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MULTI-CRITERIA ASSESMENT OF BUILDING INTEGRATED PHOTOVOLTAICS

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Abstract. To make reasonable solutions concerning integration of PV into the façade, complex assessment must be performed at the design stage of the building, taking into account all benefits and losses. The paper presents multi-criteria analysis of semi-transparent BIPV. It is based on 4 criteria: energy, ecology, economy, comfort – 3e+c. Results show that because of twice lower solar heat gains, PV window enables to save almost half of cooling energy, it also significantly improves thermal comfort. Total primary energy demand of the office after application of PV drops from 171 kWh/m^2 to 96 kWh/m^2. Multi-criteria analysis shows that office with BIPV is more sustainable than the one with transparent window.

Keywords: BIPV, office, simulation, multi-criteria assessment, comfort, energy.

Introduction

Increase of energy efficiency in buildings sector is a key objective of the European Union's (EU) energy policy, Member States of the EU are obliged by 2020 to move towards new and retrofitted nearly-zero energy buildings. Thus buildings have to become not just very energy efficient, but they also have to use renewable energy to cover their energy demand. One of the essential technologies to reach the goal of nearly-zero energy buildings is PV solar energy. In late 1990s, interest on building integrated photovoltaic (BIPV) started to grow. 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 (Cerón *et al.* 2013) and are becoming an important part of modern low- and high-rise buildings (Bayoumi, Fink 2014). The ability of buildings to supply their own electricity through PV system is considered as an attractive technology for a sustainable architecture and ecological buildings (Agrawal, Tiwari 2010; Benemann *et al.* 2001; Yoon *et al.* 2011; Chel *et al.* 2009; Park *et al.* 2010; Yoo 2011; Norton *et al.* 2011).

Advantages of BIPV system are 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 (Friling *et al.* 2009; Lu, Law 2013; Yoo 2011; Fossa *et al.* 2008). Currently adoption of this technologies varies greatly, and within, by country depending upon 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 (Norton *et al.* 2011). Cost and efficiency remain barriers to the widespread use of BIPV.

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 (Li *et al.* 2009; Lu, Law 2013). 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.* (Miyazaki *et al.* 2005). The study have found the optimum solar cell transmittance and window to wall ratio, and energy savings of the building were estimated. Chow *et al.* (2007) 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.

Lu and Law (2013) 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.

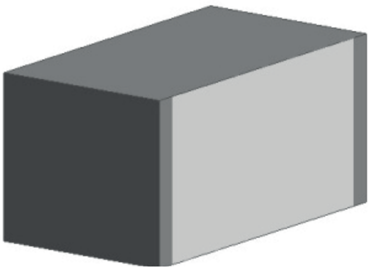
According to Wong, research on the optimization effect of semi-transparent PV on power generation, daylighting and thermal utilization on total energy balance is scarce (Wong *et al.* 2008).

Summarizing, just a few studies investigate overall building energy consumption, when BIPV are used. These studies are performed in Asian countries and there are no studies performed in Northern European climate. In order to fill this gap, the purpose of this research is to study the overall energy performance of semi-transparent BIPV module (PV window) by taking into account power generation, daylight utilization and effects on thermal energy demand. Final judgment on total performance of BIPV is done using multi-criteria analysis.

Methodology

The object of the study is an office room. Two office room cases – one with transparent façade (Fig. 1a), another with BIPV façade (PV window) (Fig. 1b) are analysed. Dimensions of the room model – 3×5×2.5 m, it is south oriented. All internal partitions are assumed to be adiabatic, U-value of the window – 0.8 W/(m^{2}K). Room has typical for office buildings engineering systems – fancoil heating and cooling system, LED lighting system with linear control. Ventilation and domestic hot water systems are not simulated, since their energy demand is not influenced by glazing.

a)



b)

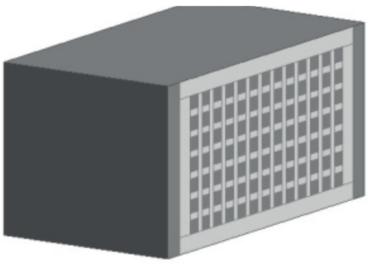


Fig. 1. (a) case with transparent façade (WWR – 88%); (b) case with PV glazed façade (WWR – 88%, transparent part – 47%). *Note*: WWR – window to wall ratio

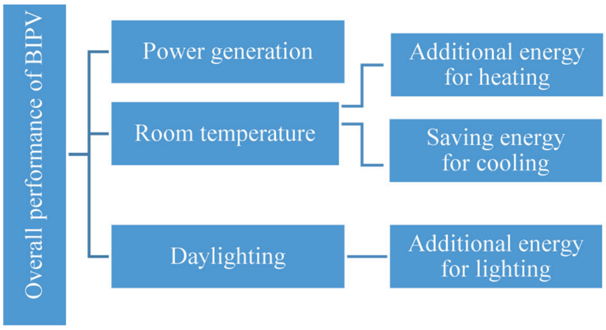


Fig. 2. Overall assessment of BIPV performance

Analysis is performed by following steps:

1. Energy simulation of the room cases with Design Builder software with the purpose to define overall effect (Fig. 2) of PV window on the room's energy demand and comfort. For this purpose, based on monitoring data, a weather data file with Meteonorm software was generated;
2. Estimation of electricity generation of simulated PV window based on energy monitoring data of Vilnius Gediminas Technical University;
3. Life cycle analysis of both glazing alternatives, estimating CO_2 emissions of production and demolotion phases;
4. Calculation of investments required for both cases;
5. Multi-criteria analysis based on 4 criteria: energy (total primary energy demand), ecology (CO_2 emissions), economy (investments), comfort (annual discomfort hours) – 3e+c criteria.

Multi-criteria analysis is performed with the purpose to assess BIPV according to different criteria: ecology, economy, energy, comfort (3e+c). To perform multi-criteria analysis, all criteria must be recalculated into non-dimensional values. Also weight coefficients for each criterion must be estimated/assumed. The best alternative is the one with the lowest value of criteria 3e+c.

There are many methods attempting to determine weight coefficients used to perform multi-criteria analysis. In the study authors seek to estimate BIPV used to make building more sustainable, therefore criteria weights are set using one of the international methodologies of green building certification – Green Star – Office (Heincke, Olsson 2012). This methodology includes many criteria; the sum of their weights is equal 100%. According to this methodology – energy criteria weight is 22%, emissions – 10%, materials – 9%, comfort – 18%. Proportionally in the study we assume that sum of weights of 4 analysed criteria is 1: energy – 0.37, ecology (emissions) – 0.17, economy – 0.15, comfort – 0.31. Non-dimensional values of each criteria are calculated according to Eqs (1–4) (Rogoža *et al.* 2006):

$$e^{en} = 1 - \frac{E^{en}_{max} - E^{en}_{n}}{E^{en}_{max} - E^{en}_{min}}, \quad (1)$$

$$e^{em} = 1 - \frac{E^{em}_{max} - E^{em}_{n}}{E^{em}_{max} - E^{em}_{min}}, \quad (2)$$

$$e^{eco} = 1 - \frac{E^{eco}_{max} - E^{eco}_{n}}{E^{eco}_{max} - E^{eco}_{min}}, \quad (3)$$

$$c = 1 - \frac{C_{max} - C_{n}}{C_{max} - C_{min}}, \quad (4)$$

where: e^{en}, e^{em}, e^{eco}, c – non-dimensional criteria values; E^{en} – primary energy demand (kWh/m^2 year), E^{em} – CO_2 emission (kg CO_2 ekv./m^2), E^{eco} – investments (€), C – discomfort hours per year (h/year); indexes: *"max"* – maximum criteria values, *"min"* – minimum criteria values, *"n"* – value of calculated alternative. General criteria 3e+c is calculated:

$$3e + c = e^{en} \cdot s_{en} + e^{em} \cdot s_{em} + e^{eco} \cdot s_{eco} + c \cdot s_c, \quad (5)$$

where: s_{en}, s_{em}, s_{em}, s_c – weight coefficient of certain criteria (energy, ecology, economy, comfort).

Results

The energy simulation of both alternatives comfirmed the assumptions that PV window influenced thermal and visual comfort of the room as well as energy demand for heating, cooling and lighting. Figure 3a shows that solar heat gains when PV window is used decreases almost twice – from 181 kWh/m^2·year to 94 kWh/m^2·year. This could be expected because of almost twice smaller transparent area of the window (see Fig. 1a). Within the day different alternative gives also different heat loss, therefore total fluctuation of daily energy balance of the window within the year is given in Figure 3b. It can be seen that higher differences between alternatives are noticed during the cold season – transparent window has much higher heat loss.

Simulation results of thermal comfort in both models show that in both cases overheating in the room occurs even in winter. Reason for that is high internal and solar heat gains and low energy loss because of envelope. Since cooling system operates just from March until October – during the rest months overheating problems cause discomfort. Discomfort hours are defined as the time when the combination of zone humidity ratio and operative temperature is not in the ASHRAE 55-2004 summer or winter clothes region (DesignBuilder 2015).

For the room with transparent window average annual air temperature is 30.7 °C, annual discomfort based on Simple ASHRAE 55-2004 methodology – 2332 hours, time when setpoint temperature is not met during occupied cooling period – 260 hours, for heating period – 0 hours. Meanwhile for the oom with PV window internal temperatures are much lower, average annual temperature is 26.4 °C, discomfort hours – 1653, cooling set temperature not met – 175 hours, heating – 0. This means that to keep good thermal comfort – cooling system has to be switched on all year round and this would cause additional energy demand for cooling.

Simulation of visual comfort (Fig. 4) in the room was performed at sky model CIE overcast day (10 000 Lux). Both for transparent window as well as for PV window case daylighting of the working plane meets requirements of LEED (the LEED plaque on a building is a mark of quality and achievement in green building) and BREEAM (BREEAM is the world's foremost environmental assessment method and rating system for buildings) standards (Heincke, Olsson 2012). Also 100% of area meets daylight factor requirements (4%).

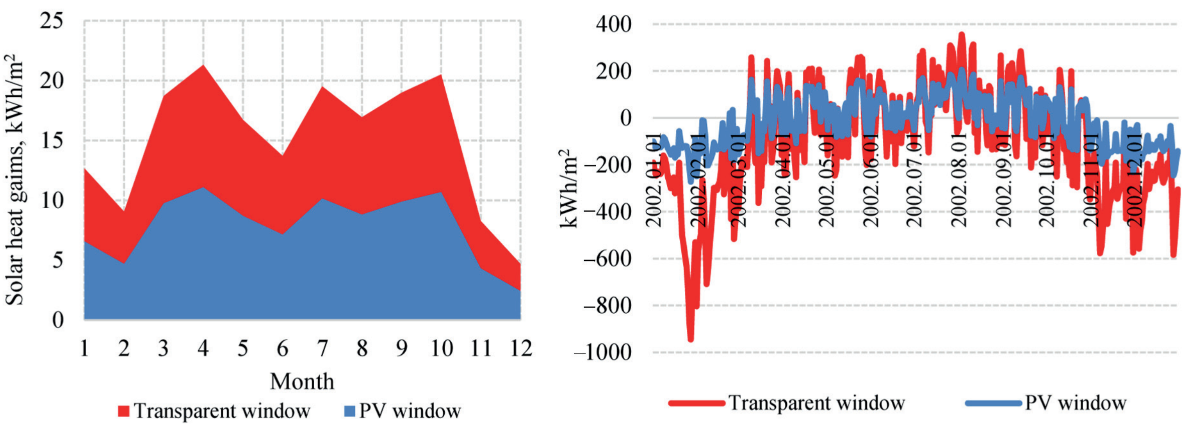


Fig. 3. Heat flows because of windows: (a) solar heat gains; (b) daily heat balance of the window

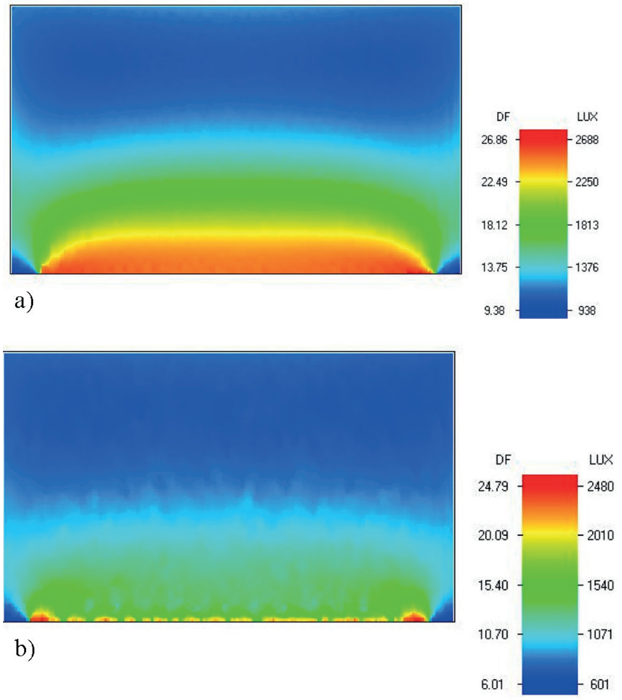


Fig. 4. Daylighting in the office room: (a) transparent window; (b) PV window

As simulation results have shown, PV window has increased primary energy demand for heating almost twice – from 2.6 to 4.6 kWh/m^2·per year (Fig. 5) (heat is produced in gas boiler, rated efficiency – 0.9). This influence for tight and well-insulated building is insignificant taking into account all energy balance of the building, but can be more significant in less insulated one. Influence on lighting energy is also slight. This is because glazing WWR remains relatively high (46%) and ensures sufficient daylighting even when PV is used. The highest influence is made on cooling energy demand (PE energy factor used for electricity is 2.8, cooling system coefficient of performance (COP) – 3.5), which is dominant component in energy balance of the office.

The BIPV system investigated in this study was applied for one of the buildings of Vilnius Gediminas Technical University (VGTU), which is located in Vilnius city (Lithuania) (the latitude 54º72′ North and the longitude of 25º 33′ East), cell efficiency 15.8%. Average electricity generation of monitored PV window system, which is installed in the same conditions as simulated office is on

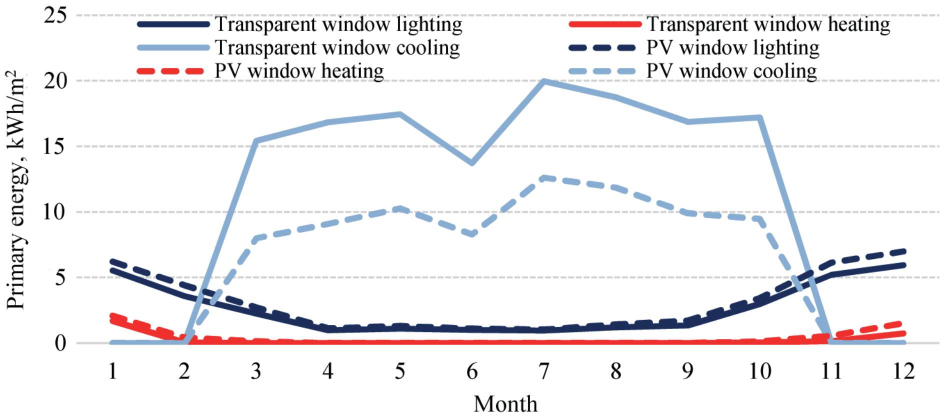


Fig. 5. Primary energy demand of the office room

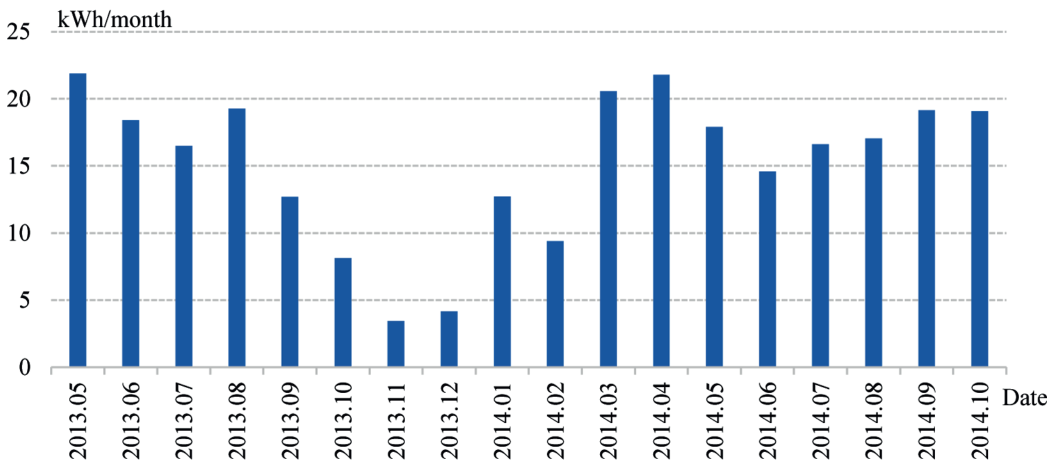


Fig. 6. PV window electricity generation monitoring data

Table 1. Multi-criteria analysis

	Primary energy demand, kWh/m²· per year	CO_2 emissions, $kgCO_2ekv/m^2$	Investments, €	Discomfort, h/year	Non-dimensional criteria values				3e+c
Weight coefficients	0.37	0.17	0.15	0.31	e^{en}	e^{em}	e^{eco}	c	
Window with PV	96	2670	6000	1653	0	1	1	0	0.32
Transparent window	171	1860	600	2332	1	0	0	1	0.68

average 177 kWh/m²·year (Fig. 6). Area of monitored cells is in total 1.68 m² and area of simulated cells – 3.64 m². Simulated cells will produce proportionally – 385 kWh, meaning that 25.7 kWh/m² of electricity demand of the office will be covered by solar energy and since it is produced inside the building, it needs no non-renewable primary energy (primary energy factor is 0). Annual primary energy demand will decrease also by 25.7 kWh/m². This energy amount may cover almost 70% of rooms lighting energy demand.

Concluding energy simulation and electricity generation results, primary energy demand for transparent window case will consitute 171 kWh/m²·year, for room with PV window – 96 kWh/m²·year.

Multi-criteria analysis (Table 1) shows that according to set weights of criteria analysed, alternative with PV window is more rational compared to transparent window.

Conclusions and discussion

1. Simulation results of two office room alternatives show that office with transparent window is less sustainable compared to the one with PV window. Solar gains of the office with PV window are twice smaller, therefore:
   - thermal comfort is better – average internal annual air temperature is lower by 4.3 °C;
   - heating energy demand because of envelope is twice smaller, but insignificant in total energy balance because of good insulation of the building;
   - influence on cooling energy demand is considerably lower – difference is 42%;
   - lighting energy demand is influenced negatively, but just slightly – 15% higher;
2. Daylighting is sufficient for both analysed cases and corresponds to requirements.
3. Annual primary energy demand because of electricity generated by PV window will decrease by 25.7 kWh/m². This energy amount may cover almost 70% of rooms lighting energy demand.
4. Total primary energy demand of the office after application of PV decreased from 171 kWh/m²·year to 96 kWh/m²·year.
5. Multi-criteria analysis shows that more sustainable is office with PV window, but we shouldn't forget that it depends a lot on the weights given for different criteria and with different priorities alternatives ranking may change.

References

Agrawal, B.; Tiwari, G. N. 2010. Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions, *Applied Energy* 87(2): 417–426. http://dx.doi.org/10.1016/j.apenergy.2009.06.011

Bayoumi, M.; Fink, D. 2014. Maximizing the performance of an energy generating façade in terms of energy saving strategies, *Renewable Energy* 64: 294–305. http://dx.doi.org/10.1016/j.renene.2013.11.054

Benemann, J.; Chehab, O.; Schaar-Gabriel, E. 2001. Building-integrated PV modules, *Solar Energy Materials and Solar Cells* 67(1–4): 345–354. http://dx.doi.org/10.1016/S0927-0248(00)00302-0

Cerón, I.; Caamaño-Martín, E.; Neila, F. J. 2013. "State-of-the-art" of building integrated photovoltaic products, *Renewable Energy* 58: 127–133. http://dx.doi.org/10.1016/j.renene.2013.02.013

Chel, A.; Tiwari, G. N.; Chandra, A. 2009. Simplified method of sizing and life cycle cost assessment of building integrated photovoltaic system, *Energy and Buildings* 41(11): 1172–1180. http://dx.doi.org/10.1016/j.enbuild.2009.06.004

Chow, T. T.; Fong, K. F.; He, W.; Lin, Z.; Chan, A. L. S. 2007. Performance evaluation of a PV ventilated window applying to office building of Hong Kong, *Energy and Buildings* 39(6): 643–650. http://dx.doi.org/10.1016/j.enbuild.2006.09.014

Designbuilder. 2015. Design Builder Help 4.1 [online], [cited 25 June 2015]. Available from Internet: http://www.designbuilder.co.uk/helpv4.1/

Fossa, M.; Ménézo, C.; Leonardi, E. 2008. Experimental natural convection on vertical surfaces for building integrated photovoltaic (BIPV) applications, *Experimental Thermal and Fluid Science* 32(4): 980–990. http://dx.doi.org/10.1016/j.expthermflusci.2007.11.004

Friling, N.; Jiménez, M. J.; Bloem, H.; Madsen, H. 2009. Modelling the heat dynamics of building integrated and ventilated photovoltaic modules, *Energy and Buildings* 41(10): 1051–1057. http://dx.doi.org/10.1016/j.enbuild.2009.05.018

Heincke, C.; Olsson, D. 2012. *Simply green: a quick guide to environmental and energy certification systems for sustainable buildings*. Swegon Air Academy.

Yoo, S.-H. 2011. Simulation for an optimal application of BIPV through parameter variation, *Solar Energy* 85(7): 1291–1301. http://dx.doi.org/10.1016/j.solener.2011.03.004

Yoon, J.-H.; Song, J.; Lee, S.-J. 2011. Practical application of building integrated photovoltaic (BIPV) system using transparent amorphous silicon thin-film PV module, *Solar Energy* 85(5): 723–733. http://dx.doi.org/10.1016/j.solener.2010.12.026

Li, D. H. W.; Lam, T. N. T.; Cheung, K. L. 2009. Energy and cost studies of semi-transparent photovoltaic skylight, *Energy Conversion and Management* 50(8): 1981–1990. http://dx.doi.org/10.1016/j.enconman.2009.04.011

Lu, L.; Law, K. M. 2013. Overall energy performance of semi-transparent single-glazed photovoltaic (PV) window for a typical office in Hong Kong, *Renewable Energy* 49: 250–254. http://dx.doi.org/10.1016/j.renene.2012.01.021

Miyazaki, T.; Akisawa, A.; Kashiwagi, T. 2005. Energy savings of office buildings by the use of semi-transparent solar cells for windows, *Renewable Energy* 30(3): 281–304. http://dx.doi.org/10.1016/j.renene.2004.05.010

Norton, B.; Eames, P. C.; Mallick, T. K.; Huang, M. J.; McCormack, S. J.; Mondol, J. D.; Yohanis, Y. G. 2011. Enhancing the performance of building integrated photovoltaics, *Solar Energy* 85(8): 1629–1664. http://dx.doi.org/10.1016/j.solener.2009.10.004

Park, K. E.; Kang, G. H.; Kim, H. I.; Yu, G. J.; Kim, J. T. 2010. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module, *Energy* 35(6): 2681–2687. http://dx.doi.org/10.1016/j.energy.2009.07.019

Rogoža, A.; Čiuprinskas, K.; Šiupšinskas, G. 2006. The optimizations of energy systems by using 3E factor: the case studies, *Journal of Civil Engineering and Management* 12(1): 63–68.

Wong, P. W.; Shimoda, Y.; Nonaka, M.; Inoue, M.; Mizuno, M. 2008. Semi-transparent PV: Thermal performance, power generation, daylight modelling and energy saving potential in a residential application, *Renewable Energy* 33(5): 1024–1036. http://dx.doi.org/10.1016/j.renene.2007.06.016

DAUGIAKRITERIS Į PASTATĄ INTEGRUOTŲ SAULĖS FOTOELEMENTŲ VERTINIMAS

V. Motuzienė, K. Valančius

Santrauka

Kad būtų priimti pagrįsti sprendimai, susiję su saulės fotoelementų integravimu į pastato fasadą, projektuojant pastatą reikia atlikti kompleksinį naudos ir nuostolių vertinimą. Straipsnyje pateikiama daugiakriterė į pastatą integruotų saulės fotoelementų analizė, pagrįsta 4 darnumo kriterijais: energiniu, ekonominiu, ekologiniu ir komforto – 3e+c. Rezultatai rodo, kad dėl perpus mažesnių saulės pritėkių esant langui su integruotais fotoelementais, beveik perpus sumažėja energijos poreikiai vėsinant patalpas bei žymiai pagerėja šiluminis komfortas. Bendras administracinės patalpos pirminės energijos poreikis integravus saulės elementus sumažėja nuo 171 kWh/m^2 iki 96 kWh/m^2. Daugiakriterė analizė rodo, kad sprendimas naudoti langą su integruotais fotoelementais yra darnesnis nei sprendimas naudoti skaidrų langą.

Reikšminiai žodžiai: į pastatą integruoti saulės elementai, administracinis pastatas, modeliavimas, daugiakriterė analizė, komfortas, energija.