Witold MARAŃDA
Technical University of Łódź

Daytime Lighting using Photovoltaic System with Short-term Energy Storage

***Abstract**. This paper investigates the idea of providing the supply for daytime interior lighting with the photovoltaic (PV) system. The match between electricity demand and availability of solar radiation allows for significant supply autonomy with moderate PV system dimensions. The simulation has been aimed at providing optimal choices for PV-generator and energy storage dimensions, relatively to the illuminated area, with view of the electrical energy savings. The best results have been observed for spaces with limited or no glazing.*

***Streszczenie.** W artykule przedstawiono ideę wykorzystania systemu fotowoltaicznego (PV) do zasilania oświetlenia dziennego pomieszczeń. Zgodność pomiędzy zapotrzebowaniem na energie elektryczną a dostępnością promieniowania słonecznego, pozwala osiągnąć znaczną autonomię zasilania przy niewielkich gabarytach systemu PV. Wyniki symulacji, pod kątem oszczędności energii, pozwalają oszacować wielkość generatora PV i bufora energii względem rozmiaru oświetlanej powierzchni. Najlepsze efekty zaobserwowano dla pomieszczeń o ograniczonym przeszkleniu. (**Wykorzystanie systemu fotowoltaicznego (PV) do zasilania oświetlenia dziennego pomieszczeń**)*

Keywords: photovoltaics, autonomous system, lighting, supercapacitor.
Słowa kluczowe: fotowoltaika, system autonomiczny, technika oświetleniowa, superkondensator.

Introduction

Lighting accounts for a considerable electricity consumption in the world. Apart from typical outdoor applications, the daytime indoor lighting is very common in modern societies. The interiors of urban architecture (halls, passageways, offices, etc.) are mostly used during the day and thus require artificial lighting especially during the daytime.

For daytime lighting there exists a very close match between electricity demand and solar radiation availability. This paper studies the possibilities of providing the power supply for this application with photovoltaic (PV) systems.

The PV-systems can be used as a power source in any scale, from powering a single lamp up to the lighting system of a whole building. The low power demand of modern light sources (LED lamps) makes the sizes and costs of the required PV-system reasonable. Moreover, the most efficient use of electrical energy is when it is produced locally on demand, without expensive storage or distribution over long distances. At present, however, such applications of renewable energy sources, especially solar, have been limited to ventilation, air conditionning or water pumping in agriculture, always without access to the utility grid. The daytime lighting has not been yet considered in this context and thus may be regarded as novelty.

The application of photovoltaics to power indoor lighting during the day may become – in author's opinion – very successful. The main advantages are the following:

- Rational energy usage - local production and consumption and perfect match between energy demand and availability.
- Coexistence with grid-powered infrastructure - without feeding electricity into the grid and the associated problems.
- Power supply autonomy - required in emergency situations when electricity is shut down, but the interior lighting must be maintained.
- Direct and efficient use of low-voltage DC modern light sources like LED or halogen bulbs.
- Scalability – equally applicable to small rooms as well as to big halls.

The last, but not the least, argument supporting this idea is the rising cost of electricity, which can make the proposed solution of daytime lighting economically justified in the near future.

Concept of Daytime Lighting

The use of natural light in architecture by means of interior glazing is always recommended, since the sunlight composition is the best for human vision. The glazing however makes the lighting system operation more complicated.

The primary goal of the lighting system is to keep the light intensity of the interior at or above the required level. The artificial light should be used only to compensate the sunlight deficiencies, to provide a stable and comfortable illumination level without unpleasant rapid changes of illumination. The primary supply is from the PV-generator, but in case of prolonged sunlight deficiency the mains serve as a backup supply.

The highly variable insolation during the day, typical in climate of Central Europe, requires the PV-system to be equipped with short-time energy storage to "shift" the solar energy from sunny to cloudy periods. The storage should be based on supercapacitor, which is suitable for handling many quick charge/discharge cycles [1, 2].

The energy savings are thus twofold:

- Using the electricity from PV and energy buffer,
- Dimming the artificial light when not needed [3].

System Configuration

The simplified architecture of the investigated lighting system is shown in Fig. 1. The system operation is based on assumption of maintaining the internal illuminance at the level of L_{norm} or higher on the floor area A_F. The illuminance of a typical workplace should be between 300-500 lx and 100-200 lx for spaces not intended for work (e.g. corridors) [4]. In this work, only the levels of 100 and 400 lx have been assumed for the simulation.

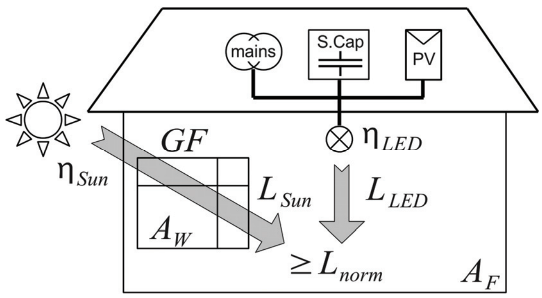


Fig.1. Lighting system configuration

The main system components are the following:

- PV-array delivering energy with instant power P_{PV}, depending on the solar radiation and ambient temperature, calculated according to [5, 6],
- Supercapacitor having the maximum capacity E_{SCmax} and delivering or receiving energy with power +/-P_{SC} in any time moment,

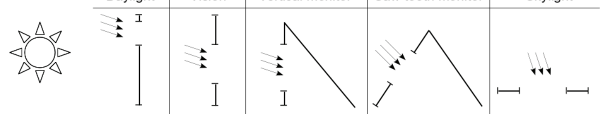
- Light source (load) with the luminous efficacy of η_{LED}, consuming power P_L, which is constant for interiors with no glazing (GF = 0) and variable otherwise.
- The auxiliary supply from the mains is only used in the case of a long deficiency of solar radiation.

The control part of the system reads the information from the illumination sensors and controls the artificial light intensity with the dimmers, switching the power supply between PV, buffer and mains, appropriately.

The electricity for indoor illuminance with LED lamps L_{LED} (with luminous efficacy η_{LED} = 50 lm/W for typical lamps), may come from PV, supercapacitor or mains.

Solar component of interior illuminance L_{Sun} contributes to the interior illumination with the product of solar radiation power, luminous efficacy η_{Sun} = 80 lm/W and glazing factor GF, which represents the glazed-to-floor area proportion. The introduction of GF parameter [7] allows for applying the same results for various types of room glazing (as in Table 1), but having the same value of this parameter.

Table 1. Parameters for various glazing configurations



	Side lighting		Top lighting		
	Daylight	Vision	Vertical monitor	Saw-tooth monitor	Skylight
Geometry Factor (*GM*)	0.1	0.1	0.2	0.33	0.5
Height Factor (*HF*)	1.4	0.8	1.0	1.0	1.0
Transmittance Minimal (T_{Min})	0.7	0.4	0.4	0.4	0.4

The glazing factor can be calculated as follows

$$GF = \frac{A_W}{A_F}\left[GM \cdot HF \cdot \frac{T_{Vis}}{T_{Min}}\right] \quad (1)$$

where A_W is the glazing area, T_{Vis} represents the glass transmittance (typically between 0.1 and 0.7) and GM, HF, T_{min} are explained in Table 1.

Insolation Data for Simulation

The system simulation requires high quality solar radiation data, collected with sufficiently short time intervals. Commonly available solar radiation data are integrated over longer periods (typically 1h or 0.5h) and although reporting correct energy amounts, lack the information about its dynamics, as shown in Fig. 2. Such a daily insolation pattern is quite common in Polish climate in summer.

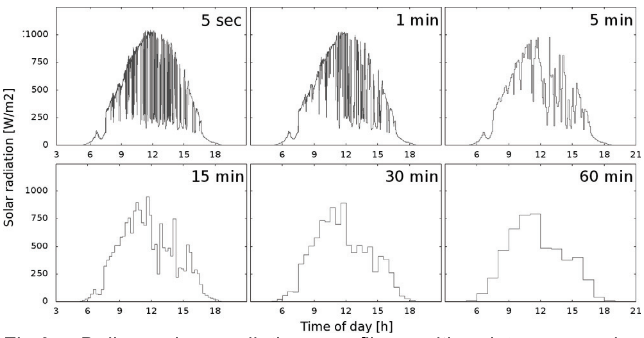


Fig.2. Daily solar radiation profiles with data averaging (Łódź, 2010.04.03)

For accurate modelling of light compensation and short-term storage the required time resolution must be in range of several seconds, but in reality the variations can be even shorter than 1 s.

The presented investigation is based on high quality insolation data, collected with 5 s time resolution, in the PV-installation at Technical University of Łódź [8], in year 2010 using the fast silicon sensor SP-Lite from Kipp&Zonen.

Working Principles

At any time moment, the interior illuminance cannot drop below L_{norm}. The electricity for LED lamps is provided from three sources according to the following rules:

1) High insolation ($L_{Sun} > L_{norm}$): the lamps are off (P_L = 0) and supercapacitor is charging from PV up to its capacity limit E_{SCmax},

2) Low insolation ($L_{Sun} < L_{norm}$): the artificial light is needed (P_L > 0):

- $P_{PV} > P_L$: the lamps are powered from PV only, supercapacitor is charging,
- $P_{SC} + P_{PV} > P_L > P_{PV}$: the lamps are powered from supercapacitor and PV, supercapacitor is discharging,
- $P_L > P_{PV} + P_{SC}$: the lamps are powered from the grid and PV, supercapacitor is empty.

The electrical properties of the system have been simplified and idealised and the simulation has been performed with view of energy flow only.

The simulation has been performed for daytime period, corresponding to the so called "office hours'" 9-17h, with the time step Δt = 5 s (~1.4 mln steps in 8-months).

The results have been expressed in terms of electrical energy savings, referred to the situation of maximal consumption when all the lamps are powered from the grid for the whole investigated period. It should be stressed, that the savings result both from the use of sunlight (for interiors with GF > 0) and the use of PV and supercapacitor.

System Dimensioning

All the results of energy savings have been expressed in function of two main parameters, both expressed per unit of illuminated floor area (A_F in m^2), for several configurations of GF and L_{norm}:

- PV_A (PV power per floor Area) in Wp/m^2 - value of nominal power of the PV-generator per unit area; the range of investigated values has been from 1 to 20 Wp/m^2;
- SC_A (S-Capacitor capacity per floor Area) in Wh/m^2 - energy storage capacity required to compensate for short sunlight deficiencies; the range of investigated values has been from 0 to 1 Wh/m^2.

The PV_A and SC_A parameters give the designer an instant answer about the dimensions (and cost estimations) of the investigated system for the given interior setup.

The typical 100 Wp crystal silicon PV module has the area of 0.7 – 1.0 m^2 and the energy density of commercially available supercapacitors is around 5 Wh/kg.

Visualization of System Operation

Fig. 3 and 4 demonstrate the system operation, showing the illumination level inside a room (with a given GF and L_{norm}) in function of time, for two different settings of configuration parameters: PV_A and SC_A.

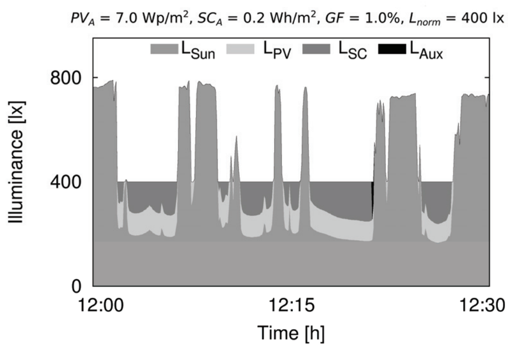


Fig.3. Simulation of light compensation – example of sufficient system dimensions (Łódź, 2010.04.03)

At any time, the four sources of energy may contribute to the indoor illumination: solar radiation (directly) and electricity from PV, supercapacitor and mains, with their illumination components: L_{Sun}, L_{PV}, L_{SC} and L_{Aux}, respectively.

In cases in Fig. 3 and 4 the glazing factor is too small for efficient use of natural light during cloudy periods.

Fig. 3 shows the lighting system behaviour set up for minimum illumination 400 lx and glazing 1.0, equipped with PV-array of 7 Wp and supercapacitor of 0.2 Wh, both per unit area of illuminated interior. Such a system can operate autonomously despite variable insolation and the external electricity usage is minimal.

On the other hand, the system from Fig. 4, operating with the same glazing, cannot reach the goal of energy autonomy. The size of PV-generator here obviously is too small to charge the supercapacitor and power the lamps.

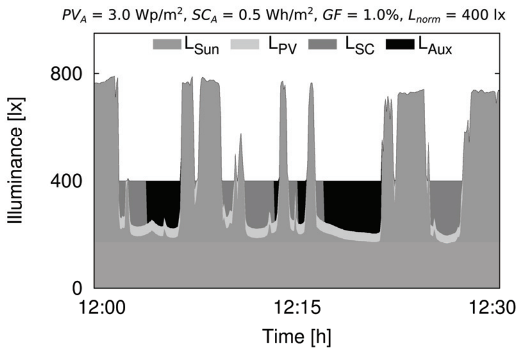


Fig.4. Simulation of light compensation – undersizing example (Łódź, 2010.04.03)

In any case, the increase of the PV size would simultaneously reduce the need for buffer capacity, making the sizing process difficult and requiring many repetitions.

The optimal choice, for given criteria, can only be obtained by numerical simulations preformed for the long periods (at least several months) with a wide set of system configuration parameters: GF, L_{norm}, PV_A and SC_A.

System Sizing Results

A number of simulations has been preformed for two most common illumination levels: 100 lx and 400 lx and typical glazing values of 0%, 0.5% and 1%. The results indicate the optimal system dimensions in terms of PV_A and SC_A, but the final choice must be made on the economy ground, which is beyond the scope of this investigation.

Single Day Results

The Fig. 5, 6, 7, 8 and 9 demonstrate the system sizing for the daily insolation pattern from Fig. 2 – the case of highly variable insolation, where the benefits of short-term energy storage in the supercapacitor are the most visible.

For interiors with no windows (GF = 0), one should invest more in PV-array size and the buffer capacity plays secondary role (Fig. 5 and 6).

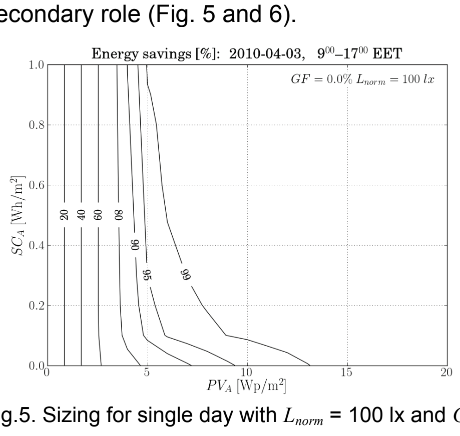


Fig.5. Sizing for single day with L_{norm} = 100 lx and GF = 0

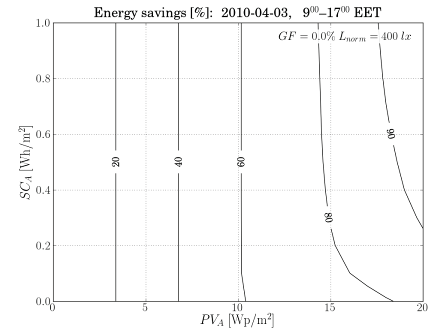


Fig.6. Sizing for single day with L_{norm} = 400 lx and GF = 0

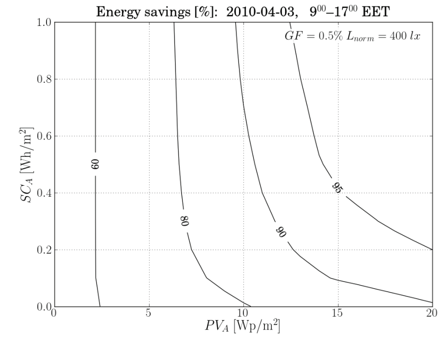


Fig.7. Sizing for single day with L_{norm} = 400 lx and GF = 0.5

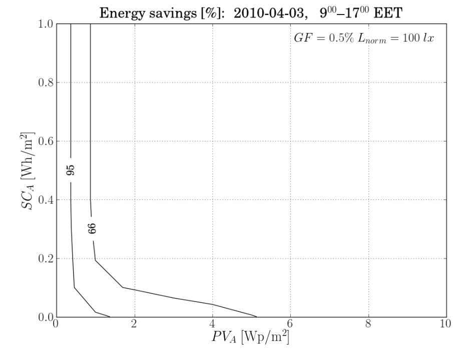


Fig.8. Sizing for single day with L_{norm} = 100 lx and GF = 0.5

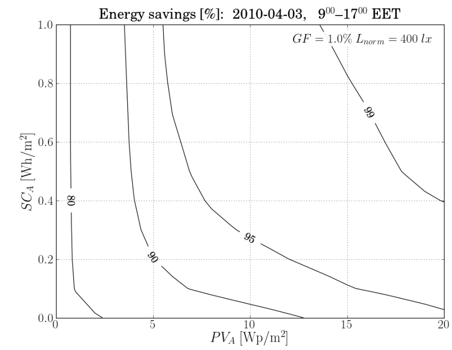


Fig.9. Sizing for single day with L_{norm} = 400 lx and GF = 1

In poorly or moderately glazed interiors, however, there is a clear compromise between PV and buffer sizes and the savings over 80-90% can be easily reached with moderate system dimensions, as shown in Fig. 7. In well-glazed interiors, the savings from the light dimming alone are very high, so the additional supply from PV system offers little improvement (Fig. 8 and 9).

On the other hand, for well-glazed spaces it is easily possible to reach almost complete energy autonomy with very small dimensions of PV-generator and supercapacitor, e.g. a poorly glazed corridor requiring 100 lx can be fully lighted from merely 2 Wp/m^2 and 0.1 Wh/m^2 (Fig. 8)!

This may also be a recommended solution in situations when the large space for PV-modules is difficult to be found, e.g. the energy savings for a moderately-glazed office room (400 lx) can easily reach 90% with PV_A as small as 5 Wp/m^2 and SC_A = 0.2 Wh/1m^2 (Fig. 9).

The single-day results refer to an average-sunny day from the beginning of April. One can expect much better results for sunny summer days. The cloudy days, on the contrary, would give the results similar to the cases with very limited glazing.

May – August Results (4 months)

The summer period include days with variable and smooth insolation profiles, but both with high availability of sunlight. Therefore the influence of the energy buffer is less pronounced.

The Fig. 10 and 11 refer to dimly lit interiors (e.g. passageways, corridors) that can easily be illuminated for the whole period almost exclusively from PV if the size of photovoltaics is sufficient (PV_A up to 10 Wp/m^2). But even a very small PV-array (5 Wp/m^2) may bring savings over 70%, even without the buffer (Fig. 10), which simplifies the whole system.

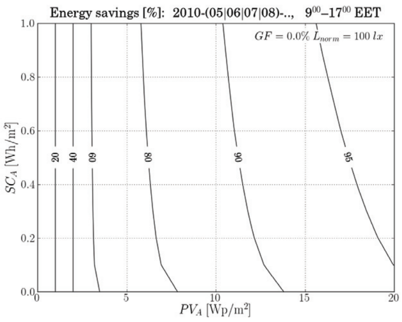


Fig.10. Sizing for summer with L_{norm} = 100 lx and GF = 0

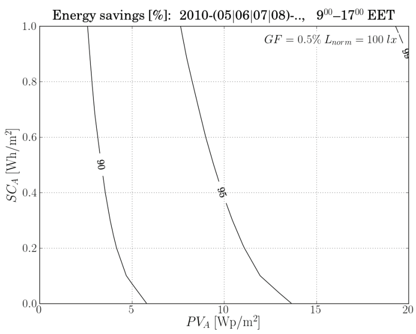


Fig.11. Sizing for summer with L_{norm} = 100 lx and GF = 0.5

The well-lit interiors (400 lx) with no glazing (Fig. 12) require PV_A over 10 Wp/m^2 to yield reasonable savings over 50%, with negligible impact from the buffer. In this case, however, the PV-system is used most efficiently, without wasting its excess of energy.

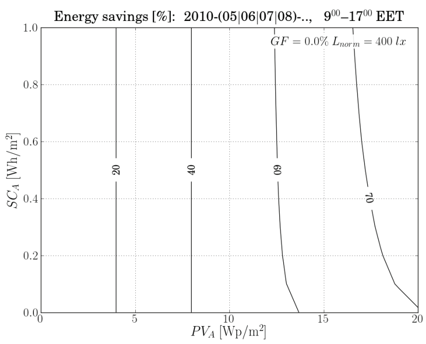


Fig.12. Sizing for summer with L_{norm} = 400 lx and GF = 0

In case of glazed offices (400 lx interiors - Fig. 13 and 14), the glazing alone contributes with over 50% of energy savings. The addition of PV and buffer allows easily for improvement up to 70-80%, but the complete operation autonomy is impossible with reasonable system dimensions.

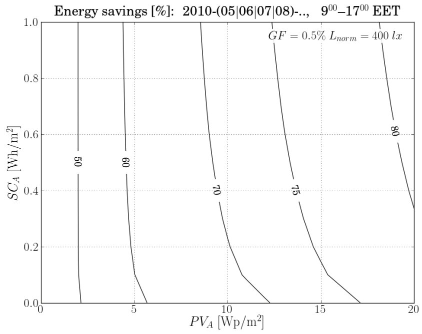


Fig.13. Sizing for summer with L_{norm} = 400 lx and GF = 0.5

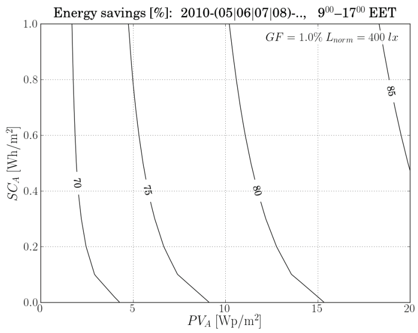


Fig.14. Sizing for summer with L_{norm} = 400 lx and GF = 1

March – October Results (8 months)

The annual distribution of solar energy in Poland is very unequal. In winter months only 20% of the yearly amount is delivered, which makes any PV-applications unfeasible.

The lighting system design for a full year would lead to unreasonably high dimensions, to compensate for light deficit in winter, therefore the simulation has been run for 8 months period only.

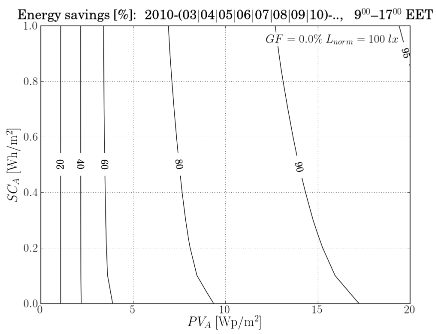


Fig.15. Sizing for 8 months with L_{norm} = 100 lx and GF = 0

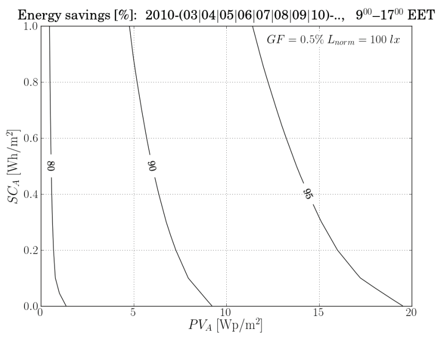


Fig.16. Sizing for 8 months with L_{norm} = 100 lx and GF = 0.5

The results for 8-months period (shown in Fig. 15, 16, 17, 18 and 19) are generally very close to summer ones. Generally, the differences do not exceed 5% of savings and confirms the previous observations. The proposed system can be best applied to power the lighting in barely glazed spaces with low illumination requirement. The Fig. 15 and 17 demonstrates that any small PV-system provides over 50% of electricity savings and even almost complete operation autonomy is still within reach (Fig. 16).

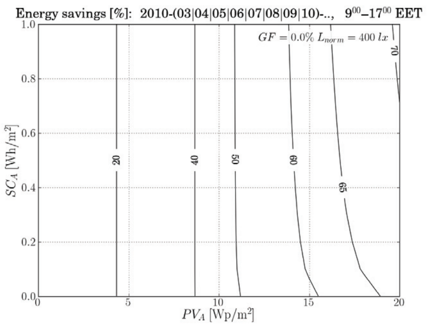


Fig.17. Sizing for 8 months with L_{norm} = 400 lx and GF = 0

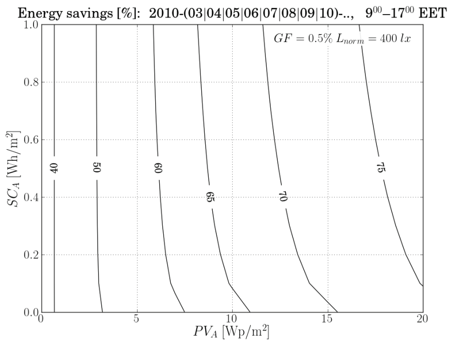


Fig.18. Sizing for 8 months with L_{norm} = 400 lx and GF = 0.5

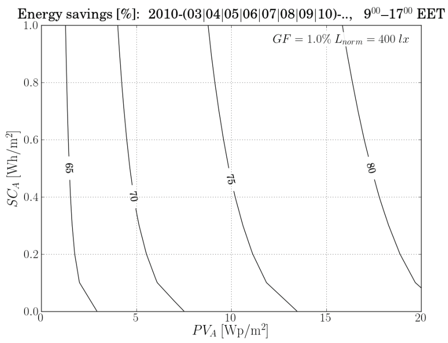


Fig.19. Sizing for 8 months with L_{norm} = 400 lx and GF = 1

The well-glazed interiors with high illumination demand will benefit mostly from artificial light dimming alone. As shown in Fig. 18 and 19, the additional PV-system makes small improvement for the whole investigated period, but the influence of the energy buffer is not negligible.

Summarizing the results, one should also remember about other aspects, not included in the simulation: system lifetime and reliability, maintenance costs, building aesthetics and finally the autonomous lighting in emergency situations, which is a valuable asset.

Conclusions

The paper investigates a novel idea of applications of photovoltaics for interior daytime lighting. The system operation has been simulated within 8-months period using the insolation data collected with 5 s time resolution to properly handle the highly variable insolation profiles. The simulation has been performed for daytime period, corresponding to the so called “office hours'” 9^{00}-17^{00} EET.

The simulation has been aimed at providing optimal choices for PV-generator and storage dimensions with view of the energy savings from the mains. The savings are referred to the consumption of all the lamps turned constantly on for the whole examined period.

The system dimensions have been expressed in terms of nominal power of PV-generator and buffer energy capacity, both per unit area of the illuminated interior.

The proper dimensioning of daytime lighting system can successfully compensate for majority of solar radiation deficiencies during the day. The glazing factor has the dominating effect on the system operation and the highest energy savings are observed for moderately lit spaces with limited or no glazing at all (e.g. corridors).

For well-glazed interiors, the artificial light dimming alone is the major contributor to the savings. The additional PV-system introduces relatively small improvement, but its size may be very small and easy to accommodate. The PV-system size is the most important parameter for interiors with no glazing, whereas the effect of the energy buffer is better visible with glazing, greatly improving the results.

In summer months, with long periods of daylight, the lighting system can operate fully autonomously with very modest dimension requirements. However reaching full energy autonomy during the year is not recommended, since it would lead to a great system oversizing and energy waste from PV in sunny periods. In this case an additional long-term storage should be provided.

All the presented results have the merit of using real-life conditions and showing practical choices for the PV–system and the buffer. The results, however, may be not applicable to other climates. Moreover, the simulation has been simplified to handle energy balance only and the results should be treated rather as the upper limit for the energy savings and autonomous operation.

Nevertheless, the daytime lighting with autonomous PV-systems with short-time storage can be - in authors' opinion - successfully used especially at low power level of a few PV-modules and small supercapacitor dimensions.

For example, lighting the 100 m^2 of a dark corridor would require 4 PV-modules of 180 Wp (about 5 m^2) and the supercapacitor of 10 Wh (about 2 kg) to offer 80% of electricity savings during summer period in Poland. With the dramatically rising electricity cost, many of PV-applications may reach economic feasibility in the near future.

REFERENCES

[1] Marańda W, Piotrowicz M., Short-time Energy Buffering for Photovoltaic System, *Proceedings of the 17th MIXDES Conference*, Wrocław, June 2010, Poland
[2] Marańda W, Piotrowicz M., Operation of Photovoltaic Array with Small Energy Buffer under Variable Insolation Conditions, *International Journal of Microelectronics and Computer Science*, Vol. 1, No. 2/2010, pp. 195-200
[3] Campo P., Piotrowicz M., Marańda W., Energy Saving by Compensation of Daylight Deficiencies in Buildings, *Proceedings of the 17th MIXDES Conf., Wrocław*, 2010
[4] PN-EN 12464-1:2004
[5] Villalva M. G., Gazoli J. R., Filho E. R., Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays, *IEEE Trans. Power Electronics*, 24, No. 5, 1198-1208, 2009
[6] Marańda W., Numerical Modeling of Photovoltaic Devices with Python Scripting Language, *Proceedings of 17th International Conference on Information Technology Systems*, 2010, Łódź,
[7] Leadership in Energy and Environmental Design (LEED) Green Building Rating System, http://www.usgbc.org
[8] Marańda W., Jabłoński G., Makowski D., 1kWp PV System at Technical University of Lodz in Poland, *Proc. of the 19th European PV Solar Energy Conf.*, vol.3, 2915-2917, 2004, Paris

***Authors**: dr inż. Witold Marańda, Politechnika Łódzka, Katedra Mikroelektroniki i Technik Informatycznych, ul. Wólczańska 221/223, 90-924 Łódź,e-mail: maranda@dmcs.p.lodz.pl.*