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Dimensioning of household electricity storage for PV-systems and load scheduling based on Nord Pool Spot prices

Abstract. *This paper analyzes global irradiance data measured in the Tallinn-Harku Aerological Station (Estonia). Dimensioning of a PV-panel area and electricity storage for a typical household is discussed. The final part describes electricity storage dimensioning based on a combination of Nord Pool Spot (NPS) prices and a grid connected household PV-system generation.*

Streszczenie. *W artykule są analizowane całościowe dane pomiarowe oświetlenia słonecznego na stacji metrologicznej Tallinn-Harku. Na tej podstawie jest dyskutowany dobór paneli PV i zasobnika energii w warunkach typowego gospodarstwa domowego. Końcowa części opisuje wymiarowanie zasobnika energii elektrycznej, w oparciu o ceny dystrybutora energii i połączonego z siecią domowego systemu PV. (**Wymiarowanie zasobnika energii elektrycznej w gospodarstwach domowych dla systemów PV i planowanie obciążeń w oparciu o ceny Nord Pool Spot**).*

Keywords: Solar energy; global radiation; photovoltaics; dimensioning of electricity storage, electricity balance.
Słowa kluczowe: in the case of foreign Authors in this line the Editor inserts Polish translation of keywords.

Introduction

Energy storage (ES) is crucial component of distributed generation systems in order to comply with power peaks, to reduce installed generation capacity and to balance missing long and short term coincidence between power generation and demand [1]. Variable nature of solar radiation makes it impossible to deliver energy from a photovoltaic (PV) system at a constant power level, and energy backup and torage are always needed [2]. As described by B. S. Borowy and Z. M. Salameh the optimum mix of PV modules and batteries depend on the particular site, load profile, and the desired reliability of the hybrid system [3].

Optimal dimensioning of electricity storage according to the energy production of micro-scale renewables (in residential areas and households) and electricity consumption are important topics in the development of micro- and smartGRID technologies to increase system reliability and to reduce the profitability time. Flourishing use of an electric grid needs permanent online balancing of supply and demand, including grid losses. Correctly chosen electricity storage technologies will smooth out these surges and allow electricity to be dispatched at a later time.

Good overview about effects of demand response on the end-customer distribution fee and experiences from spot-market based price response of residential customers is described in [4, 5]. Opening of electricity market gives new opportunities to optimize microgrids topologies, including surface and storage capacity of PV-system. Optimization of renewable systems (including hybrid renewable systems and PV-systems with energy storages) is well analyzed research topic, but it can be found only few analysis about optimization of energy storages and PV-systems according to open electricity market prices (e.g. Nord Pool Spot)

Solar Radiation Analysis in North Estonia

Solar surface irradiance depends first of all on astronomical factors, but is greatly modified by cloudiness, atmospheric transparency and snow cover. The latter factors show significant spatial and temporal variability, which is reflected in the variability of solar fluxes [6]. Detailed long-term global irradiance data about Estonia is described in [7]. The analysis below is based on global irradiance data measured in the Tallinn-Harku Aerological Station (latitude N 59°23´53´´; longitude E 24°36´10´´, height above sea level 33 m), and average household energy consumption data described in [8]. As a result of the global radiation analysis, the global radiation of an average day in June compared to December is up to 50 times higher. In June at peak hour (11 o'clock) the total radiation is up to 18 times higher than in December. About 85% of the resource is concentrated on the summer season from April until September, when energy generation is over average (Fig. 1).

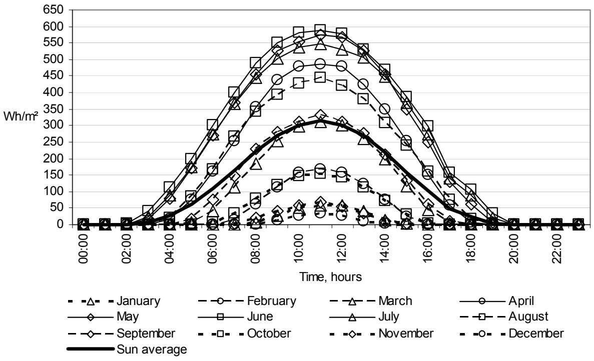

Fig. 1. Average daily radiation by months (Harku 2005-2009)

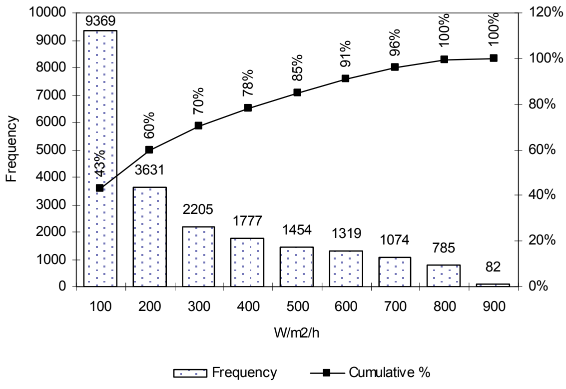

Fig. 2. Histogram of global radiation (Harku 2005-2009)

Today the efficiency (*η*) of common PV-panels can be up to 20%. New triple-junction metamorphic cells have an efficiency of about 40% (laboratory tested). Commonly the high efficiency solar cells are used in concentrating photovoltaic systems for solar power stations in the countries with a large fraction of direct solar radiation. In Estonia due to the high share of diffuse radiation, concentrators are not feasible and only flat plate collectors (PV-modules) can be recommended [9]. Also, the high share of diffuse radiation means a lower rate of radiation. As shown in Figure 2, during the last five years about 60% of sunset hours solar radiation was above 200 W/m^2/h.

Using of a 2-axis solar tracking system (2ASTS) in the winter season, it is very important to take into account apparent altitude of the sun (α_{aas}). In December the 2ASTS system produces approximately up to 2.5 times more energy than a horizontal system, but apparent amplitude of the sun is lower and shadows are longer. For example, if an apparent altitude of the sun is 10° (December), the shadow is five times longer than the object length (1).

$$l_{shw} = l_{obj} \cdot \frac{\sin(90 - \alpha_{aas})}{\sin(\alpha_{aas})}, \tag{1}$$

where l_{shw} – length of a shadow; l_{obj} – height of an object; α_{aas} – apparent altitude of the sun.

In June the difference of energy generation of ASTS and horizontal systems is 1.5 times. Using a 2-axis tracking system, the difference found between energy generation in June and December is about 20 times. Using a horizontal PV-system, the difference between energy generation in these months is about 50 times.

PV-System Dimensioning for Typical Estonian Households

The following calculations (2-3) are simplified and do not take into account the PV-system performance ratio, including system losses, and temperature coefficient of module efficiency. Solar modules based on crystalline cells can even reach a performance ratio of 85 - 95 % [10].

$$A_{pv} = \frac{1}{k_{pr}} \cdot \frac{E_c}{E_{pv}} = \frac{1}{k_{pr}} \cdot \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s} \tag{2}$$

$$A_{pv,ideal} = \frac{E_c}{E_{pv}} = \frac{1}{\eta_{pv}} \cdot \frac{E_c}{E_s}, \tag{3}$$

where A_{pv} – PV-module area; k_{pr} – performance ratio; E_c – electricity consumption; E_{pv} – electricity generation of a PV-system; E_s – global irradiance in Wh; η_{pv} – efficiency of a PV-system.

Average electricity consumption (about 0.5 kWh per hour) [8], without consumption of an electrical water heater, in June can be covered by flat PV-panels with an area of 10.4 m^2 (η = 0.2). To cover an average electricity consumption (A) in December, PV-panels with an area up to 524 m^2 should be installed. Based on annual electricity generation and household consumption, the area of PV panels should be approximately 24 m^2. This calculation does not take into account the huge surplus in the summer season and the shortage in the winter season. At least the calculations should be based on average day data of solar radiation and electricity consumption for a month. A PV area calculation for an on-grid system is based on average daily electricity generation and the highest consumption day in the lowest global solar radiation month (in the summer season). As described, about 85% of the resource is concentrated on the summer season from April until September. To use this resource efficiently, during that period the highest consumption day should be found. For a PV area, calculations an average holiday (HD) and workday (WD) electricity consumption (accordingly 0.66 kWh/h and 0.38 kWh/h) should be compared. If the holiday total electricity consumption is greater or equal to the workday electricity consumption, then the PV area calculation is based on the holiday data, otherwise on the workday data (4).

$$E_c = \begin{cases} E_h, E_h \geq E_w \\ E_w, E_h < E_w \end{cases} \tag{4}$$

where E_h – total electricity consumption of a holiday; E_w – total electricity consumption of a workday;

Here the total electricity consumption of an average holiday is the sum of electricity consumption of 24 hours. Total irradiance of an average day is the sum of each hour in a day.

The largest average electricity consumption is on holidays. The smallest electricity generation in the summer season is in September. Based on these data the largest area of PV-panels in the summer season should be approximately 34 m^2 (holiday in September) (Fig. 3).

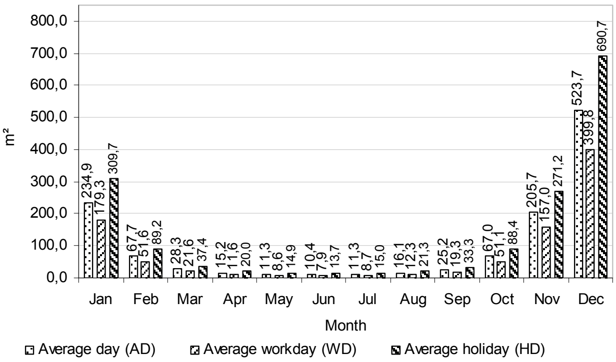

Fig. 3. Area of horizontal PV-panels

Based on the formula (3), a PV system with an area of 34 m^2 and efficiency of 20% will have theoretically the maximum total day generation of 54 kWh (June) and the minimum 0.1 kWh (December).

In different seasons of the northern regions the deviation of global solar irradiation and PV-system generated energy is relatively high. The coefficient of variation V_R of monthly generation is 72% (5).

$$V_R = \frac{\sum_{i=1}^{n} \left| E_{pv,i} - \overline{E_{pv}} \right|}{n \cdot \overline{E_{pv}}}. \tag{5}$$

where $E_{pv,i}$ – generated electricity at the hour i; n – 24 hours in a day; $\overline{E_{pv}}$ – average daily electricity generation.

High variations in annual electricity generation are the main problem to define an optimal PV-system and electricity reserves for an energy storage system for load coverage.

In Northern regions it is not reasonable to plan PV-systems because of the lowest global radiation. If a horizontal PV-system is used, the difference of the calculated areas for September and December is 20 times. Even, if 2ASTS is used, the difference of the calculated areas is 8-10 times. In an OFF-grid system for load coverage in the winter season, it is reasonable to use a PV system with a micro-CHP or a wind turbine. Average wind speed in the winter season is higher than in the summer season, and this can compensate the shortage of energy caused by lower solar radiation. Micro-CHP produces additional thermal energy, which can be fully used in the winter season. In an ON-grid system, in the winter season covering the shortage of electricity with low-tariff energy stored in the PV-system energy storage is a suitable solution. Next, energy balance of a household PV-system and energy reserve dimensioning for a storage system are analyzed. Also, it should give an answer to the question: "Is it possible to use electricity storage of a PV-system for Nord Pool Spot price based consumption scheduling or *vice versa*?"

Electricity Reserve Dimensioning of a Household PV-system for Load Coverage

Energy balance of a PV-system can be described according to the following simplified formula:

$$(6)\qquad E_{pv} = E_c + E_{sp} + E_{los}\quad E_{pv} = \underbrace{E_{dir} + E_{res}}_{E_c} + E_{sp} + E_{los},$$

where E_{pv} – electricity generated by a PV system; E_c – electricity consumption; E_{sp} – surplus of generated electricity; E_{los} – total losses; E_{dir} – direct consumption of electricity generated by a PV system; E_{res} – indirect consumption of electricity generated by a PV system (stored energy reserve of PV generated energy).

In the calculations system losses are not taken into account (E_{los} = 0).

Balance between generation and load

The first step to define the dimensions needed for electricity reserve for load coverage of a household PV-system is the analysis of balance between PV generation and load consumption on an average day of each month (7). While the WD and HD have different consumption curves the analysis should be made separately for both days.

$$(7)\qquad E_{bal,i} = E_{c,i} - E_{pv,i},$$

where $E_{bal,i}$ – energy balance at the hour i.

According to calculations (7) at WD the surplus of generated energy is very high on midday, when the load is trivial. Load maximum prevails in the evening. This means that direct load coverage is very low and on midday generated energy should be stored for the evening period (Fig. 4).

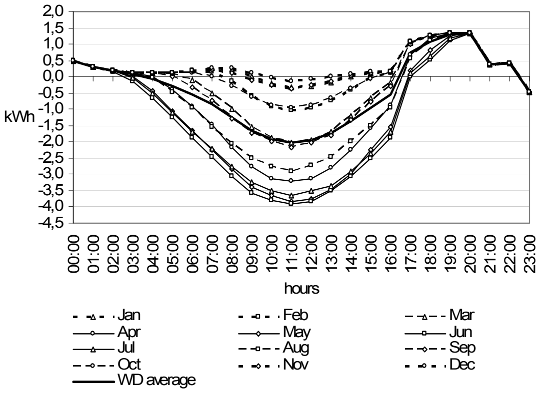

Fig. 4. Balance of WD consumption and generation

Measures should be taken to solve this huge surplus problem. At HD the direct load coverage is better than at WD. Balance between generation and load is better. In the summer season also energy reserves are similar to the reserves used in WD. In the winter season main problems are shortage and higher needs for energy reserves (Fig. 5).

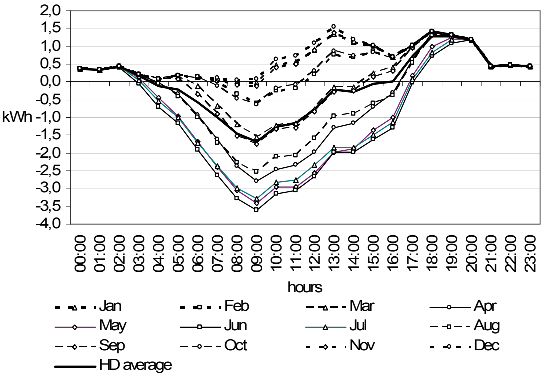

Fig. 5. Balance of HD consumption and generation

Electricity surplus and shortage

The analysis (8) below shows that PV-systems with an area of 34 m^2 can cover electricity consumption from April to September (Fig. 6).

$$(8)\qquad k_{sp} = \frac{E_{sp}}{E_c} = \frac{\sum_{i=1}^{n}(E_{pv,i} - E_{c,i})}{\sum_{i=1}^{n} E_{c,i}};\ n = 24\ ,$$

where $E_{pv,i}$ – generated electricity at the hour i; n – 24 hours in a day; $E_{c,i}$ – electricity consumption at the hour i.

In the winter season theoretically about 43 % of an average consumption can be covered by a PV-system. In workdays and holidays these numbers are 56% and 33%, respectively. With a 2-axis solar tracking system theoretically up to 95% of electricity consumption in the winter season can be covered.

Without losses the average annual surplus of electricity generation of a PV-system in holidays and workdays is 11% and 92%, accordingly. In the summer season an average surplus is 150%, at WD and HD accordingly 227% and 89%. In the winter season the average shortage is 57%, at WD and HD accordingly 44% and 67%.

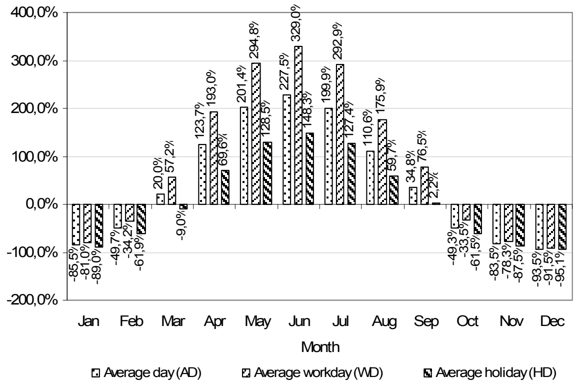

Fig. 6. Surplus/shortage of an average day of a month

Dimensioning of electricity reserve

Approximately 17% of PV-generated energy can be directly used in workdays and 50% in holidays. This is about 32% of a workday and 56 % of a holiday total electricity consumption (9-11).

$$E_{dir} = \sum E_{c,i} - \underbrace{\sum_{E_{pv,i} \le E_{c,i}} (E_{c,i} - E_{pv,i})}_{E_{res,i}} \tag{9}$$

$$E_{dir} = \sum_{E_{pv,i} \le E_{c,i}} E_{pv,i} + \sum_{E_{pv,i} > E_{c,i}} E_{c,i} \,, \tag{10}$$

where E_{dir} – directly from PV-system consumed electricity.

$$k_{dir} = \frac{E_{dir}}{E_c} \tag{11}$$

About 30% of an annual average PV generated energy is used directly, which makes approximately 44% of the annual average consumption.

The easiest way to calculate needed energy reserve (storage capacitance) for indirect load coverage is based on the difference of average hourly electricity generation and consumption (12 - 13).

$$E_{pv,i} \le E_{c,i} \,, \tag{12}$$
$$\Downarrow$$

$$E_{res} = \sum_{i=1}^{n} E_{res,i} = \sum_{i=1}^{n} (E_{c,i} - E_{pv,i}) = \sum_{i=1}^{n} \left| E_{pv,i} - E_{c,i} \right| , \tag{13}$$

where $E_{res,i}$ – needed energy reserve at the hour i; E_{res} – needed average daily energy reserve.

Depending on the consumption pattern, about 35 to 40 % of the generated energy should be stored for the darkness period, making up 44 to 68 % of the consumption. In WD, if horizontally installed PV-panels are used, the highest energy reserve is needed in December (8.23 kWh) and the lowest in June (4.67 kWh) (Fig. 7).

In holidays in turn, the highest energy reserve needed is 15.17 kWh and the lowest is 5.44 kWh (Fig. 8). Use of panels with an optimal inclination or 2ASTS, the calculated energy reserve can be reduced up to 10%. The reduction of an energy reserve depends directly on the daylight time and consumption pattern.

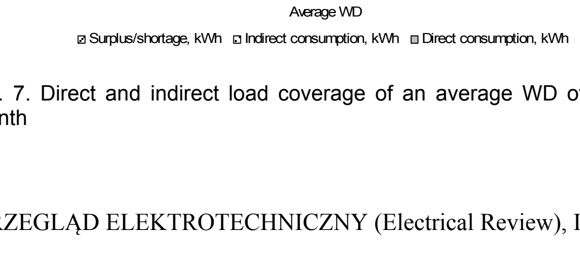

Fig. 7. Direct and indirect load coverage of an average WD of a month

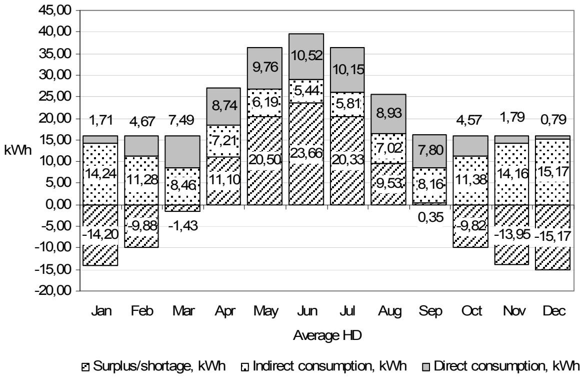

Fig. 8. Direct and indirect load coverage of an average HD of a month

Another calculation method of the energy reserve but rarely used is based on the analysis of the frequency of the duration of darkness hours and average electricity consumption. The following histogram (Fig. 9) shows that 99% of darkness periods are shorter than 20 hours. In the winter season the longest period without generation is about 18 to 22 hours (in December). Based on an average daily (0.5kWh/h), workday and holiday consumption (without electrical water heater) [8], the calculated energy reserves for the darkness period in December on an average day should be accordingly 10, 8 and 13 kWh. An error between the described calculation method of the energy reserves based and formula (13) depends on the difference of the consumption and the generation pattern. For example, as compared to workdays the calculation error of energy reserves in holidays is greater. The error of the calculated energy reserves for December is ≤ 15 %. Rough calculations show that energy reserve for 20 darkness hours can cover about 90% of the total energy consumption. The longest average darkness period is 17 hours in December and the shortest one is 5 hours in June.

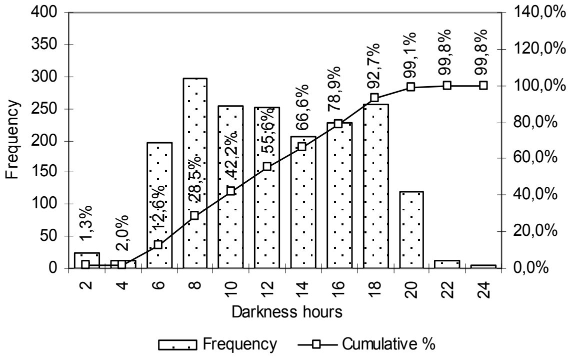

Fig. 9. Histogram of darkness hours

Electricity Reserve Dimensioning Based on NPS price and Grid connected Household PV-System generation

Average NPS (Nord Pool Spot) price during the measured period (April 2010 to March 2011) in the EE (Estonia) area was calculated as 46.30€/MWh. The NPS price curve is similar on workdays and at weekends. The average price of workdays is 47.81 €/MWh and that of weekends is 42.62€/MWh (Fig. 10). The main difference of WD and HD curves is higher midday peak on WD and higher evening peak on HD (Fig. 11, Fig.12). More detailed analysis of first half year is described in [11].

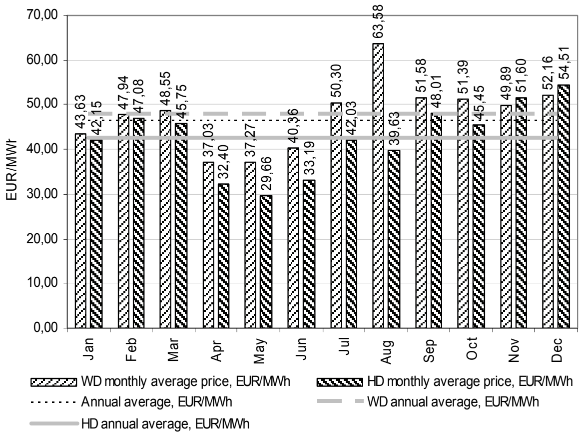

Fig. 10. NPS average day prices of months

The highest average price is in December, caused by weather conditions in Estonia. The lowest average prices are from April to June. In the summer season price fluctuations between night and day are higher; this makes the use of a PV-system during this period more feasible. High WD peak in August last year was caused by failures in the Estonian Power Plant (Fig. 11).

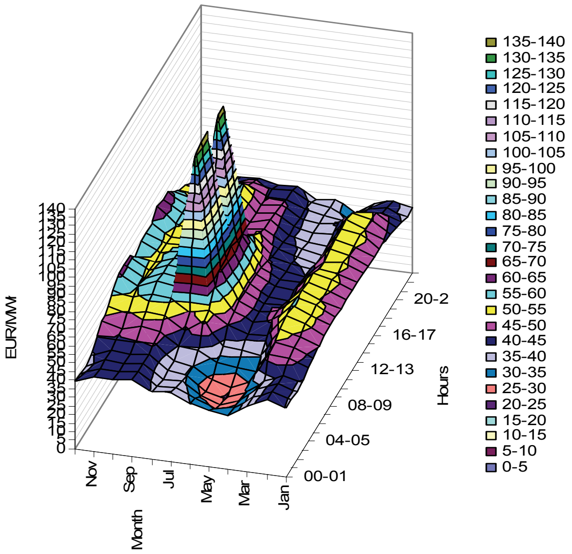

Fig. 11. NPS price fluctuations of WD

An advantage of a PV system on workdays is the similarity of NPS price and electricity generation dynamics. Energy surplus on workdays is relatively high on the peak time of NPS price. A disadvantage of a residential area PV-system is a relatively low local consumption of solar energy on the peak time of NPS WD price. High surplus of electricity generation at the peak time of price should be stored for the consumption peak-time. An advantage of a PV system on holidays is the similarity in the NPS price and electricity generation dynamics at midday (Fig.1 and Fig.12).

Also, energy surplus is relatively high at the first peak time of the NPS price at midday. The first disadvantage is energy deficit in the evening, when generation does not coincide with consumption and the NPS price has the second peak. The second disadvantage is very low energy generation in the winter season at the highest electricity consumption level.

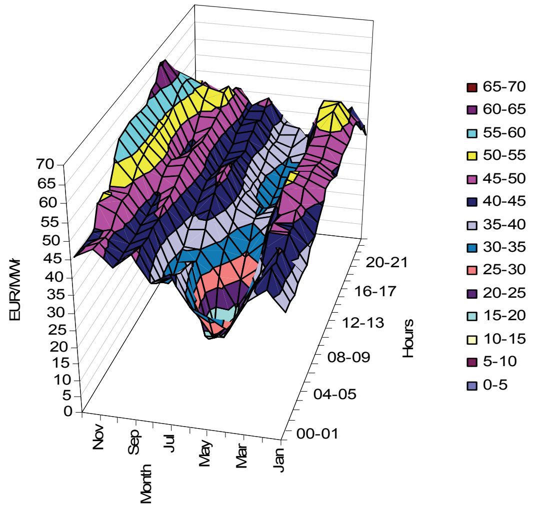

Fig. 12. NPS price fluctuations of HD

The following electricity reserve calculations are based on hourly prices of an average day in months (14). If the hourly price is lower than the average WD or HD price of the month, the electricity consumption and storage charging are covered from the grid. If the hourly price is over the average WD or HD price of the month, the electricity consumption is covered by the PV-system and electricity storage. Based on the described calculations the highest needed energy reserve is needed on holidays in December, which is 12.1 kWh (Fig. 13). On workdays in July and August there is no need for an energy reserve (Fig. 12).

$$p_{m,i} > \overline{p_m} \Rightarrow E_{pv,i} \leq E_{c,i} \Rightarrow E_{res} = \sum_{i=1}^{n} (E_{c,i} - E_{pv,i}) , \tag{14}$$

where $p_{m,i}$ – average price of the hour i in a month m, $\overline{p_m}$ – average price of a month m

According to the presented energy reserve calculations (Fig. 13, Fig.14), by the combined control of solar irradiance and NPS price based storage control, the storage capacity can be reduced. As compared to the control of PV generation and load balancing, at an annual average WD and HD, combined control allows the energy reserve capacity to be reduced by 46% and 26%, respectively. As compared to the control of the NPS price based load scheduling, at annual average WD and HD, combined control enables the energy reserve capacity to be reduced by 30% and 45%, respectively.

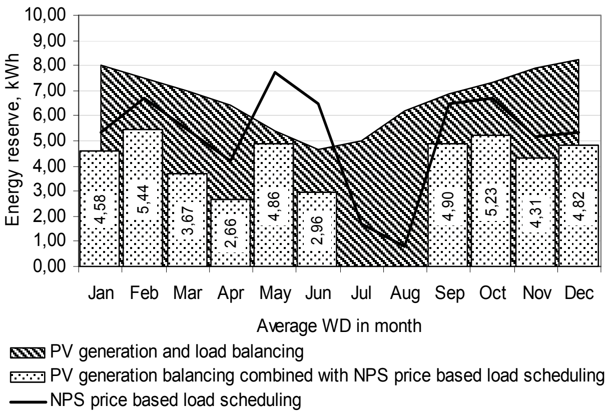

Fig. 13. Energy reserve based on monthly average WD prices

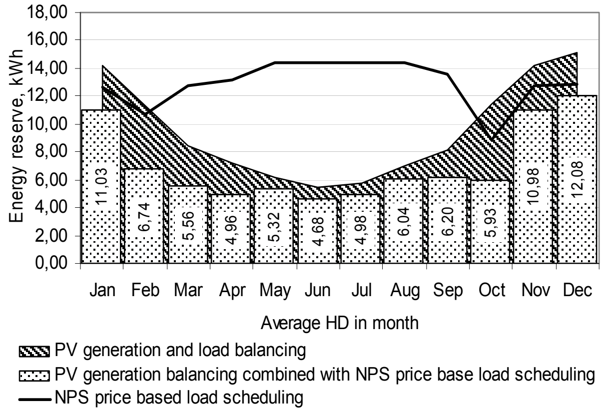

Fig. 14. Energy reserve based on monthly average HD prices

If electricity reserve calculations are based on the annual average WD or HD price as compared to hourly average prices of a month, from April to June in WD and HD, the energy reserve is not needed. Also, in the WD of January and August the energy reserve is not needed. Based on the described calculations the highest energy reserve is needed on holidays in December, which is 15.17 kWh. While in the summer season the monthly average prices are significantly lower than the annual average, it is questionable if a PV-system is suitable on that time-period.

Thus it can be concluded that the energy reserve calculated for a PV system is sufficient in the winter season for consumption scheduling from the peak-time to the off-peak time.

If the energy reserve and the prospective cycle lifetime of the storage system are known, the needed DoD (depth of discharge) and the required energy capacity of the storage system can be calculated (15).

$$E_{st} = \frac{E_{res}}{DoD} = \frac{E_{res}}{k_1 \cdot {n_{cycles}}^{-k_2}}, \qquad (15)$$

where k_1 – coefficient 1; k_2 – coefficient 2; n_{cycles} – amount of charge/discharge cycles.

Conclusion

An increase in the efficiency of a PV system will reduce the area of PV-panels, but it has a relatively small impact on the storage system capacity. Double efficiency of a PV-system will decrease the storage system capacity only up to 10%. The higher consumption on workdays and holiday evenings has the highest impact on the dimensioning of storage capacitance. Thus it can be concluded that the profitability of a PV-system depends mostly on the price of electricity and the consumption pattern. To assure the shortest profitability time, electricity consumption and real-time dynamic price should be increased and decreased synchronously with the PV system generation. In northern regions PV-systems are most feasible in OFF-grid systems, where the grid connection is not economically feasible. In ON-grid PV-systems, according to seasonal differences of solar radiation, it is not feasible to plan a PV area by solar radiation of the winter season. It is more feasible to cover shortage with cheaper energy stored from the grid in the OFF-peak time.

Combining both wind power and PV power would lead to minimizing the storage requirement and cost of the systems [3]. For Nordic countries it needs additional investigations, is it more profitable to combine PV power with wind power or it is more feasible to use mCHPs combined with wind or with PV power. Also price fluctuations in open energy market (like Nord Pool Spot) should be taken into account to optimize topology of microgrids.

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