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COMPARATIVE ANALYSIS OF SEMI-TRANSPARENT BIPV SYSTEMS IN FAÇADE OF OFFICE BUILDING – CASE STUDY

POROVNÁVACIA ANALÝZA ČIASTOČNE TRANSPARENTNÝCH FOTOVOLTICKÝCH SYSTÉMOV INTEGROVANÝCH VO FASÁDE KANCELÁRSKEJ BUDOVY – PRÍPADOVÁ ŠTÚDIA

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Tomáš Hakszer pôsobí ako interný doktorand na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojom výskume sa venuje problematike simulovania adaptívnych fasád. Peter Hanuliak pôsobí ako odborný asistent na Stavebnej fakulte Slovenskej technickej univerzity v Bratislave. Vo svojom výskume sa venuje najmä problematike denného osvetlenia budov a konštrukčnej tvorby budov.

Tomáš Hakszer works as an internal PhD student at the Faculty of Civil Engineering of the Slovak Technical University in Bratislava. His research is focused on simulation of adaptive facades. Peter Hanuliak works as an assistant professor at the Faculty of Civil Engineering of the Slovak Technical University in Bratislava. In his research, he mainly deals with the problematics of daylighting and constructions of buildings.

Abstract
Photovoltaic (PV) transparent panels represent one part of a subset of Building-integrated photovoltaics (BIPV). These elements hold a great potential to develop and find new and innovative solutions to utilize most of the energy generated from renewable sources. So the buildings can be operated more energetically independent. In this paper we focused on the possibility of BIPV application as a replacement for standard glazing for office building in the climatic conditions of Slovakia. The first part is theoretical, introducing on the basic concepts and types of transparent PV panels, as well as a comparison of the properties of commonly used glazing and selected PV panels. The aim of the second part is to evaluate the application of transparent PV panels in the conditions of Bratislava on the office building. For this case study a high-rise administration building of the Faculty of Civil Engineering was selected. A computer simulation was performed using a climatic data in various alternations.
Key words: building-integrated photovoltaics, transparent photovoltaics, office buildings

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Abstrakt
Fotovoltické (PV) transparentné panely predstavujú jednu časť z podmnožiny fotovoltiky integrovanej do plášťa budovy. Toto odvetvie má veľký potenciál na vývoj a hľadanie nových inovatívnych riešení ako čo najviac využiť energiu získanú z obnoviteľných zdrojov tak, aby sa budovy stávali čo najviac energeticky nezávislé. V práci sme sa zamerali na možnosť aplikácie takýchto systémov ako náhradu za tradičné zasklenia v klimatických podmienkach Slovenska. Prvá časť je teoretická, zameraná na zakladené pojmy a druhy transparentných PV panelov a zároveň porovnanie vlastností tradične používaného zasklenia a vybraných transparentných PV panelov. Cieľom druhej časti je zhodnotiť pomocou simulačných metód použitie transparentných PV panelov v klimatických podmienkach Bratislavy na výškovej budove Stavebnej fakulty – blok C.
Kľúčové slová: fotovoltika integrovaná do plášťa budovy, transparentná fotovoltika, kancelárske budovy

Introduction

The need and demand for energy is very high worldwide. In the energy production process, commonly fossil fuels are still widely used, of which the reserves are limited and therefore finite. Energy from them is obtained by burning and it is an irreversible process that also has a negative impact on climate change, pollutes the environment, causes global warming, acid rains, and negatively affects people's health. For these reasons, there is a worldwide effort in all sectors to replace fossil fuels with renewable energy sources. Renewable energy is produced from natural sources. Technologies using renewable energy are cleaner and more environmentally friendly. The main source for renewable energy is the Sun. Solar radiation also affects wind, water and geothermal energy, as well as biomass.

The building construction sector contributes to approximately 39% of global greenhouse gas emissions. Emissions are produced during the manufacturing of building materials, during the construction itself and subsequently by the operation of buildings, where emissions are mainly produced by heating and cooling systems. The aim in the building industry is to operate buildings with almost zero energy needed and/or to maximize utilisation of renewable energy systems directly in the building.

In order to achieve a reduction in the building energy needs, the façade construction plays an important role. The façade is the outer envelope of the building, which creates a filter between the internal and external environment. In recent years, new building cladding materials, new facade elements and components have been developed in the construction industry, which optimize energy efficiency, provide greater comfort and convenience for users, their health and are more environmentally friendly. Worldwide, there is a growing interest in the integration of photovoltaics into the building, where the PV panels become part of the building structures [1].

Photovoltaics and Photovoltaic (PV) Panels

PV panels play an important role in the scope of renewable energy sources. Photovoltaics is a technical field dealing with the process of light conversion, i.e. solar energy into electricity. The name photovoltaic is derived from the words "photo" which means light and "volt" is a unit of electric voltage. The conversion process takes place in photovoltaic panels [2]. A PV panel (module) is made of a larger number of PV cells that are connected in series with each other. A PV cell is a large-area semiconductor component that directly converts light energy into electrical energy (direct current) using the photoelectric effect. The energy conversion process occurs immediately after the sun's rays hit the PV panel surface, where electrons are released in layers of PV cells. A difference in the collection of positive and negative electric charge carriers on opposite sides of the cell creates a DC voltage, which drives a current to flow between the front and back. To use the energy obtained in this way for typical appliances, it is necessary to change the direct voltage to alternating voltage, using an inverter. This element is a basic part of a local photovoltaic power plant or power generator [3].

Building-integrated Photovoltaics (BIPV)

Building-integrated photovoltaics means all the PV systems that are integrated mostly into the building envelope or any other part of the building components. It provides an aesthetic, economic and technical solution with very high efficiency of energy production. Components can be integrated into façades, roofs structures, shading systems, also in the form of semi-transparent elements in windows, in roof tiles or in roof waterproofing systems. [4] The BIPV system has a dual function. PV panels replace traditional building materials and ensure the protective function of the building envelope. It protects the building against weather conditions, provide thermal insulation, fire and noise protection, facade ventilation and daylighting. From an architectural point of view, it provides an expressive element that can enhance the overall aesthetics of buildings and thus create the desired visual effect. PV panels mainly transform part of the incident solar energy into electrical energy, defined by its efficiency [5]. Integrated photovoltaics in buildings is a modern, architecturally trendy and also meet the requirements of energy independence by producing ecologically clean energy from renewable sources [4]. For these reasons, the BIPV system is the subject of various scientific researches [6, 7, 8, 9] and studies that bring new solutions.

In the work [10] authors evaluated BIPV systems from the scope of energy performance and economical yield. Their testing took place in a real environment with 35 different BIPV systems. The obtained results indicate that 62% of the tested systems have insufficient performance, mainly façade systems. At the same time, based on the findings in the work, they provided possible solutions and techniques that should be integrated into the technical solutions of the BIPV systems, resulting in higher system performance achievement. The common problem is that part of the solar radiation falling on the PV cell is not converted into electrical energy but into thermal energy. This condition causes an increase in the temperature of the PV panel, which becomes overheated and subsequently the performance decreases and the efficiency of the conversion of solar energy into electricity diminishes. The proposed solution to reduce the high operational temperatures of PV panels is ventilation of the its substructure. Air movement can be natural (passive) or mechanical (active). Another solution is to actively use the excessive thermal energy for activation of the PCM materials [11] Another reason for the decrease in system performance can be caused by the shading of photovoltaic panels by neighbouring buildings or envelope elements, and therefore it is necessary to take into account the orientation, distance and height of them or other potential sources of shading.[12]

Transparent integrated Photovoltaics

Transparent BIPV is a transparent building material in the form of a PV glass panel that offers a replacement for traditional glazing systems in buildings envelopes. It is made of thin-film materials such as amorphous silicon (a-Si PV) or crystalline silicon (c-Si PV). It exhibits high strength and resistance to impact. Transparent modules convert solar radiation into electrical energy and at the same time transmit part of the visible light spectrum.[13]

PV Modules based on Amorphous Silicon (a-Si PV)

Amorphous silicon is a non-crystalline form of silicon, used as a semiconductor material for a-Si solar cells or thin-film silicon solar cells, deposited in thin layers on various flexible substrates such as glass, metal, plastic or films [14]. PV modules made of amorphous silicon, unlike traditional modules, can provide daylight penetration into the interiors. The light transmission factor of these panels can reach a level of up to 30%. These photovoltaic modules offer architects design flexibility with various shapes, colours, sizes, thicknesses, and degrees of clarity, so that they can meet desired aesthetic and technical requirements. The advantage of this technology is that in cloudy weather they produce more energy compared to crystalline silicon modules, and thanks to the low values of solar heat gain coefficient (g-value), the total overheating of interiors is reduced. The disadvantage is that they have a shorter lifetime and overall efficiency than crystalline silicon modules.[14,15]

PV modules based on Crystalline Silicon (c-Si PV)

The crystalline form of silicon can be produced either in the form of monocrystalline or polycrystalline silicon. Crystalline silicon is the dominant semiconductor material used in photovoltaic technology to manufacture solar cells [14]. From the perspective of architectural needs, PV modules can be designed in various shapes (e.g. trapezoids) with the possibility of regulating the amount of light passing through the module. Overall transmittance rate is achieved by placement of the solar cells, denser or thinner in the arrays over the glass panes. The disadvantage is the creation of unwanted shadows, which are created by passing light between the individually placed cells depending on their distribution, so the light transmittance is not uniform over the whole area of a glass pane. The light transmission factor of the panels can reach a level of up to 40%. Compared to amorphous silicon, this technology has a greater nominal power per m^2 and therefore the modules are also suitable for a smaller area of the façade [14,16].

Work methodology

The specific aim of this paper is to evaluate the possibilities of selected various types of PV glazing application in the climatic conditions of Bratislava. We focused on transparent BIPV systems. We evaluated the amount of electricity produced and subsequent variation in the availability of daylight in the interiors. Transparent PV panels from the catalogue of Onyx Solar Group LLC were used for the computer simulations. Presented PV modules are made of amorphous silicon (a-Si PV) and crystalline silicon (c-Si PV) respectively. The properties of a-Si and c-Si modules were extracted from technical documentation of the producer (Table 1.) The PV panels and glazings with the best thermal insulation properties were selected with considered layers composition.

The high-rise office building of the Slovak University of Technology, Faculty of Civil Engineering in Bratislava was chosen as a representative object. The examined building has 23 overground floors and a total height of 77.5 m. External dimensions are 46.6 m x 15 m of the rectangular shape of its floors.

The model of the high-rise building of the Faculty of Civil Engineering and its surroundings was created in the Rhinoceros software environment (Fig. 1). The geometry of the building model as well as the surrounding shading obstructions, which will affect the amount of incident sunlight, was determined on publicly available information from the OpenStreetMap portal (Fig. 1). The different PV panels were applied in the simulation program on the patches of the façade (Fig. 2). The PV panels were installed on the upper half of the window openings. The lower half of the openings was glazed with an insulating triple glazing system to maintain full visual contact for the occupants of the buildings in seating position (Fig. 2).

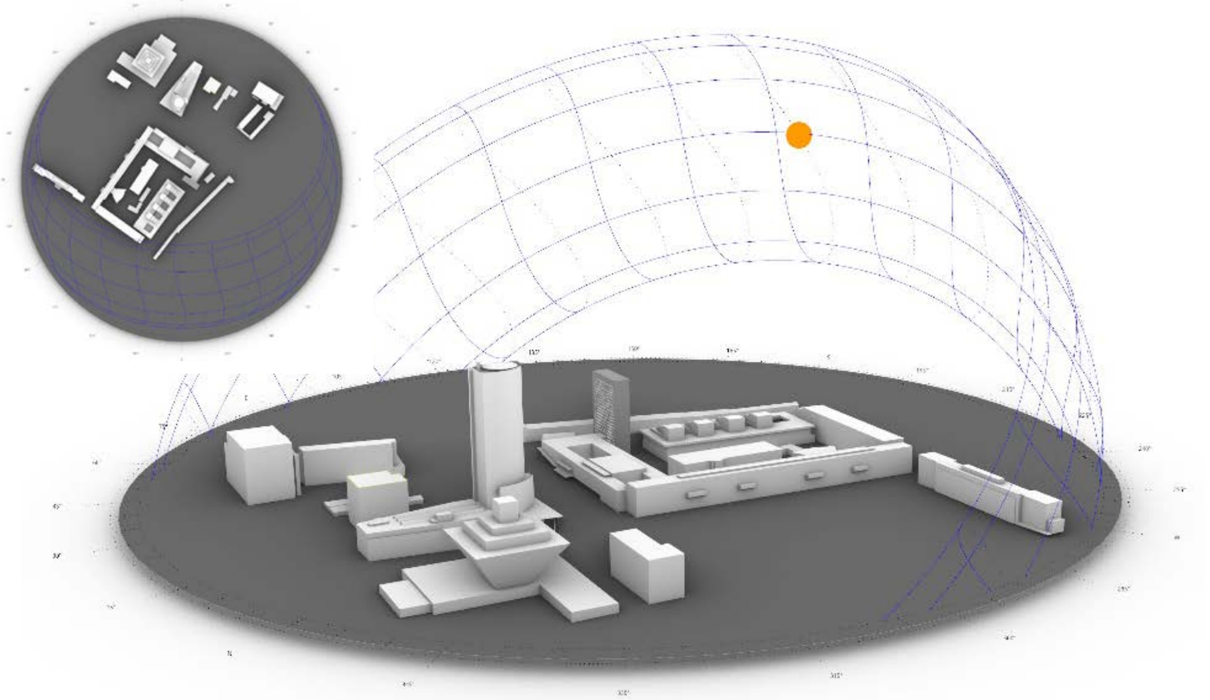

Fig. 1 – 3D Model of the evaluated buildings in izometry (bottom)
and in top-view with cardinal directions (left)
Source: authors

The high-rise building of the STU, Faculty of Civil Engineering is located in Bratislava, the capital of the Slovak Republic (48,15°N, 17,11°E). Based on the Atlas of the Slovak Republic [17] this location belongs to the climate of warm, slightly dry area with mild winter. Climatic data (Fig. 3) including the amount of incident solar radiation (Fig. 4) were considered in the simulation in the form of a reference climatic year (SVK_BL_Bratislava-

Stefanik.AP.118160_TMYx.2004-2018) with an hourly time step, which was selected from the extensive Climate Studio software library.

Glazing System type / PV Module type	Reflectance ratio (visible light) [-]	Transmittance ratio (visible light) [-]	g-value [-]	U - value [W/(m^2. K)]	Nominal peak power of the PV module [Wp/m^2)]
Double glazing[2]	0,11	0,77	0,65	1,0 – 1,6	-
Triple glazing[3]	0,17	0,70	0,60	0,5 - 1,2	-
a-Si PV module, non transparent[4]	0,073	0,002	0,05	1,0	57,6
a-Si PV module low transparency[4]	0,073	0,108	0,09	1,0	40,0
a-Si PV module medium transparency[4]	0,070	0,16 - 0,17	0,12	1,0	34,0
a-Si PV module high transparency[4]	0,071	0,26 - 0,28	0,17	1,0	28,0
c-Si PV module PV high cell density [5]	0,083	0,15	0,07	1,0	174,0
c-Si PV modul PV low cell density[5]	0,083	0,38	0,20	1,0	126,0

Table 1 - Comparison of properties of a-Si/c-Si modules and conventional glazing sytem used in Slovakia
Source: authors

[2] Low-e double glazing system with Ar filling
[3] Low-e triple glazing system with Ar filling
[4] glazing 6 mm + a-Si cells over 3,2mm float glass + glazing 6 mm – Ar filled gap 12 mm - glazing 4 mm – Ar filled gap 12 mm – low-e glazing 6 mm
[5] glazing 6 mm + c-Si cells + glazing hr. 6mm – Ar gap filling.12 mm - glazing 4 mm – Ar filled gap 12 mm – low-e glazing 6 mm

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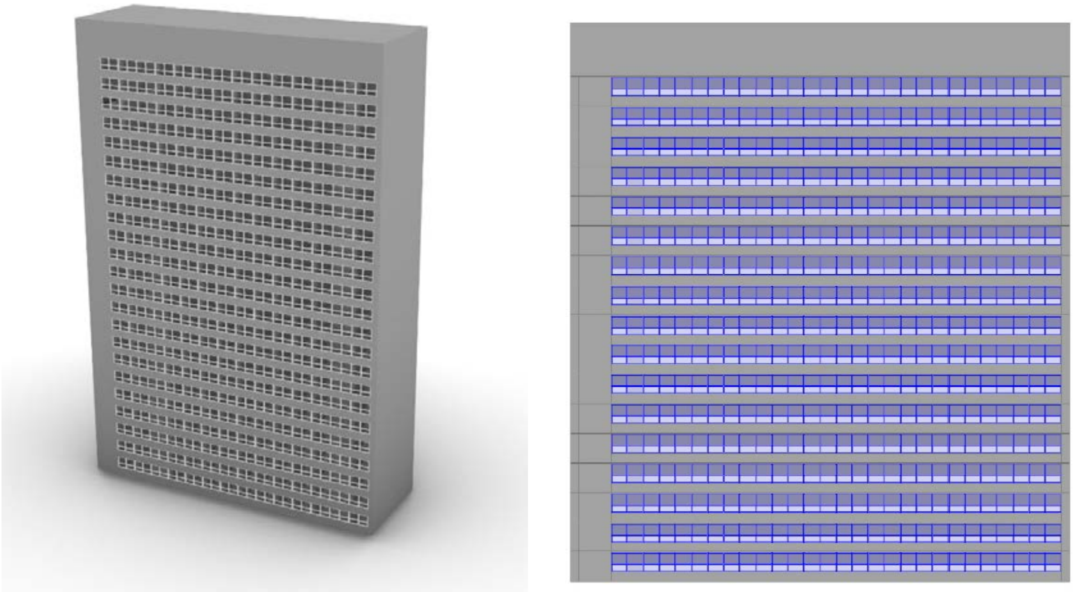

Fig. 2 Evaluated model of the office building with the layout of the PV modules placement (clear glazing – light blue in bottom parts of the windows, PV modules – dark blue in upper part of the windows)
Source: authors

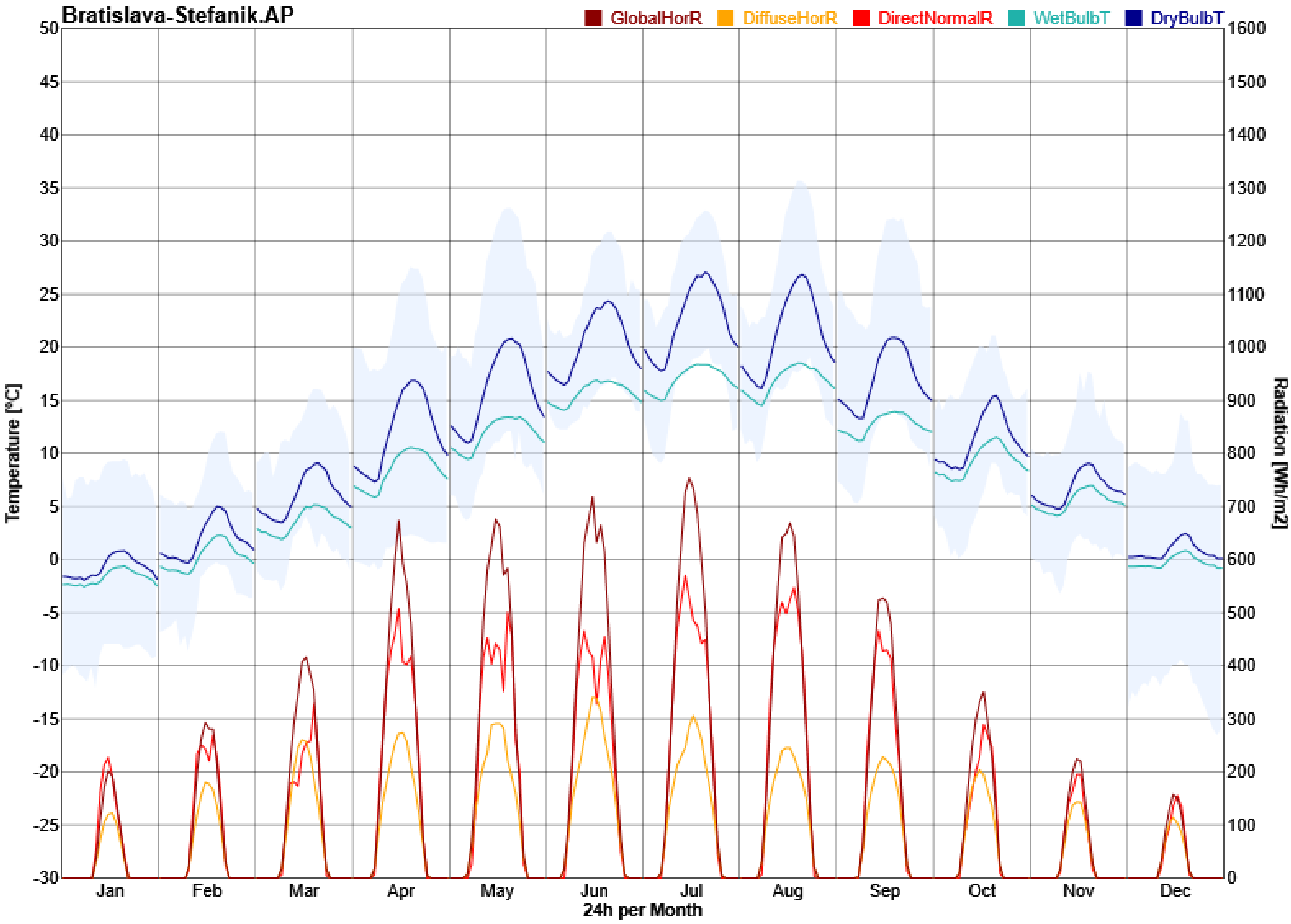

Fig. 3 – Annual climate data for Bratislava (Climate Studio)
Source: authors

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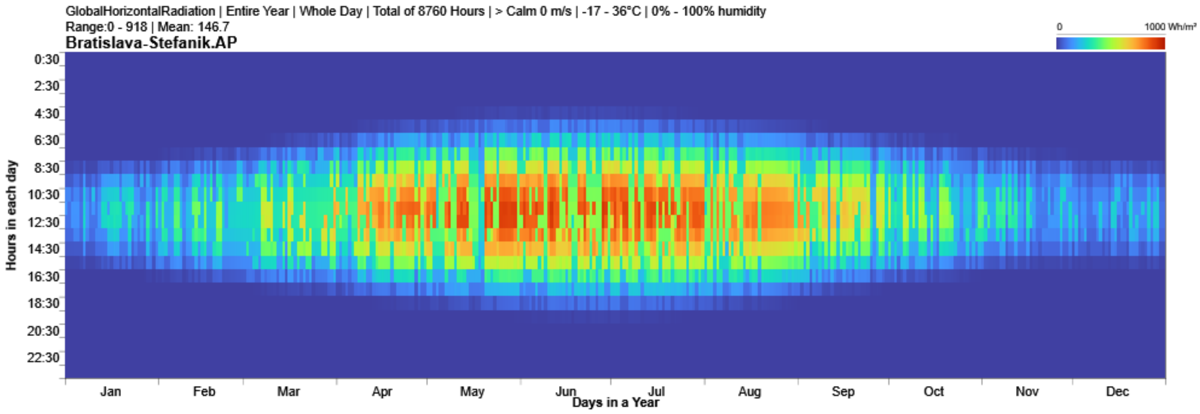

Fig. 4 – Annual course of global solar radiation on the horizontal surface – Bratislava
Source: authors

The following variants were examined:

- Variant 1: the glazing of all openings in the structure consists of the clear insulating triple glazing τ = 0.7 in the whole window area.
- Variant 2: the glazing of the upper part of the window forms an a-Si PV module with high transparency τ = 0.26. Nominal power of PV module 28 Wp/m^2. The glazing of the lower part consists of the clear insulating triple glazing τ = 0.70.
- Variant 3: the glazing of the upper part of the window consists of an a-Si PV module with medium transparency τ = 0.16. Nominal power of PV module 34 Wp/m^2. The glazing of the lower part consists of the clear insulating triple glazing τ = 0.70.
- Variant 4: the glazing of the upper part of the window consists of c-Si PV with a low cell distribution density τ = 0.38. Nominal power of PV module 126 Wp/m^2. The glazing of the lower part consists of the clear insulating triple glazing τ = 0.70.
- Variant 5: the glazing of the upper part of the window consists of a-Si PV module with low transparency τ = 0.10. Nominal power of PV module 40 Wp/m^2. The glazing of the lower part consists of insulating triple glazing τ = 0.70.

The selected variants were evaluated to determine how the given solutions would affect interior daylight levels. A typical - 7th floor of a high-rise building was selected for assessment (Fig. 5).

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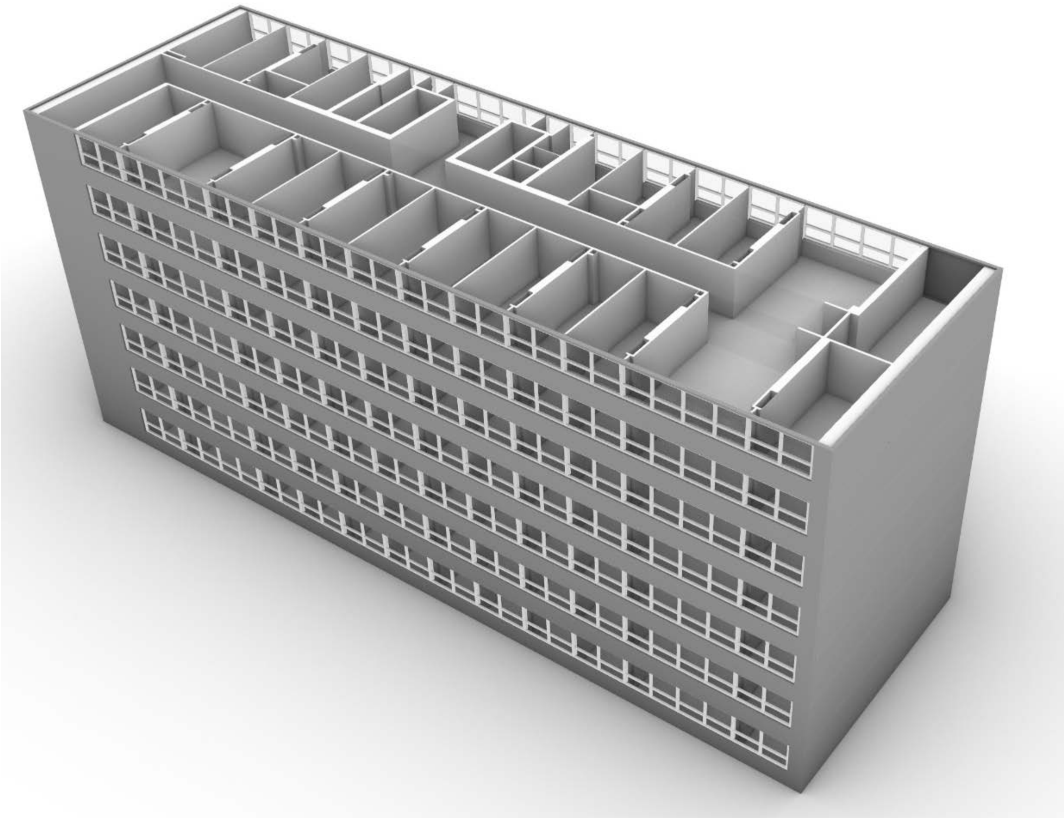

Fig. 5 – Model of a building with a horizontal section through 7th floor of a building
Source: authors

The ClimateStudio software was used as a tool for simulation and calculation of daylight distribution and availability. To calculate the amount of electricity produced from photovoltaic panels, a script was created in Grasshopper, in which Energyplus computing core was integrated. (Fig. 6).

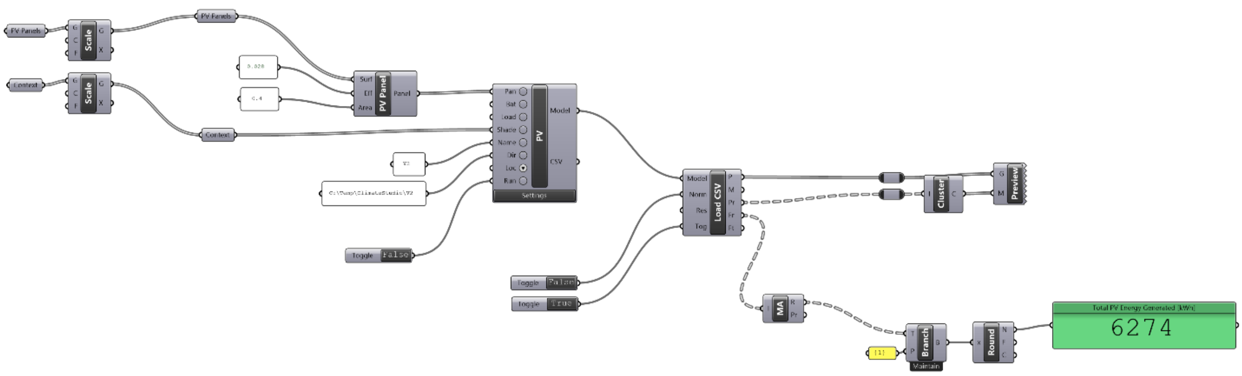

Fig. 6 – Visualisation of a computing script in Grasshopper
Source: authors

Three metrics were selected for comparison of the daylight availability in the interior of the building: Annual sunlight exposure (ASE1000,250 - Annual Sunlight Exposure), spatial daylight autonomy (sDA300,50% - Spatial Daylight Autonomy) and Average illuminance from daylight.

- ASE1000,250 refers to the percentage of space that receives too much direct sunlight (1000 lux or more for more than 250 hours per year).

- Spatial Daylight Autonomy (sDA300,50%) measures the effectiveness of daylight utilization within buildings and workspaces. This metric indicates the percentage of the area that receives at least 300 lux of daylight for at least 50% of the annual occupied hours. This reveals the suitability of the space for natural lighting during regular use, potentially minimizing the reliance on artificial lighting.

- The average workplane illuminance from daylight describes the average annual amount of daylight in lux incident on or illuminating a given work plane (standard height 850 mm above floor).

Results

To determine the amount of solar radiation incident on the façade of the building, an analysis of the total solar exposure of the building envelope per year was made (Fig. 7 and 8). Subsequently, a simulation of the annual amount of electricity produced was processed for the selected variants.

The total area of PV panels on both facades of the building is 1676 m^2. The results can be found in Table 2. For the selected variants, an annual simulation of the daylighting of the 7^{th} floor of the building was processed based on the selected metrics. The results are shown in Fig. 9 to Fig. 13 and summarized in Table 3.

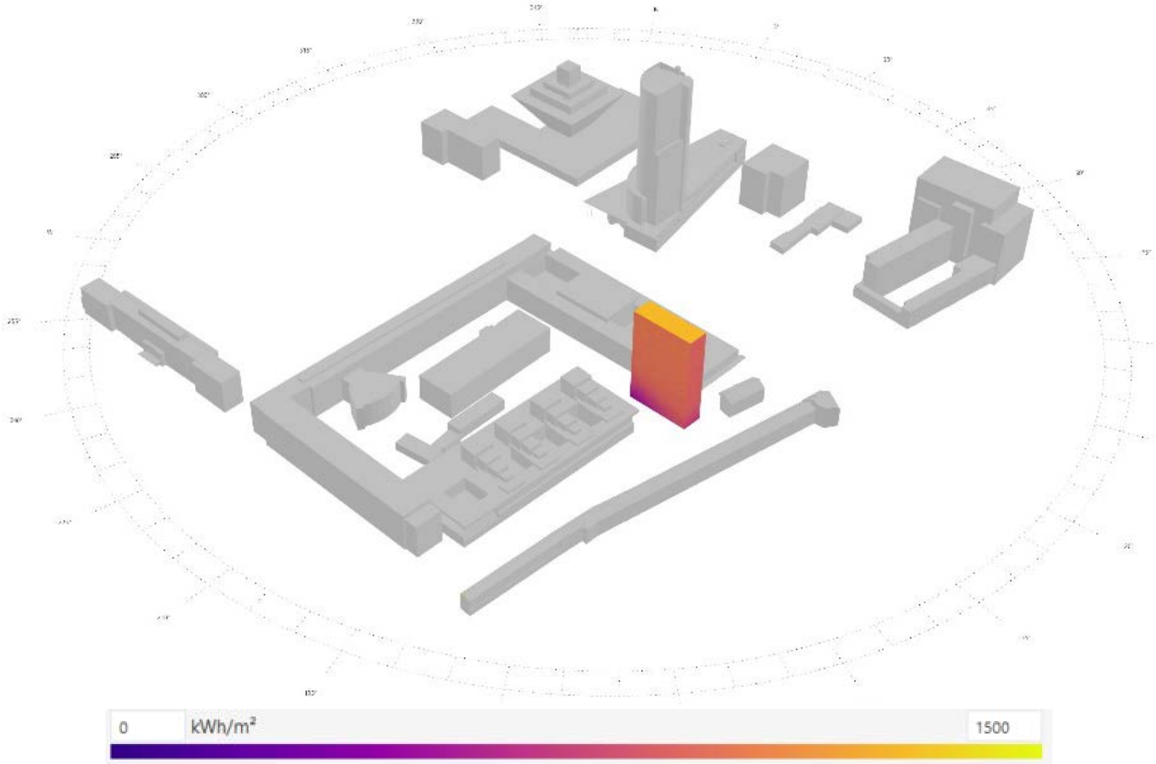

Fig. 7 – Total solar exposure of the building envelope – south and east façade
Source: authors

Fig. 8 – Total solar exposure of the building envelope – north and west façade
Source: authors

Variant	Glazing type / PV module	Annual amount of energy produced [GJ]	Annual amount of energy produced [kWh]
1	Clear triple insulation glazing system	0	0
2	a-Si PV module high transparency	23	6 274
3	a-Si PV module medium transparency	28	7 619
4	c-Si PV module PV cells high density distribution	102	28 235
5	a-Si PV module low transparency	32	8 963

Table 2 – Amount of produced electricity for individual variants
Source: authors

Variant	Glazing type / PV module	ASE1000,250 [%]	sDA300,50% [%]	Average workplane illuminance [lux]
1	Clear triple insulation glazing system	20.8	92.3	1673
2	a-Si PV module high transparency	17.6	60.8	963
3	a-Si PV module medium transpareny	17.0	50.5	818
4	c-Si PV module PV cells high density distribution	18.4	72.7	1146
5	a-Si PV module low transparency	15.6	44.0	735

Table 3 – Results of ASE1000,250, sDA300 and average workplane illuminance for different variants
Source: authors

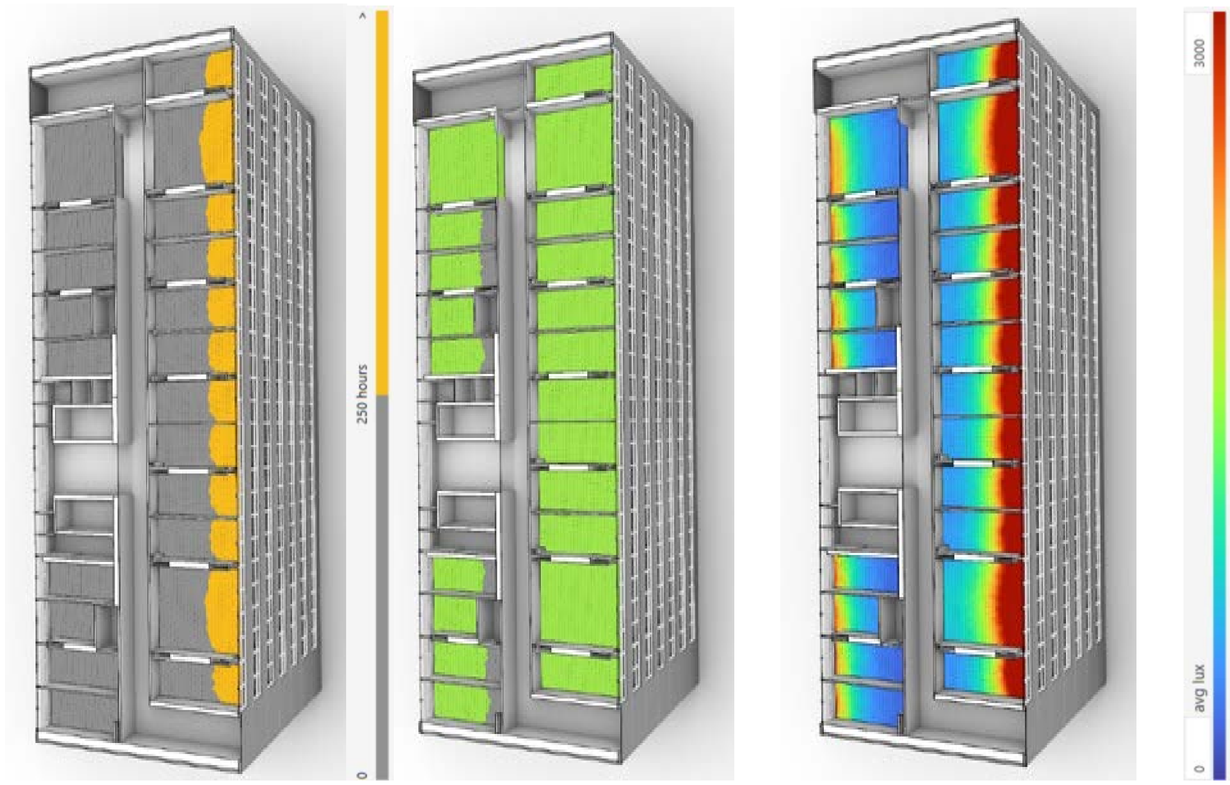

Fig. 9 – Simulation results of V 1 and distribuiton of the results:
ASE1000,250 [%] – left, sDA300,50% [%] – middle, Average workplane illuminance [lux] – right
Source: authors

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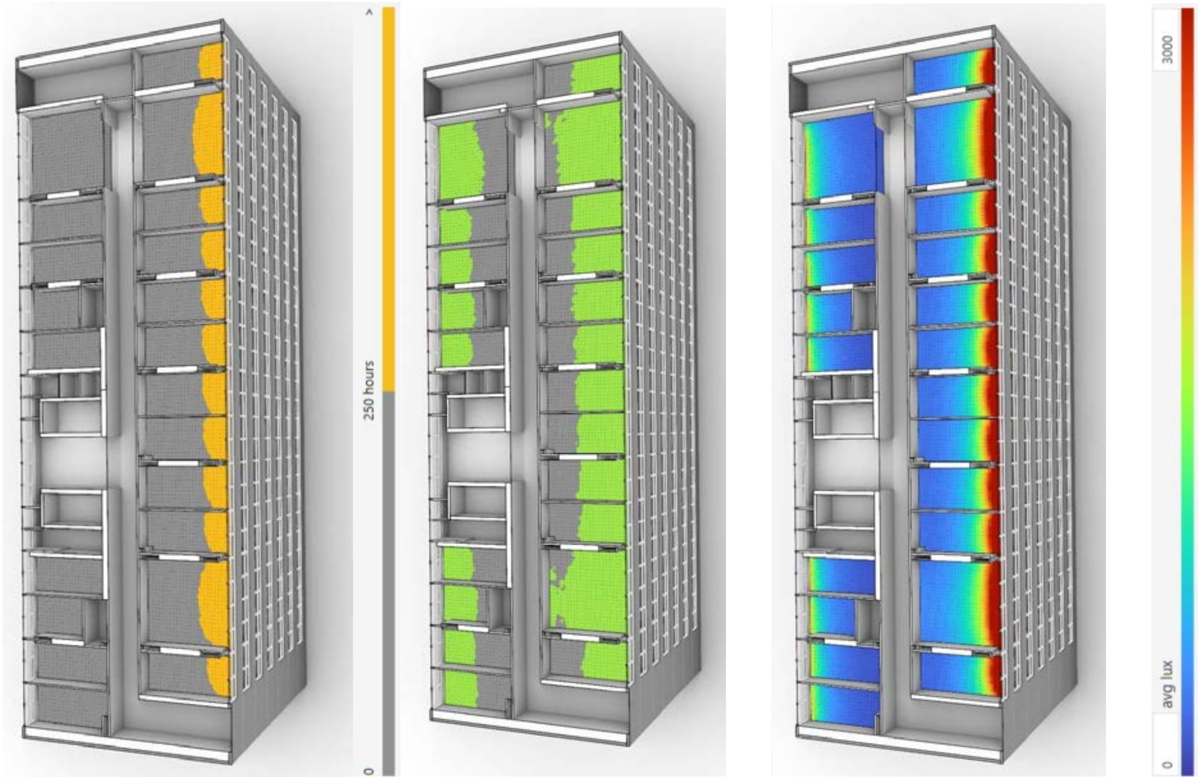

Fig. 10 – Simulation results of V2 and distribuiton of the results:
ASE1000,250 [%] – left, sDA300,50% [%] – middle, Average workplane illuminance [lux] – right
Source: authors

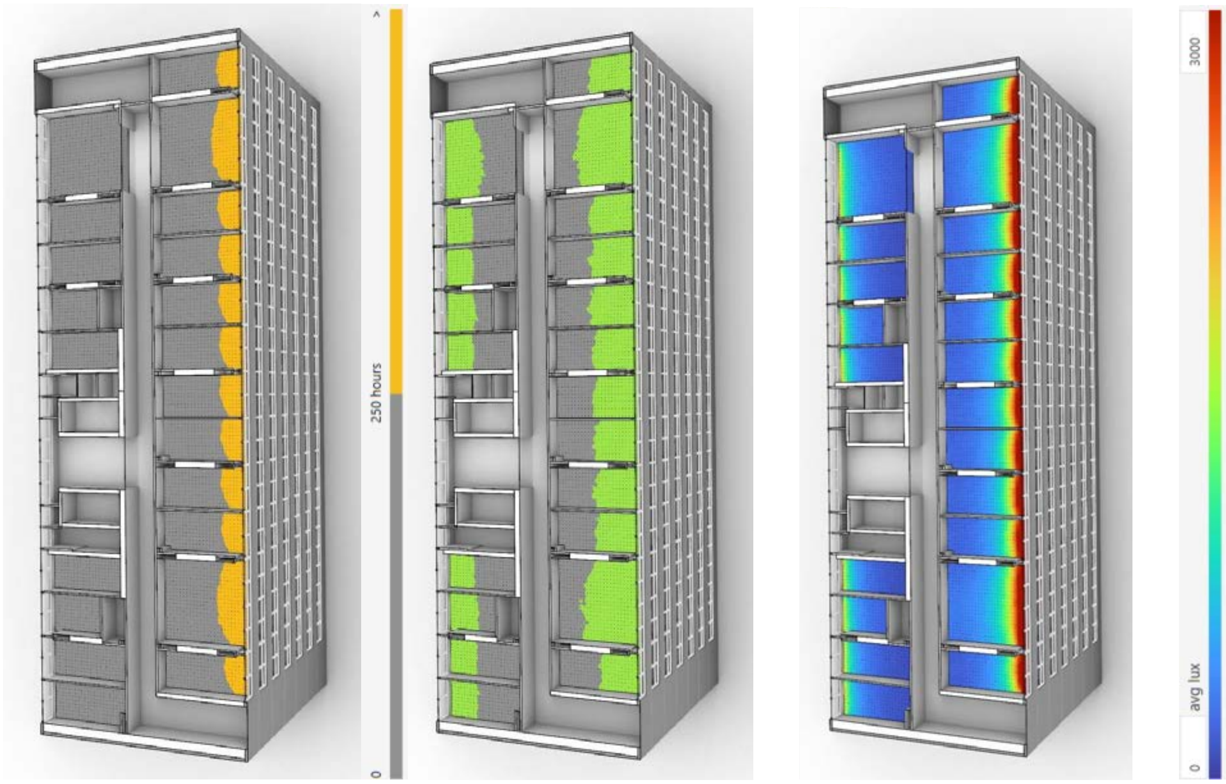

Fig. 11 – Simulation results of V3 and distribuiton of the results:
ASE1000,250 [%] – left, sDA300,50% [%] – middle, Average workplane illuminance [lux] – right
Source: authors

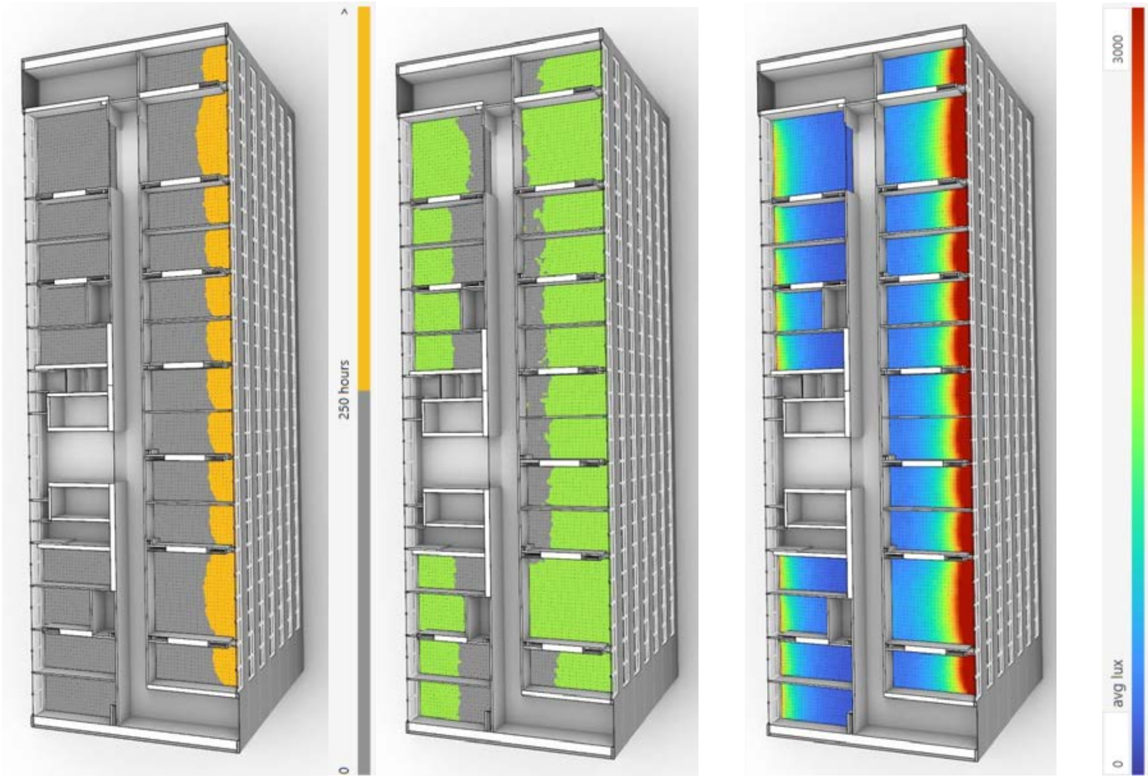

Fig.12 – Simulation results of V4 and distribuiton of the results:
ASE1000,250 [%] – left, sDA300,50% [%] – middle, Average workplane illuminance [lux] – right
Source: authors

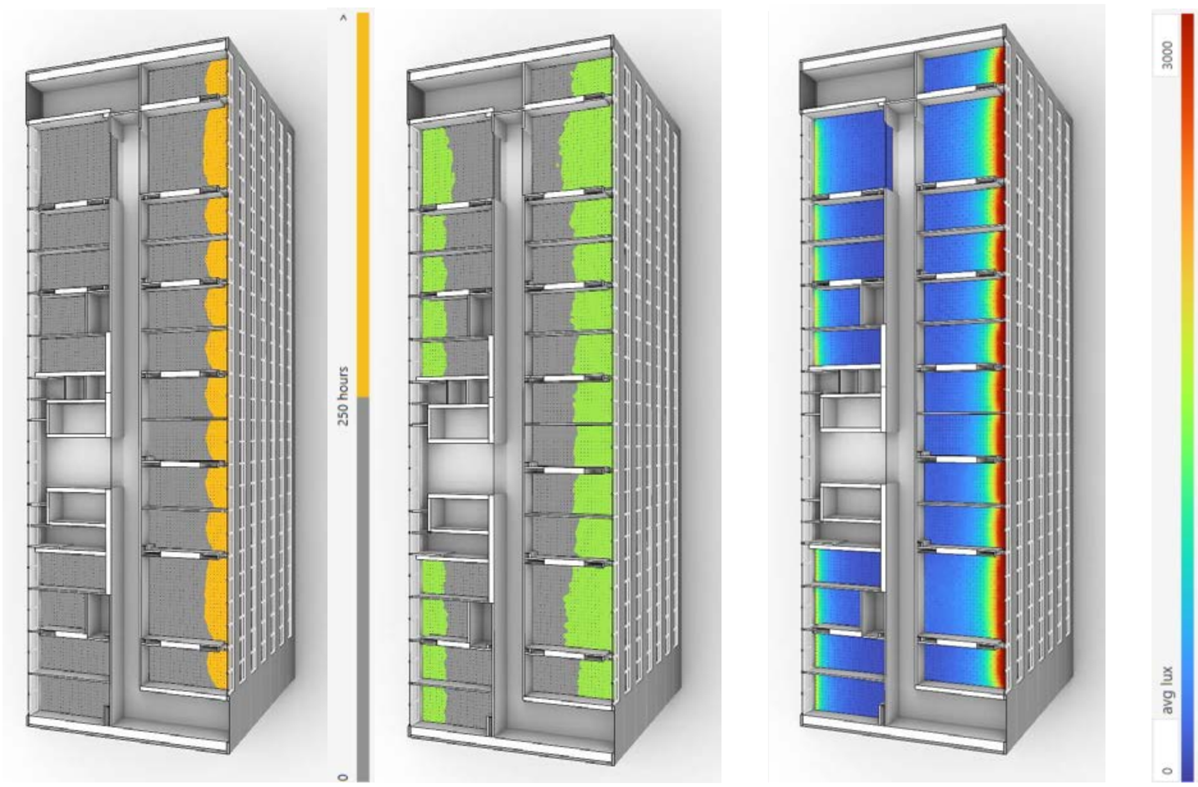

Fig.13 – Simulation results of V5 and distribuiton of the results:
ASE1000,250 [%] – left, sDA300,50% [%] – middle, Average workplane illuminance [lux] – right
Source: authors

Discussion

In the first variant (V1), standard insulation triple glazing system is applied in the windows over the entire opening area of a windows. For the other variants (V2-V5), transparent PV modules were installed on the upper half of the openings on the each floor. The lower half of the openings remained fully transparent to.

The value sDA300,50%, describing the use of daylight in the building and at the workplace, reached a value of 92.3% in V1 when insulating triple glazing was used in the entire area of the openings. We can conclude, that almost the entire area of the working spaces of the evaluated floor of this office building achieved the illuminance of more than 300 lux from daylight in V1 simulation during at least 50% of the time of use over the year course. When using a-Si PV modules, the value decreased and ranged from 44.0 - 60.8% based on the chosen transparency rate of the panels. A c-Si PV modules achieved a value of 72.7% thanks to the higher value of the light transmission factor compared to a-SI panels. When using the metric sDA300,50%, it is required that at least 55% of the floor area of a rooms with long-term residence of people reaches more than 300 lux from daylight during at least 50% of the annual time of use [18]. Based on the calculated light levels, we can conclude that V1, V2, and V3 achieve at least 300 lux for more than 50% of the year, satisfying the design criteria However, it should be noted that with V2 and V3 there is a significant decrease in the value of sDA300.50%, which tends to a higher use of artificial lighting in the premises during the overcast sky conditions.

The ASE1000,250 metric tells us the percentage of space that receives too much direct sunlight, which can cause glare or can lead to increased cooling load. For V1, the value was 20.8%, for the other variants with a-Si PV and c-Si PV, the value ranged from 15.6 to 18.4%. When using the ASE1000,250 metric, it is required that a maximum of 10% of the used space can exceed this limit [18]. Although the use of photovoltaic modules reduces the value of ASE1000,250, but only to a small extent. None of the variants meet the design requirements. To ensure sufficient comfort in the interior, it is necessary to design a form of fixed shading devices from sunlight on the south-west facade, even when using PV glazing is present.

Compared to other technologies, c-Si PV modules achieved higher annual energy, primarily due to their higher nominal power. However, other factors like efficiency, weather conditions, and installation can also influence energy output in the real life.

V4 appears to be the most promising in terms of performance and daylighting provision among the compared variants - with the use of c-Si PV modules with high density PV cells distribution. In this variant, the greatest availability of daylight was ensured with other compared PV modules. Since these are panels based on crystalline silicon, the highest values of produced energy was also achieved. The biggest problem of their application to buildings of a similar type with long-term residence of people is the creation of unwanted shadows and lower uniformity workplane illuminance in the interiors. Thanks to this feature, they are more suitable for spaces where the creation of shadows in spaces can be a targeted architectural intention.

Of the a-Si PV modules, the V2 variant with high transparency appears to be the best, but the annual amount of electricity produced is significantly smaller compared to c-Si PV.

Conclusion

Our work focused on the utilisation of the transparent PV systems. We examined these systems focusing on the annual amount of electricity produced and the influence of the availability of daylight in the interiors using simulation methods with dynamic climatic data sets. From the results, we concluded that transparent PV panels cannot fully replace normal glazing but can be a suitable addition to it on particular parts of the façades. This is to ensure optimal electricity output performance of the panel and at the same time to provide visual comfort and proper daylighting of the internal spaces and working environments.

Currently, due to the relatively higher prices and lower efficiency compared to standard opaque standalone PV systems the usage is limited. But the demand from architects and investor towards BIPVs and transparent PV systems is growing. The positive perspective, the present shows new qualitative knowledge and points to some shortcomings. Actual efforts focus on increasing the functionality and sustainability of climate-adaptive facades. These dynamic facades hold great potential to reduce energy consumption, enhance user comfort, and promote building resilience in a changing climate. Therefore, continued investment in their development and optimization is crucial for a sustainable future.

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