Hybrid Daytime Lighting System with Photovoltaics and Short-term Storage

Witold Marańda, and Maciej Piotrowicz

***Abstract*—Most efficient utilization of electrical energy takes place when energy is consumed locally, avoiding its distribution over long distances or costly storage technologies.**

Finding such applications for renewable energy sources, like wind or solar, is difficult. The main obstacle is the their limited predictability and the mismatch between energy availability and demand.

Nowadays the daytime lighting in modern urban architecture causes a considerable electricity consumption. For such applications, there exists an excellent match between energy availability (solar irradiance) and consumption demand (interior illumination). Moreover, the demand can be met with relatively small PV-generators with modern energy efficient lighting technology.

In this paper a hybrid lighting system for daytime, using both natural and artificial light, has been proposed. The supply for artificial lighting is provided from photovoltaic (PV) system or the utility grid, when solar irradiance cannot meet the illumination and electricity demand.

The paper presents the results of simulation of full year energy savings in a daytime lighting system. The system maintains the indoor illumination level to be equal or higher than required by the norms, using natural sunlight and artificial lighting. The artificial lighting is used only to compensate the deficiencies of sunlight and is powered with autonomous PV-system in the climatic conditions of Central Europe.

The PV–system is also equipped with short-term energy storage, based on super capacitor, allowing for only several minute of backup supply. Such storage is used only to mitigate the rapid solar power fluctuations, providing energy from PV supply at more stable power level during the day, but the excess of energy is not fed to the utility grid.

The numerical simulation is using the solar irradiance data collected with 5 s time resolution during the whole year 2010 at Lodz University of Technology, in center of Poland.

***Keywords*—photovoltaics, autonomous system, lighting, supercapacitor.**

I. Introduction

PHOTOVOLTAIC generators can be scaled to suit the energy demand of an application without any restrictions. There is no ”critical size” or ”critical power” to make the system feasible. The real-life sizes of PV–systems range from mW applications (or even less) up to hundreds MW power plants.

Moreover, the clear-sky conditions are not the necessary requirement, since PV-systems may also be used successfully in less favorable climatic conditions. Typically they are used with some energy storage (autonomous systems) or feeding energy directly to the mains (grid–connected systems). Applications of PV-systems without any auxiliary power supply and storage system are very limited due to the variable nature of solar radiation, which makes it rather poor power supply.

On the other hand, energy from PV is used most efficiently when it is produced on demand and consumed locally, without lossy distribution lines and costly storage. In case of renewable energy sources, this requires a good match between energy availability and demand. Finding applications that satisfy that conditions may be the key to its economic feasibility.

This paper presents the concept of application of photovoltaics to power indoor lights during the daytime, which — in authors opinion — has many advantages and the potential to become successful.

II. Daytime Lighting with PV

Interior lighting of modern urban architecture (for offices, passageway, halls, etc.) consumes significant share of their total electricity consumption. Most of that is needed mostly during the day. Providing the supply from PV can not only reduce the energy bills, but there are several other positive side–effects.

The arguments to support the idea of daytime indoor lighting with PV are the following:

- rational energy usage — local production and consumption with a perfect match between energy demand and availability;
- lighting autonomy — supply is required in emergency situations when electricity is shut down, but the interior lighting must be maintained for a certain period;
- best application for modern lighting technology — possibility of direct and efficient use of low-voltage DC modern light sources like LED or halogen bulbs;
- easy scalability – the solution can be equally applicable to single small rooms as well as to big halls, the required area of PV–generator is always in the same proportion to the illuminated interior area;
- coexistence with grid-powered infrastructure - PV–system is fully autonomous, sized to provide the amount of energy that can be immediately used, without feeding electricity into the grid and the associated problems such as islanding;

Finally, the last important argument supporting this idea is the rising cost of electricity, which can make the proposed concept of daytime lighting supply economically justified in the near future.

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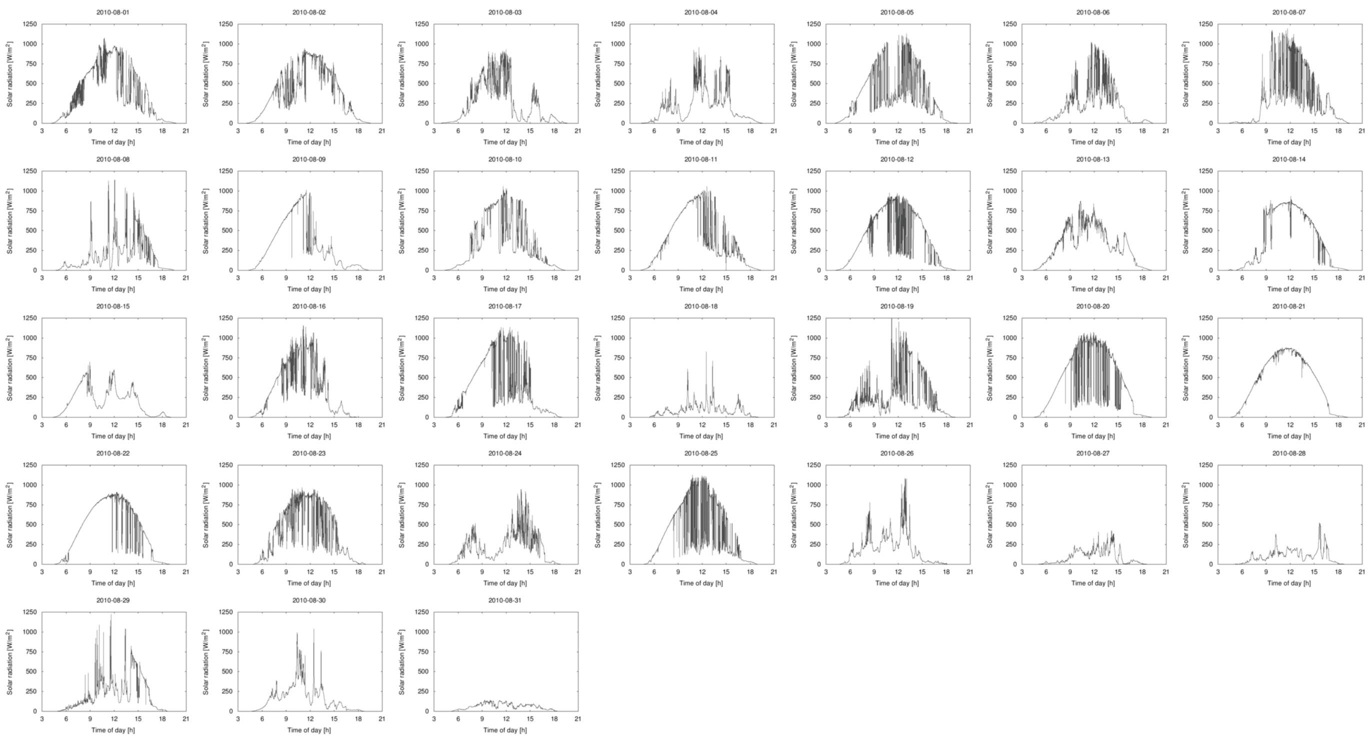

Figure 1. Daily Irradiance Profiles in August 2010

III. Short–term Energy Storage

The natural sunlight has beneficial influence on human vision and the interiors for daytime human activity should be generously glazed.

However, glazed interior spaces will suffer from unpleasant effect of rapid illumination changes which can be remedied with artificial lighting powered from PV, compensating the natural light deficiencies [1].

Figure 1 shows the daily irradiance profiles for the month of August 2010 to demonstrate that high variability is a very common situation, rather than an exception, in the climate of Central Europe and light compensation is a key requirement for the lighting system.

In order to deal with highly variable irradiation pattern, the PV-generator must be equipped with short time energy storage with super capacitor. The optimal sizing of such energy storage has been found [2], [3] to provide backup supply in term of 3-8 minutes only and its implementation with super-capacitors is realistic.

The short-time energy storage shifts the solar energy from sunny to cloudy periods. Due to the frequent occurrences, the only the supercapacitor is suitable for handling many quick charge/discharge cycles.

The important issue for carrying the simulation in variable conditions is the quality of irradiance data. Typically solar radiation measurements, integrated over longer periods, are stored with 0.5h or 1h time intervals.

These radiation measurements, although reporting correct energy amounts, lack the information about its dynamics and are useless for the purpose of lighting system simulation.

The Fig. 2 presents the daily irradiation patterns collected with different time intervals for the same day. It can be seen that 0.5h or 1h sampled profiles report the day as clear-sky, but in reality this was very unsettled weather.

The assessment presented in this paper is based on high quality irradiance data, collected with 5 s time resolution. Although the real irradiance fluctuations may be even shorter, the 5 s interval reflects well the inertia of human response to illumination changes and is suitable for the purpose of energy saving estimations.

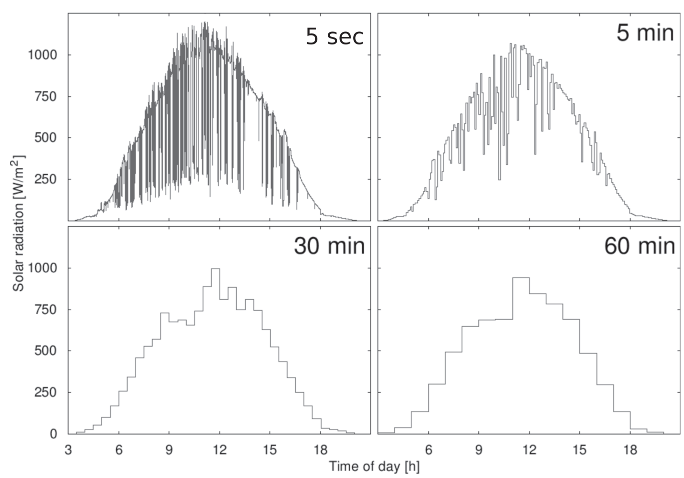

Figure 2. Daily irradiance profiles with data integration (Łódź, 2010-06-13)

IV. Lighting System Concept

The investigated lighting system (shown in Fig. 3) is based on assumption of maintaining the internal illuminance (in lux = lm/m^2) at a level of L_{norm} or higher on the floor area A_F. According to the norm [4], the typical work place should have illuminance 200-500 lux and at least 100 lux for spaces not intended for work (e.g. passageways).

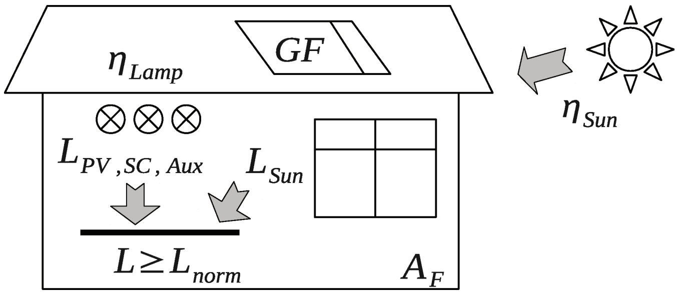

Figure 3. Key parameters of lighting system

The different components of indoor illuminance L (L_{PV}, L_{SC}, L_{Aux}), as shown in Fig 3, originate from four types of energy sources: electricity from PV, super capacitor or mains and solar radiation.

Solar component $L_{Sun} = G\eta_{Sun}GF$ contributes to the interior illumination with radiation power G, luminous efficacy $\eta_{Sun} = 80$ lm/W and glazing factor GF, which represents glazed-to-floor area proportion and configuration.

The glazing factor parameter GF can be calculated as follows [5]:

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

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 Fig 4.

	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

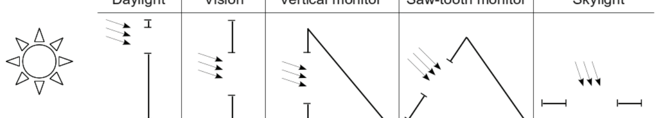

Figure 4. Glazing Factor parameters

The advantage of using GF in calculations consists in applying the same results for various types of room configuration (e.g. roof or wall windows), but having the same value of this parameters. In practice, GF ranges between 0% (no glazing) to 3–4% (well sunlit space).

The system is composed of the following elements (Fig. 5):

- Light source of power P_L and luminous efficacy $\eta_{Lamp} =$ 50 lm/W, corresponding to budget LED lamps. Lighting power demand and thus consumption is constant for spaces with $GF = 0$ and variable otherwise, which is made possible with the light dimmer.
- PV–generator delivering power P_{PV} depending on instant values of G, ambient air temperature and nominal power of the PV–generator. The simulation is based on PV model from [6] and uses custom software [7]. The generator is coupled to the common bus with the DC/AC inverter .
- Energy storage made with super capacitor due to the requirement of many quick charge/discharge cycles. The coupling is done with charge controller, adjusting the voltage levels and allowing for bidirectional energy flow, with power $\pm P_S$. The storage can be charged up to its maximal capacity E_{Smax}. The maximal discharge power is limited to $E_{Smax}/\Delta t$.
  The dimensions of super capacitor for a given storage energy can be estimated taking into account energy density for commercially available super capacitors of around 5 Wh/kg.
- The auxiliary supply is used in the case of a prolonged deficiency of solar radiation. Its only parameter in this simulation is instant power P_{Aux}.

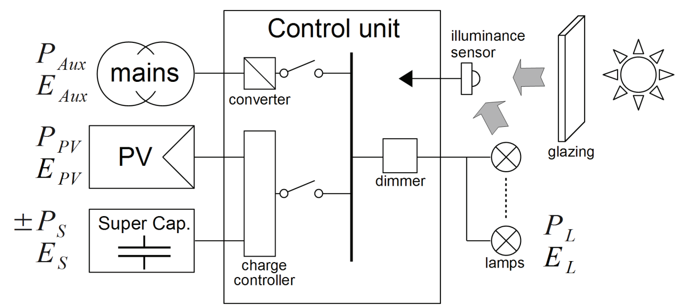

Figure 5. Lighting system components

Energy delivered or consumed by the system components are E_L, E_{PV}, E_S and E_{Aux} respectively. The efficiencies of the inverter and charge controller have been assumed as 90%.

The solar radiation data used for the simulation have been collected during the year 2010 at Technical University of Lodz with 5 s time resolution, using the fast silicon sensor SP-Lite, from Kipp&Zonen at the 30°S inclined surface. The measurements of ambient air temperature have been performed with a calibrated thermo-hygrometer [8].

V. Operation Algorithm

The simulation objective has been not to let the interior illuminance drop below the level of L_{norm} during the daytime “office hours”, i.e. 9h–17h. The illuminations may be higher due to excess of sunlight, but a drop below L_{norm} will be compensated with electric lighting.

The investigated parameters are: illuminated floor area (A_F in m^2), nominal power of PV-generator (P_{PVnom} in Wp), energy storage capacity (E_S in Wh) and L_{norm}.

The energy flow has been evaluated with the time step Δt = 5 s. The two main operation mode are are following:

1) Excess of sunlight

$$L_{Sun} \geq L_{norm} \quad (2)$$

No artificial lighting needed, thus no power consumption by the lamps ($P_L = 0$).

2) Light compensation

$$L_{Sun} < L_{norm} \tag{3}$$

Artificial lighting is needed and the power consumption by the lamps is:

$$P_L = (L_{norm} - L_{Sun})A_F/\eta_{Lamp} \tag{4}$$

During the light compensation mode, the required electric energy can be consumed in three configurations:

1) PV-generator alone:

$$P_L \leq P_{PV} \tag{5}$$

Supply is from the PV–generator only and its energy surplus:

$$+\Delta E_S = (P_{PV} - P_L)\Delta t \tag{6}$$

is stored in the super capacitor (up to the capacity limit) in each time step.

2) PV and supercapacitor:

$$P_{PV} < P_L \leq P_{PV} + P_S \tag{7}$$

Supply is from PV–generator and the storage; in each time step the storage is depleted by energy:

$$-\Delta E_S = (P_L - P_{PV})\Delta t \tag{8}$$

3) PV and grid:

$$P_{PV} + P_S < P_L \tag{9}$$

Supply is from PV–generator and the auxiliary source; the storage is empty and the auxiliary energy consumption is:

$$-\Delta E_{Aux} = (P_L - P_{PV})\Delta t \tag{10}$$

This operation is also takes place when there is no sunlight ($P_{PV} = 0$), for example after sunset.

The simulation has been performed in terms of power and energy flow only, without making any detailed assumptions about the electrical characteristic of the components and the control unit.

VI. System Dimensioning

The system dimensioning consists in the choice of the two parameters, both in respect to the illuminated area A_F, with fixed illuminance (L_{norm}) and glazing factor (GF):

- $PA^{GF}_{L_{norm}}$ (Power to 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;
- $SA^{GF}_{L_{norm}}$ (Storage to Area) in Wh/m^2 — energy storage capacity required to meet lighting power demand; the range of investigated values has been from 0 to 2 Wh/m^2.

The system operation for $PA^{1.0}_{400} = 5$ and $SA^{1.0}_{400} = 0.5$ is demonstrated in Fig. 6. At any time moment, the illuminance

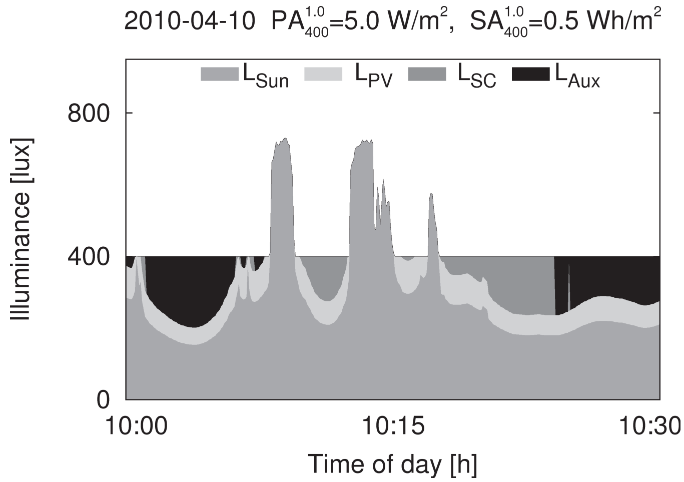

Figure 6. Example of indoor illuminance composition for undersized system (Łódź, 2010-04-10)

never drops below L_{norm} and the demanded illuminance from lamps is met by contribution from L_{PV}, L_S and L_{Aux} in various proportions. The Fig. 6 corresponds to a system with undersized parameters and a great contribution from auxiliary energy.

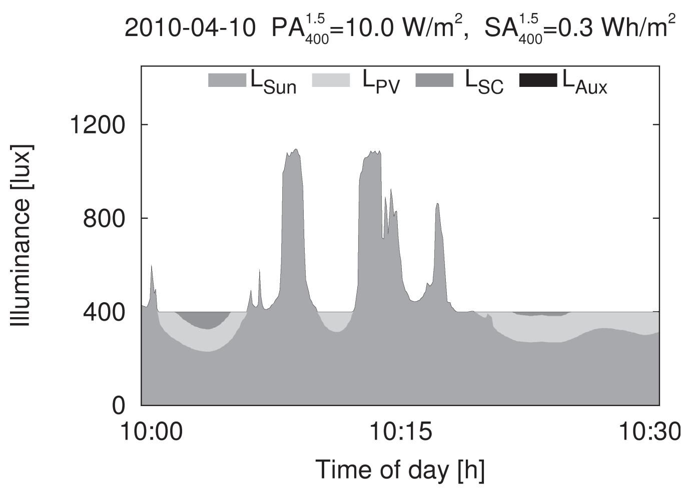

Figure 7. Example of indoor illuminance composition for oversized system (Łódź, 2010-04-10)

The proper dimensioning can successfully compensate for majority radiation deficiencies during the day. Obviously, the glazing factor has the dominating effect on the system operation, as shown in Fig. 7, where the system parameters are clearly oversized.

VII. Simulation Results

The annual distribution of solar energy at latitudes above 50° (as in Poland) is very nonuniform making the use of photovoltaics limited to the period between March and October, when 90% of the yearly amount is available. In winter, the use of photovoltaics is economically unjustified in most cases.

The simulation daylight period have been restricted to 8 “office hours”, i.e. between 9:00 and 17:00 EET, which matches well the daylight availability and offices’ activities.

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

In summer months, with long periods of daylight, the lighting system can operate fully autonomously with very modest dimension requirements, even for days with less favorable insolation as shown in Fig. 2.

For single summer day, the target of low illuminance 100 lx can be achieved with only 4 Wp/m^2 and 0.1 Wh/m^2 for spaces with no glazing (Fig. 8).

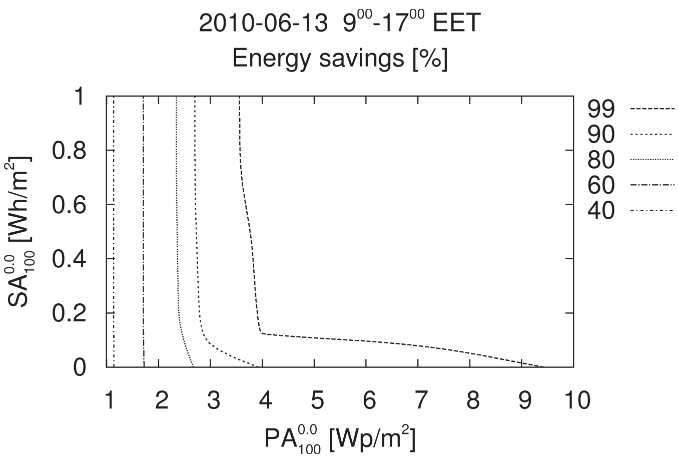

Figure 8. Interior with no glazing and low illuminance (Łódź, 2010-06-13)

Normal illuminance of 400 lx in summer can be maintained with 8 Wp/m^2 and 0.5 Wh/m^2 for very limited glazing of 0.5% (Fig. 9) , which itself contributes with almost 70% of energy savings.

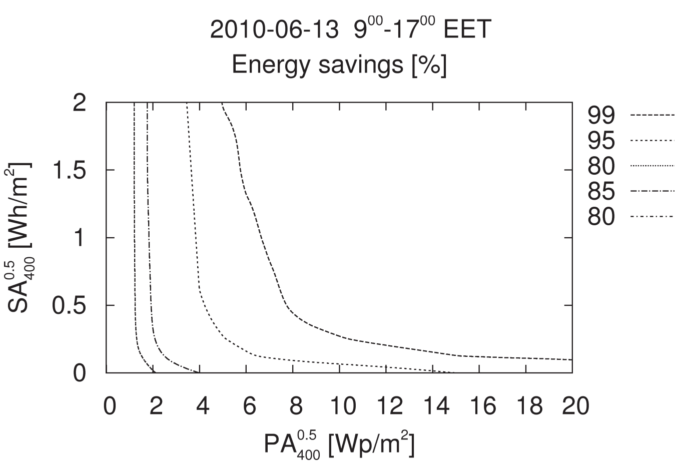

Figure 9. Interior with poor glazing and normal illuminance (Łódź, 2010-06-13)

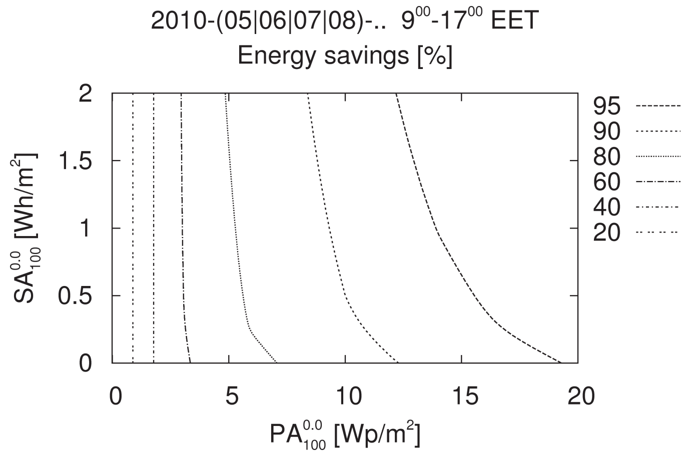

Figure 10. Interior with 100 lx and no glazing (Łódź, May–August)

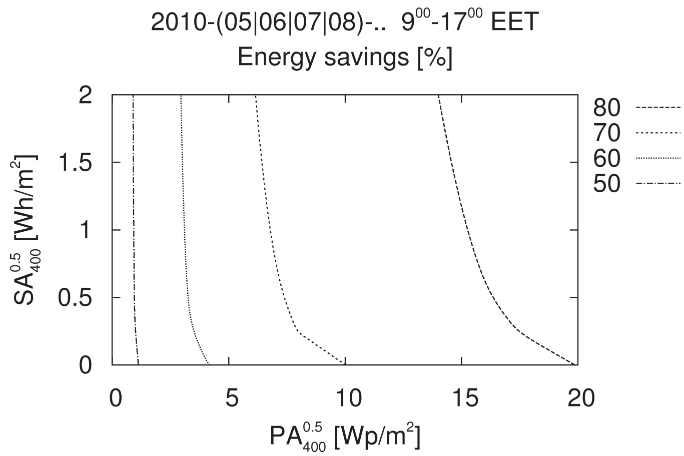

Figure 11. Interior with 400 lx and 0.5% glazing (Łódź, May–August)

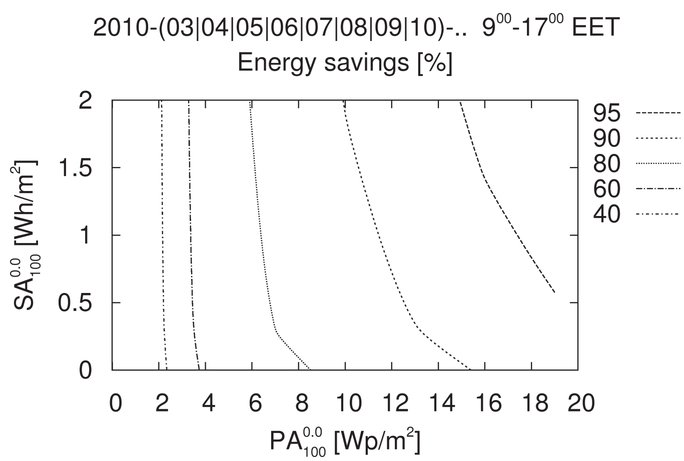

Figure 12. Interior with 100 lx and no glazing (Łódź, March–October)

Fig. 10, 11, 12, 13 show the cumulative results of energy savings for the 4– and 8–month periods. They correspond to two typical cases: dimly lit internal passageways (100 lx, no glazing) and mildly sunlit offices (400 lx, 0.5–1.0% glazing).

VIII. Conclusions

The paper studies a novel concept of using autonomous photovoltaic systems with short–term energy storage for interior daytime lighting.

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

The best effects for indoor lighting are observed for spaces

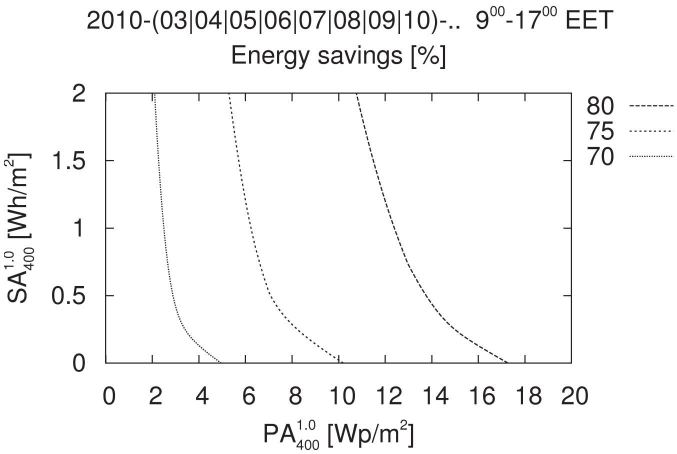

Figure 13. Interior with 400 lx and 1.0% glazing (Łódź, March–October)

with limited or no glazing, where the energy savings can reach 80-90% from March to October. When glazing factor is sufficiently high, the light control system, that compensate the natural light deficiencies with artificial light, provides sufficient savings on its own and additional PV–system offers little advantage.

If the application that can tolerate occasional power limitations, e.g. passageways lighting, then the complete autonomy of operation can be achieved for very long time intervals.

The results presented in this paper have the advantage of using the real-life conditions for calculating the results that are practical choices for the PV–system, expressed per unit area of illuminated space and depending on the glazing factor and illumination requirements.

The valuable applications can be found at low power level of a single PV–module and small super capacitor dimensions.

The daytime lighting represents the application for autonomous PV–systems with limited storage that can — in authors' opinion — successfully coexist with grid-powered infrastructure, reducing the electricity costs and offering a valuable asset of energy independence in case of emergency.

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