysis of spectral beam splitting approach for solar applications Selective filters for incoming solar spectrum for PV and the unfiltered part used as heat separately |
| PV/Spectrum filter             | [122], 2010 | Different spectrally-selective photonic structures improve solar PV cell systems (Rugate filter, edge filter and 3D photonic crystals)          |
| PV/Spectrum filter             | [123], 2013 | May achieve high efficiency solar energy conversion Suggests improvements for optical efficiency (including geometrical limitations) and fabrication costs of spectrally splitting solar receivers |
| PV/Spectrum filter             | [124], 2017 | Analysis of PVT with easily available and less expensive liquids as spectrum filters (UV–VIS–NIR) Average efficiency of 12.53% electrical and 47% thermal |
| PV/photonic crystal cooling    | [125], 2013 | 3-D metallic photonic crystals modified to be within emission spectrum for useful solar PVT High quality tungsten photonic crystals maintain stability to 1400°C |
| PV/photonic crystal cooling    | [126], 2014 | Micro-photonic design approaching ideal performance scheme to cool PV panel via radiative cooling                                               |
| PV/photonic crystal cooling    | [127], 2016 | Thermo-photovoltaic (TPV) diodes are a trade-off to increase potential short-circuit current, but to maintain a reasonable open circuit voltage The best TPV system can give up to 23% efficiency around 1050°C, with potential for up to 50% conversion at reasonable temperatures |
Table 2. (continued from previous page).

| Technology | Reference | Relevant information |
|------------|-----------|----------------------|
| PV/TEC     | [128], 2011 | Thermoelectric (TE) converters attached to back part of PV panels. Energy yield increase of 24.9% for developed model and 10% for experimental work. |
| PV/TEC     | [129], 2011 | Water pipelines used for more effective heat transfer. Evaluation of theoretical conversion efficiency limit of system. PV/TE/GEHW system superior to PV/GEHW and conventional PV systems as electrical efficiency increases by 30%. |
| PV/TEC     | [130], 2012 | Model developed to determine temperature in different sections and calculate required power for TEC and excess heat generated. Simulation results validate efficiency improvements. |
| PV/TEC     | [131], 2013 | Model determines system temperatures and required power for cooling. Temperature maintained within limits at maximum output power. |
| PV/TEC     | [132], 2014 | Studies on thermoelectric power generation using large pn-junction. Efficiency increases from 6.8% to 10.92% at 83°C. |
| PV/TEC     | [133], 2014 | System increases overall efficiency by keeping temperature constant. Model developed to evaluate performance and reveals improved overall efficiency. |
| PV/TEC     | [134], 2015 | TEC module used to cool PV panel in hot climatic areas. Efficiency increased. |
| PV/TEC     | [135], 2016 | Heat rejected by heat sink may be useful in domestic applications. Experimental results in agreement with proposed geometric model. |
| PV/TEC     | [136], 2016 | Performance analysis of pin shaped thermoelectric generator. Increased output power of PV module corresponds to more efficient air flow duct design. |
| PV/TEC     | [137], 2016 | Formulate equations for cooling capacity, heat rejection rate and input power for PV generator. Future analyses required (technical, economic and environmental). |
| PV/TEC     | [138], 2016 | Model derived for geometry optimization of TEC modules. Simulation confirms the increase in electrical efficiency. |
| PV/TEC     | [139], 2016 | Hybrid PV/TE modules are integrated with heat sink specific design requirements. Simulation results in agreement with experimental measurements. |
| PV/TEC     | [140], 2016 | Dynamic model simulates thermal and electrical characteristics of TEM material. Simulation results for dynamic perturbation reveal maximum energy harvesting. |
| PV/TEC     | [141], 2017 | Combining the TEC module and water block heatsink improve output performance of the PV panel. Reducing PV panel temperature by 16.04%, the average output power has been increased from 8.59 W to 9.03 W. |
| PV/TEC     | [142], 2017 | A thermal model for semitransparent PVT-TEC collector is proposed. The two-proposed cases of semitransparent PVT-TEC collector exhibit electrical efficiency higher than regular semitransparent PV collector by 7.266% and 4.723%, respectively. |
| Technology | Reference | Relevant information |
|------------|-----------|---------------------|
| PV/TEC     | [143], 2017 | Fifteen TEC air duct modules assisted by a 300 Wp PV system to cool a 9.45 m\(^3\) test room investigated through experiments and simulations. Optimum temperature difference of 6.8°C, cooling capacity 517.24 W and COP 1.15. Combined system saves 1806.75 kWh/year. |
| PV/TEC     | [144], 2017 | Temperature based maximum power point tracking (MPPT) scheme presented to find optimal temperature of PV system. Simulated results demonstrate performance improvement of PV system with TEC. |
| PV/TEC     | [145], 2017 | Optimal total photovoltaic device size has been found to be around 127 μm and 1.25 μm for the mono- and poly-crystalline silicon, respectively, leading to efficiencies up to 20%, depending on photovoltaic recombination characteristics. With the cooling device, the overall efficiency was increased by up to an additional 10% (an increase of almost 50%), leading to overall efficiencies around 25%. |
| PV/TEC     | [146], 2017 | Performs a detailed thermal resistance analysis of PV-TE hybrid system and specifies criteria for selecting coupling devices and optimal design. c-Si PV and p-Si PV cells are proved to be inapplicable for the PV-TE hybrid system and practical PV-TE hybrid design process is provided. |
| PV/TEC     | [147], 2018 | An opaque photovoltaic integrated thermoelectric cooler (PV-TEC) collector has been proposed, wherein thermoelectric (TEC) module is integrated at the base of opaque photovoltaic (PV) module for the enhancement of an overall electrical efficiency. |
| PV/TEG     | [148], 2009 | Thermoelectric generator used for low-temperature waste heat recovery. The TE modules stacked in a parallel-plate heat exchanger. |
| PV/TEG     | [149], 2010 | Proposes a low-temperature waste heat thermoelectric generator setup. To enhance performance: increase waste heat temperature, TE modules series setup, expand heat sink surface area and enhance cold-side heat transfer capacity in a proper range. |
| PV/TEG     | [150], 2011 | Describes a solar heat pipe thermoelectric generator (SHP-TEG) unit. Basic parameters that influence maximum power output and conversion efficiency: solar irradiation, cooling water temperature, TE length and cross-section area, and number of TEs. |
| PV/TEG     | [151], 2011 | A system of 24 thermoelectric generators (TEG) recover and convert heat to electrical energy, at low temperature. Enhances the TEG efficiency. |
| PV/TEG     | [152], 2012 | Developed an analytic model to incorporate thermoelectric modules in glass evacuated-tube heat-pipe solar collectors and validated against the experimental data. Used to optimize design and operating parameters of prototype for combined water heating and extra electricity generation. |
| PV/TEG     | [153], 2013 | Solar-driven hybrid generation system (HGS) that integrates a silicon thin-film solar cell (STC), thermoelectric generators (TEGs) and a heat collector. Twice the generated power of a single (STC). |
| PV/TEG     | [154], 2013 | The optimal required number of TEG modules needed in order to achieve the highest overall output power by the system for fixed weather conditions is evaluated and discussed. |
| Technology | Reference | Relevant information |
|------------|-----------|----------------------|
| PV/TEG | [155], 2013 | A micro plate-fin heat exchanger applied to a TEG is optimized to maximize output power and cost performance of generic TEG systems. Channel width, channel height, fin thickness of heat exchanger, and fill factor of TEG are optimized for a wide range of pumping power. |
| PV/TEG | [156], 2013 | Characterization and optimization of a mTEG integrated with a two layer mHTS. A net output power of 126.3 mW/cm² was achieved with a $ZT$ of 0.1 at $\Delta T$ of 95 K. |
| PV/TEG | [157], 2013 | Low-cost solar thermoelectric co-generator (STECG) based on ETCs incorporating TEMs, to supply both electricity and heat simultaneously. STECG can generate 0.19 kWh of electrical energy and about 300 l of hot water at 55°C per day, when the figure of merit of thermoelectric module, $ZT_m$, is 0.59 and solar insolation is less than 1000 W/m². |
| PV/TEG | [158], 2014 | Proposed 3D electro-conjugate heat transfer model for an embedded microfluidic/TEG system (μF/TEG) system. Identifies heat transfer, fluid flow and electrical parameters to optimize the system to generate enough electricity to cool itself. Maintains the temperature of the electronic device below 80°C. |
| PV/TEG | [159], 2016 | Performance of a tandem PV–TEG hybrid, employing poly-Si as well as dye-sensitized solar cells, has been examined experimentally. Utilization of TEGs with shorter thermo-elements results in enhanced power output levels, under actual operation conditions. |
| PV/TEG | [160], 2016 | A thermally coupled model of PV/TEG panel is established to precisely predict system performance under different weather conditions. Critical parameters: radiative heat loss from top surface and wind speed. |
| PV/TEG | [161], 2016 | Presents thermal concentrated PV-TE hybrid power generation system with high performance, achieving a high efficiency of 23%. |
| PV/TEG | [162], 2017 | Efficiency constrains of different PVT configurations and performance of TEG integrated PV modules, and different natural (wind velocity, ambient temperature, solar irradiation) and design (glazing, coolant and its flow type, flow rates, thermal resistance) factors and their impact on performance of different hybrid configurations (PV/T, solar thermal-TEG, and PV-TEG). |
| PV/TEG | [163], 2017 | Underlying concepts of PV and TE and research accomplishments are reviewed. Various approaches used to optimize hybrid PV/TE systems. Future prospects and suggestions of potential approaches for further development of these generators are also discussed. |
| PV/TEG | [164], 2017 | Investigated experimentally power and efficiency of a hybrid PV/TEG system, for five different cooling methods for TEM’s cold side: natural cooling, forced cooling, water cooling, SiO₂/water nano-fluid cooling and Fe₃O₄/water nano-fluid cooling. TEG contributes extra electrical energy of 648 J even in absence of sun. |
| PV/TEG | [165], 2017 | A novel hybrid system with a PV cell and four TE generators. A theoretical model is developed and experimental setup is designed to test the new PV - TE hybrid system and its performance. Experiments were performed for a hybrid PV-PCM-TE system, but the results demonstrate insignificant improvements. |
5. Conclusions

The exhaustive review on PV panel cooling presented attempts to classify known cooling technologies published to date in literature. Beside classic solutions of PVT with air cooling and water cooling, the last decades witnessed theoretical analyses, numerical modeling and simulations, and experimental work on novel cooling solutions using phase-change materials (PCM), heat pipes (HP), microchannel heat sinks (MCHS), nano-fluids (NFs), floating, tracking, concentrating and cooling (FTCC), fluid immersion, jet impingement, spectrum filtering or transparent coating. Given research interest of the authors in the area of thermo-electric cooling, the emphasis or the review was placed on thermoelectric cooling (TEC) and thermoelectric power generation (TEG).

The relevant information covered various aspects and characteristics presented in analyzed papers, not only thermal, electrical or economic (conversion efficiency, power enhancement, space reduction, financial benefits related to cost, installation, operation, management or warranty), but also uniformity and architectural aesthetics, functionality, liquid tightness, roof protection or life cycle extent.

Some general conclusions are briefly mentioned:
- Different parts of solar spectrum are used by PV (infrared wavelengths) and thermal collectors and use of spectrum filtering (beam splitting) technology would control PV panel temperature.
- PV panel power output, and consequently the conversion efficiency, decreases with increasing operational temperature and, therefore, cooling technologies may be employed.
- Hybrid PVT systems may decrease, optimize and control the PV panel temperature, improve the overall energy conversion efficiency, as well as minimize the space required.
- PVT system may increase the surface shading during summer, reducing the thermal load.
- Architectural aesthetics may improve, having only one type of front panel (usually PV) exposed on the outside building facade.
- PVT air cooling is the simplest solution and is very effective for space heating applications in the cold regions and for building integration applications (BIPVT).
- PVT water cooling with channel(s) below PV module is most efficient, but freezing during cold seasons may limit their applications.
- Forced circulation of liquids is more efficient that of air, but the required pumping power is also higher for liquids than for air.
- Natural circulation is more economical, but less efficient, for both air and water.
- Air is readily available everywhere, while water usage may be restricted.
- Performance of PV or PVT may be improved by hybridization with PCM, HP, MCHS, nF, TE or complementary technologies (spectrum filtering, surface coating, jet impingement etc.)
- PCM increase the electrical efficiency, maintain constant lower temperature and store energy for night time applications, however, material properties may degrade over time.
- HP and MCHS have a beneficial effect on hybrid PV system performance, but manufacturing cost and localized cooling may reduce their use.
- NFs clearly improve thermal output of the system, but technology is still under development and influences of material characteristics are not yet completely determined.
- Other aforementioned technologies may improve overall system efficiency, but may also incur higher costs, technical difficulties and require more research for proper development.
- Liquid cooling, liquid immersion, jet impingement and FCCC that use non-encapsulated liquid cooling solutions may incur corrosion and leak-proofing problems.
- Surface coating improves conversion efficiency on the electrical side, but useful heat is rejected into surroundings as waste heat.
- TE modules are capable to recover and convert low-temperature energy from the waste heat at the back side of PV panel or PVT collector, producing extra electricity at a minimum system cost, thus improving electrical conversion efficiency and controlling system temperature.

This review demonstrates that studies on TE-based solar systems are limited and significant only for the current decade. The development of technology advances at a high pace and new TE materials or structures with high figure of merit will soon represent the next generation of PVT-TE systems.
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24