Operation of Photovoltaic Array with Small Energy Buffer under Variable Insolation Conditions

Witold Marańda, and Maciej Piotrowicz

***Abstract*—Photovoltaic systems can operate successfully also in less favorable climatic conditions, however, their performance can be improved by better adjustment to the local conditions. The specific feature of climate in Central Europe is the frequent occurrence of short and deep changes of solar radiation, especially during summer months.**

This highly variable nature of solar radiation makes it impossible to deliver energy from photovoltaic (PV) system at a stable power level in short terms. For grid-connected PV-systems it has negative effect on power condition devices, forcing them to continuous search for maximum power point and lowering the overall efficiently. For autonomous systems it means constant switching between charging and discharging cycles, shortening batteries life.

In this case, the small energy storage can mitigate the rapid power fluctuations, providing energy with a stable power level from the photovoltaic generator for a longer intervals during the day. The paper presents the guidelines for dimensioning the small energy buffer versus PV–generator nominal power and targeted load. The simulation is based on solar radiation data from Poland, measured with 5 s time resolution.

***Index Terms*—Photovoltaic system, energy storage.**

I. Introduction

PHOTOVOLTAIC devices, exposed to sunlight, deliver energy at unstable power level, reflecting the instantaneous intensity of solar radiation. Primary objective for any power supply system, including PV, is to meet the load power demand for the required period of time. Since the output power level of a PV–generator is not guaranteed due to the variable nature of solar radiation, the energy backup and storage (typically lead–acid batteries or utility grid) is always needed.

Applications of PV–systems without any auxiliary power supply and storage system are limited to few rare cases, when energy consumption can follow the radiation availability, e.g. water pumping in agriculture applications.

The sizing of long–term energy storage for autonomous PV–systems have been extensively studied [1], both for overnight and longer period storage. The generator oversizing and storage capacity may be significant, if the required supply reliability is high. The alternative approach is adopted in grid–connected PV–systems, where the grid serves both as infinite energy buffer and auxiliary power supply, which is always available.

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In contrast to long–term, the short–time energy storage, i.e. intended for providing only a few minutes power backup at daytime, has not drawn much attention so far. However, the arguments for the short–time buffering come from highly variable insolation, very common in the climate of Central Europe. Fig. 1 shows the daily radiation profile, which accounts for majority of days in Summer 2009 in Poland.

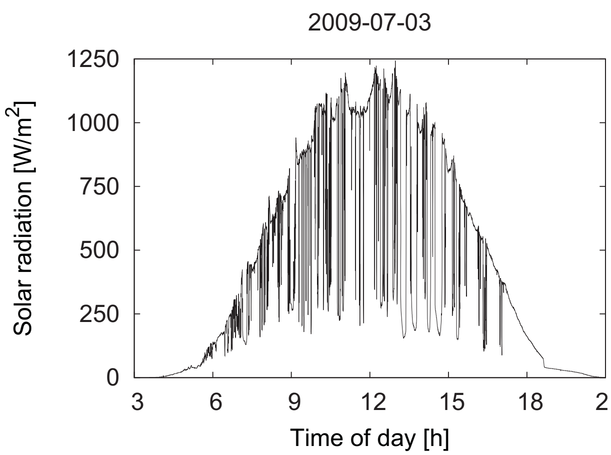

Figure 1. Daily profile of highly variable radiation (Łódź, 2009-07-03)

The short–time buffering might be used for both system architectures: autonomous and grid–connected. In the former case, it can smooth lead–acid charging/discharging patterns and in the latter — to improve DC/AC inverter performance in grid–connected systems.

The short–time energy storage for PV–systems also opens a field of new applications, dedicated to daytime operation only, with or without auxiliary support. In this case, the constant energy demand can be fully satisfied from PV, even under highly variable insolation. Since the power of PV–systems scale down very well, the applications can be found at the level of even hundreds watts or less (down to a single PV–module), as e.g. supply for daytime indoor lighting for office spaces.

This paper presents the study on short–term storage for PV–generator intended for autonomous operation to meet a declared power demand during daytime hours only. The system objective is to provide the long uninterrupted supply from the PV generator and save the energy from the auxiliary supply. No long–term storage is present. The results are obtained from numerical simulation of the system with the solar radiation data collected during the year 2009 in Łódź, Poland

II. SYSTEM CONFIGURATION

The opportunities for the short-term energy storage have been investigated for the system presented in Fig. 2.

All the system components are connected to the common bus, with the energy converters. The simulation has been performed in terms of power and energy flow only, without making any detailed assumptions about the electrical characteristic of the bus — in practice it might be DC or AC, depending on the load. The energy losses in the converters have been neglected.

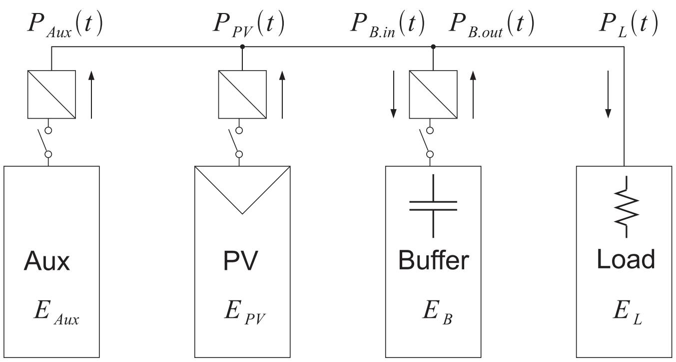

Figure 2. Block diagram of simulated system

The investigation has been only focused on the energy balance during the daytime, "office hours", i.e. 9h–17h.

Although, the simulation assumes a high level of abstraction, the technology used for energy buffer technology deserves more attention. The key requirements are the fast charge/discharge rates and ability to withstand a great number (at least hundred thousands) of cycles.

The chemical batteries offer very good energy density, but usually lack the fast charging rate and long lifetime. Moreover, partial charging and discharging conditions shorten their lifetime. The supercapacitors are better suited for this operating conditions (fast charge/discharge, over 1 mln duty cycles and more than 10 years lifetime) although their energy density (J/K) is 2–4 times lower.

A. Load

The key parameter for the load is its power level $P_L(t)$ and the consumed energy E_L. The power demand must be fully satisfied by the combination of the power sources in the system: PV–generator, buffer and auxiliary supply at any time during the required time interval.

The constant load power level has been assumed for the calculations.

B. PV–generator

The PV–generator is characterized by its nominal (peak) power $P_{PV.nom}$ for Standard Test Conditions (T_{STC}=25°C module temperature and 1000 W/m^2 solar radiation). Among many parameters, only its instant power level is required. Also, it assumed that energy from PV is delivered do the load or energy buffer without losses.

At any time moment, the generator operates at power $P_{PV}(t)$, is proportional to the radiation intensity, corrected for temperature effect [2] and calculated as:

$$P_{PV}(t) = P_{PV.nom} \frac{P_{Rad}(t)}{1000\frac{\mathrm{W}}{\mathrm{m}^2}} \left[1 - \beta(T(t) - T_{STC})\right] \quad (1)$$

where the temperature $T(t)$ and radiation $P_{Rad}(t)$ are the measurement data and β is the temperature coefficient, assumed $0.5°\mathrm{C}^{-1}$ for silicon solar cells. The energy delivered by the generator is E_{PV}

C. Energy buffer

The energy buffer can either absorb and accumulate energy with power $P_{B.in}(t)$ or deliver it with power $P_{B.out}(t)$. Within the period Δt, the buffer with stored energy E_B, can maintain maximal power of $P_{B.out.max}(t) = E_B/\Delta t$

The total energy in the buffer cannot exceed its maximal capacity $E_{B.cap}$ (in Wh). It is convenient to express this capacity in relation to the time interval (in minutes) during which the fully charged buffer can deliver constant power P_L:

$$E_{B.tcap} = 60\frac{E_{B.cap}}{P_L} \quad (2)$$

The short–time buffering is intended to provide power supply for the periods not longer than 15 minutes, which corresponds to $E_{B.cap}$ up to $0.25P_L$ Wh. Having the energy density of about 5 Wh/kg for commercially available supercapacitors, the dimensions of the buffer can be easily estimated for the given P_L.

For example, a small system with demand of P_L=100 W would require supercapacitor of about 3 kg weight to fully compensate for 10 min blackout. In reality, the insolation level never drops below 20% of its maximum, thus the required capacitor dimensions would be smaller.

D. Auxiliary power supply

The auxiliary power unit is used to supply the load in case the prolonged deficiency of solar radiation. This may be either utility–grid or long–term battery storage. For the purpose of this simulation, its only relevant parameter is the power level $P_{Aux}(t)$ and the delivered energy E_{Aux}.

The system objective is to minimize this energy consumption (E_{Aux}) and operate as long as possible fully autonomously (T_{Aut}). This two factors have been used for system evaluation, later on.

III. DATA FOR THE SIMULATION

The simulation of short–term buffering requires the data collected with a sufficient time resolution. In most cases, however, the measurements of solar radiation are focused on determination of correct energy amounts only, leaving aside the details of daily radiation profiles.

The effect of time resolution rate on quality of daily profile is shown in Fig. 3, where in all four sub-figures the amount of

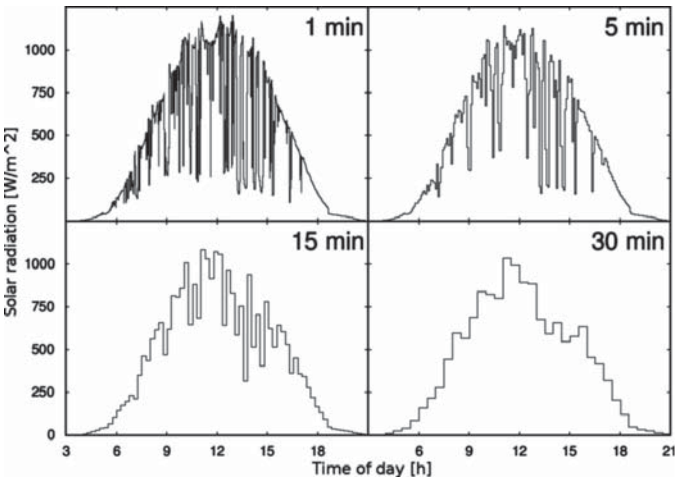

Figure 3. Daily profile (Fig. 1) with various time resolutions (Łódź, 2009-07-03)

delivered solar energy is identical, but the information about its dynamics is partially or totally lost.

In practice, the time resolution must be in order of seconds, to reflect real nature of rapid variations of solar radiation.

The solar radiation measurements have been done with a high precision pyranometer CM21 and 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. The temperatures of several PV-modules have been measured with a custom-built system using silicon sensors DS18B20 from Maxim, attached to the backside of the PV-modules [3].

All the measurements were conducted at 1 kWp PV-system at DMCS. The monitored part of the installation consists of 20 multi-crystalline modules, 50 Wp each (Solar-Fabrik SF50), working with Top-Class Spark 1500 grid inverter. The monitoring system records all the important meteorological and electrical parameters, from both DC and AC side [4].

The data from sensors have been read every 5 seconds and stored in a database. The presented results are based on data collected in the second half of year 2009.

IV. System Simulation

The simulation has been carried out with the measurement data acquired at DMCS with the time step Δt = 5 s. At each time step, the system may operate in 1 out of 3 possible modes: PV only, PV+Buffer and PV + Aux, according to the following conditions:

a) PV only:

$$P_{PV}(t) \geq P_L(t) \tag{3}$$

Full supply is from the PV–generator. The energy surplus $(P_{PV}(t) - P_L(t))\Delta t$ is stored in the energy buffer (up to its capacity limit).

b) PV + Buffer:

$$P_{PV}(t) + P_{B.out.max}(t) \geq P_L(t) \tag{4}$$

PV supply is backed with the buffer. During each time step the buffer energy is depleted by $(P_L(t) - P_{PV}(t))\Delta t$,

c) PV + Aux:

$$P_{PV}(t) + P_{B.out.max}(t) < P_L(t) \tag{5}$$

The energy buffer is empty and PV supply is backed with the auxiliary source. During each time step the auxiliary energy consumption amounts to $(P_L(t) - P_{PV}(t))\Delta t$.

The system operation can be visualized showing the power composition during the day. At any time, the load power $P_L(t)$ is satisfied by the power delivery from $P_{PV}(t), P_{B.out}(t)$ and $P_{Aux}(t)$ in various proportions. The simulation parameters are the PV–generator oversizing and buffer capacity.

Obviously, the benefits of short–term buffering are negligible for clear sky conditions, as in Fig. 4, where the buffer operation is limited to only one discharge cycle in the afternoon, as shown in Fig. 5. However, such conditions are rare in Poland and the short–term buffering is not proposed for such conditions.

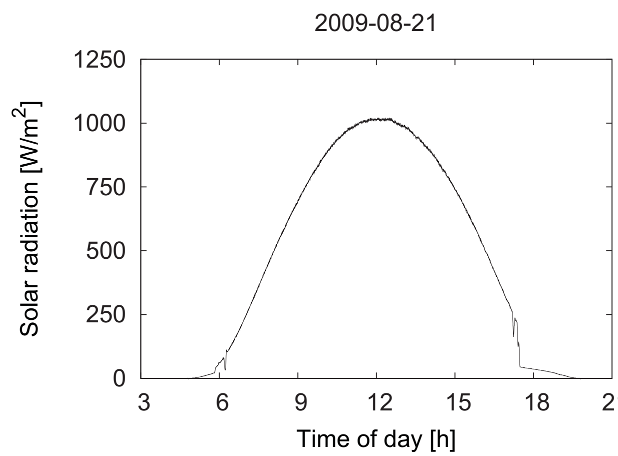

Figure 4. Clear sky daily radiation profile (Łódź, 2009-08-21)

During the day, the demand P_L is satisfied either with PV and auxiliary supply or PV only. The buffer contribution is minimal. It is also clear that operation interval must match the daylight period, if the auxiliary energy consumption is to be minimized.

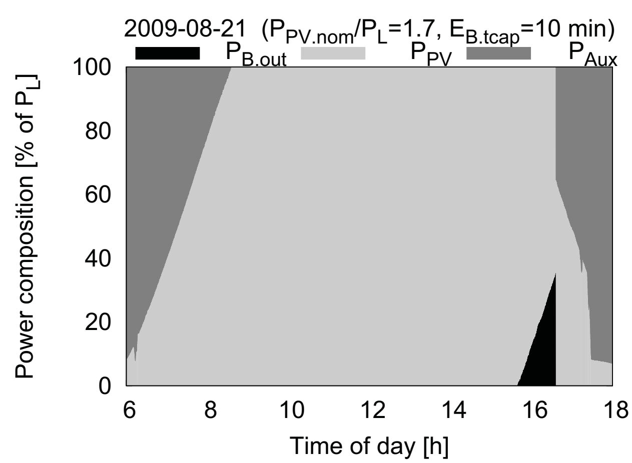

Figure 5. Power delivery composition for radiation profile in Fig 1

In contrast to clear sky conditions, Fig. 6 shows another power delivery composition for the day with radiation pattern in Fig. 1.

The proper dimensioning of the short–time buffer and PV–generator can successfully compensate for majority radiation deficiencies during the day. In the case shown in Fig. 6 the system parameters have been set up arbitrarily to 1.7 for PV oversizing and 10 minutes for the buffer capacity.

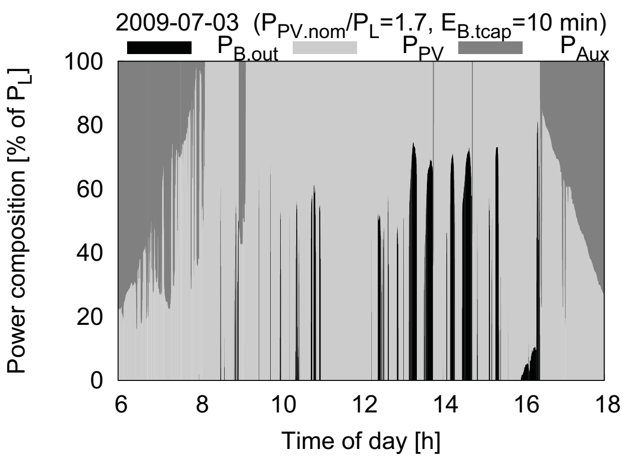

Figure 6. Power delivery composition for radiation profile in Fig 1

The close examination of variable radiation daily patterns, such as in Fig 1, reveals that majority of rapid fluctuations duration does not exceed a few minutes and the buffer size may be limited to 15 minutes for further simulations.

V. System Dimensioning

The annual distribution of solar energy at latitudes above 50° (as in Poland) is very nonuniform: more than 80% of the total is received between April and September. In winter, the use of photovoltaics is economically unjustified in most cases. Therefore, the system evaluation have been divided into three case:

- single day with highly variable radiation (Fig 1), to demonstrate the best-case results (section V-B),
- July—September 2009 — 3-months period, for which the application is targeted, (section V-A)
- October–December 2009 — 3-months period, when use of PV is economically unjustified (section V-C).

The dimensioning consists in the choice of two parameters:

- $P_{PV.nom}/P_L$ — PV–generator oversizing in relation to load power demand; in the range between 1 and 2.
  The upper limit for oversizing ratio has been found experimentally and bigger oversizing has not offered any significant advantage.
- $E_{B.tcap}$ — buffer capacity required to meet load power demand; in the range between 0 and 15 minutes.

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

The evaluation of the simulation has been focused on two quantities:

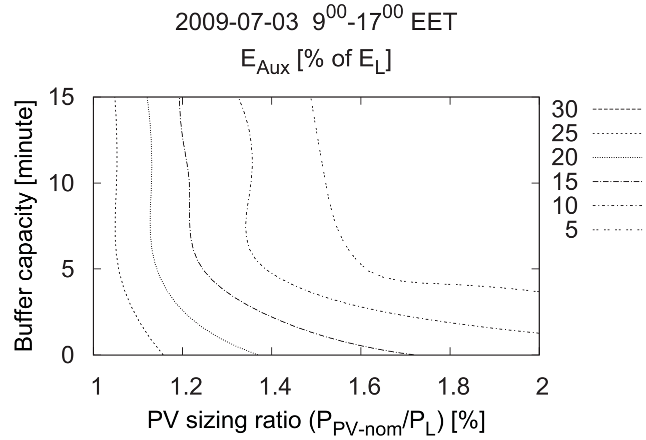

Figure 7. Auxiliary energy backup for one day (see Fig. 1)

- E_{Aux} — auxiliary energy needed as backup,
- T_{Aut} — time of fully autonomous operation of the system.

Both quantities have been calculated as the percentage of the total load energy consumption and total system operation time, respectively.

Having all the input dimensioning parameters ($P_{PV.nom}/P_L$, $E_{B.tcap}$) load-dependent and output results (E_{Aux}, T_{Aut}) dimensionless, makes the dimensioning guidelines universally applicable for the investigated climatic conditions.

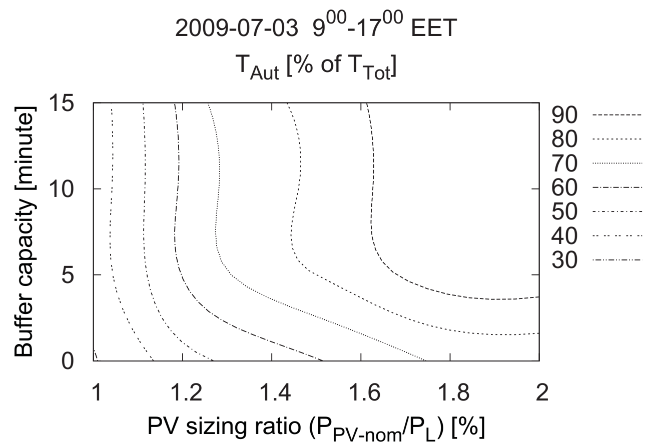

Figure 8. Autonomous operation time for one day (see Fig. 1)

A. Single day with highly variable radiation

The greatest benefits of short–time storage are for highly variable radiation. Fig. 7 and 8 show the one–day results for the solar radiation profile from Fig 1, which may be considered as the best-case scenario for the shot–therm energy buffering.

The contours in figures exhibit a pronounced corner, which seems to be is a good choice for system dimensioning parameters. Precise criterion for optimum should also involve the economical aspects (system cost vs energy savings in time), which is beyond the scope of this work.

For the best-case scenario (Fig. 7 and 8), the 60% oversizing of the PV–generator and 5 minutes buffer capacity allows to save 95% auxiliary energy and provide autonomous supply for almost 90% of the required operation time. It turns out that greater oversizing would not improve the results and as well as increasing the buffer capacity over 5 min, which matches the length of majority of radiation drops.

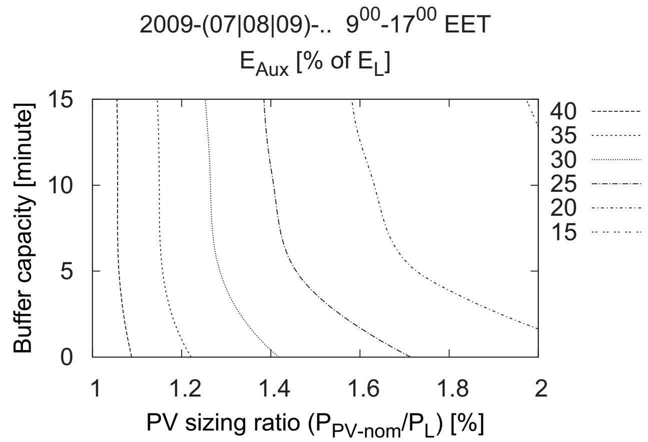

Figure 9. Auxiliary energy backup in July—September 2009

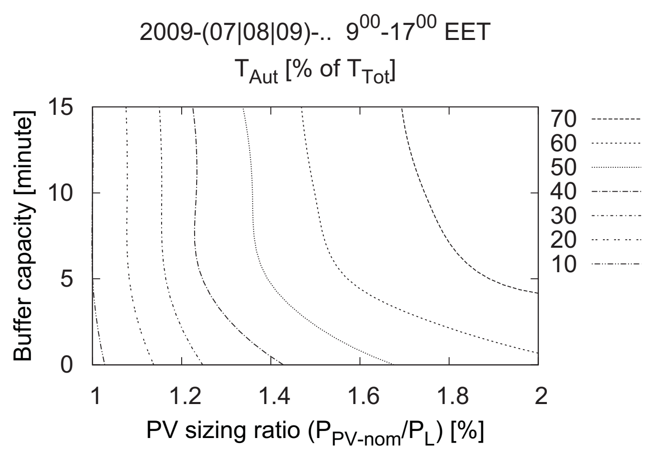

Figure 10. Autonomous operation time in July—September 2009

B. July—September 2009

Fig. 9 and 10 show the cumulative results for the 3–months' summer period. The contours in figures also exhibit a pronounced corner in roughly the same place. With moderate PV oversizing of 70% it is sill possible to reach 80% auxiliary energy saving and 65% of autonomous operation time.

The results for 3-months period are very close to the best case scenario in terms of system parameters — 1.6. . .1.8 PV oversizing and 5 minutes buffer capacity. Further increase of neither of both parameters is not recommended. The fact, that the recommended buffer capacity is still around 5 minutes, for the period of three months suggests that highly variable radiation conditions are similar throughout the year and this might be a specific feature of the climate.

C. October–December 2009

For the autumn–winter period the results are dramatically worse. Fig. 11 and 12 show very small dependence on buffer capacity. All improvements relay on increasing buffer oversizing, far beyond the ratio of 2, which would make the system too big and costly, with no benefits from short-term buffering.

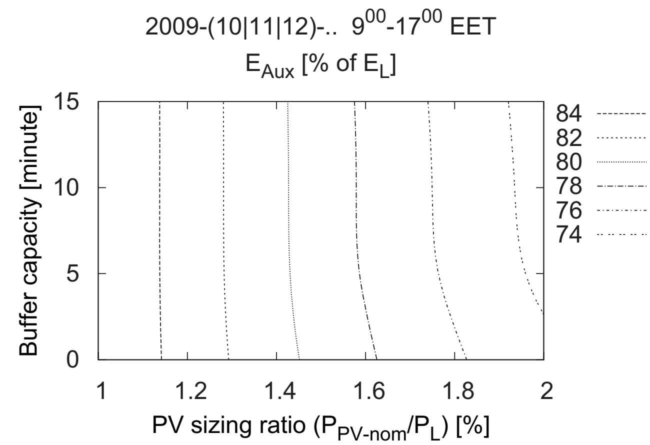

Figure 11. Auxiliary energy backup in October—December 2009

Assuming the same dimensioning parameters as for summer period (1.6. . .1.8 oversizing and 5 minutes buffer), the auxiliary energy savings amounts to less than 25% of consumption in this period and autonomous operation time is shorter than 10% of total time.

Clearly, the winter insolations conditions (low radiation intensity and short day duration) are not suitable for reasonable use of photovoltaics, leading to great oversizing of PV-systems in regard to the power needs.

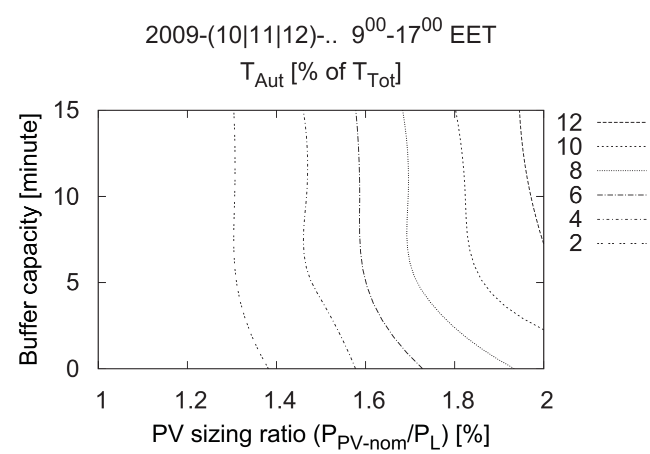

Figure 12. Autonomous operation time in October—December 2009

VI. Conclusion

A number of successful applications for renewable energy sources is growing, despite the still relatively high cost of delivered energy.

PV–systems have already been valued as autonomous supply units for remote and difficult-to-reach locations with long–term storage and as grid–connected residential power generators with support of feed-in tariff.

The short–time energy storage for PV–systems opens — in authors' opinion — a new range of daytime applications for use with or without utility grid. The PV–generator with short–time buffer only, can be designed to meet the required power demand during specified period, with a desired level of reliability.

It may be very attractive for applications that can tolerate occasional power shortages, e.g. daytime lighting system. Lighting applications seem to be especially attractive, since the daylight may also be used directly to lower the artificial lighting power demand and allowing for further reduction of PV and buffer size.

The results presented in this paper have the merit of translating the real-life conditions into practical choices for the PV–system and the buffer. The results, however, may be not transferable to other climatic conditions. Moreover, some phenomena in the simulation have been neglected (e.g. energy converters efficiency), which makes the results to be the upper limit for the energy savings and autonomous operation time.

Nonetheless, the PV–generator oversizing of 60. . .70% in relation to load power and the buffer capacity of around 5 minutes are the guidelines for climate in Poland, for the period with high insolation, i.e. April–September. In winter months, the solar radiation cannot be reasonably utilized and all simulation results suggest too big oversizing of PV system components.

Especially interesting perspective for short–time buffering is for applications at low power level of a single PV–module, where the complexity of building the PV-generator can be avoided and the required supercapacitor dimensions are small.

References

[1] E. Lorenzo, *Solar Electricity. Engineering of photovoltaic systems*. PROGENSA, Spain, 1994.

[2] M. G. Villalva, J. R. Gazoli, and E. R. Filho, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.*, vol. 24, no. 5, pp. 1198–1208, 2009.

[3] M. Piotrowicz and W. Marańda, "Temperature analysis system for photovoltaic installation," in *Proceedings of the 16th MIXDES Conference, Łódź, Poland*, Jun. 2009.

[4] W. Marańda, G. Jabłoński, and D. Makowski, "Advanced monitoring system for photovoltaic generator," in *Proceedings of the 11th Electronic Devices and Systems Conference, Brno, Czech Republik*, Sep. 2004.

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