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Hybrid photovoltaic-thermal systems in buildings – a review

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Abstract

This paper presents a review of projects where hybrid photovoltaic-thermal (PV/T) systems are used in buildings. PV/T systems convert solar radiation to electricity and heat simultaneously, in one module. The output of both electricity and heat suggests that the technology can be suited for use in buildings, especially when the available area for installation is limited. The market and research activities related to PV/T technology has increased in recent years. This article adds to existing reviews on PV/T technology by focusing on the building perspective. Different strategies for the use of PV/T in buildings are discussed, and examples of building projects are presented. An attempt is also made to assess to suitability of different PV/T technologies for use in buildings. Finally, the regional variations in market and applications are discussed.

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1. Introduction

Hybrid photovoltaic-thermal (PV/T) modules generate heat and electricity simultaneously in one module. The basic idea of the concept is to utilize more of the solar radiation by also harvesting the waste heat that is generated in photovoltaic (PV) modules. Since PV cells generally become less efficient with increasing cell temperature, the heat removal has a double benefit: the waste heat is utilized and the modules are cooled.

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The technology is not new; the first studies were published in the mid-1970s, and several different concepts and ideas have been studied during the past decades. A number of reviews have been published on the topic of PV/T technology in the last couple of years, for example by Zhang et al.[1], Tyagi et al. [2] and Chow et al. [3]. The focus of these reviews spans from laboratory work on new concepts to examples of applications. There are also a number of publications describing pilot installations of PV/T systems for different applications in many parts of the world, including buildings. This paper adds to the existing literature by focusing on the use of PV/T in buildings. Although there are a large number of laboratory and experimental installations of PV/T systems worldwide, the focus of this paper is largely on commercial systems. Different technologies and strategies that are used in buildings are discussed, and examples of building projects are presented. An attempt has also been made to assess the suitability of the different technologies for use in buildings by the use of specific indicators.

On a global scale, the building sector accounts for a third of the total energy demand. Increasing the use of renewable energy sources in buildings is therefore of great importance in the effort to reduce global greenhouse gas emissions. Since buildings require electricity as well as energy for heating and cooling, PV/T systems are a potentially attractive solution for buildings. Other claimed benefits of PV/T systems are that they require less space than separate solar thermal and PV systems, and can provide a more uniform architectural appearance.

2. Method

A number of different sources are used to collect the information presented in this paper. The paper is based on a review of relevant scientific publications and projects, as well as communication with PV/T system manufacturers and installers.

The list of projects and producers that was gathered in IEA SHC Task 35 – PV/Thermal solar systems have been used as a starting point [4]. This international project, which was active during the years 2005-2010, had partners from Canada, Denmark, Sweden, Italy and the Netherlands. Manufacturers, universities, and research institutes from Germany, Greece, Hong Kong, Italy, South Korea, Thailand, and Spain several other nations are also reported to have participated.

Other sources of information are publications in peer-reviewed journals and conference proceedings, as well as company information, case studies and personal communication. The review presented here is not intended to be a complete list of PV/T projects, but rather to provide an overview of the market development and some examples of the different cases.

A thorough evaluation of collector performance is beyond the scope of this publication, but the performance of PV/T technologies have been assessed on more general terms according to their suitability for use in buildings. The assessment was made using four indicators, described below. The evaluation is based on findings from the literature review, and information from producers and installers.

- <u>Building integration potential</u>. This indicator describes an estimation of how well the technology can be integrated into buildings. The focus is on the functional integration and not the aesthetic integration. Indicator values are *high* (the technology is well suited for building integration), *medium* (integration is possible, but the integration options are limited), *low* (not suitable for integration).
- <u>Electricity output.</u> This indicator describes if the electricity output *increased*, *similar* or *decreased* compared to a normal PV module without utilization of thermal energy.
- <u>Thermal output.</u> This indicator describes if the thermal output is most promising for *direct* use, such as heating of domestic hot water, or if it needs to be used *indirectly*, such as input to a heat pump.
- <u>Available products.</u> The number of available products. Indicator values are *low* (below 10 products), *medium* (10-40 products) and, *high* (above 40 products). Note that these indictor values cannot be directly compared to the number of available products for pure solar collectors or PV modules, where the market is much larger.

3. Results

3.1. PV/T collector technologies

There are several types of PV/T collectors, and the concepts are so different that is makes little sense to discuss 'PV/T systems' without further specification. Other reviews have also found that a more precise language needed to be defined in order to characterize the different systems [5]. In general, a distinction can be made between PV/T collectors with liquid heat transfer medium (PV/T-liquid), PV/T collectors with air as the heat transfer medium (PV/T-air) and concentrating PV/T collectors. In addition, the collectors can be made using PV technologies such as crystalline of thin film PV, and different solar thermal technologies such as flat plate collectors, evacuated tube collectors or heat pipes.

For flat plate PV/T modules (with either liquid or air as heat transfer medium), a distinction is made between covered and uncovered collectors (sometimes called glazed and unglazed). The nomenclature is in this case somewhat confusing, since both types are actually covered by a protective glass sheet like the one used for PV modules. The covered or glazed PV/T collectors have an additional transparent cover at a distance from the absorber surface for thermal insulation.

The basic idea of PV/T collectors is to utilize the waste heat from solar cells, but there is also a dilemma: the solar cell output is highest when the modules are cool, while the temperature should be high to maximize the thermal output. A high temperature may also damage the materials in the PV module, leading to e.g. delamination.

The thermal output of flat plate PV/T-liquid collectors is lower than that of pure solar thermal collectors, especially for the unglazed PV/T collectors where the heat loss to the surroundings is high. The design and integration of PV/T into the rest of the building energy system is therefore of high importance in order to reach good efficiencies. So far, covered PV/T collectors are relatively rare in the market [5].

In PV/T-air systems, air is used as the heat transfer medium. The heated air can be used in directly in the ventilation system, or it can be connected to a heat pump. In a ventilated PV system, such as a façade, both the electricity and the waste heat can be utilized, but specific PV/T components are not always needed. PV/T-air systems can also be ducted, so that the heated air can be transported from the modules to the ventilation system.

A few examples of evacuated tube PV/T collectors were also found. In addition, a small number of "add-on collectors" are also available on the market. These are can be added to the backside of a normal PV-module to turn it into a PV/T module. There are also a few other concepts under development, such as PV/T windows, PV/T roof tiles and PV/T ventilation units. The PV/T solar assisted heat pump (SAHP) can also be considered a concept of its own.

3.2. PV/T in buildings

Based on the findings in the literature review, four general types of installations can be identified: ventilated PV installations and air-based PV/T, small scale PV/T-liquid systems, large-scale PV/T-liquid systems with ground source heat pumps, and industrial and non-residential buildings with concentrating PV/T installations. In addition, a division can be made between projects with building integrated PV/T systems and projects where PV/T collectors are added onto building roofs. The ventilated PV/T projects are generally building integrated, at least to a certain degree. Ducted PV/T-air systems are both found integrated and added onto roofs. PV/T-liquid installations were found in both categories, but the concentrating PV/T installations are not suitable for building integration.

3.2.1. PV/T-air and ventilated PV systems

In their review of recent PV/T developments, Chow et al. [3] reports that, at least in published research, building integration of air-based PV/T systems are more popular than that of water-based systems. The overview of projects that were published by Task 35 in 2007 lists around 20 projects where PV/T products were developed as a part of the energy system [4]. Air-based PV/T systems were the most common type in these projects, and only two of the PV/T systems (one of which was a concentrating PV/T) used a liquid heat transfer medium.

One reason for the relative abundance of air-based projects may be that it is a quite simple step up from installing a PV system. An air gap is usually provided behind PV installations to ensure proper ventilation and cooling of the modules. Making active use of this heated air in such a ventilated PV system turns it into a PV/T system. One early example of this type is the Mataró Library in Spain, which has a 20 kWp ventilated PV façade with solar air collectors for preheating of the ventilation air [6].

The Canadian company Conserval Engineering specializes in transpired solar collectors, a type of solar air collector. The company has also developed a PV/T air system (SolarWall PVT), and has made several large scale installations around the world with both façade integrated systems and roof mounted systems with air ducts. The PV/T concept was developed at Concordia University, Montreal, and demonstration system (Fig. 1, left) was installed at the university in 2007 [7]. The gross area is close to 300 m^2 and has is rated at 24.5 kW electric and 75 kW thermal power. The installation provides heating to the ventilation system, and the system performance is monitored by the university.

An example of the ducted type of installation is the system at the Beijing Olympic village [8]. The 50 m^2 system, shown in Fig. 1 (right), is rated at 10 kW electric and 20 kW of thermal power, and was built to showcase renewable energy during the Beijing Olympics. The heat from the PV modules is ducted to the ventilation system of the building. The panels on the upper edge of the roof in Fig. 1 are building integrated transpired solar thermal collectors (without PV) from the same company.

Fig. 1. The SolarWall PV/T facade at Concordia University, Montreal (left), and the SolarWall PV/T installation on the Olympic village in Beijing (right). SolarWall® PV/T system, photos courtesy of Conserval Engineering.

3.2.2. Small and medium scale PV/T-liquid systems

While having the advantage of being simpler, air based systems are generally found to be less efficient than liquid based ones, and recent projects incorporate liquid-based PV/T systems to a greater extent. Since the Task 35 overview from 2007, there has been a large increase in the number of PV/T projects. There also appears to have been a shift in the type of installations, from mostly ventilated or PV/T-air systems to now also including a high share of projects with PV/T-liquid collectors. However, the markets still appear to be quite country-specific and are sometimes dominated by one manufacturer or installer.

The use of PV/T-liquid collectors makes it possible to integrate the PV/T system into hydronic heating systems in buildings, which can be adapted to low temperature heat sources. The collectors can be connected to a storage tank and combined with other heat sources, such as different typed of heat pumps or biomass boilers. The systems can be used for space heating, domestic hot water (DHW) preparation or both. Examples of these types of systems are found in several countries.

In the U.K., the number of PV/T installations has increased rapidly in the past decade. The company Newform Energy claims to have hundreds of installations across the country, from small systems up to complex multi-source energy installations [9]. Based on the available case studies, most of the systems are grid-connected in the range 2-10 kWp and a majority is installed on residential buildings. Both covered and uncovered PV/T collectors are used, sometimes also together in the same system.

In France, the PV/T startup DualSun has around 30 monitored installations throughout the country. Most are in the range of 6 to 12 modules (1.5-2 kWp), but there are also larger installations. The smaller residential systems typically include both flat plate PV/T collectors and regular PV modules. A system of 6 modules and a 300 l storage tank, shown in Fig. 2 (left), is reported to cover around 65% of the hot water demands for a single family building in Marseille in southern France [10].

Several of the small and medium scale installations that were found use heat pumps for auxiliary heating as a part of the energy supply system. Fang et al. [11], also reports that PV/T hot water systems and PV/T heat pumps are the most commonly studied systems in China. On type of system that is studied is the PV/T solar assisted heat pump (SAHP), where the PV/T module is integrated in the heat pump and used directly as evaporator. According to REN21 [12], there are 130 hybrid solar thermal-heat pump systems available from 80 producers, although it is not clear how many (if any) of these incorporate PV/T collectors.

Fig. 2. A roof integrated PV/T system in Marseille, southern France (left, photo courtesy of DualSun), and the Absolicon PV/T installation to the local hospital in Härnösand (right, photo courtesy of Absolicon).

3.2.3. Large scale PV/T-liquid systems with ground source heat pumps

Ground source heat pumps and borehole thermal storage is also used in combination with PV/T systems. In such systems the low temperature thermal output can be used either directly in the heating circuit or, when heating is not needed, to regenerate the ground. Three examples of such systems were installed in the Gothenburg region of Sweden, where the heating from PV/T collectors is used to improve the performance of under-sized bore holes [13]. The largest of the installation is Jättens Gömme, where 400 m^2 of unglazed PV/T collectors from German producer Wiosun, 272 kW collected heat pump power, and 28 bore holes provide heating and hot water to 90 apartments.

The housing complex Bern Oberfeld in Switzerland is still under construction, but it will, when it is finished, include around 1000 m^2 hybrid PV/T collectors which are expected to generate 190 MWh of electricity per year. The thermal energy will be pumped into boreholes to thermally regenerate the ground, from which energy is extracted by a heat pump system. The project is designed according to the requirements of the Swiss MINERGIE-P-ECO code for energy efficient buildings .

3.2.4. Concentrating PV/T

Concentrating PV/T collectors of parabolic trough type provide water of a higher temperature than most flat plate collectors, making them interesting for industrial and other non-residential projects. While these types of collectors are not suitable for building integration, they have been used in building added rooftop installations in several larger projects, such as hospitals and schools. The technology is proven to work in both hot and cold climates. An example from Sweden is shown in Fig. 2 (right), where Swedish manufacturer Absolicon's concentrating PV/T collectors are installed on a local hospital in Härnösand. The installation provides electricity, heating and solar cooling to the operation theatre and the dental clinic [14].

An example from a hotter climate is the Cogenra installation on a building at the University of Arizona Tech Park, which delivers 191 kW thermal and 36 kW electric power to the building [15].The project was funded partly through a local incentive program.

3.2.5. PV/T in buildings

The assessment of the suitability of the different technologies for use in buildings was performed using the indicators presented in Section 2. The assessment was based findings from the literature review, and information from producers and installers. The results are presented in Table 1.

It should be noted that while the number of ventilated PV is low, this type of systems can also be achieved with regular PV products. Judging from previous projects, these systems do also tend to be custom made to a larger extent. This flexibility is also the reason that this category is given a *high* value for the building integration potential.

Table 1. Result of the evaluation of the suitability for use in buildings of different PV/T technologies based on four indicators.

Indicator/Technology	**Ventilated PV**	**Air-based PV/T**	**PV/T liquid (covered)**	**PV/T liquid (uncovered)**	**Concentrating PV/T**
Building integration potential	*High*	*Medium*	*Medium*	*Medium*	*Low*
Electricity output	*Increased*	*Increased*	*Decreased*	*Increased*	*N/A*
Thermal output	*Indirect*	*Direct/indirect*	*Direct/indirect*	*Indirect*	*Direct*
Available products	*Low*	*Low*	*Low*	*Medium*	*Low*

Covered PV/T-liquid collectors may be used directly in in DHW systems, in a similar way to solar thermal systems, but can also be used in combination with heat pumps or other heat sources. Several authors conclude that uncovered flat plate PV/T collectors are a promising technology when used in combination with heat pumps (i.e. indirect use) [3, 5], also in combination with bore holes [13, 16]. The choice of technology is of course also dependent on the location and climate of the project. As for example Ille et al. [5] point out, the electricity output is directly dependent on the solar radiation, while the thermal output is to a larger degree influenced on the systems design.

Architectural integration potential of solar technologies has been extensively studied in for instance IEA SHC Task 41, which defines it as the combination of functional and formal (aesthetic) integration potential [17]. The aesthetic integration of the PV/T technologies has not explicitly been investigated in the study presented here. Farkas [18] describes the architectural potential of photovoltaics as depending on the possibility of structural integration, the formal flexibility (the availability of different shapes, colors etc.), the product system (availability of components available for mounting etc.) and the availability of dummies (fake modules used for creating a uniform appearance). The PV/T market is still relatively small, but if it continues to increase more products dedicated for building integration might enter the market, including modules of different colors and shapes as well as dummies.

3.3. The PV/T market

The market for PV/T systems is still very small compared to the markets for pure photovoltaic or solar thermal systems, but an increase in the number of commercially available products can be identified in the last decade. The increased interest in PV/T is probably, at least to a certain extent, driven by the increasing interest in energy efficient buildings worldwide. Stricter energy requirements for buildings, such as the European Commission's goal that all new buildings shall be 'nearly zero energy buildings' by 2020 [19], puts pressure on building industry to find solutions for on-site renewable energy generation.

A market survey published in Task 35 in 2007 found ten producers of commercial PV/T products, and six that had gone out of the market [4]. In addition, the study found 25 concepts that were under development. A recent study in the project PVT-Norm in Germany found 41 producers of PV/T collectors, showing a significant increase in commercially available products [5]. The large majority of these, around 80%, were uncovered PV/T collectors. Even though the PV and solar thermal markets are both dominated by Chinese companies, most of the PV/T producers found in the study were European.

Task 35 also published a study in which architects, engineers, building owners and solar dealers in Canada, Germany, Denmark, Sweden, Italy and Spain were interviewed [11]. One conclusion from the survey was that the markets were very country-specific, and depended to a large degree on the composition of the existing PV and solar thermal markets. The PV/T market maturity was found to depend mainly on to what degree PV was a part of the previous market.

The type of PV/T systems that was dominating the market was also found to be country-specific. In Canada, the aforementioned Conserval Engineering who produces transpired solar collectors and PV/T-air systems was found to be dominating the market with their SolarWall. Sweden has traditionally had a stable market for liquid-based solar thermal collectors, and air-based PV/T systems were regarded with skepticism by the Swedish interviewees, even though the climate in Sweden and Canada is relatively similar. (However, the number of PV/T systems installed in Sweden to this date is very small.)

China is by far the largest solar thermal market in the world with 86% of the market and 64% of the total installed capacity [12]. Most of the solar thermal systems in China are evacuated tube collectors for water heating, while glazed flat plate collectors dominate in the rest of the world. PV/T-air systems is not at the focus of research and development in China, but more interest is put in PV/T systems for water heating and with direct connection to heat pumps. According to Fang et al [11], it is expected that PV/T hot water systems will become one of the main solar systems in buildings in China.

3.4. Market drivers and barriers

Favorable government policies and economic incentives are probably the largest drivers for all types of solar installations. However, since a PV/T system delivers both electricity and heat, there may be confusion related to how it should be classified. Different approaches are seen in different countries. In the U.K., PV/T systems owners are eligible to receive feed-in tariffs from the export of electricity, but they are not eligible for economic support through the Renewable Heat Incentive (RHI) [20]. In Norway as another example, PV/T systems can receive funding as solar collectors, but no incentives are available for PV modules.

As mentioned above, there is also a lack in adequate terminology to describe PV/T systems, which can also influence the incentives. Ille et. al [5] mentions that the word 'uncovered' previously made this type PV/T collectors not eligible for funding within the German market incentive program for solar collectors, which excludes uncovered swimming pool collectors. However, the description in the program was then updated to 'panels without transparent cover on the front panel', which means that uncovered PV/T collectors should now be eligible.

The relation between standards and innovation, and the effect on market development, has been analyzed by Kramer and Helmers [21]. They find that the lack of standards and certifications is a strong barrier to market development. It leads to a lack of technical information on the products, restrictions in government incentives and an uncertainty among consumers. The recent developments in certifications specifically for PV/T products, such as the Solar Keymark [22], can therefore be expected to have a positive influence on the market.

4. Discussion

The PV/T market is still very small and it shows in different countries a strong dependence on individual companies. The respondents in the Task 35 market survey pointed to economic benefits and the possibility of building integration as the two most important factors. In the PV/T installations found in this review, however, PV/T systems are rarely or never reported to be cheaper than alternative installations. The choice of PV/T seems to be driven by other factors. The economic benefit of PV/T systems today depends to a large degree on the availability of subsidies, or funding of pilot projects.

5. Conclusion

In the past decade, PV/T installations have gone from largely project-specific developments to relatively standardized systems. The market is still very small compared to the PV and solar thermal markets, but a number of commercial products are now available. Different types of systems have gained ground in different countries based on the composition of the earlier markets for PV and solar thermal, but also depending on the success of individual companies. The available economic subsidy schemes may also have contributed to shape the markets in the different countries.

There seems to have been a shift from PV/T-air systems to a larger share of PV/T-liquid systems, including PV/T systems with heat pumps. A few large scale projects with seasonal storage in bore holes were also found. The thermal energy output of PV/T collectors are generally of low temperature, and several authors emphasize the importance of the complete system design, e.g. the connection to heat pumps, thermal storage solutions and other HVAC equipment, in order to make good use of this energy.

Recent developments in certification and testing has also led to more standardization, which may encourage more installers to choose PV/T systems in favor of pure PV or solar thermal systems.

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