**Lukáš PROKOP[1], Stanislav MIŠÁK[1], Emil PELIKÁN[2], Pavel JURUŠ[2], Ivan KASANICKÝ[2]**

VSB – Technical University of Ostrava (1), Institute of Computer Science of the ASCR (2)

# Analysis of PV system energy balance based on meteorological data

***Abstract**. Energy concept for family house power supply using photovoltaic power plant (PV) with possibility to operate in off-grid mode was analyzed in this paper. We present partial results from analysis of power consumption of selected house. These results were used as input data for energy concept evaluation and compared with potential energy production calculated from meteorological and climatological data gained from meteorological satellite data.*

***Streszczenie.** W artykule analizowano możliwość zastosowania systemu fotowoltaicznego do zasilania energią elektryczną budynku. Analizowano szereg przypadków z uwzględnieniem warunków meteorologicznych. (**Analiza systemu fotowoltaicznego zasilania budynku z uwzględnieniem warunków meteorologicznych**)*

**Keywords:** Photovoltaic Power plant, Energy concept, energy consumption, PAX system, solar radiation
**Słowa kluczowe:** system fotowoltaiczny, zasilanie budynku w energię elektryczną

## Introduction

Energy self-sufficiency as well as safety are on the top burner of modern society. Modern society of the third millennium is dependent on energy supplies. The main priority of each country is, whether at national or worldwide benchmark, to provide safety and reliability of energy system. A weak point of energy system is the unbalanced distribution of the energy sources and supplies of energy.

Providing an extraction access as well as transport access of these sources to the consumption place are one of the most geo-political goals. Providing safety and reliability of central operated energy systems is going to be more and more demanding in the future.

One of the possibilities to decrease partly the risks mentioned above is progressive introduction of automation or information technology into the system of operation energy systems and switchover to so called distributed power system where the central energy system will be constituted by independent parts which will enable a flow of energies among each other as well as information flow, but will be able to be in operation in “pseudo“ off-grid mode in case of failure or other unpredictable actions of the central level of energy system. Part of this conception is maximum use of renewable energy sources of electric power in compliance with [1] but to respect suitability of individual locations for individual kinds of renewable energy sources of electric power as well as to respect of economical efficiency [2] of installation of individual kinds of electric power. The whole system of distributive power system is necessary to control with sophisticated control system [3,4] which will meet the requirement of distributive access to the system operation when the operation will be autonomous within the particular area but with the intervention possibility from the superior system in case of need at the same time. The principles mentioned above are possible to monitor for example at the agent based systems. Due to this complicated problem which stands beyond power engineering itself, it is necessary to make headway from the lowest output (elementary energy units) while implementing agent systems into the controlling of energy complex. It includes for example family house or block of flats, administration buildings, from energy micro-region (for example towns, villages), particular parts systems (for example transmission/transfer system of the Czech republic) to European complex energy system, so called Pan European grid.

The main goal of this article is to review the energy evaluation of a family house based on meteorological data. Model that enables an easy result presentation is selected a family house with home appliances and with presumptive regular electric power consumption.

The first chapter applies to analysis of power consumption and the brief description of how to operate it with the aid of PAX system when we expect the operation during full or partial off-grid mode. As the effort is maximum use of renewable energy sources, especially photovoltaic, the second chapter is dedicated to assessment of the selected location from the point of view of meteorological and climatologic conditions. Based on these analysis and determination of energy profits, potential power energy production value is calculated, which is presented in the fourth chapter. The fourth chapter also deals with the evaluation of possibility of electric power production in a sufficient capacity for different options of statistical assessment of produced electric power.

## Analysis of consumption

Basic criterion of dimension of individual components of energy units is planned consumption of electric power. In this case we talk about a family house with built-up area of approximately 200 square meters with the gas boiler heating. Electric power is used to supply all appliances, including the ones designated for cooking. Detailed description of the considered appliances including their input power is stated in [5].

In the Figure 1, there is shown a household load curve of a specific weekday when we expect the maximum electric power consumption. Based on this data, we will make a proposal of storage and energy sources.

We can summarize the data for energy system dimension as a power consumption 32 kW·h a day (day with the maximum consumption), week power consumption approximately 100 kW·h and a peak off take more than 8 kW. Due to the effort to hold a reasonable economical dimension while proposing the energy concept is appropriate to consider a possibility of a peak off take reduction to enable decreasing of initial conditions of energy concept. A consumption measured on the particular days is written in the Table 1.

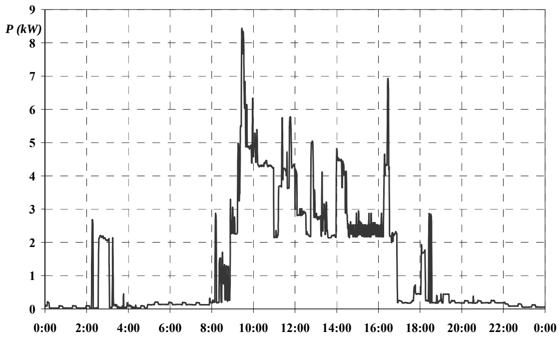

Fig. 1 One day active power consumption

Table 1. Electrical Energy consumption

| | Energy consumption (kW·h) |
|---|---|
| Monday | 17.33 |
| Tuesday | 7.89 |
| Wednesday | 14.83 |
| Thursday | 9.94 |
| Friday | 13.65 |
| Saturday | 32.04 |
| Sunday | 8.87 |
| Total | 104.55 |

One of the possibilities is the use of PAX system which is designated for intelligent controlling operation of small off grid modes. System function PAX is described in detail in [7]. It is an operating system which controls switching on of particular appliances on the basis of pre-set priorities. System PAX determines priority figures of individual/particular appliances on the basis of regular users habits of individual applications with the goal/aim not to limit user´s everyday household running. Example of system function PAX is stated in the Figure 2. PAX system is looking for available electric power on the basis of information about availability of utilized power energy sources and priorities value of particular appliances.

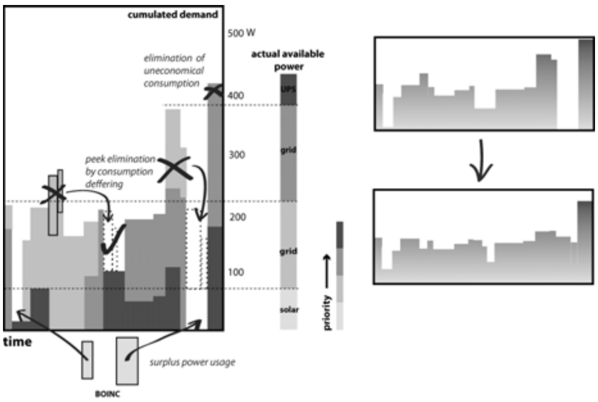

Fig. 2 PAX system operating scheme

Use of PAX system or different system with similar principle enable to change input figures for accumulative system dimension and lower figures of power source dimension at the same time. In this specific case, the decreasing of the peak off-take from Figure 1 to 4 kW was reached without perceptible restriction of analysed household running.

**Solar radiation for selected locality**

Due to nowadays energy politics and economic situations, PV panels mounted on a roof has been considered as a power supply for the house. Using of a wind energy has not been considered, because of difficulties with installation permissions and its costs. The goal is to consider operating the house in off-grid mode, nevertheless the economical efficiency of selected solution should be retained.

**Estimation of the solar energy**

Estimation of energy balance has to be based on historical data of solar radiation. There are different data sources, which could be used such as surface or sounding measurements, data from satellites etc. Other types of data could be obtained by numerical weather prediction models. Data from meteorological reanalysis falls into the second category. Reanalysis aims to produce the best estimation of historical states of the atmosphere for a long time period, usually few decades, by using modern data assimilation method together with complicated physical models of the atmosphere. One of the crucial objectives of reanalysis is to create dataset, which has homogeneous distributions of errors in time. In general it is a very challenging exercise since new measurement methods are still being developed – for example satellite observations has been widely spread in last 50 years and nowadays they are the main data source, when the state of the atmosphere is estimated.

To fulfil the goal of this article we have chosen MERRA (Modern-Era Retrospective analysis for Research and Applications), a global reanalysis product created in NASA [1]. It covers the time interval starting from 1979 till present. In contrast to other reanalysis mainly satellite data are assimilated in MERRA, although surface and sounding measurements are used too. State-of-the-art assimilation method of system GEOS-5 (Goddard Earth Observing System) with the method of incremental analysis updating is used to create resulting meteorological fields with 1 hour frequency and high spatial resolution ½ times 2/3 degree.

**Typical month solar energy**

A historical data covering 34 years (1979 - 2012) for the selected locality (LAT 49°52'57.909"N, LON 18°28'59.569"E) from MERRA reanalysis has been used.

So long time series allow us to compute statistical characteristics of the solar irradiance and to estimate its variability. For modelling purposes global horizontal irradiance from MERRA has been split into direct and diffuse components using cloud optical depth. Direct horizontal solar irradiance has been transformed into actual irradiance on elevated panels based on the solar zenith angle and the solar azimuth. For Europe optimal elevation of PV panel is 35 degrees.

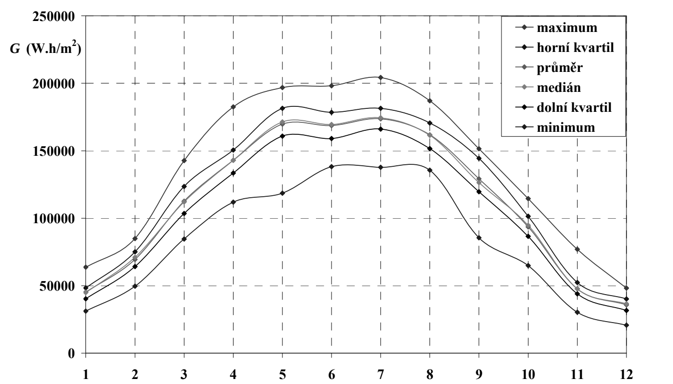

Fig. 3 Statistical characteristics of monthly sums of solar irradiance for selected locality (49°52'57.909"N, 18°28'59.569"E) based on historical data (1979 - 2012). Solar irradiance has been transformed to irradiance on elevated panel with optimal elevation angle 35° and oriented South

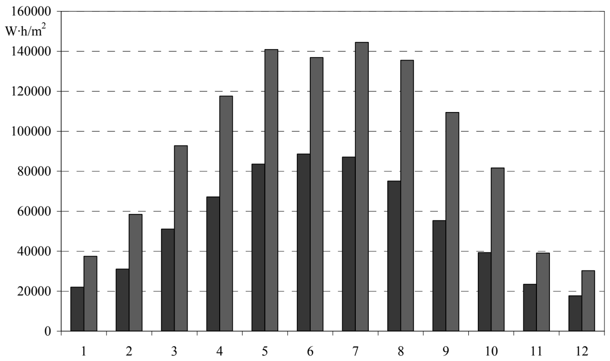


Fig. 4 Monthly statistical characteristics of solar irradiance for years 1979 - 2012. Monthly sums divided into the direct normal irradiance and diffuse irradiance on a horizontal surface

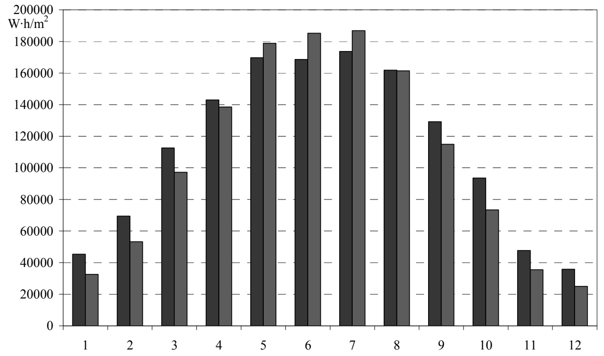


Fig. 5 Monthly statistical characteristics of solar irradiance for years 1979 - 2012. Monthly sums of irradiance on horizontal surface and on tilted panel

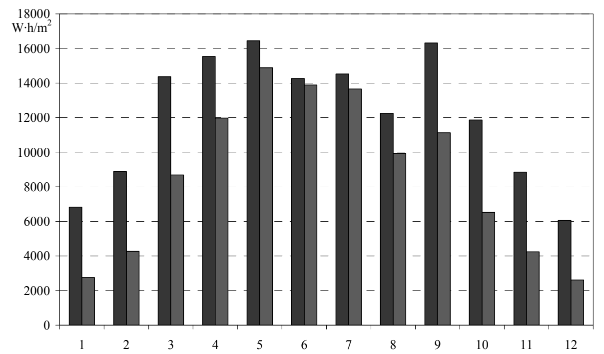


Fig. 6 Monthly statistical characteristics of solar irradiance for years 1979 - 2012. Standard deviation of monthly sums of irradiance on horizontal surface and on tilted panel

Basic statistical characteristics, plotted on the figures 4, 5 and 6, show that during summer sum of total irradiance on a panels with optimal elevation angle is lower than sum of irradiance on a horizontal surface. Figure 6 shows standard deviations of monthly sums of irradiance. The values for horizontal surface are around 10% of monthly totals. It means that between years variation is quite high. The variation of irradiance on tilted plane is even higher. One possible explanation is, that irradiance on tilted plane is more sensitive to unstable cloudiness, when the solar zenith angle is high. This effect could brings higher variability especially in winter and transition months of year.

**Energy evaluation**

If we use the figures from Figure 3 and if we count with maximum and minimum figure, all the other figures will lay between of these outer/side points. For this calculation we use common PV system mounted on the roof of common family house with installed capacity around 5 kWp. One PV module usually takes area about 2 $m^2$ with 280 Wp of active power. For 5 kWp of mentioned PV system we must use about 18 PV modules with total installed area about 35 $m^2$.

For minimal value 20,667.07 W·h /$m^2$ from Figure 3 which is responsible for minimal curve for December for PV system with these real parameters, PV system can produce only about 2.41 kW·h .

On the other side when we use maximum power curve from Figure 3 the maximum value is 204,274.91 W·h/$m^2$ and total produced for similar PV system we can reach 23.83 kW·h. In the real situation the PV system will produce energy with total amount between 2.41 and 23.83 kW·h. These values were calculated for monocrystalline PV system with PV module efficiency 10%. When we use top PV modules with excellent parameters and PV module efficiency about 18% we can estimate span of produced energy between 4.34 and 42.89 kW·h. When we compare estimated produced energy of PV system shown in Table 1 together with respecting PV system parameters we can find that it is not possible to operate in full off-grid mode because of lack of total amount of electrical energy to cover energy consumption. Design of PV system for all-year off-grid mode operation is not sufficiently cost effective. Estimated values of produced energy for PV system with PV modules with 18% efficiency are shown in Table 2.

After comparison of values from Table 1 and Table 2 we can find that only a few months we can operate mentioned PV system in full off-grid mode.

Table 2 Estimated electrical energy (kW·h)

| month | max | upper quartile | average | median | lower quartile | min |
|---|---|---|---|---|---|---|
| 1 | 13.37 | 10.15 | 9.51 | 9.42 | 8.46 | 6.56 |
| 2 | 17.84 | 15.76 | 14.59 | 14.94 | 13.47 | 10.42 |
| 3 | 29.97 | 25.95 | 23.66 | 23.53 | 21.73 | 17.77 |
| 4 | 38.34 | 31.62 | 30.02 | 30.01 | 28.03 | 23.50 |
| 5 | 41.33 | 38.12 | 35.64 | 35.98 | 33.78 | 24.91 |
| 6 | 41.61 | 37.48 | 35.42 | 35.59 | 33.40 | 29.01 |
| 7 | 42.90 | 38.09 | 36.47 | 36.64 | 34.87 | 28.93 |
| 8 | 39.28 | 35.83 | 33.98 | 33.90 | 31.82 | 28.48 |
| 9 | 31.80 | 30.31 | 27.14 | 26.55 | 25.13 | 17.96 |
| 10 | 24.06 | 21.30 | 19.65 | 19.91 | 18.18 | 13.62 |
| 11 | 16.18 | 11.01 | 10.02 | 10.00 | 9.24 | 6.37 |
| 12 | 10.11 | 8.42 | 7.51 | 7.68 | 6.63 | 4.34 |

Averaged values of produced energy (for months with sufficient amount of energy are marked light grey) are shown in Table 2. The problem is unbalanced total amount of consumed energy on Saturday which is significantly higher than the rest of the week. If it is possible to decrease total amount of consumed energy on Saturday to usual values around 15 kW·h we can operate mentioned PV system on off-grid mode next 5 month. This new situation is shown in Table 2 and marked dark grey.

PV system with full off-grid mode operation respecting these values of consumed energy must take about 70 $m^2$ area for PV modules. This area of PV modules means approximately twice the amount of investment costs and of course there is also problem with total area of roof which is oriented on south to reach optimal solar radiation conditions. PV system for full off-grid operation together with respecting actual power consumption about 15 kW·h will take area about 120 $m^2$.

## Conclusion

Installation of renewable energy sources for off-grid mode operation seems to be good alternative of grid mode operation.

Operation of PV system in full off-grid mode is not at this time sufficiently cost-effective. In some cased we can use more than one renewable energy sources to make off-grid system more cost-effective. For example we can use PV system and wind power plant, which is able to produce energy also in period with lower PV system production.

Climatologic and meteorological data are necessary as input for energy estimation during off-grid system design.

We use data analyzed by meteorological reanalysis in this text. Long time climatologic and meteorological data are the main part of the data source for energy system design.

Next research and development in area of application of climatologic and meteorological data we will focus on useful data sources for localities with specific wether conditions.

***Acknowledgements***

*This work has been partly supported by the Czech Science Foundation under the project 102/09/1842 and by the Ministry of Education, Youth and Sports of the Czech Republic (ENET No. CZ.1.05/2.1.00/03.0069), project SP2013/68 and by the European Regional Development Fund in the IT4Innovations Centre of Excellence project (CZ.1.05/1.1.00/02.0070) and by the Bio-Inspired Methods: research, development and knowledge transfer project, reg. no. CZ.1.07/2.3.00/20.0073 funded by Operational Programme Education for Competitiveness, co-financed by ESF and state budget of the Czech Republic and also project MŠMT č. LD12009.*

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***Authors**: Lukas Prokop, VSB - Technical University of Ostrava, Department of Electrical Power Engineering, ul. 17. listopadu 15, 708 33 Ostrava, E-mail: lukas.prokop@vsb.cz; Stanislav Misak, VSB - Technical University of Ostrava, Department of Electrical Power Engineering, ul. 17. listopadu 15, 708 33 Ostrava, E-mail: stanislav.misak@vsb.cz; Emil Pelikan, Institute of Computer Science of the ASCR, v. v. i., Pod vodárenskou věží 2, 182 07 Praha 8, E-mail: pelikan@cs.cas.cz, Pavel Jurus, Institute of Computer Science of the ASCR, v. v. i., Pod vodárenskou věží 2, 182 07 Praha 8, E-mail: jurus@cs.cas.cz, Ivan Kasanicky, Institute of Computer Science of the ASCR, v. v. i., Pod vodárenskou věží 2, 182 07 Praha 8, E-mail: kasanicky@cs.cas.cz.*