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Section: Energy for Buildings

Assessment of Overall Performance of Building Integrated Photovoltaics

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Abstract

Recently photovoltaic (PV) is widely used technology in modern buildings as part of the façade. Building integrated photovoltaic (BIPV) might be transparent or opaque, mounted on the envelope or might be a construction element of the envelope – a window. Energy production and efficiency of 3 different BIPV systems is simulated and economical assessment of the projects is performed. It shows that attractive solution when energy is consumed for own purposes is opaque PV system and also one of the cases with PV window system.
PV window is transmitting light into the space at the same time producing electricity and performing as shading of the window. Therefore PV window should be assessed taking into account more criteria than just electricity generated. The effect of PV shading on heating, cooling and lighting energy has to be taken into account. The paper presents analysis of overall performance of PV window based on the simulations and measurements. Results show that even though electricity generation of the window is relatively small, in summer it works as an efficient sun shading thus giving a potential for the reduction of investments for cooling equipment and savings on cooling energy demand.

Keywords: building integrated photovoltaic (BIPV); simulation, experimental data; lighting; cooling demand; energy generation.

1. Introduction

Along with the rapid development of technology and the economy, the energy consumption in building sector is expected to continue globally to rise [1]. The increase of energy efficiency in buildings sector is a key objective of the European Union's (EU) energy policy. With the adoption of the recast Directive 2012/31/EU [2] – the main legislative measure in buildings energy efficiency sector, Member States of the EU were obliged to move towards new and retrofitted nearly-zero energy buildings by 2020. Thus, buildings have to become not just very energy efficient, but they also have to use renewable energy to cover their energy demand. Global environmental concerns and increasing energy demand, coupled with steady progress in renewable energy technologies, are creating new opportunities to utilize renewable energy resources [3].

Already in late 1990s, interest on building integrated photovoltaic (BIPV) started to grow and during the last decades, the photovoltaic (PV) modules and their associated architectural materials are increasingly being integrated into the construction of the building envelope such as façade, roof and skylights [4] and are becoming an important part of modern low- and high-rise buildings [5]. The ability of buildings to supply their own electricity through PV system is considered as an attractive technology for sustainable architecture and ecological buildings [6–12] which has been developed rapidly in the past decade [13].

Advantages of BIPV system is that energy production can be combined with other functional features of buildings, such as solar shading (decrease of cooling energy), protection of the building envelope, preheating air or water [11, 14–16]. The BIPV systems may be either semi-transparent or opaque type. The semi-transparent type systems with daylighting can be integrated with walls, roofs and windows of a building. Opaque type systems can only be installed directly on walls, roofs or used as local window shading.

As reported by [17], BIPV panels cost slightly more than the conventional material that they replace, especially if they are deployed in the form of thin film technology. The cost of PV declines continuously, the conversion efficiency of cells increases constantly, and the forms of PV are increasing [3]. Incorporating PV materials into products such as roofing materials, windows and awnings provides the opportunity for cost reduction by replacing common building materials with PV materials at marginal costs [12, 18].

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Currently adoption of this technologies varies greatly due to climate, built environment, electricity industry structure, government policies, local product offerings, market stimulation mechanisms, consumer demand, existing industrial capabilities and the forms of tariff arrangement for grid-connected PV power generation of a country [12]. Cost and efficiency still remain barriers in Northern European countries to the wide-spread use of BIPV.

However, considerable enhancement of BIPV system performance is achievable without improvement in PV cell performance. For BIPV systems to achieve multifunctional roles, various factors must be taken into account, such as the photovoltaic module temperature, shading, installation angle and orientation. Among these factors, the irradiance and photovoltaic module temperature should be regarded as the most important factors because they affect both the electrical efficiency of BIPV system and the energy performance of buildings where BIPV systems are installed [3].

Over the last three decades a significant research on PV solar cells and modules has been carried out, while less are performed on BIPV systems. Wong *et al.* [19] has investigated influence of the semi-transparent PV integrated into residential building's roofing. Yoon *et al.* [8] have performed power output analysis of BIPV (a-Si thin-film solar cells modules applied on the front glass of the building in Korea) depending on the azimuth and shading. Sun and Yang [20] have analysed the impact of the tilt angles on the energy performance of the shading-type BIPV claddings in terms of annual electricity generation and annual cooling load reduction for a building in Hong Kong. The solar cell temperature of BIPV module is higher than the free standing PV module at normal operating cell temperature condition. Based on that fact Huang *et al.* [21] have proposed the thermal model to predict the electrical power of BIPV which takes into account the ambient temperature, solar radiation of tilted plane and wind speed to evaluate the solar cell temperature. Song *et al.* [22] have analysed power output of PV modules depending on incidence angle and the azimuth using a transparent thin-film solar cell in a mock-up model at various slopes to the south, as a building integrated photovoltaic system. Lu and Law [15] have developed an overall methodology for investigating the thermal and power behaviours of semi-transparent single-glazed photovoltaic window for office buildings in Hong Kong. Their findings show that thermal performance is the primary consideration of energy saving in the entire system whereas electricity consumption of artificial lighting is the secondary one.

Yoo and Lee [23] have presented analysis of the BIPV system, where opaque PV are mounted as shading on the southern façade. They have stated that some distance from the panel to the façade should be kept in order to promote natural ventilation around the panel surface for reducing its surface temperature. Later study of Yoo [11] presents a sunshade system simulation with semi-transparent solar cell module on a vertical south façade of the building in Korea. He came to the conclusion that an effective application of BIPV could be even more important rather than improvement of cell efficiency itself.

Chow *et al.* [24] presented an assessment of overall performance of PV ventilated window system executed for different window orientations, using a small office room in Hong Kong. Authors have found that a solar cell transmittance in the range of 0.45–0.55 could achieve the best electricity saving. Friling *et al.* [14] analysed ventilated BIPV and have concluded that high forced velocities result in a higher production of electricity. Han *et al.* [25] have analysed thermal behaviour of glazing with integrated semi-transparent PV module. The effect of cavity air thickness between semi-transparent PV and clear glass layer on the overall heat transfer through the window has been evaluated, and the optimum thickness for the air layer has been found to be in the range of 60–80 mm for the case study.

The semi-transparent BIPV facades produce electricity, reduce solar heat gain and facilitate daylighting schemes that save lighting energy consumption and lower cooling requirements. When semi-transparent PV panels together with the dimming controls were used, the annual building electricity saving and peak cooling load reduction was found to be significant [15, 18]. Lu [15] have concluded that thermal performance is the primary consideration of energy saving in the entire system, whereas electricity consumption of artificial lighting is the secondary one. The effect of the PV window on energy consumption of office buildings in terms of heating and cooling loads, daylighting, and electricity production was also analysed by Miyazaki *et al.* [26]. The study have found the optimum solar cell transmittance and window to wall ratio, and estimated energy savings of the building. Wong stated, that research on the optimization effect of semi-transparent PV on power generation, daylighting and thermal utilization on total energy balance is scarce [19].

During the last decade, the idea of additionally exploiting the rejected heat of the photovoltaic modules is gaining attention [27]. Investigations on building integrated photovoltaic thermal (BIPVT) system have been performed by some authors [6, 28]. They state that BIPVT has the potential to become a major source of renewable energy in the urban environment.

Summarizing, just a few studies investigate total building energy consumption, when PV window is integrated into the façade. These studies are performed in Asian countries, where climate (temperatures, solar radiation, etc.) differs from the Lithuanian one and there are no studies performed in similar climate conditions as well. In order to fill this gap, the purpose of this research is to study the overall energy performance of semi-transparent BIPV module by taking into account power generation, daylight utilization and effects on energy demand, since they are all interrelated.

2. Methodology

The analysis of BIPV is performed for the university building using the following steps: 1) theoretical simulation of power generation efficiencies of 3 different cases of BIPV; 2) analysis of the measurement results of existing semi-transparent

BIPV installation; 3) simulation of overall effect of semi-transparent PV installation on indoor temperatures and energy demand.

2.1. Description of the object

The BIPV system investigated in this study was applied for one of the buildings of Vilnius Gediminas Technical University (VGTU) (Fig. 1), which is located in Vilnius city (Lithuania) (the latitude 54º72′ North and the longitude of 25º33′ East). This is the first practical application of PV window in Lithuania.

2.2. Simulation of power generation performance of BIPV systems

The performance of a grid-connected system depends on PV efficiencies, local climate, the orientation and inclination of the PV array, load characteristics and the inverter performance. An explicit overview of these factors is given by Norton *et al.* [12]. In this study mainly 2 different types of BIPV are analysed: 1) opaque attached to the building façade PV modules and 2) PV semi-transparent PV windows of two different sizes. Opaque attached modules perform mainly a function of power generation and some other less important functions, such as façade protection, aesthetical function, etc. Meanwhile PV windows apart from power generation, perform a function of shading, thus affecting comfort, daylighting and energy demand of the building. PV window also replaces a standard window, thus performing all of its functions. Therefore, additional installation costs, compared to opaque attached PV, partly can be accounted for construction costs.

In this study PV window energy generation performance, according to its technical data (Table 1), was simulated with PV*SOL Expert 5.5 (R6). Also, an alternative for PV window – opaque PV fixed on the façade under the windows was simulated and compared. Detailed description of the analysed alternatives is supplied below. PV*SOL Expert 5.5 enables to create 3D objects, to assess the effect of shading of trees and other buildings. It's possible to enter parameters of the real analysed PV.

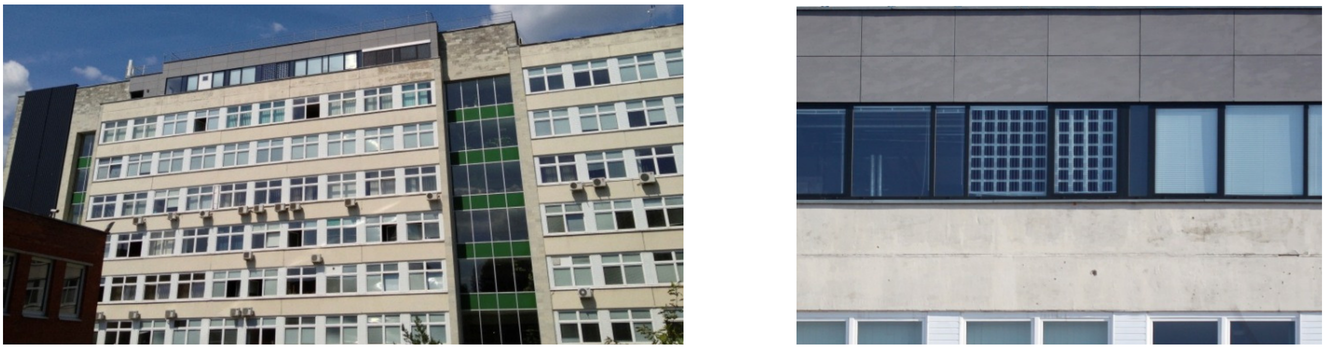

Fig. 1. Southern façade of the analysed building of VGTU

Table 1. Technical characteristics of simulated PV and BIPV

	Opaque PV module	PV window
Parameter	Value	Value
Standard temperature (°C)	25	25
Mean irradiance (W/m^2)	1000	1021
Modules total area (cm^2)	16 335	6 812
Short circuit current (A) I_{sc}	8.71	8.39
Current at maximum power (A), I_{mp}	8.20	7.757
Maximum power (W), P_{max}	250	107
Cell efficiency (%)	15.3	15.8
Open circuit voltage (V), V_{oc}	38.1	17.4
Voltage at maximum power (V), V_{mp}	8.20	13.83

Case 1. Non transparent (opaque) PV panels are mounted vertically on the South façade above the windows (Fig. 2). Installed power capacity of one solar module – 250 W_p (it corresponds to model YNGLI YL250C-30b, which was randomly selected). In general 200 modules with an area of 326.70 m² and total capacity of 50 kW_p are installed.

Case 2. Upper parts of the window (dimensions – 1085×585 mm) of the southern façade are replaced with semi-transparent PV windows (Fig. 3a). Each of the windows has 10 PV cells integrated in it. Total area of cells of one glazing unit is 0.243 m² with installed power capacity – 39 W_p. Total numbers of PV glazing units on the façade – 232, total capacity 9.06 kW_p with total area of PV windows – 147.26 m².

Case 3. Similar to case 2, just larger glazing units (1085×1135 mm) of the windows are replaced with PV glazing (Fig. 3b). In such a glazing unit, 25 solar cells with an area of 0.608 m² are inserted. Installed capacity in one glazing unit is 95 W_p. Total number of PV glazing units on the façade – 232, total capacity 22.04 kW_p with total area of PV windows – 285.70 m².

For all 3 cases SMA Solar Technology AG Sunny Tripower inverters are selected. The case when PV is integrated on the roof is not analysed since the roof is equipped with different technical installations.

Fig. 2. Southern facade view with opaque BIPV system – Case 1

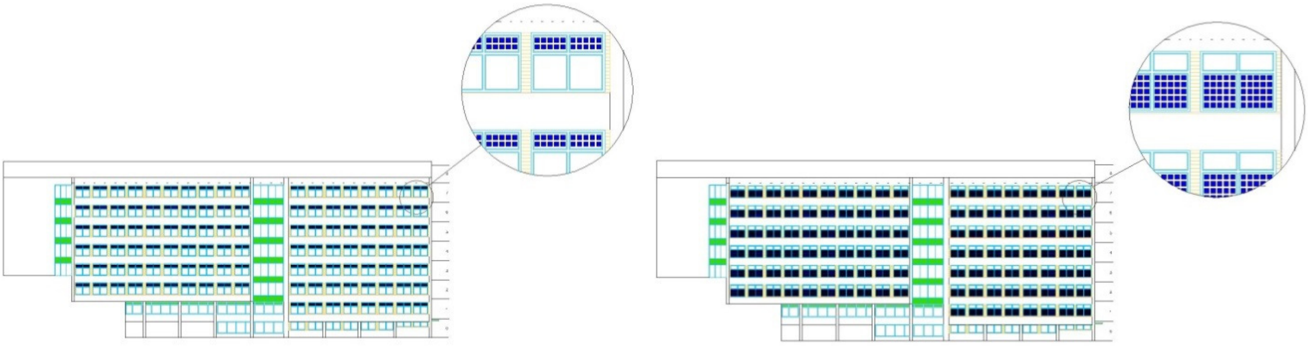

Fig. 3. (a) Case 2 – size of PV window unit – 1085×585 mm; (b) Case 3 – size of PV window unit – 1085×1135 mm

2.3. Experiment and simulation of BIPV window overall effect

To assess overall effect of the real installed PV window on the room indoor temperature and as a consequence – potential energy savings, two identical models (boxes) of the room were created. One was fixed to the PV window, while the other fixed to transparent window (Fig. 4). Such solution was chosen because there was no possibility to perform measurements in two real identical offices. Data were collected within the period of 10th to 20th July 2013. The following parameters were measured: inside temperature of the boxes, temperature of the surroundings of the boxes, solar radiation and temperatures of the outside.

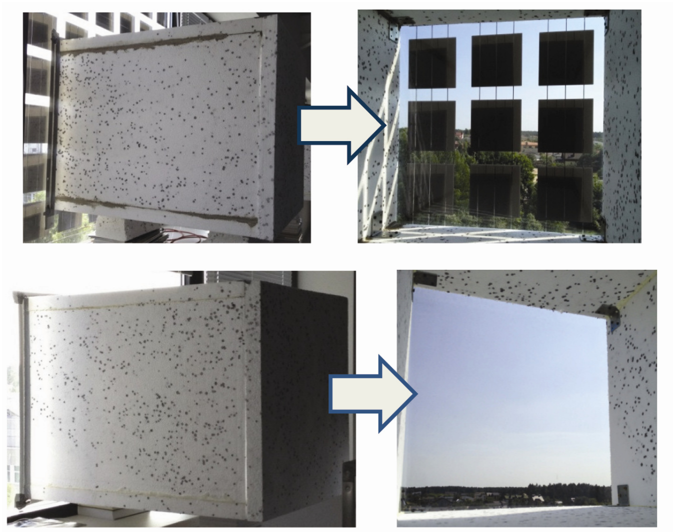

Fig. 4. Experimental boxes from outside and inside

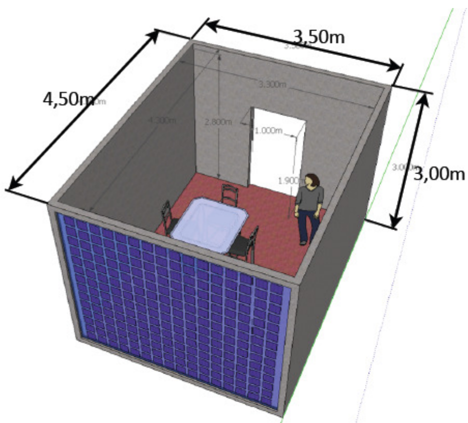

Fig. 5. Simulated with DesignBuilder office room

The same 2 boxes were also simulated with DesignBuilder to compare experimental data with simulation results. Afterwards, two models of identical office rooms, one with fully glazed transparent façade and the other with PV window façade, were created and simulated. Dimensions scale between boxes and rooms is 1:5. The sketch of the room model is shown in the picture (Fig. 5).

3. Results

3.1. Simulated power generation efficiency of vertical PV and PV window

Total annual simulated average efficiency of all the modules used in Case 1 is 13.8%, energy production is 34 161 kWh/year. When all the system including inverters is assessed, calculated efficiency is 12.8%. As seen from the Figure 6, the best efficiency is during the winter season, when the sun is at low position. Despite this fact, amount of energy produced during November-February is very low, because of short and cloudy days. System of Case 1 includes 3 inverters: 2 with capacity of 10 kW each and one of 17 kW. As practice shows, it is more reliable to install more than one inverter since they have tendency to fail and consequences may cost much more.

Total annual average efficiency of all the modules for Case 2 (Fig. 6) is 14.3%, energy production is 6 155 kWh/year. For this case 2 inverters, 12 kW and 8 kW, are designed. Compared to the Case 1, efficiency is just 0.5% lower. Accordingly for the Case 3 (Fig. 6) total annual average efficiency of all the modules is calculated as 13.9%, energy production is 14 918 kWh/year. When all the system together with inverters is assessed, calculated efficiency is 13.1%.

Comparing simulation results for all 3 cases it is defined that efficiency and energy production by m^2 of opaque PV and PV module integrated into the window varies just slightly. Therefore, total annual energy production plays the most important role in comparing alternative systems. Incorporation of opaque modules on the southern façade enables to employ all empty space of the façade and produce few times more electricity, compared to PV windows. Still question concerning the payback of the system stays an important issue. Figure 7 and Table 2 show comparison of investments required for all 3 alternatives. Calculating investments (Table 2) additional variations of Case 2 (A and B) and Case 3 were analysed. Also for the more correct comparison, case 4 was added.

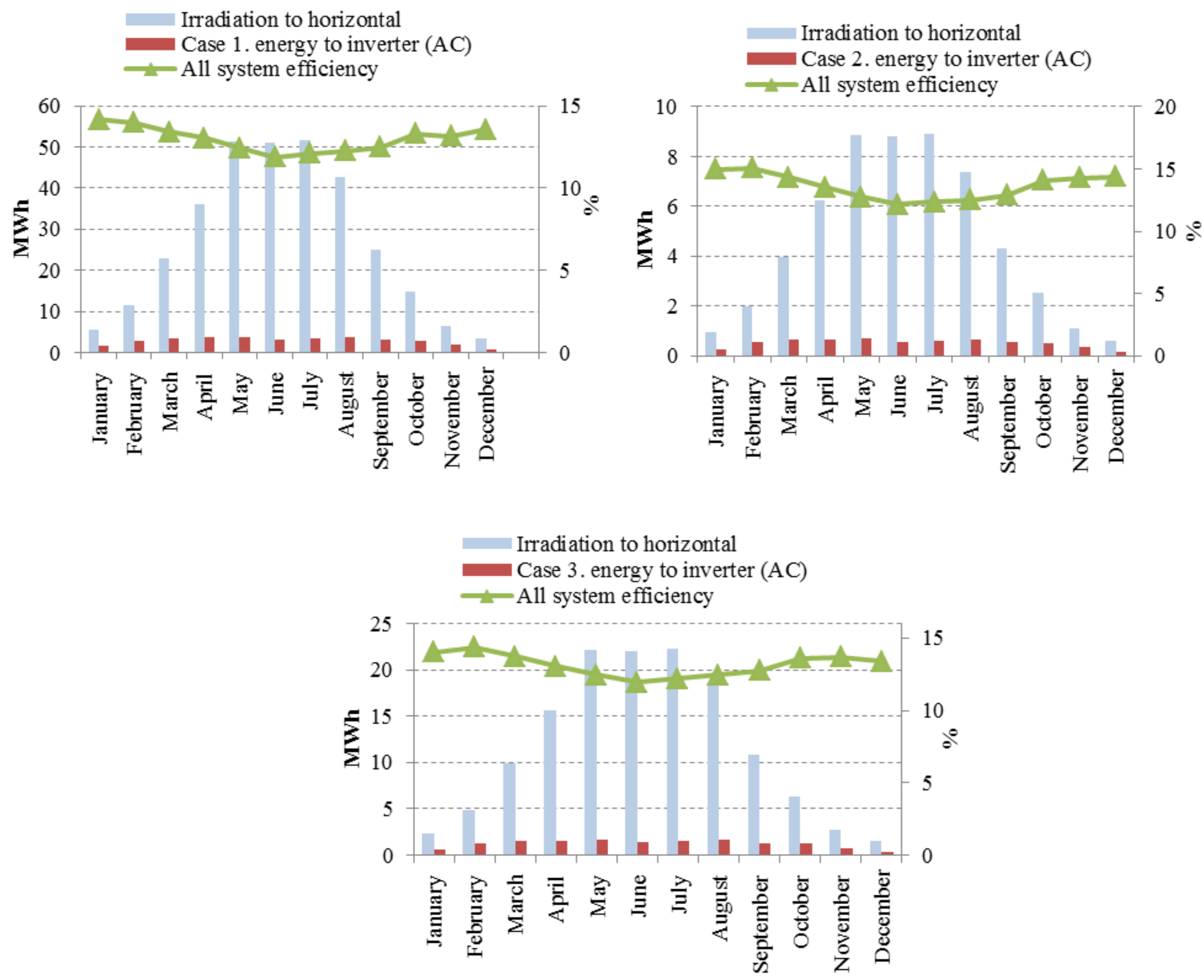

Fig. 6. PV Simulation results for different cases: (a) Case 1, (b) Case 2, (c) Case 3

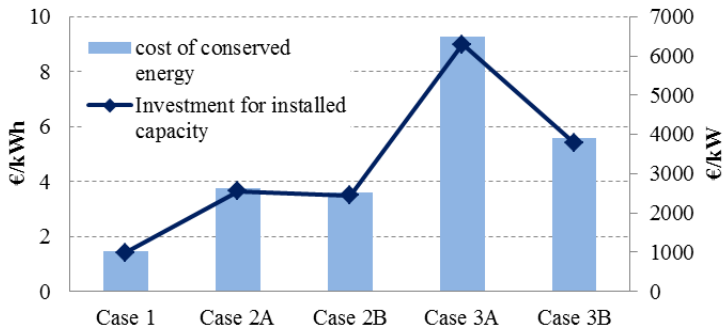

Fig. 7. Economical comparison between the cases – CCE and price of one kW installed

Table 2. Investments required for different cases

Case	Desription	Total investment, €
1	Opaque PV modules installed	49 565
2A	Changing to new PV glazing (dimensions – 1085×585 mm) – frames are not replaced	23 158
2B	Changing to new PV window (dimensions – 1085×585 mm) – both frames and glazing are replaced	53 776
3A	Changing to new PV glazing (dimensions – 1085×1135 mm) – frames are not replaced	56 957
3B	Changing to new PV window (dimensions – 1085×1135 mm) – both frames and glazing are replaced	83 115
4	Changing windows without PV – both frames and glazing are replaced	40 315

As seen from Table 2, investment for Case 1 is not the lowest one if we compare total need for investments. But such comparison is not very informative, because different alternatives produce different amount of electricity. Therefore, investments for one installed kW and for one kWh produced per year (CCE – cost of conserved energy) is a more appropriate way to compare the cases (Fig. 7).

Attractiveness of the project (case) depends on the price for which solar electricity may be sold. Currently in Lithuania there is no governmental guarantee for feed-in tariff for new projects. Therefore, the owner of the building has two choices – to sell electricity to the grid (average price 0.048 €/kWh) or to consume it for their own needs (average price 0.13 €/kWh). In case if electricity is sold to the grid simple payback time is not acceptable for any of investigated cases (it is 20 years and more for all alternatives). If electricity is consumed for one's own needs, then opaque PV modules (Case 1) can be considered as possible investment with a simple payback time of 11 years. All other cases of BIPV do not look attractive also for that price of electricity.

If a new building is being constructed or the existing building needs windows to be replaced, then just difference between the standard window and PV window should be considered. In that situation Case 3A with a payback time of 7 years seems to be promising investment. As it was mentioned above, PV windows also give another additional benefits and savings, which may compensate that difference and raise their attractiveness. These benefits are analysed below.

3.2. Experiment and simulation of BIPV window overall effect

Monitoring results of 2 installed windows (see Fig. 1) in investigated building with integrated 70 cells, show that actual energy produced by both PV windows from 2013-04-08 (date of installation) to 2013-12-30 is 130 kWh. This means that each PV cell has produced 1.85 kWh during that period, meanwhile simulations discussed above show that for Case 2 and for Case 3 energy production per cell is accordingly 2.03 and 1.98 kWh. Difference is less than 10 %, thus it can be stated that simulation results of PV*SOL Expert 5.5 conform well to monitoring data.

Measurement results of the installed experimental boxes are presented in Figure 8. It is obvious that PV window cells make positive effect on reduction of summer overheating. In the boxes without PV cells peak temperature varies from 29 to 65 ºC. Simulation shows slightly higher temperatures in box without PV varying between 33–69 ºC (Fig. 8, 9). For the window with PV, peak temperatures during the measured period are within the interval of 25–49 ºC, meanwhile simulations show variation from 24–43 ºC. The average temperature during the measured period is 30.73 °C in the box without PV Cell and 27.07 °C in the other giving a difference of 3.66 °C.

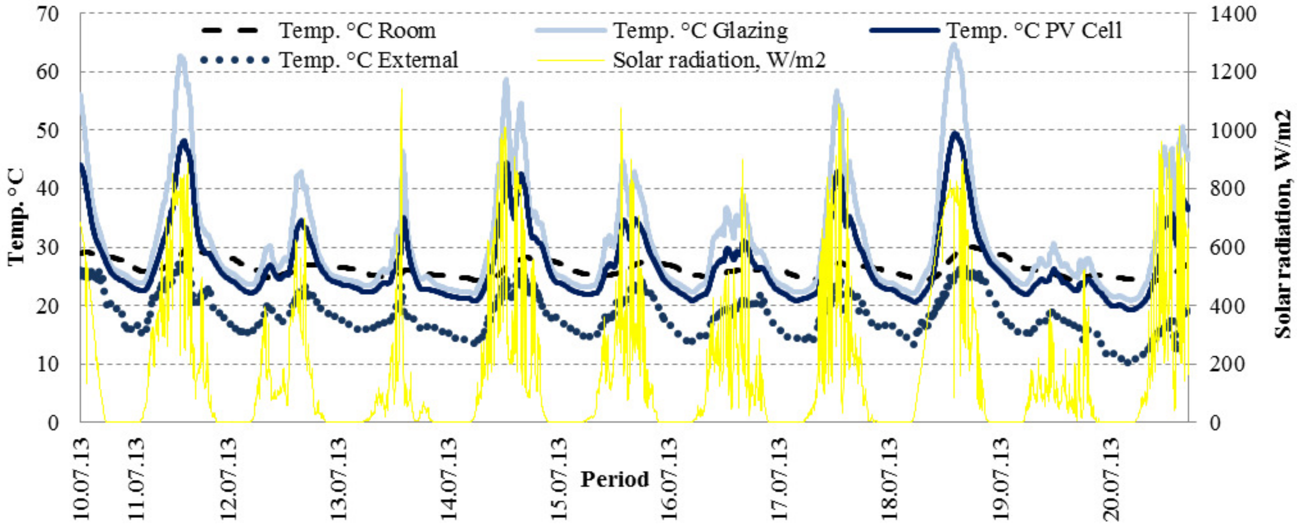

Fig. 8. Measured data (from 10th to 20th July 2013)

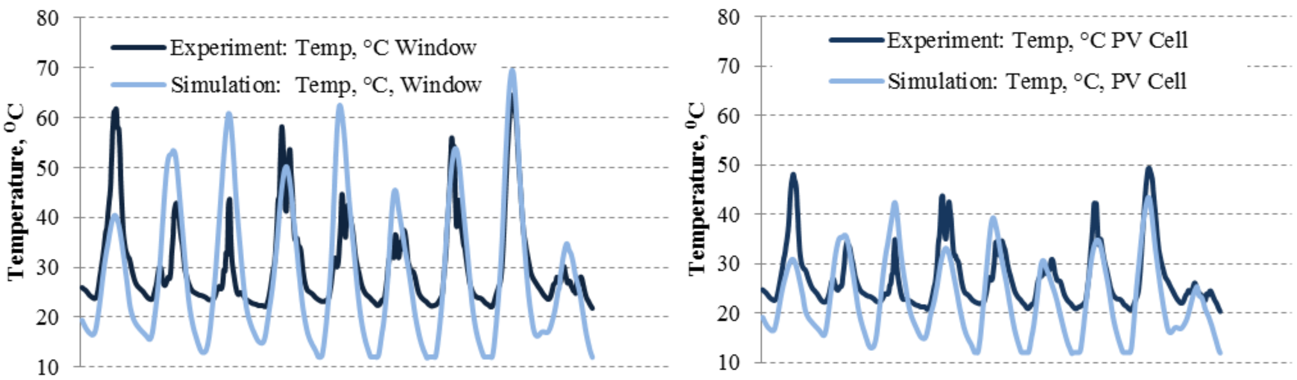

Fig. 9. Simulation vs experimental data of the boxes (from 11th to 19th July 2013)

Differences between measured and simulated data mainly occur because of the simulation of statistical weather data, used in DesignBuilder. Simulations also show much lower temperatures during the night, because experimental boxes were mounted inside the room (temperatures can be seen in Fig. 9) and variation of the room temperatures as one of two existing surroundings could not be taken into account in the simulation tool. Nevertheless, the agreement between simulation data and experiment is considered being good.

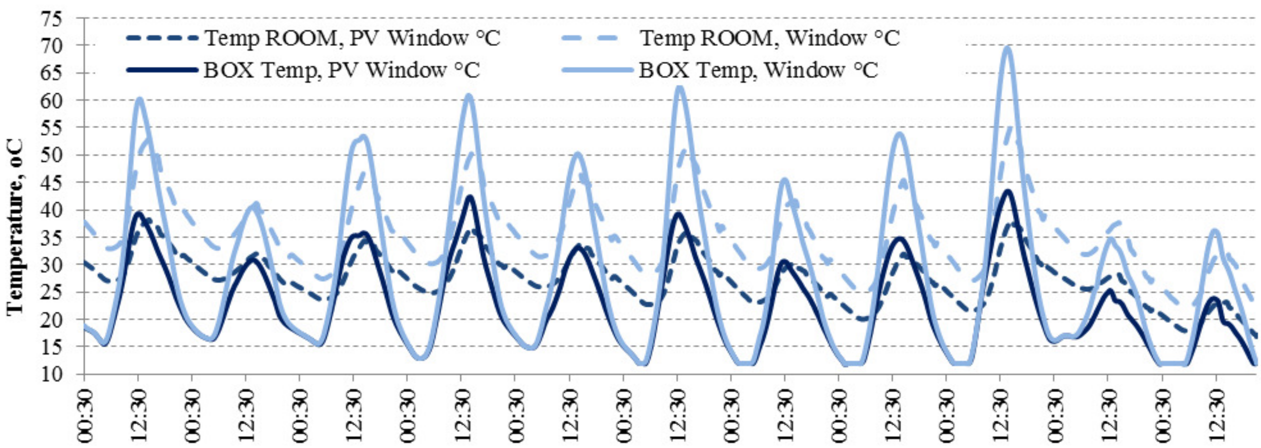

Fig. 10. Comparison between simulated boxes and rooms

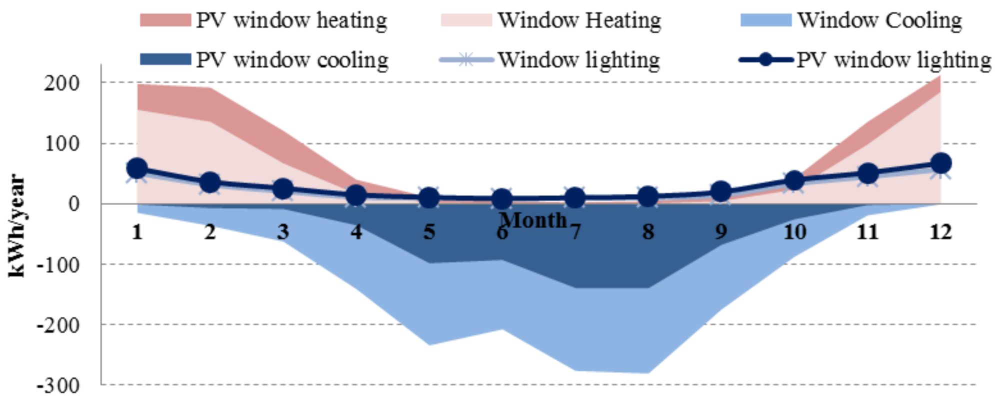

Fig. 11. Simulated annual energy demand (cooling demand is considered as negative demand)

The purpose of simulation was to perform assessment of additional benefits from PV window. Simulation results both for boxes and rooms with and without PV window show that temperature of the room is highly affected by PV window. During simulation and measurements it was assumed that boxes and rooms will have neither natural or mechanical ventilation nor other cooling system. Considered models had 100% glazed façade, thus also increasing possibilities for overheating. Therefore, air temperatures, especially during the day seem enormously high. During the simulated period, peak temperatures differences between simulated room without PV window and with PV window vary between 7–16 ºC, on average peak difference for the analysed period is 12 ºC. It is logical, that temperatures in the boxes are higher than in the room and cannot be directly compared because of the different scale of the models. For the simulated boxes difference in peak temperatures varies between 10–26 ºC, on average by 16 ºC. These differences in the summer peak temperatures show that there is a high potential for savings on installed capacity of the cooling equipment.

Average simulated annual temperature reduction in the room with PV is 1.8 ºC. Differences are higher during the summer compared to winter. In winter beneficial heat gains are stopped by PV window. Therefore, annual heating energy demand for heating increases by 42% (Fig. 11). PV windows also negatively affect lighting energy demand, which is raised by 17%. But since lighting energy demand is low compared to the total energy demand, it should be considered as the least important one. For the summer reduction of the room's temperature gives reduction of cooling energy demand by 62%. The operational hours of the office building coincide with the peak power production time of PV systems. Therefore generated electricity may be used to cover partly energy demand for cooling, which is lowered by PV windows.

At the current stage of the research it is difficult to assess total economic benefits of energy savings, since ventilation and cooling systems were not considered and the type of the system may have significant influence on the final decision. Future research will be fulfilled with the measurements and simulations of ventilated and cooled room models, which are accepted to give more applicable results.

4. Conclusions

The significance of this study is the practical evaluation of the measurement data and simulation on the BIPV window system installed, especially for the first application in the practical building as the window system in Lithuania.

Simulations of alternative power generation BIPV systems have shown that few times higher amount of energy, compared to PV windows, may be produced, if opaque PV modules are mounted on the southern façade. Any of the analysed alternatives is economically attractive if energy is sold to the grid. When energy is consumed for own purposes, the most attractive investment with the simple payback time of 11 years is also Case 1 (opaque PV on the façade). If the part of the investments of the PV window is assigned to a windows construction costs (if a new building is built or the existing one needs refurbishment), then the attractiveness of the PV window also is raised. In such situation the most acceptable is Case 3A (changing to new PV glazing dimensions – 1085×1135 mm) with a simple payback time of 7 years.

Performed measurements and simulations seeking to assess additional benefits of the PV window also show that influence on the indoor temperatures of the room is high, especially in summer during the peak hours. For the simulated period in July, the average difference of peak room temperature is 12 ºC. This shows high potential for savings on investments for the cooling equipment. Annual energy simulations also show negative effect made by PV windows on heating and lighting energy demand, but there is a high potential for energy savings for cooling. Since operational hours of the office building coincide with the peak power production time of PV systems, this reduced cooling demand may be partly covered by PV generated electricity. So, there are multiple benefits from BIPV's which need further research on more realistic models to give more exact numbers on additional energy savings and pay-back times. The recommendations outgoing of this study could be utilized as basic design materials for transparent window BIPV systems for public and commercial buildings, which have a significant potential market in the future.

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