Characterization and parametrization of a photovoltaic-thermal façade in the context of Building Information Modeling

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Abstract

The use of Building Information Modeling (BIM) for special applications like solar energy as well as for the operation stage of the building process is not yet established and still under development. The paper addresses both topics and presents a methodology for using BIM to monitor a solar façade consisting of novel photovoltaic-thermal (PVT) modules intended for building integration. For this purpose, a digital twin of a real laboratory with its PVT façade was developed in a common data environment (CDE). Main goal of the work is to use the BIM platform to identify possible malfunctions of the façade and to ensure an efficient system operation. For a correct parameterization in the BIM environment as well as for the analysis of the deviation between the usually available laboratory performance data and the behavior under real conditions, we perform a detailed experimental characterization of both the PVT module and the whole PVT façade. Results, critical aspects and future developments are discussed.

Keywords: Building Information Modeling (BIM), building integration, photovoltaics, solar thermal collectors, photovoltaic-thermal collectors, monitoring

1. Introduction

To reduce CO_2 emissions in the building sector, a significant increase in the use of available renewable energies such as solar energy is required, both in existing and new buildings. The combination of photovoltaic-thermal collectors and heat pumps can significantly contribute to this goal. For this purpose, the façade offers a promising untapped potential and design synergies arising from building integration can additionally lead to cost savings and aesthetical advantages compared to common installations. However, as part of the building envelope, a PVT façade must meet several requirements not only with regard to energy but also to building physics and aesthetics.

In the frame of a current research project, a new type of PVT façade is being planned, constructed and measured. The central task is to model the façade using the BIM method in order to analyze and improve its use over its entire life cycle. As a holistic approach, the BIM method is suitable, among other things, for applications in the field of technical building equipment as well as for the analysis of energy supply systems. Early BIM-based planning of a building energy supply system also brings advantages with regard to the use of renewable energy sources such as solar energy. For the operational phase, the BIM method can be used to monitor, for example, the expected thermal or electrical yield of a system. However, there are still fundamental limitations to the specific use of the BIM method in the solar energy field. The available BIM-based object models of solar energy components such as photovoltaic (PV) and solar thermal (ST) are neither uniformly nor fully parameterized for common application scenarios. For photovoltaic thermal collectors, no specific object model exists to date. In addition, the BIM method has so far been used primarily for the planning process.

In this paper, the use of BIM for monitoring the innovative PVT façade is methodically presented. For this purpose, a BIM model of an existing real laboratory with its PVT façade was developed at the Institute for Solar Energy Research in Hamelin (ISFH). Based on this, a digital twin for monitoring in a common data environment was created. This is intended to illustrate the ability to display measured thermal and electrical yields and compare them to target data. This can allow a rapid identification and solution of possible malfunctions thus ensuring an efficient system operation. The BIM parameterization of the PVT collector is based on a previous work (Mandow et al., 2022a). For a correct parameterization in the BIM environment as well as for the analysis of the difference between the usually available laboratory data and the real application, we performed a detailed experimental

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characterization of the PVT module as well as of the whole PVT façade.

2. Building Information Modeling method

Building Information Modeling has established itself as one of the generic terms for digitization in the value chain of designing, building and operating structures. With the BIM method, all lifecycle-relevant information of a building can be recorded, managed and exchanged centrally, model-based, digitally and consistently (VDI 2552, 2020). This enables optimal transparent communication between the parties involved in the various construction project phases (architects, planners, installers, operators, etc.). Fig 1 shows this relationship graphically.

All building-relevant data are stored in a Common Data Environment (CDE), and are thus accessible to all project participants at any time. Computer-aided filtering and evaluation - combined with visualization - helps to focus and control project-related activities.

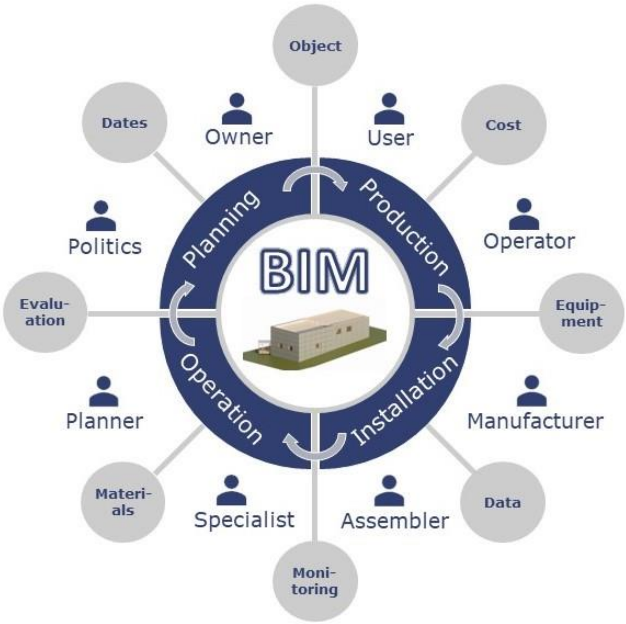

Fig 1: Building Information Modeling, central information management based on models

Building Information Modeling, as a holistic method, holds benefits in all life cycle phases of a structure. Currently, this method is particularly used in the planning phase, but its application in the operational phase also offers great potential. In Germany for the implementation of the BIM method in national projects, the two BIM strategies “Masterplan BIM for Federal Buildings” (BMI, 2021) and “Masterplan BIM for Federal Highways” (BMDV, 2021) recommend initially implementing BIM use cases in the planning phase. The successful use of the BIM method in planning for the generation of the corresponding BIM models is directly related to its use in the subsequent life cycle phases. The data generated over the life cycle of a structure can be continuously aggregated in the BIM model and thus provide an optimal basis for an operation as well as maintenance management of a structure.

There are already comprehensive BIM-based approaches and software products for the application to conventional structures and especially for their planning phase. The application of the method in the field of solar energy is still under development and is a current research topic. There is still considerable potential for development both in the planning and especially in the operation of photovoltaic and solar thermal plants (Mandow et al., 2022b).

In the planning phase, for example, the use of BIM enables solar energy to be considered as part of the energy supply system at an early stage of the integral planning of the building. Furthermore, BIM modeling allows the building to be modeled with its surroundings, which makes it possible to predict the solar energy yield more correctly, by considering any module shading.

To facilitate the planning and modeling process, product manufacturers can make their products available to the general public as BIM objects. On browser-based databases such as BIMobject (BIMobject, 2023), Bimetica (Bimetica, 2023), on the National BIM Library (NBS, 2023), which is widely used in the UK, and on the Autocad/Revit portal for BIM-Apps MEPcontent (MEPcontent, 2023), BIM objects of photovoltaic and solar thermal modules with information on geometry and semantic properties already exist. However, the available parameterization is unsuitable for application scenarios in the field of energy simulation due to lack of some crucial properties like some performance parameters or inconsistent naming.

With regard to semantics, manufacturer information about warranty and maintenance of the actual physical objects can be integrated into their digital images and thus contribute to better operation. By coupling measurement technology and the BIM model, a digital twin of a solar plant can be generated. Within such a BIM-based monitoring approach for the operation of solar plants, the actual measurement data can be compared with target data. The target data can be determined from the available design data or manufacturer specifications by means of appropriate simulation programs. In the event of a deviation above a predefined critical value in the monitoring data, a possible malfunction (e.g. a defective photovoltaic module or solar thermal collector) can be detected at an early stage, communicated to the operator via the BIM platform (CDE) and, if necessary, a repair or replacement can follow. In case of any repair or replacement, the BIM model is updated to show the actual as-built condition. In the case of disassembly, the preparation of cost and work plan analogously to the first installation can be facilitated by the BIM-based approach. Existing information on the recyclability of the dismantled components can also be stored in the BIM model of the project. In principle, all lifecycle-relevant information of a construction project can be stored in a BIM model.

There are a number of proprietary and vendor-neutral approaches for the data management of BIM models. The Industry Foundation Classes (IFC) represents a manufacturer-neutral standard for the data exchange of building information models, which is established as an international standard (DIN EN ISO 16739, 2021). The use of the IFC standard enables the collaboration in BIM projects between different stakeholders and any different software products. This data schema is developed by buildingSMART (buildingSMART, 2023), an international competence network for digital design, construction and operation of buildings. The main task of the non-profit organization is the further development and standardization of the open exchange of information in BIM projects as well as the definition and standardization of corresponding work processes and interfaces.

A BIM-based approach for monitoring a façade-integrated PVT system (BIPVT system) is presented in the coming chapters.

3. BIM use case: yield monitoring

The "yield monitoring" use case is located in the operation life cycle phase of a BIPV(T) system. By combining the BIM model with live monitoring data, a digital twin of the PVT façade is created. For the representation of the digital twin, a suitable BIM platform is developed, which meets the requirements for digital twins of BIPV(T) systems.

The digital representation of the BIPV(T) system, its surroundings and the given location by geo-referencing the BIM model provide essential geometric and meteorological information. In addition, stored semantic information, such as the thermal as well as electrical efficiency of the modules, can be easily retrieved and used for the calculation of the target data for the monitoring. Information on the surface conditions of the structure and the surrounding area can be used directly for the determination of any shading by ray tracing and for the yield analysis.

Fig 2 shows the BIM model of the BIPVT façade (real lab) at the SolarTec building at ISFH modeled in the authoring software Autodesk Revit. Furthermore, Fig 2 shows the basic hierarchy in a building project in the IFC standard and a schematic representation of a PVT module as an object of the IFC class "IfcSolarDevice" together with an extract of possible information (buildingSMART, 2023).

For processing the presented BIM use case, the BIM model must be parameterized with corresponding information so that the calculation of the expected target data (e.g. electrical or thermal yield) can be performed using current weather data. For this purpose, a PVT module was electrically and thermally characterized in the ISFH laboratory. The entire façade was being characterized in field according to quasi-dynamic test method (DIN EN ISO 9806, 2017).

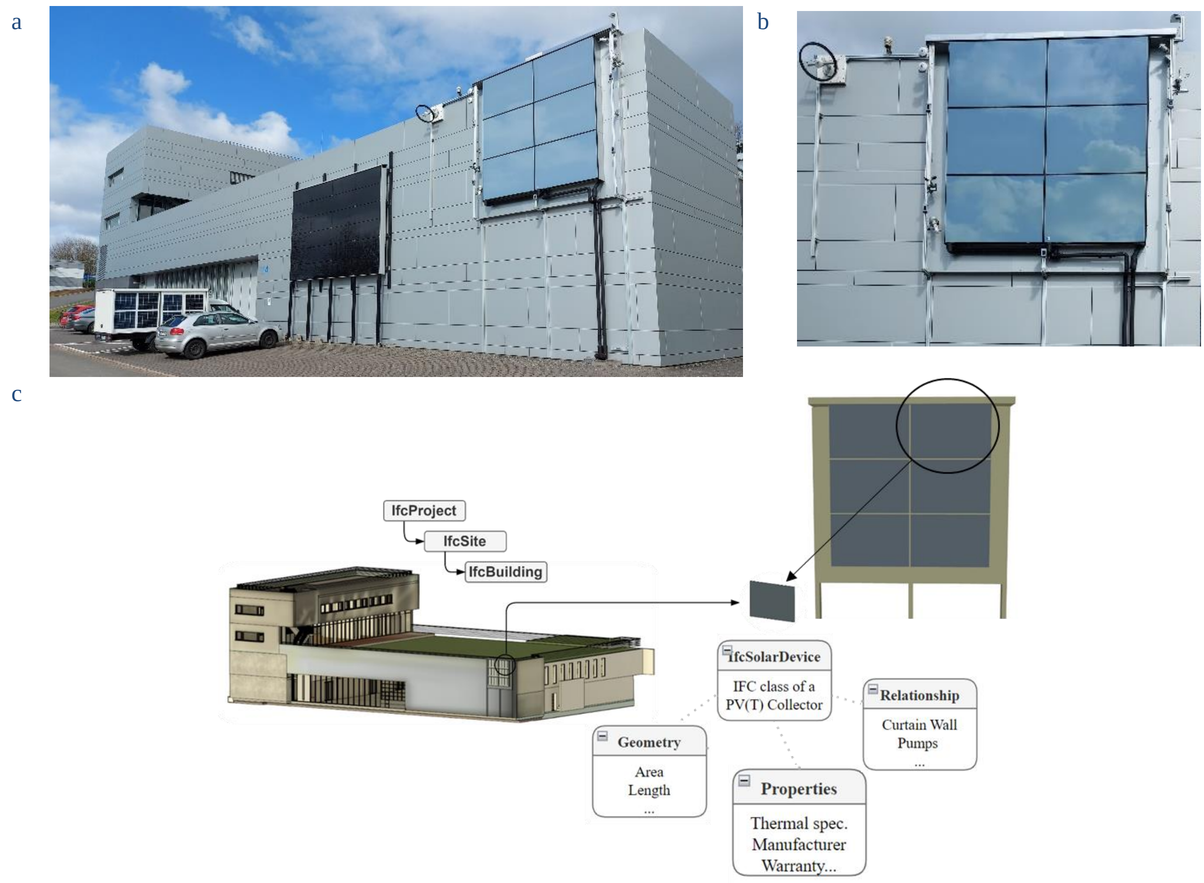

Fig 2: BIM model (digital twin) of the building with the PVT façade at ISFH, a: real building, b: PVT façade, c: BIM model of the building and the PVT façade with schematic explanation of the IFC structure of the PVT façade

4. Module characterization

The PV module used was specifically designed for building integration. It is a light gray, frameless and 1095 x 1620 mm large glass-glass module, where the PV cells are not visible due to the translucent cover glass. Back rails are glued to the back of the c-Si PV module, with which the PV module is clamped onto an aluminum heat exchanger. Fig 3 shows the PVT façade module in detail.

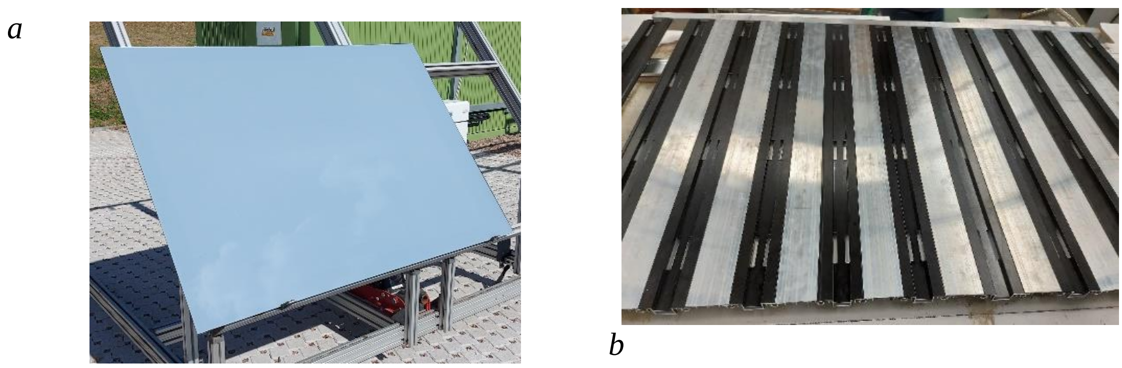

Fig 3: The innovative PVT façade module, a: PV module, b: Aluminum heat exchanger

The PVT façade module was measured at ISFH in the solar simulator of our laboratory according to the Standard (DIN EN ISO 9806, 2017) for uncovered collectors (WISC), both with maximum electrical load (MPP operation) and with open electrical circuit (OC operation). Fig 4 shows the module -installed on an insulated white plate - at a tilt angle of 90° in the solar simulator. The distance between the installed module and the white plate was 50 mm, and the investigation was carried out for two cases: PVT façade collector with closed and open-air gap, as a rear-ventilated façade. Due to the installation situation in the test and on the basis of previous experience with similar building integrated solar modules (Frick et al. 2022), a higher air flow velocity is expected on the back side of the ventilated single module compared to the flow velocity in the air gap of a real façade. This has a strong influence on the efficiency parameters of the module, which is why the PVT module was also measured with a closed air gap. The mass flow rate of the fluid (water) was set to a constant value of 130 kg/h (0.02 kg/s), the indoor air temperature and sky temperature were set to 25 °C and the irradiation (G) to 960 W/m².

Fig 4: Laboratory measurement of the PVT collector as a façade collector in the solar simulator according to DIN EN ISO 9806

The thermal power output is determined according to the following model for uncovered fluid collectors under steady-state conditions described in the (DIN EN ISO 9806, 2017):

$$\dot{Q} = A_G(\eta_{0,hem}G_{hem} - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_3u'(\vartheta_m - \vartheta_a) + a_4(E_L - \sigma T_a{}^4) - a_6u'G_{hem} - a_7u'(E_L - \sigma T_a{}^4) - a_8(\vartheta_m - \vartheta_a)^4) \quad \text{eq 1}$$

The calculated collector parameters are listed in Tab. 1 (for the symbols s. Annex).

Tab. 1: Collector parameters according to DIN EN ISO 9806 (2017)

Installation mode	Operating mode	Collector parameters				
		$\eta_{0,hem}$ -	a_1 W/m²·K	a_3 J/m²·K	a_4* -	a_6 s/m
With air gap	MPP	0.436	15.32	6.01	0.53	0.063
Without air gap	MPP	0.434	9.24	1.63	0.54	0.043
With air gap	OC	0.487	15.48	5.98	0.53	0.066
without air gap	OC	0.495	9.44	1.23	0.54	0.049

*a_4 is calculated according to the following equation:

$$a_4 = \eta_{0,hem}\frac{\varepsilon}{\alpha} \quad \text{eq 2}$$

Whereas α is the solar absorption grad of the module which was measured (α=0.769). Fig 5 and Fig 6 show the thermal efficiency determined from measured data as a function of wind velocity, temperature difference between heat transfer medium and ambient air, and the air gap for both MPP and OC operation mode. The investigation shows the impact of the different installation on the results.

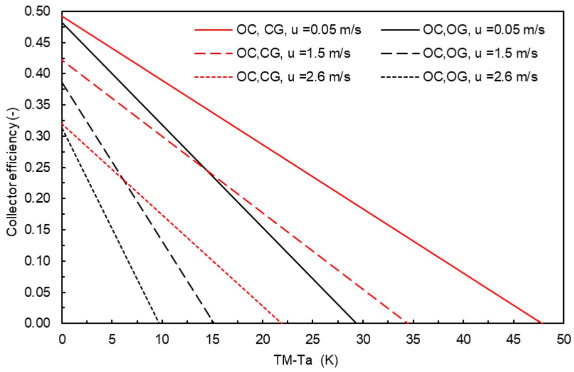

Fig 5: Thermal efficiency of the PVT façade collector according to DIN EN ISO 9806 with (OG) and without 50 mm air gap (CG) in OC mode

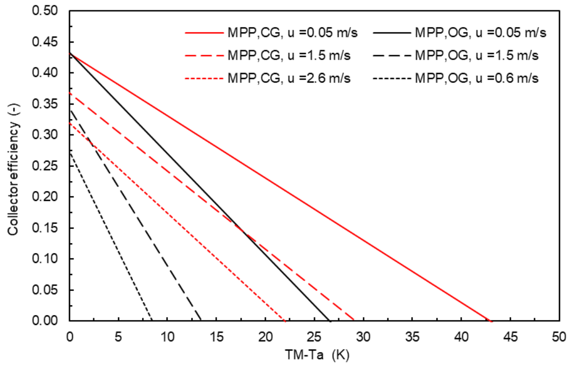

Fig 6: Thermal efficiency of the PVT façade collector according to DIN EN ISO 9806 with (OG) and without 50 mm air gap (CG) in MPP operation mode

5. Façade characterisation

The use of the BIM method in the operational phase for monitoring the façade-integrated PVT (in this case a ventilated curtain wall) as well as the general use of the BIM method for solar components is investigated as real laboratory in an experimental building (SolarTec) at the ISFH. The BIM model is parameterized based on the thermal, electrical and building physics characterization (U-value) of the façade. For the use case "Yield monitoring" the PVT façade was equipped with high-quality measurement sensors to record and analyze the thermal and electrical yield.

The façade consists of 6 PVT modules with a total area of 10.6 m². The PV modules are connected in two strings with 3 modules each in series. The PVT modules are hooked to the heat exchanger using the back rails shown in Fig 3. The heat exchanger is in turn suspended from transverse support rails by means of hooks. The support rails are attached to the wall with Isolink connectors (Schöck Bauteile GmbH, 2023). The special connectors serve to minimize the thermal bridge between the PVT façade and the building. A 50 mm air gap is formed between the PVT façade and the wall insulation. The PVT façade is installed on an existing façade. In order to investigate the thermal interaction between the PVT façade and the building, a heating system was implemented between the wall and the PVT façade to emulate indoor temperature. A heat flow plate was installed to measure the heat flow density between the PVT façade and the building. The surface temperature of PV front and back side as well as of the heat exchanger are measured by temperature sensors (PT-100). The temperature and relative humidity of the air is measured in the upper and lower part of the air gap.

As meteorological data, the hemispherical irradiation, the diffuse irradiation, the long-wave irradiation in the façade plain, the wind speed and direction, the ambient temperature, as well as air pressure and the relative humidity are measured. Fig 7 shows the measurement concept of the PVT façade. In addition, the temperature and mass flow of the heat transfer medium (water-Tyfocor mixture) at the PVT façade inlet as well as the temperature at the façade outlet are measured. To detect shading (possibly caused by surrounding trees), five silicon irradiance sensors were placed at different heights at the edge of the façade. The latter mentioned sensors are used for yield monitoring and comparison with the values of the simulation.

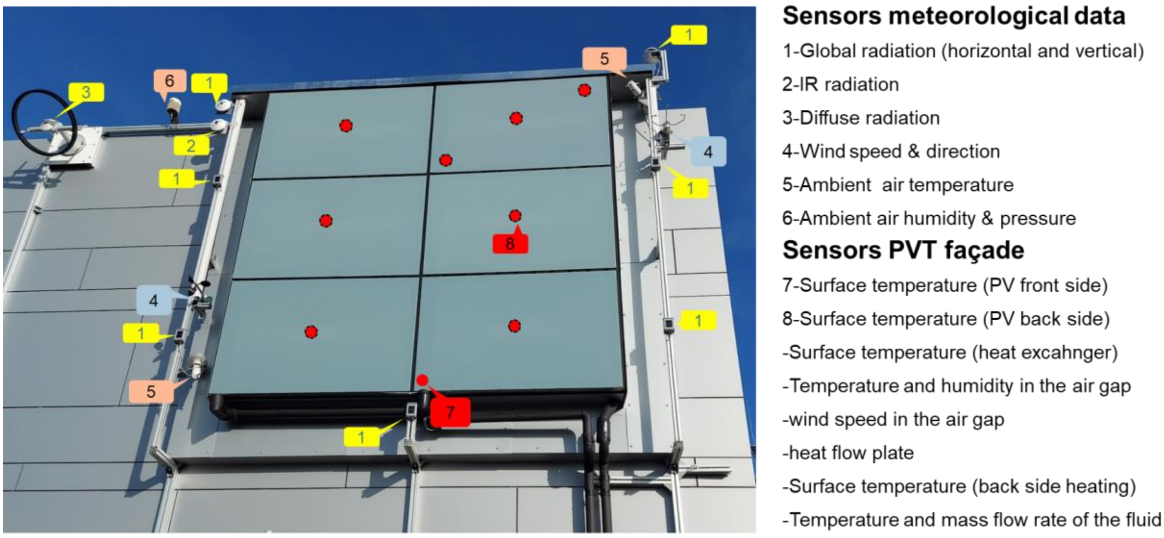

Fig 7: The PVT façade at the ISFH SolarTec building with its measurement concept, azimuth: -5°, location: Hamelin

The measurement started in November 2022. The PVT façade is characterized by means of quasi-dynamic test method according to the Standard (DIN EN ISO 9806, 2017) for liquid collectors described by the following equation:

$$\dot{Q} = A_G(\eta_{0,b}K_b(\Theta_L,\Theta_T)G_b + \eta_{0,b}K_dG_d - a_1(\vartheta_m - \vartheta_a) - a_2(\vartheta_m - \vartheta_a)^2 - a_3u'(\vartheta_m - \vartheta_a) + a_4(E_L - \sigma T_a{}^4) - a_5\left(\frac{d\vartheta_m}{dt}\right) - a_6u'G - a_7u'(E_L - \sigma T_a{}^4) - a_8(\vartheta_m - \vartheta_a)^4) \qquad \text{eq 3}$$

The calculated PVT façade parameters are listed in Tab. 2.

Tab. 2: PVT façade parameters by means of quasi-dynamic test method according to DIN EN ISO 9806 (2017)

$\eta_{0,b}$	$K_b(b_0)$	K_d	a_1	a_3	a_4	a_5	a_6
-	-	-	W/(m²·K)	J/(m³·K)	-	J/(m²·K)	s/m
0.48	0.036	0.99	9.99	0.508	0.54*	56736	0.0321

*a_4 is calculated according to eq 2

The outdoor thermal efficiency is significantly higher than the indoor one due to higher thermal capacity effect (field comparing to one module) and the solar spectrum as well as the long-wave thermal radiation in the laboratory are different from the solar and sky radiation in the field. The heat loss coefficient a_1 is lower in the field measurement than in the laboratory measurement with air gap (see Tab. 1), thus confirming our expectations and experiences with previous investigations.

Fig 8 shows an example of a daily measurement curve on a sunny day in March 2023. The hemispherical irradiance (G) reaches a maximum of 900 W/m². The temperature of the heat transfer medium at the inlet of the PVT façade (T_{in}) was set to 6 °C. The ambient air temperature (T_a) increases from 0 °C and reaches a maximum of 8 °C at 14:34 o'clock and decreases thereafter. The specific thermal power (q_dot exp) tends to run analogously to the global radiation and reaches a maximum of 315 W/m² (max. temperature increase of the heat transfer medium is about T_e-T_{in} = 7.6 K). Electrically, the PVT façade achieves a maximum specific power ($P_{ele\ exp}$) of about 82 W/m².

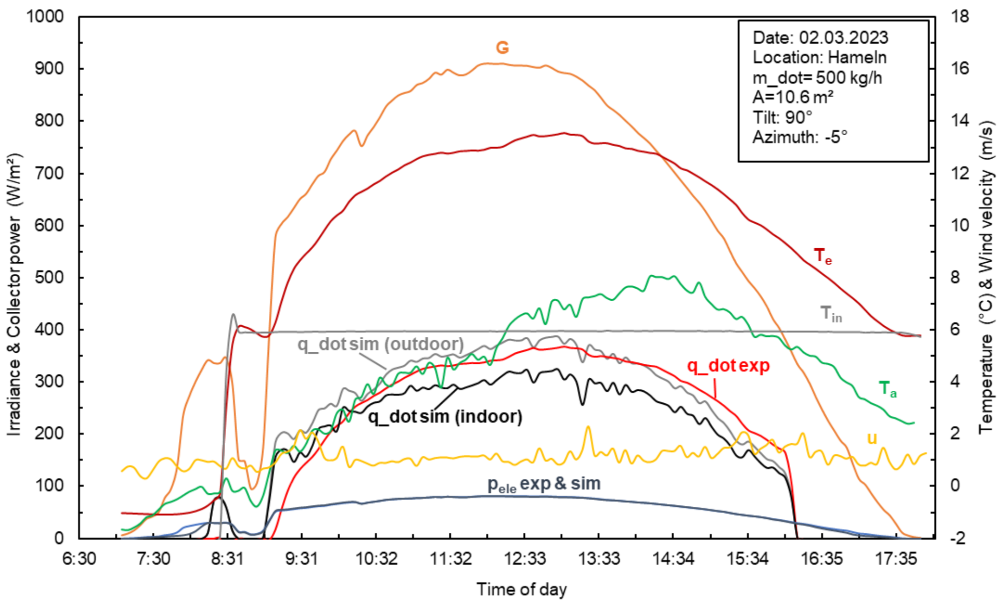

Fig 8: A daily measurement and simulated curve of the PVT façade at ISFH

In order to monitor the measured electrical and thermal yield, the characteristic values from the laboratory measurement on the one hand and the determined characteristic values of the PVT façade on the other hand are used for parameterization. Fig 8 shows the respective calculated thermal yields, whereas: q_dot sim (indoor)is based on the laboratory characterisation according to (eq 1) and q_dot sim (outdoor) on the field characterisation according to quasi-dynamic method (eq 3).

For q_dot sim (indoor), the collector coefficients for the closed air gap case and in MPP mode (see Tab. 1) were used, which better reproduce the behavior of the real façade. The simulated thermal yield depicts the measured one with a deviation that is mostly less than 20% (measurement uncertainty of q_dot is about 5%). The deviation can be due to the following reasons:

- In the field, the measurement of the wind velocity shows a high variation over the façade area and the position of the sensor used can have a strong impact on the results (Frick et al. 2022). The maximum velocity was used in the calculation of the simulated thermal yield.
- The laboratory measurement is done with artificial wind, which characteristics (turbulence, direction, homogeneity) differ from those of the real wind in the field measurements. As a result, there is a significant influence on the heat transfer between the collector and the environment (Frick et al. 2022).
- Installation situation is different (dimension of modules and façade as well as edge effects).
- The solar spectrum as well as the long-wave thermal radiation in the laboratory are different from the solar and sky radiation in the field.

By using the second approach, the simulated thermal yield q_dot sim (outdoor) shows as expected a better agreement with the measurement. From 10:20 onwards the deviation is below 15% and from noon onwards it is significantly lower than 10%. The deviation could be significantly reduced especially due to the more precise determination of the wind velocity.

For monitoring the thermal yield with the BIM method, the first approach can be implemented with manageable effort (laboratory characterization), because the parameters are either available from data sheets or can be determined with a standard test procedure in the lab. Both possibilities are much easier than a field measurement. However, the deviation is significantly larger compared to the use of field measurement parameters and this aspect should be considered for the further development of the method.

Analogously to the thermal yield, the electrical efficiency measured in the laboratory according to standard conditions (STC) is used to monitor the electrical yield. Fig 8 shows that the simulated electrical yield represents the measured electrical yield with high accuracy. The deviation is less than 3%. It should be mentioned that the dependence of the simulated electrical yield on the module temperature is not considered.

The measured data (thermal as well as electrical yield and global radiation) are linked in the CDE with a time resolution of 5 min to the BIM model as described in the next sections. For the BIM-based monitoring approach, the selected sensors listed in Tab. 3 were used if the target data are determined according to eq 1.

Tab. 3: Sensors for the BIM-based monitoring concept

1	Pyranometer (G)	**5**	Coriolis (m_dot)
2	Pyrgeometer (IR)	**6**	Anemometer (u)
3	PT-100 (T_{in})	**7**	Ambient air temperature sensor (T_a)
4	PT-100 (T_e)		

6. CDE as a central basis for yield monitoring and other use cases

The CDE serves as a central communication and collaboration platform in a BIM project (so-called single source of truth). The main functions of a CDE are information exchange, collaboration, visualization and quality assurance. The CDE is used to exchange BIM models, documents, and collaboration assets, with various open data formats, such as IFC, to ensure successful project delivery regardless of the software products used by the stakeholders. For the operational phase the browser-based CDE allows users to visualize retrieved monitoring data in real time (dynamically). Deviations from target data (in our case thermal and electrical yield) can be detected and the failure of specific components (in our case a PVT module) can be diagnosed automatically. In case of a failure, the faulty component can be located easily and visualized by the 3D representation of the system (in our case the PVT-façade).

The possibilities of using a CDE as a platform in projects with PVT façades and their monitoring are manifold. As shown in Fig 9, a CDE (in this case Squirrel CDE developed by the project partner albert.ing) displays and links the component objects and their semantic properties of an IFC model. For the considered yield monitoring, a CDE mockup was created, which allows the import of target and measured data of PVT systems. The measured data include global radiation, specific thermal as well as electrical yield (see Fig 8). The determination of the target data is listed under 5.

The platform highlights deviations of the actual yields from the predicted values that exceed a predefined tolerance threshold. If this occurs, the corresponding PVT string is colored red to enable clear evaluability and thus ensure practicable operation of the PVT façade, otherwise the corresponding PVT string is colored green (as shown in Fig 9). The maximum permitted deviation between actual and target data is exemplarily selected in the representation in order to illustrate the BIM-based method for monitoring.

If one or more strings are colored red, the person responsible for the system operation is contacted and informed automatically. If maintenance is necessary, all required data such as warranty, manufacturer and installation data are available in the CDE. After repair or replacement, the correspondent data have to be updated. Other BIM model-based use cases can be processed in a similar way.

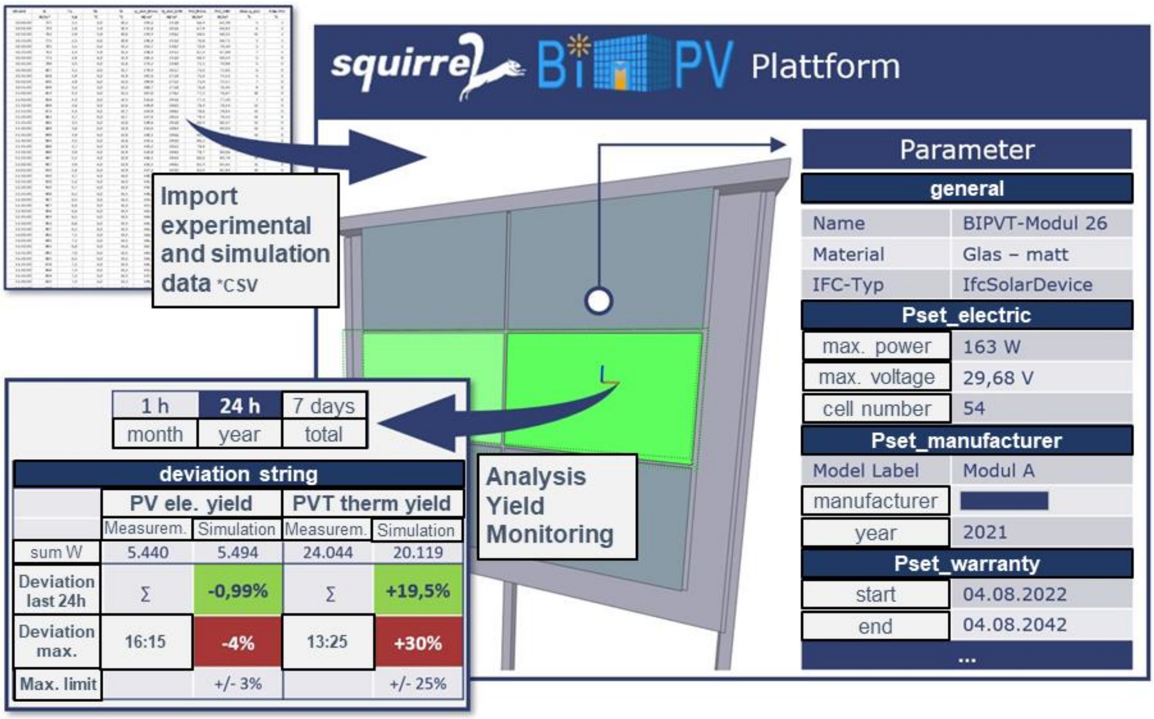

Fig 9: BIM-based monitoring concept of a PVT façade

7. Summary and outlook

Building Information Modeling is a not yet well-established but very promising method for the planning, construction and operation of buildings (building envelope, technical building equipment, etc.). It generally improves collaboration and data exchange between the stakeholders involved in the entire construction process and can be fundamentally applied to all life cycle phases of a building. With regard to the energy supply system, its application can reduce errors due to data loss, manual data transfer, traditional communication methods or model duplication, thus saving time and costs. However, there are still many limitations to its use, especially for solar components and systems. The available models of PV or ST are neither consistent nor fully parameterized. To date, there are no object models for PVT. In addition, the use of the BIM method has so far mainly been limited to the planning process due to its complexity.

In order to use the BIM method in the operational phase to monitor a PVT façade, a BIM model of the existing plant was developed in Autodesk Revit BIM authoring software. The BIM model was further used to create a digital twin on a BIM platform (CDE). The CDE not only stores all necessary data of the PVT façade, but also allows the display and evaluation of the measured thermal as well as electrical yield. It also compares the measured data with the target data, which is based on performance parameters of the module and measured weather data. If the deviation between the measured and simulated data is higher than allowed, the affected PVT string is marked in red. In this case, the responsible person is requested to check the strings and possibly repair or replace defective components.

Within the scope of the project, the first steps for the representation of solar components as BIM models as well as for the methodical linking with the BIM platform both for the planning and for the operation of the façade have been developed so far. For a practical application, the following crucial questions remain to be answered:

- Is the data from available laboratory measurements sufficient for parameterization and especially for BIM-based monitoring of building-integrated solar systems, or is operating data required as target data for this purpose?
- Which minimum measurement equipment is required for successful BIM-based monitoring of a PVT façade to make the concept feasible and economical?

- Which deviation tolerance in terms of target data and uncertainty of measured data is plausible?
- Which time resolution of the actual data is plausible for BIM-based monitoring?

In answering these central questions, one can draw on the existing, extensive know-how of monitoring and fault detection in the field of solar thermal systems like (Pärisch and Vanoli, 2007)and (Schmelzer et al. 2021).

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Appendix: Units and Symbols

Quantity	Symbol	Unit
A_G	*Gross Area of collector*	m²
a_1	*Heat loss coefficient*	$W/(m^2K)$
a_2	*Temperature dependence of the heat loss coefficient*	$W/(m^2K^2)$
a_3	*Wind speed dependence of the heat loss coefficient*	$J/(m^3K)$
a_4	*Sky temperature dependence of the heat loss coefficient*	-
a_5	*Effective thermal capacity*	$J/(m^2K)$
a_6	*Wind speed dependence of the zero loss efficiency*	s/m
a_7	*Wind speed dependence of IR radiation exchange*	$W/(m^2K^4)$
a_8	*Radiation losses*	$W/(m^2K^4)$
G	*Hemispherical solar irradiance*	W/m^2
G_{hem}	*Hemispherical solar irradiance*	W/m^2
G_b	*Direct solar irradiance (beam irradiance)*	W/m^2
G_d	*Diffuse solar irradiance*	W/m^2
Kb	*Incidence angle modifier for direct solar irradiance*	-
Kd	*Incidence angle modifier for diffuse solar radiation*	-
Qth	*Thermal power output*	W
q_dot	*Specific thermal power output*	W/m^2
m_dot	*Mass flow rate*	kg/h
u	*Surrounding air speed*	m/s
$\eta_{0,b}$	*Peak collector efficiency based on beam irradiance G_b*	-
$\eta_{0,hem}$	*Peak collector efficiency based on hemispherical irradiance G_{hem}*	-
ϑ_a	*Measured ambient air temperature*	°C
ϑ_m	*Mean temperature of heat transfer fluid*	°C
ε	*Hemispherical emittance*	-
α	*Solar absorptance*	-