Performance evaluation towards improved BiPV-Systems – Simulation of BiPV-systems installed on existing building facades using TRNSYS

Sascha Lindig   **– EURAC – sascha_lindig@gmx.de**

David Moser   **– EURAC – david.moser@eurac.edu**

Stefano Avesani – EURAC – stefano.avesani@eurac.edu

Roberto Lollini   **– EURAC – roberto.lollini@eurac.edu**

Abstract

The main focus of this work was the simulation and optimization of a BIPV-façade-system configuration through the development of simulations using the "TRNSYS" software. First, several limitations and constraints within the TRNSYS framework needed to be solved to develop a reliable simulation environment. Various parameters were detected which influence the temperature distribution over a BiPV-system and thus the PV-efficiency. Several configurations were selected and optimized in order to maximize the energy yield of the system by varying the air gap between the building structure and the external pane of the BiPV-installation. Furthermore, the impact on the building behavior was examined. The achieved results showed the positive contribution of the integration of PV in a façade system to the building energy balance.

1. Introduction

1.1 Building integrated PV

Building integrated photovoltaic (BiPV) systems are conventional building applied photovoltaic systems with additional functions. PV-modules, which are integrated in or on a building envelope, replace parts of the building construction components and need to fulfill partly their properties. Often PV-modules are applied or integrated on buildings without taking into account influences of the temperature effect on the PV-production, the heating and cooling exchange with the building, and ultimately the indoor comfort.

Further to electricity production, possible benefits of BiPV-systems can be achieved by taking into account the thermal behavior of the system and the impact on the building itself (Sinpasis et al., 2012). The temperature distribution between the building where the PV-array is applied and the system has a significant effect on the overall performance of the system and the indoor conditions (Gan, 2009). The distribution of the temperature depends on different parameters. These parameters need to be clarified and investigated in order to improve the temperature distribution within the air gap between the building envelope and the installed PV-array. The temperature in the channel rises together with the height of the system. This temperature gradient directly influences the PV-cell temperature and thus also the overall efficiency of the installed system.

The first aim of this work was to specify the parameters that affect the PV-efficiency. Two different target buildings (one residential and one office) were investigated and thus two simulation set-ups with PV-system - with a certain size installed on the façade of the target buildings – were created. Additionally, the height of the PV-array was investigated. Since the PV-array is installed along the façade of the building envelope, the module angle is 90° and the azimuth angle was fixed to 0° (south oriented). Several simulations within the TRNSYS simulation environment were carried out while varying the air gap size (range 1-200 mm). Every simulation covered one year with a one-hour resolution and the chosen location was Bolzano. Based on the results, optimal air gap sizes

between the system and the buildings were investigated by evaluating the energy yield and thus the annual power output of the system.

1.2 Effect of temperature on PV-performance

The temperature dependency of solar cells is one of the most critical points while installing a photovoltaic system. Depending on the used photovoltaic technology, the power output decreases up to 0.6%/K of increased cell temperature (Kamalanathan et al., 2002). However, not just the direct energy conversion is negatively influenced by higher temperature working conditions. In fact, the degradation rate increases significantly. Already in the FSA project, which was funded by the U.S. Government and carried out in the mid-eighties with the purpose of the investigation of the applicability of terrestrial photovoltaic systems, it was mentioned that the degradation rate of PV-modules doubles for an increase of 10 K in temperature (Smokler et al., 1986). Many factors besides the ambient temperature affect the operating temperature, such as the radiation intensity or the airflow behind the PV-application.

Every PV-module has a specific temperature coefficient γ, which is given by the manufacturer. The coefficient mainly depends on the chosen photovoltaic material. The higher this value is, the higher is the temperature dependency of the respective system. Crystalline silicon (c-Si) solar cells are highly dependent on the temperature. Temperature coefficients of around -0.45%/K are usual. This value expresses that if the cell temperature rises by 1 K the power output decreases under constant irradiation by 0.45 percent. Amorphous silicon cells in turn are less affected by temperature what can be seen in lower coefficients of about -0.13%/K. The temperature coefficient of modules made out of copper-indium-(gallium)-selenide is with roughly -0.36%/K slightly lower than the one of c-Si (Virtuani et al., 2010). These three kinds of modules are the most commonly used systems. Crystalline silicon modules were considered in this work as they represent the highest share on the market.

2. BiPV-simulation

Based on the temperature dependent behavior of photovoltaic systems, it is possible to carry out simulations with which a specific installation might be evaluated as well as optimized. A simulation environment which suits this purpose is TRNSYS (Klein, 2012). It is a FORTRAN-based simulation software and consists of subroutines, called "Types". Each type represents a specific system with several inputs, outputs and parameters. To create a simulation, different types need to be chosen and linked together in a logical way.

One of such a type is the multi-zone building type 56. It is used to simulate a specified target building. In order to create a proper TRNSYS simulation of a BiPV-installation, multiple steps are required.

First, the defined target building, divided in an appropriate number of thermal zones, needs to be modelled within Google SketchUp with help of a TRNSYS-3D-plugin. Each thermal zone can be considered independently from each other and it is possible to specify the zones later on in an appropriate level of detail. While modelling the building in SketchUp, the outside boundary condition of each wall has to be set. These conditions are outdoor, ground, zone and other side coefficients. The outdoor condition relates to walls which are facing the outer world, the ground condition needs to be chosen if the wall is the floor of the basement and walls between thermal zones are set as zone. Other side coefficients are inputs that will be defined later.

By starting a new "3D Building project" the SketchUp model will be integrated into the TRNSYS Simulation Studio. The desired location, in our case Bolzano, needs to be set and the weather characteristics are automatically linked to the building type. The building itself has to be specified in TRNBuild, an add-on of TRNSYS, which can be accessed through type 56. The wall and window constructions will be defined as well as ventilation and infiltration values, temperature set points and additional gains for each thermal zone. Desired inputs and outputs might be chosen as well. Additionally, the connection to the

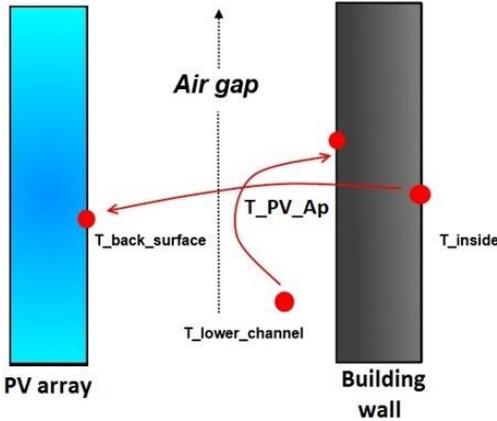building integrated photovoltaic system has to be prepared.

Fig. 1 – Connection between BiPV-type & building wall

The heart of the simulation is the BiPV-type 567. It has to be coupled to the multi-zone building type 56 within the TRNSYS Simulation Studio. The connection is illustrated in Fig. 1.

One TRNSYS BiPV-type 567 needs to be used for each façade of each floor of the building which is covered by the PV-array in order to provide a well-connected BiPV-system along the whole building. If an installed PV-system is located in more than one position per floor, more BiPV-types need to be included. One floor corresponds to one thermal zone within TRNBuild.

In Fig. 1 it is visible that the connection between the building envelope and the PV-array is realized by a two-sided temperature transfer. This transfer provides the heat exchange between the BiPV-modules and the building. The inside surface temperature of the relevant wall is given to the BiPV-type as an input called the "back surface temperature". The category of the corresponding wall was set to "other side coefficients", which means that the wall requires a temperature value as an input. This temperature is provided by the output "lower channel temperature" of type 567. It is the temperature in the air gap between the PV-array and the building. The multi-zone building model calculates the temperature of the inside surface of the corresponding wall depending on this input. This value is then sent back again to type 567, and it re-calculates the temperature of the lower air channel. The exchange repeats until convergence is reached (Bradley et al., 2004).

Further types need to be included to design the final simulation such as output-types, calculators and conversion routines.

Furthermore, the photovoltaic type 194 is used to simulate a specific free-standing photovoltaic module to consider its properties and its temperature behavior. The resulting efficiency of this PV-type under the prevailing conditions is used in the following equation:

$$\eta_{BiPV} = \eta_{PV} * (1 - \gamma_{P_{nom}} * (T_{BiPV} - T_{PV})) \tag{1}$$

Here, the efficiency of the BiPV-type is calculated. The temperature coefficient γ of the given PV-system is multiplied by the temperature difference between the well-ventilated free-standing PV-module and the BiPV-installation. Due to higher operating temperature conditions, the product reduces η_{PV} and results in the BiPV-efficiency, which is given as an input into type 567. That allows us to include the effect of higher temperatures due to a non-optimal ventilation of the system while installing it along a building façade.

Furthermore, with help of equation 2, the airflow within the air gap between the building envelope and the PV-system is considered:

$$\dot{m}_{vent} = \rho_{air} * (\dot{V}_{wind} + \dot{V}_{thermal}) = \tag{2}$$
$$\rho_{air} * (C_V * A_{in} * U_\infty + C_D * A_{in} * \sqrt{2g * \Delta H_{NPL} * \frac{T_{cav} - T_{amb}}{T_{cav}}})$$
$$(if\ T_{\ } > T_{\ })$$

The incoming air mass flow from natural forces $\dot{m}_{vent}$ is calculated by the product of the air density and the volumetric flow rate of air ventilating in and out of the cavity from wind and buoyancy-driven flows. C_V and C_D are fixed coefficients, g is the standard gravity, the wind velocity U_∞ and the ambient temperature T_{amb} are outputs given from the weather data and T_{cav} is the temperature in the air channel. If T_{amb} is higher than T_{cav} these values are exchanged with one another in equation 2. A_{in} is the opening of the airflow and it changes with the size of the air gap and the width of the PV-system. ΔH_{NPL} is the height from the midpoint of the lower opening to the neutral pressure level, in case of a vertical symmetric air gap it is the half

length of the air channel and thus of the PV-system (Griffith, 2006).

In order to create an airflow along the whole cavity the flow rate and the air temperature in the air gap of one type 567 is always given as an input to the next one which is located above.

The modelled buildings are a multi-family house and an open space office building. Both consist of five floors (88 m² each apartment and 140 m² the open office) with a height of 2.7 m each (see Fig. 2). The U-values for the external wall and window are 0.81 and 2.83 W/(m²K) and 0.42 and 1.43 W/(m²K) for the residential and office building, respectively.
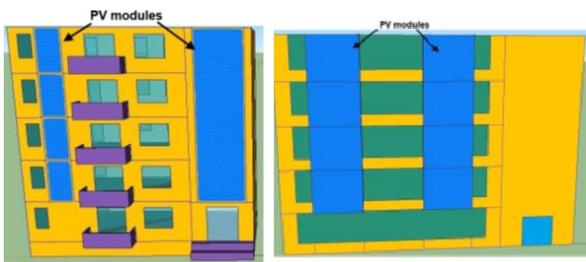

Fig. 2 – SketchUp models of simulated buildings (residential building on the left and office building on the right

The residential building is designed for four people per apartment, the office building for 16 people per office. The PV-system is installed along the façade wall of the residential building. In the case of the office building, it also covers a part of the glazing and it has the double width compared to the installation in front of the apartment envelope of the residential building. Here lies an important achievement of this work. The positioning of the PV-systems in front of the windows is not yet implemented within TRNSYS. Because of that, the explained process of the connection of the types 567 and the building needs to be expanded. For each BiPV-type an extra thermal zone has to be modelled in TRNSYS. An example is shown in Fig. 3.
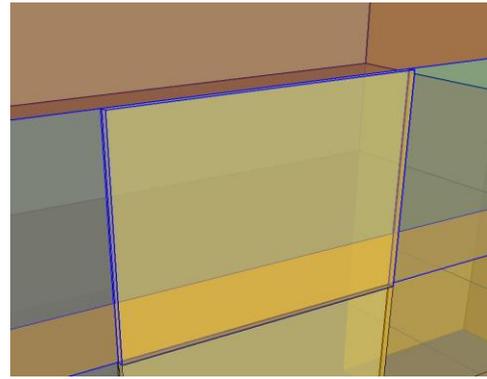

Fig. 3 – Extra thermal zone SketchUp

The area of the additional thermal zone, which is placed partly in front of a window and partly in front of an opaque part of the building envelope, is equal to the size of the PV-array. The depth of the zone corresponds to the depth of the air gap. The adjacent wall of the zone that faces the building consists of an adjacent window. The category of the wall, which represents the BiPV-array, is "other side coefficients". This wall needs to be connected to the BiPV-type 567 as explained before. The other four walls are set as virtual surfaces, which means that they are practically nonexistent in the simulations and not visible in TRNBuild.

3. Results and Discussion

Simulations on two different target buildings to simulate BiPV-systems were performed using TRNSYS. This was done to investigate the buildings, which are used for different purposes, especially in relation to the needs of the occupants and the building structure. Apart from the actual electricity generation of the BiPV-system, the heating demand (provided by an ideal heating system with infinite power) of the buildings was compared with and without installed PV-modules. The same was additionally done in case of the office building for the cooling demand based on electrical cooling.

The BiPV-type 567 has optical parameters which lower the final power output of the system and thus the performance ratio (PR) and the energy yield. The energy yield gives information about the system behavior depending on the amount of absorbed irradiation and the prevailing cell

temperature. It is the relation between the power output and the installed capacity and given in kWh/kWp. The PR, however, describes the temperature dependency of a system since it includes the incoming radiation of the sun. It is given in percentage and is an indication of how well an installed system works.

Within this study the default optical parameter values of type 567, given by TRNSYS, were used (transmittance-absorptance $\tau\alpha$ = 0.85, IAM constant = 0.1). They overestimate the losses and thereby underestimate the power generation of the PV-array. These parameters do not affect the efficiency output of type 567. For that reason, the results of the efficiency and the generated power show similar trends but the absolute values do not match.

Generally, expected trends were seen. Time periods with higher insolation in module level lead to a higher amount of generated power. Higher working temperatures of the observed system due to high ambient temperatures decrease the performance, expressed in the performance ratio. This can be also seen while investigating larger PV-systems. Because of the higher installed capacity, the annual power output increases. In turn, the PV-temperature increases and thus decreases the PR. There are mainly two reasons for the mentioned effects.

First, the higher amount of irradiation heats a larger system to a greater extent. Second, the chimney effect within the air gap based on wind driven and thermal buoyancy causes a temperature gradient ascending with the height of the system. The higher the system is, the greater is the temperature at the top of it and thus the maximum operating temperature of longer systems. Nevertheless, a PV-array should not be too small in size. An appropriate installed capacity is important.

The investigated photovoltaic material is crystalline silicon. Based on the high temperature coefficient of the selected material the performance of the system is strongly affected by high temperatures. The performance of the system is dropping under non-optimal installation conditions. The advantage of this technology is the

higher installed capacity per m² compared to thin film systems.

While considering a selected system that shall be installed on a façade, the air gap between the array and the building determines optimal working conditions of the PV-array. The closer the system is installed along the building the more significant is the temperature gradient within the air gap. This can be seen in Fig. 4.
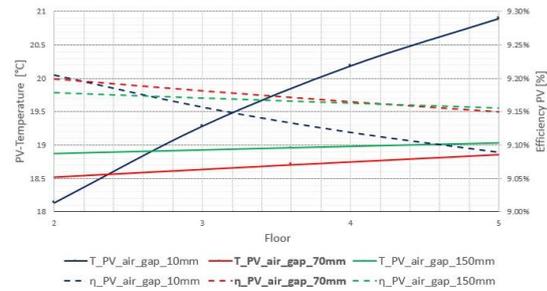

Fig. 4 – Res. Building – Aver. T & η-distribution along the air gap. Values are averaged over the year excluding nights.

The annual averaged values of the temperature and the corresponding efficiency distributions for three different air gap sizes are plotted against an ascending building height. The investigated building is in this case the residential one. The distribution of an air gap size of 70 mm is plotted under which the system performance is at an optimum while the BiPV-system is installed on the residential building. Additionally, the temperature in air gaps with sizes of 10 mm and 150 mm are shown. The solid lines represent the operating PV-temperature, the dotted one the PV-efficiency.

It can be seen that the temperature propagation depends strongly on the size of the air gap. The smaller the air gap, the steeper the temperature curve becomes. Although the temperature is lower at the lower part of the PV-system which is installed close to the building, it becomes higher at the top, compared to a bigger air gap size. If just the lowest part of the PV-system is considered, the efficiency of it is higher for systems which are installed in the smallest possible distance to the façade. However, over the whole array the non-optimal temperature distribution results in a performance drop along the PV-system. Considering the highest part of the system, a large air gap has a beneficial effect on the efficiency. The

optimum for the whole array lies between the investigated extremes.

Similar observations were made while investigating the office building. Optimal conditions have been reached under an air gap size of 100 mm. The higher value for the optimized air gap in comparison to the residential building is due to different installation conditions since the system is located partly in front of a glazed part of the building envelope and also on the width of the system. The optimization of the energy yield is shown in Fig. 5. The 3D-plot illustrates the dependence of the energy yield on the PV-system length and the air gap size.

It is visible that the energy yield decreases in a certain frame with an increasing length of the PV-system. An optimum in terms of the air gap size is reached between 40 and 100 mm depending on the array size (e.g. 40 mm for an array size of 2.7 m, 100 mm for an array size of 10.8 m). The larger the opening becomes, the less the energy yield is affected by the array length.
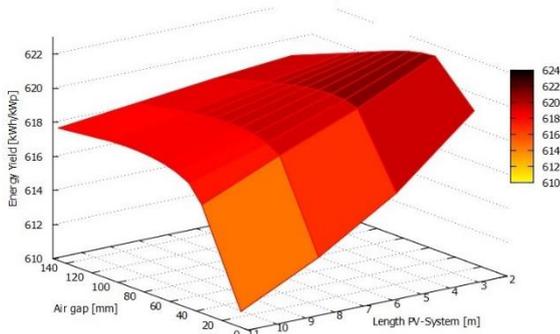

Fig. 5 – Office Building - Energy Yield Dependence

The temperature rise within smaller air gaps as well as larger PV-systems is higher. For the size of a given PV-array a suitable air gap needs to be found. This arrangement determines the created flow rate within the gap and thus the distribution of the cell temperature.

It was shown that the PV-temperature increases with a decreasing air gap. This is due to the smaller flow rate in the air channel. Warm air rises with low speed and heats up the upper part of the system. The wind speed in the gap rises together with the size of it. A higher wind speed in the channel cools the air itself and lowers the buoyancy driven chimney effect. This results in a

decreasing temperature gradient, visible in the comparison of the PV-temperature gradient in Fig. 6. Here, the temperature distribution from the bottom to the top of a PV-system, which is installed in distances of 100 mm as well as 1 mm to the envelope of the office building, is shown at an irradiation of 900 W/m² and an ambient temperature of -3 °C.
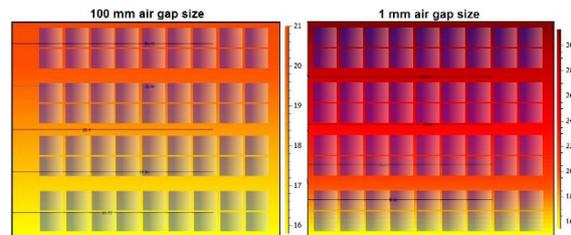

Fig. 6 – T-gradient depending on the air gap size – 900 W/m²

At the lowest part of the system, the PV-temperature and therefore the efficiency difference is relatively small in comparison. It rises with an increasing system height. The gradient increases with a decreasing air gap. The observed temperature rise of more than 15 °C in case of an air gap of 1 mm leads to the discussed efficiency drop and a decreasing power generation from the bottom to the top of the PV-array. The working temperature in case of the 100 mm wide air gap increases just about 5 °C.

While investigating a PV-array which is installed on a consisting building façade, not just the performance of the system but also the impact on the building is an important issue. The environmental influence on building parts which are covered by PV-modules changes. For example, the amount of incoming sunlight or the air flow along the surface is affected. These changes have an impact on the amount of energy needed to ensure a desired room climate.

In case of the observed residential building, this amount is equal to the heating demand. The heating demand is the amount of supplied energy that is used to provide a specified minimal room temperature. The office building is additionally cooled. It is assumed that these demands are provided by electrical energy. If no PV-system is installed the residential building requires 60.38 kWh/m² per year and the office building 14.55 kWh/m² for heating and 38.8 kWh/m² for

cooling needs. These values serve as a reference. Fig. 7 shows, in how far these amounts change while installing the BiPV-system along 10.8 m respectively 4 floors.

Fig. 7 – Energy Demand Buildings

The stated values are relative. Additionally the absolute differences between the reference cases and the buildings including installed photovoltaic systems are given. The plotted values refer to the adjusted air gap size, under which the energy yield of the PV-system reached a maximum. It is visible that the heating demand of the residential building can benefit from an installed BiPV-system. The amount of supplied energy is lower compared to the reference case. Furthermore, the variation of the air gap has just a small effect on the building behavior. BiPV-systems applied along a building façade affect the covered wall in different ways.

Less irradiation hits the building envelope. Because of that, less heat, produced mainly by shortwave radiation of the sun, is transferred to the façade. The applied system acts as kind of a protection layer in terms of low ambient temperatures. The chimney effect within the air gap creates an airflow along the building. These effects lead to the observed savings.

In contrast to the residential building, the heating demand increases while installing a PV-system along the envelope of the office building. At the same time, the cooling demand decreases to a greater extent. The increasing heating demand is mainly due to the large photovoltaic installation. The wide PV-system creates a strong airflow in the channel between the modules and the building. This cools the outer wall of the building. Since the PV-system is partially installed in front of

windows, the cooling effect has even a greater impact on the interior.

Another issue is the reduced solar gain. The panels absorb or reflect a substantial part of the insolation. The absorbed part is then converted into heat or into electrical energy. The portion that is converted into heat will be again submitted to the outside world. Due to the shading, less solar energy is transmitted into the building interior. More than 50% of the office window area is covered with photovoltaic panels. In turn, the transmitted solar gain is roughly halved. The thermal energy, which is lost by shadowing must be compensated by electrically supplied heat. On the other hand, the previous observations are also the reason for the savings in cooling energy. The BiPV-system acts like a shading system, avoiding solar gain to reach the building façade and the indoor environment. Additionally, the created air stream is cooling the building interior. During warm months in summer, the building has to be cooled to a lesser extent.

Table 16 – Overview of annual Energy Balance

	Res. Building Heating	Of. Building Heat. & Cool.
Energy Demand without BiPV	60.38 kWh/m²	53.34 kWh/m²
Energy Demand with BiPV	58.36 kWh/m²	45.78 kWh/m²
Difference: Reference – BiPV	2.02 kWh/m²	7.56 kWh/m²
Energy Generation	3,762 kWh	4,983 kWh
PV-system efficiency	9.17%	9.17%
Energy Demand Savings	**10.57 kWh/m²** **17.51%**	**14.67 kWh/m²** **27.51%**

Table 16 summarizes the discussed results. The annual values of the energy demand with and without an installed BiPV-system and their differences are given as well as the maximum achievable energy output, the system efficiency and the possible energy savings.

It is visible that both investigated building types benefit from the installation of a PV-system in matters of the energy balance. In addition, a part of the needed energy can be saved if the generated energy is used directly in the building. The amount

of savings depend on the installed capacity. For the considered cases, the savings are between 17% and almost 28%. The higher value in the case of the office building is due to the large number of possible savings in terms of the cooling demand and the higher installed capacity of PV. It can be seen that the efficiencies of the systems, using similar PV-modules, are similar under optimized conditions. As indicated above, the resulting amount of the annual energy output is reduced by TRNSYS provided parameter.

4. Conclusion

Within TRNSYS, a BiPV-installation on the opaque as well as the glazed envelope of buildings was simulated. It was demonstrated, that the simulation is not straightforward and has to be adapted in order to receive meaningful results. While developing the simulations some mistakes and ambiguities were clarified and solved.

In future simulations, a closer investigation of the power reducing parameters of the BiPV-type 567 has to be carried out.

Nevertheless, a certain understanding of the behavior of an installed PV-system on the façade of a building was gained. It was simulated that various parameters affect the performance of a BiPV-system. In the selection of a suitable PV-array, the cell temperature behavior and the nominal power of the PV-modules should be taken into account. Furthermore, it is important to pay attention on the dimensions of the array and the distance between the PV-system and the building envelope to ensure a beneficial temperature distribution within the air channel. The results proved the importance of proper simulations of BiPV-systems. A better knowledge and a deeper understanding of the dependency of the parameters and adjustments of building integrated photovoltaic systems to each other are necessary to optimize the build-up and to ensure the best working conditions of the PV-array. The aim of future simulations will be an improvement of the result accuracy as well as an increase of the level of the simulation-detail.

5. Acknowledgement

6. Nomenclature

A_{in}	Opening area of the air flow [m²]
BiPV	Building integrated photovoltaic
C_D	Opening discharge coefficient
C_V	Effectiveness of openings
c-Si	Crystalline silicon
g	Standard gravity [9.81 m/s²]
$\dot{m}$	Air mass flow [kg/h]
PR	Performance ratio
T	Temperature [°C]
U_∞	Wind velocity [m/s]
$\dot{V}$	Volumetric flow rate [m³/s]
ΔH_{NPL}	Height from midpoint of lower opening to neutral pressure level [m]
η_{PV}	Efficiency photovoltaic-system [%]
γ	PV-temperature coefficient [%/K]
ρ_{air}	Air density [kg/m³]

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