Development of a photovoltaic thermal facade system

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Abstract. A photovoltaic thermal (PVT) collector is made of a photovoltaic (PV) module and a solar thermal collector and thereby delivers electrical and thermal energy at the same time. These systems can contribute significantly to the renewable energy supply of residential, public, and commercial buildings. This paper gives insight into the development of a facade-integrated PVT system within the research project PVT Fassade. Thermal simulations evaluated useful operating conditions and efficiency-decreasing factors. Thus, 10 kg/(hm²) and 60 kg/(hm²) were identified as lower and upper limits for the mass flow and the losses by the internal heat transfer resistance of a 3.5 mm air layer between the PV module and the heat exchanger were determined to 35 % and 48 % for 10 and 60 kg/(hm²). These findings and structural, aesthetical, and general building law requirements were taken into consideration for the design of the facade-integrated PVT system. The functionality and feasibility of the developed system is shown through a constructed prototype facade where an intensive monitoring of the thermal and electrical performance of the PVT system is conducted. The performance of the PVT facade collector is described on the basis of an exemplary day of this monitoring. On this day, an area-specific thermal yield of 4.13 kWh/m² with a temperature spread of up to 10.7 K is reached. At the same time, the thin film PV modules of the PVT system achieve an electrical yield increase of 2.5 % compared to a reference PV facade system.

1. Facade-integrated photovoltaic thermal (PVT) collectors for a renewable energy supply

To reach more sustainability and energy efficiency in the building sector, the demand for nearly-zero energy buildings (NZEBs) is legally specified by the European Union [1]. This will also lead to an increasing demand for energy from renewable sources, produced on-site or nearby the building, as this is one special requirement of NZEBs. Thereby, the need for efficient and economic renewable energy generating technologies within the building envelope will rise. Building-dependent factors such as limited space on roofs or a high ratio between facade surface and roof surface will also make unused facade surfaces interesting for the utilization of solar energy.

As photovoltaic thermal (PVT) collectors combine a photovoltaic (PV) module and a solar thermal system, they produce electrical power and thermal energy at the same time and reach a higher utilization of the solar irradiation per square meter of the surface area. Moreover, the dissipation of heat from the PV module leads to an increase of electrical efficiency of the PV module. A further application possibility can be found in the cooling of buildings at night by directing the longwave infrared radiation from the collector surface to the night sky. [2]

The described demand for energy producing facades and the potentials of PVT systems qualify facade-integrated PVT collectors as promising applications. However, especially in the field of
facade-integration of PVT systems, there is still a great need for research and development. This need is set out clear in a research strategy paper about low-temperature solar thermal technologies [3] and it gets highlighted by a Swiss market analyses, which showed that the annually installed PVT area in 2015 and 2016 adds up to only 0.14 % of the annually installed PV area in the same time [4].

Addressing this research gap, a facade integrated PVT collector was developed within the PVT Fassade project in cooperation with the developer and producer, blue energy systems GmbH. The main objective of the project was to develop an efficient and architecturally appealing PVT facade collector with a modular and scalable design that can be realized under building law requirements.

As PVT systems evolved from two inherently versatile technologies, various types of collectors can be found today. They are characterized by the heat transfer medium used – which can be air or liquid – and by the design of the heat absorber and the general set-up. Figure 1 shows different types of liquid-cooled and flat plate PVT collectors which differ in terms of utilizing a glazing cover on the front side, a thermal insulation on the back side, or none of the above. By using an insulation and glass cover, the heat losses of the collector are reduced whereby the temperature level of the system and the thermal efficiency at high temperatures are increased. However, as the efficiency of the PV module decreases with increasing temperature, a PV system should run in a cool state to maximize the electrical output. This leads to a conflict of the adequate temperature level between the thermal and the electrical technology, which has to be taken into account while dimensioning the PVT system.

As it can easily be integrated into buildings as a rear-ventilated facade at energetic renovations or at new constructions, an unglazed and non-insulated collector, as shown in figure 1 on the left side, was favored in the PVT Fassade project. This type of collector has the lowest temperature level but reaches higher electrical earnings compared to the other three types shown. For this reason, this type of PVT collector without glass cover and insulation is particularly suitable for low-temperature applications like the combination with heat pump systems. However, depending on the environmental conditions and the efficiency of the system, the direct use of heat for preheating of service water or for panel heating systems is also possible, even in the transition periods in autumn and spring. [4]

![Figure 1. Different types of PVT collectors, from left to right: unglazed and non-insulated collector, unglazed and insulated collector, glazed and non-insulated collector, glazed and insulated collector.](image)

As the solar irradiation is the driving force of a PVT collector, the installation situation and inclination of the collector have a great impact on the yield of the PVT system. Figure 2 shows the solar irradiation in kWh/m² on different roof and facade surfaces for the location of Dresden.
Figure 2. Solar irradiation in the course of the year and in total on west-, south-, and east-oriented surfaces with different inclinations for the location of Dresden, Germany, in kWh/m².

It can be seen that the solar irradiation varies strongly with the orientation and inclination of the surface. In the facades, a reduction of the total solar input between one quarter and one third compared to the 40° inclined roofs must generally be accepted. Comparing the facades, the west facade gets the highest solar input in summer. However, considering the whole year, the south facade is the most profitable facade orientation with higher inputs in spring and autumn. Compared to the 40° inclined roofs, the south facade has similar or even higher irradiation values in the winter months. In these months, when the heat demand of the building is at its highest, the irradiation of the low-positioned sun can be collected best in the south facade. Therefore, the south facade was chosen as the favorable orientation for the facade integration of the PVT collector for the location of Dresden.

2. Thermal studies on the PVT system

The yield of the collector depends on the solar input on various plant-specific, environmental, and constructional boundary conditions. To determine efficiency-decreasing factors and to develop a profitable collector, thermal simulations were carried out with the numerical software DELPHIN 5.9.3.

As part of the results of these simulations, i.e. the influence on the system’s performance of mass flow, flow temperature, wind speed, sky temperature, rear ventilation, and an air gap between the PV module and the heat exchanger is presented in the following.

The simulations were run under static conditions with constant values. This has to be kept in mind while interpreting the results, as the analyzed conditions do not meet a real dynamic situation.

If not presented differently, the simulation model and conditions were as shown in figure 3 and table 1. The mass flow is referred to the collector surface in kg/(hm²) and water with 40% antifreeze agent is used as heat transfer medium. As the transformation of irradiation into electrical energy by the PV layer could not be simulated with the software, an effective absorption coefficient, according to [5], was determined at the value of 0.703 for the considered thin film PV modules for the solar spectrum of AM1.5. Thereby, the real thermal state of the PV modules was met.

As small tolerances due to the manufacturing and mounting process have to be considered, a small air layer of 0.5 mm between the PV module and the aluminum heat exchanger is assumed. Due to the symmetrical structure of the harp-shaped collector and the static simulation conditions, a one-pipe section of the collector was used for the simulation model.
2.1. Plant-specific boundary conditions

To determine the collector’s proper operating conditions, the influence of the mass flow was analyzed. The diagrams in figure 4 show the collector’s gained heat flow and the medium liquid temperature in the upper diagram, and the electrical efficiency of the thin film PV module and the temperature of the PV module in the lower diagram, both as a function of the mass flow for otherwise static conditions, as shown in Table 1.

The diagrams clearly show that the heat flow, the temperatures, and the PV efficiency reach an approximate value through an increase of the mass flow. At a mass flow of about 10 to 20 kg/(hm²), the heat flow into the collector, the cooling, and the efficiency increase of the PV flatten compared to the range of 0 to 10 kg/(hm²). The PVT system reaches a kind of thermal saturation. Higher return temperatures are achieved in the range of 0 to 10 kg/(hm²), while the higher range should be aimed at to increase the electrical yield.

![Simulation model](image)

**Figure 3.** Simulation model.

**Table 1.** Boundary conditions for static simulations.

| Condition            | Value | Unit   |
|----------------------|-------|--------|
| G_dif.               | 1000  | W/m²   |
| v_wind               | 1     | m/s    |
| h_convective         | 8     | W/(m²K) |
| h_radiative          | 5     | W/(m²K) |
| T_ambient            | 20    | °C     |
| T_supply             | 10    | °C     |
| air layer gap size   | 0.5   | mm     |
| rear ventilation size| 50    | mm     |
| rear ventilation exchange rate | 20 | 1/h    |

![Heat flow, liquid temperature, PV efficiency](image)

**Figure 4.** Heat flow gained by the collector, medium liquid temperature, efficiency of the thin film PV module and PV module temperature as a function of the mass flow for otherwise static conditions.
The thin film PV module’s nominal efficiency of 11.96% at a module temperature of 25 °C drops to 10.7% due to the module temperature rising to 78 °C if the liquid cooling is not used. A mass flow of 60 kg/(hm²) and a supply temperature of 10°C almost compensate these efficiency losses and achieve a degree of efficiency of 11.75%. If the supply temperature was decreased, the losses could be completely compensated and the nominal efficiency of 11.96% would be preserved.

Regarding these results, it has to be considered that the simulations were carried out under static conditions with an irradiation of 1,000 W/m², which is not a representative situation. However, values for the orientation are gained by qualitative evaluations, which are useful for the design and the operation of the collector. So, for the plant-specific design, useful mass flow rates were located between 10 and 60 kg/(hm²) as higher mass flows will deliver just a small surplus and lower mass flows will achieve too low outputs.

2.2. Environmental boundary conditions

Uncovered PVT collectors are also called wind and infrared sensitive collectors (WISC) as the thermal losses by convection and radiation on the front side have to be considered for the determination of the thermal performance [6]. Thus, wind velocity and sky temperature have a significant influence on the thermal output. However, this has to be seen in context with the mass flow of the fluid and the supply temperature as these conditions also affect the heat flow. The first graph in figure 5 shows the reduction of the thermal output of the analyzed PVT collector by an increasing wind velocity from 0 to 3 m/s. The upper limit of 3 m/s was chosen according to the requirements of [6] for the determination of the collector performance by the stationary method and is not to be understood as the maximum possible wind speed. The second graph shows the reduction of the thermal output by a decreasing sky temperature from 20 °C to 5 °C. Both graphs show the reduction of the output for mass flows of 10 kg/(hm²) and 60 kg/(hm²) and supply temperatures of 10°C, 5°C, 0 °C, and -6°C.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Reduction of the thermal output of the analyzed (WISC) PVT collector by an increasing wind velocity from 0 to 3 m/s and by a decreasing sky temperature from 20 °C to 5 °C in percentage, shown for different supply flow temperatures and mass flows.

Considering the upper diagram in figure 5, it becomes clear that a lower supply temperature and a higher mass flow reduce the convective heat losses on the front side of the collector. The reason is the
thereby rising temperature gradient between the PV module and the heat transfer medium, which decreases the losses at the front surface to the surroundings as the heat flows along the higher gradient to the fluid. Nevertheless, it has to be considered that thereby the return temperature will also turn out low.

Regarding the radiative losses from the surface of the analyzed PVT collector by infrared (heat) radiation in the lower diagram in figure 5, it becomes apparent that the impact of the supply temperature and the mass flow is significantly lower. This can be explained by the lower contribution of the radiative part to the total heat transfer compared to the convective part. According to the characteristic values in Table 5 of [7], the convective heat transfer coefficient on the outside is approximately four times bigger than the radiative heat transfer coefficient.

As a further result, it seems advisable to use a supply temperature as low as possible and a mass flow as high as possible to reduce the thermal losses at the front side of the collector. However, the supply temperature and the mass flow have to match with the operating limits of the plant technology used and with the energetic input from the environment. If certain return temperatures must be reached, certain efficiency losses must be accepted.

2.3. Constructional boundary conditions
By varying certain constructional boundary conditions, their effect on the thermal collector yield becomes apparent. This was taken into account in the design process to develop an optimized collector. For instance, the rear ventilation showed almost no influence on the output of the analyzed PVT collector since the temperature level of the collector is low and thereby the gradient between the medium fluid temperature and the temperature of the rear ventilation air is also low. Thereby, the thermal losses induced by the rear ventilation appear quite low for the analyzed static scenario, which can be seen in the left-hand diagram in figure 6.

A much more decisive factor is a thermal resistance between the PV module, which absorbs the solar irradiation, and the heat transfer medium in the heat exchanger that dissipates the thermal energy. These thermal resistances can, for example, consist of disturbing layers of adhesives, air, or materials with poor thermal conductivity. The right-hand diagram in figure 6 shows that the thermal yield of the collector is reduced significantly by 35 % resp. 48 % for 10 and 60 kg/(hm²) by an air layer of 3.5 mm and 7 % resp. 10 % for an air layer of 0.5 mm.

As a result, a thermal insulation on the back was not planned for this collector with its low temperature level. However, an air layer below 0.5 mm was set as constructional target in the design process to ensure a good thermal coupling between the PV module and the heat exchanger.

3. Developed PVT system
The aim of the development process was to integrate a PVT collector into a rear-ventilated facade system. Thanks to a modular design, scalability and different collector sizes but also the independency of certain PV module manufacturers and PV technologies were intended. A revision of the modules
should be possible and the reduction of all visible and mechanical fasteners was defined as design specification for aesthetical reasons. Instead, the load transfer of dead weight and wind loads should be ensured by using load-bearing adhesive joints on the back of the PV modules. The decisive design criterion was always to ensure a high energetic performance of the collector for which the findings of the thermal studies proved to be of great use.

3.1. Structure of the developed PVT system

Following these boundary conditions, a special fastening system was developed that optimally compensates the manufacturing and installation tolerances and thus ensures good thermal coupling within the component. The PV modules are fastened by means of mounting profiles which are attached to the back of the modules by linear load-bearing adhesive joints. CNC-controlled machining of the mounting profiles and the substructure and the use of spacers to maintain the thickness of the adhesive joint ensure precise fastening and thus good thermal coupling through an air gap of less than 0.5 mm between the PV modules and the heat exchanger. A revision of the PV modules is possible.

The rear mounting profiles and the heat exchanger are designed as a hanging system whereby a temperature expansion is possible while the dead weight and wind loads are transferred safely to the substructure. This avoids temperature stresses in the structure and allows exact positioning of the modules. Figure 7 shows schematically the PV module with the adhesive joints and mounting profiles on the back, the heat exchanger with pipes and cutouts, and the composed PVT collector. More detailed information cannot be published at the moment due to non-disclosure agreements.

![Figure 7. Components and set-up of the PVT collector.](image)

As this type of structural bonding is not permitted under German building law, a special technical approval by the building authorities is needed. The reason for this is that the adhesive joints are permanently loaded and therefore under risk of creep. This and the fact that adhesives are ageing under weather conditions, whereby their mechanical properties deteriorate, have led to the situation that in Germany a mechanical dead weight support is required for load-bearing bonded glass constructions. Above an installation height of 8 meters, additional safety brackets are required for the case of failure of the adhesive joints. [8] [9]

For this reason, the load-bearing adhesive joints of the PVT system were designed on the basis of the guideline for European technical approval of load-bearing bonded glass constructions and numerical mechanical simulations verified their load-bearing capacity and serviceability. In addition, tensile tests...
were carried out on unaged and artificially-aged test specimens in order to test and prove the adhesion and durability of the adhesive in connection with the substrates used. The test results were within the permissible limits of the approval guideline, which is why sufficient durability and adhesive strength of the adhesive bonding is assumed. The glasses of the selected PV modules were dimensioned in accordance with [10] and [11] and assessed as sufficiently load-bearing and serviceable for the installation in a 20-meter-high building in wind zone 2 in Germany, which corresponds to approximately 80% of the area of Germany.

4. Prototype facade at an outdoor exposure test rig
After the development, a prototype was constructed at an outdoor exposure test rig at Technische Universität Dresden to analyze the PVT facade system under real environmental and various operating conditions. Thereby, the thermal and electrical performance of the collector is to be determined and control strategies for the operation are to be developed. Thus, the collector is operated with different mass flows and supply temperatures during an energetic monitoring. The recorded measurement data are to be used to determine the efficiency curve of the collector according to ISO 9806. As a result, the properties of the PVT facade collector can be implemented in energetic building simulations.

4.1. Set-up of the test rig
The installation situation at the test rig, which can be seen in figure 8, is identical to the integration into the south facade of a building. The heat sink or heat source required to provide different flow temperatures is realized by a reversible air-water heat pump together with a buffer storage tank. The collector and the heat pump are connected to the buffer tank by diffusion-resistant insulated piping.

To determine the thermal yield of the PVT collector, two fluid-measuring sections – one in the supply flow and one in the return flow – record the temperature, flow, and pressure of the fluid. A pyrgeometer, a pyranometer, an air flow sensor, a shell anemometer, and various temperature sensors measure the decisive influencing variables from the environment and record the thermal state of the collector. By comparison of the electrical output of the PVT collector to the output of a rear ventilated PV facade with identical PV modules, the electrical efficiency of the PVT system is identified.

Figure 8. PVT facade collector (2.9 m²) and rear-ventilated reference PV facade at the outdoor exposure test rig on the left side. Schema of the technical components of the PVT system with measuring sections (ms 1 and ms 2) on the right side.

4.2. First results of the energetic monitoring
First results of the monitoring can be seen in figure 9 on the basis of an exemplary chosen day. The upper diagram shows the temperatures of the surroundings, of the rear-ventilated reference PV modules (ref.-PV), and of the PVT-PV modules (PVT-PV) and the irradiation on the facade over the
course of the day on 4th July 2019. It also shows the temperature spread between supply flow and return flow in K. The lower diagram shows the normalized electrical output of the reference PV modules and the PVT-PV modules, by relating the actual electrical output of the PV string to the installed nominal output of the PV string. The thermal output of the PVT system per square meter of the collector surface is shown for the same day. Throughout the day, the supply flow temperature was at 7.1 ± 1.6 °C and the fluid mass flow was at 40.8 ± 1 kg/(hm²), which means that the system was operated primarily to generate electrical energy and secondarily to generate low-temperature heat.

**Figure 9.** Temperatures of the surroundings, the reference PV and the PVT-PV modules, the temperature spread between supply and return flow, and irradiation in the upper diagram. Normalized electrical output of both facades and thermal output of the PVT facade in the lower diagram.

Although the day belongs to the astronomical summer, it can represent a spring day too, due to the medium temperatures and irradiation. As the supply temperature was set very low, the PVT collector gained thermal energy from the surroundings almost throughout the day, even if there is no irradiation falling on the collector. As the irradiation sets in, the facades heat up and the thermal output of the PVT system rises. The collector forms a heat source that can be used, for example, to preheat drinking water. On this day, the total thermal output is 4.13 kWh/m² and a maximum temperature spread of +10.7 K is achieved. Due to the low supply temperature and the high fluid flow rate, the maximum return temperature is only at 16.0 °C. If the flow temperature was higher and the flow rate was lower, a higher return temperature would be gained. Additionally, the collector could work as a heat sink at night that could be actively used to cool buildings in summer.

Since the heat exchanger absorbs the heat from the PVT-PV modules, they reach a significantly lower temperature and an additional electrical yield of 2.5 % compared to the reference PV modules on this day. This is slightly below the assumed additional yield, which can be estimated at 2.98 % using the temperature coefficient of the thin film modules (0.2 %/K) and the average temperature difference between the reference PV and the PVT-PV modules during the irradiation phase (14.9 K). For crystalline modules, the additional yield would be about twice as high as the thin film modules.
5. Conclusion and outlook

During the PVT Fassade project, a novel PVT collector was developed together with the developer and producer, blue energy systems GmbH. The development focused not only on design, building regulations, and constructional requirements, but also on a high energy efficiency of the system. Thermal simulations helped to develop the system and to determine decisive boundary conditions. Thus, 10 and 60 kg/(hm²) were evaluated as limits for the mass flow and a potential air layer between the PV module and the heat exchanger had to be avoided or minimized to less than 0.5 mm. The facade system is carried out with load-bearing bonding, which is why special building approvals may be required. A prototype facade proves the constructional and energetic functionality of the system. The monitoring of the prototype shows that the electrical yields of the PVT-PV modules are increased by 2.5 % and additional 4.13 kWh/m² of low-temperature heat are gained on the described day.

On the basis of these results further research is needed for the integration of the system into buildings and for the development of control strategies. It is essential to determine the collector characteristic curve of the PVT facade collector to implement the system in energetic building simulations and to develop plant-specific concepts. Following, real pilot projects can be carried out.

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