Influences of time resolution and recording period of energy consumption on the assessment of photovoltaic battery systems

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***Abstract*— Low feed-in tariffs for power generated by photovoltaics in Germany cause increasing efforts to raise the amount of self-consumed energy. Battery systems can be used to temporally decouple energy production from consumption in order to achieve a higher percentage of on-site consumption. To decide whether this investment is economically viable for a specific household, the interaction between PV plant, battery and consumer is simulated. Load profiles of the simulated household are important input data for these calculations and are obtained by smart metering. In the ideal case, profiles are recorded for a whole year in sub-second resolution, but for real-world applications, this is usually not feasible. This paper attempts to quantify the effect of both short recording periods and low time resolution on simulated on-site consumption.**

The simulation tool models PV plants with different types of modules, power, efficiency and orientation. Batteries are also specified by various input parameters such as capacity, efficiency and power. Time series data of temperature and radiation are used to simulate PV production. Thus, the amount of energy produced, consumed and stored can be determined for each time step. This allows evaluating the profitability of the examined battery system under given conditions. Energy consumption is modeled based on real household load profiles measured in 1 minute intervals. Due to this high input resolution, it is possible to vary the simulation resolution in a wide range. The simulation results with the highest available resolution are considered to be exact, thus lower resolutions are evaluated in comparison. The same principle is applied to recording periods: Results for the whole year are used to rate the quality of results for randomly chosen shorter periods.

The simulations show that the effect of time resolution is important for reliable results. Coarse resolution cannot model short consumption peaks which may exceed the battery system's power. Recording periods of one week are likely to produce misleading results. Load profiles covering three to four weeks allow for tolerable projections, if data is recorded in spring or fall. To achieve reliable results concerning the profitability of potential battery systems, it is recommended to record the energy consumption for about one month with a time resolution of one minute.

Keywords-photovoltaics; storage systems; smart metering

I. INTRODUCTION

Since feed-in tariffs for residential photovoltaics in Germany have been significantly reduced in the last years, battery systems are applied to increase the amount of self-consumed photovoltaic energy and therefore to improve the overall profitability. This can be evaluated for specific cases by simulation of photovoltaic production and the interaction with consumer and battery.

A prerequisite for performing these simulations is data of the household's electric load. Since in most cases smart meter data is not available, the consumption has to be recorded for this application. This raises questions about the time resolution and recording period necessary to obtain accurate results. In this paper, answers to these questions are derived by using smart meter data from two pilot projects and a simulation model of a photovoltaic battery system.

II. SIMULATION

A. *Simulation model*

A simulation model is used in order to quantify the percentage of photovoltaic on-site consumption. The model consists of several modules which represent the components of a residential photovoltaic system [1]:

1) *Photovoltaic module*

This module computes the energy production of a photovoltaic cell based on characteristic curves for different types of cells. Input variables are cell type (thin film, mono-crystalline or poly-crystalline), size (power), temperature coefficient, relative efficiency, nominal operating temperature, azimuth angle and angle of elevation. Meteorological conditions are represented by time series of temperature and radiation. These can be retrieved from the software Meteonorm for arbitrary locations.

2) *Residential load*

To examine the amount of photovoltaic energy that can be used directly or through storage in battery systems, a model residential load curve is necessary. For simplicity, standard load profiles can be used. However, these profiles are designed to map the consumption of a high number of households, and therefore cannot accurately represent the characteristics and peaks of a single one. Real (measured) load data allow for higher quality results and is therefore used in this study. For comparison, the simulation is also performed using standard load profiles.

3) Battery

The battery is modeled by the characteristic curve of a lithium cell, which is parameterized by capacity, maximum and minimum state of charge, efficiencies for charging und discharging and maximum power for charging and discharging. In addition, aging processes can be simulated.

For every time step, excess energy that cannot be used immediately is stored in the battery, considering the defined maximum power. In the case of lower photovoltaic production than load, the battery is discharged. This model allows the calculation of charging and discharging processes over time.

B. Load data

As described above, measured load data from real households are used to model electric consumption. The sources are two different smart metering pilot projects:

For the evaluation of measurement resolution, data from a project in northern Germany are used [2]. In this project, several thousand households are equipped with smart meters which record energy consumption in intervals of 10 seconds [3]. Due to incomplete data in the installation process, the calculations are based on one particular month. 100 data sets with good data quality, that means less than 0.5 % missing values, can be extracted and used for the simulation. For further improvement of data quality and reliability, 1 minute is used as minimal simulation interval.

Since very few data sets of this project are available for a whole year, the assessment of the recording period is based on smart meter data from another project which was conducted in western Austria. There, several hundred smart meters have been installed and used to record electric load for four years in a resolution of 15 minutes [4]. For the simulation, one year with good data quality for 79 data sets is used.

For comparison, the simulations are also performed with standard load profiles [5].

C. Parameters

The simulations are performed for a thin film photovoltaic module with typical parameters and 5 kW power. As described before, the battery is modelled as a lithium cell. For SOC limits and efficiency, typical values are applied. To fit the photovoltaic system, charging and discharging power is also defined as 5 kW. Varying charging and discharging power of the battery might influence the results, but is not considered here. The simulations use varying capacities: 0 kWh, 2.5 kWh and 5 kWh.

For the investigation of the effect of time resolution, the calculations are repeated for resolutions of 1 minute, 5 minutes, 15 minutes and 30 minutes. Resolution means both the resolution of the input data (load and photovoltaic generation) and simulation interval. This allows comparing the results with coarser resolution with the assumed "true" value, i.e. the value for minimal intervals.

To examine the influence of recording periods, different parts of the measured year are extracted and used as an approximation for the whole year. The simple approach for this is to repeat the extracted part until the end of the year. Another approach uses dynamic factors known from standard load profiles to scale the daily load values and achieve a better representation of seasonal effects.

Extracted time periods are 1, 2, 3 and 4 weeks. In a real world application, this range can be measured with reasonable effort. Since the behavior of consumers can vary significantly with weather conditions, the extraction is performed for each month of the year in order to find the optimal seasonal choice for this computation.

III. RESULTS

The results of the simulation show the influence of both time resolution and recording period on the computed percentage of on-site consumption. The achieved percentage of on-site consumption is used to compare the results. This means that a result may differ from the exact solution in individual time steps, but can still be seen as exact if it matches the value of on-site consumption, which is calculated for a resolution of 1 minute.

A. Time resolution

As described above, the simulations are performed for resolutions of 1 minute, 5 minutes, 15 minutes and 30 minutes and 3 different battery capacity values from 0 kWh to 5 kWh. Table I shows the mean values of on-site consumption for these parameter sets.

TABLE I. MEAN VALUES BY RESOLUTION

Resolution	On-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
1 min	20.80 %	54.40 %	56.02 %
5 min	21.34 %	54.42 %	56.05 %
15 min	21.96 %	54.41 %	56.05 %
30 min	22.55 %	54.36 %	55.99 %

On average, the amount of self-consumed energy of photovoltaic systems with battery can be predicted well with coarser resolutions, whereas systems without battery show larger deviations compared to the results for fine resolutions. In this case, the approximated value is always larger than the assumed correct value for a resolution of 1 minute, whereas with battery, errors in both directions occur. For further investigation, the mean differences to the respective value for a resolution of 1 minute are shown in table II.

TABLE II. MEAN ABSOLUTE ERROR BY RESOLUTION

Resolution	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
5 min	0.54 %	0.12 %	0.13 %
15 min	1.16 %	0.27 %	0.28 %
30 min	1.75 %	0.37 %	0.39 %

This confirms that systems with included batteries can be modeled relatively accurate with resolutions of up to 30 minutes. Both battery sizes evince similar behavior. For photovoltaic modules without combined storage, finer resolutions lead to significantly higher quality of the results. In this case, every simulated household shows larger values for on-site consumption when coarser resolutions are applied.

For a worst-case estimate, table III shows the maximum absolute error values of all investigated data sets.

TABLE III. MAXIMUM ABSOLUTE ERROR BY RESOLUTION

Resolution	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
5 min	2.42 %	1.60 %	1.58 %
15 min	4.60 %	4.43 %	4.38 %
30 min	6.29 %	4.92 %	4.89 %

In contrast to the examination of mean values, the resolution is also critical for systems without batteries when the maximum error is considered. Therefore, it is recommended to use the highest possible resolution to avoid inaccurate results in the assessment of hypothetical photovoltaic plants.

B. Recording period

To evaluate the effect of recording time on calculated on-site consumption, periods of one to four weeks are extracted from the original data sets over one year (resolution of 15 minutes). For additional examination of seasonal influences, this is repeated for all twelve months.

1) Length of recording period

For the assessment of potential systems in real residential applications, the ideal case is to use smart meter data for at least one year. Since the smart meter rollout is still in progress, these data are not always available. The alternative solution in these cases is the installation of a measurement device to log energy consumption for a limited time span of several weeks. Therefore, it is important to evaluate the accuracy of results deduced from such limited data sets. Table IV shows the mean absolute error regarding on-site consumption for different time spans and battery sizes. As described, load for the year is extrapolated by repeating the extracted part. Photovoltaic generation is still simulated for a whole year.

TABLE IV. MEAN ABSOLUTE ERROR BY RECORDING LENGTH

Recording length	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
1 week	4.52 %	4.73 %	4.84 %
2 weeks	3.81 %	3.96 %	4.12 %
3 weeks	3.51 %	3.65 %	3.83 %
4 weeks	3.40 %	3.53 %	3.70 %

Limited recording time causes significantly larger errors than suboptimal resolution. For all examined combinations, the mean error is in the range of 3 % to 4 %. As expected, longer recording periods yield better results. Maximum errors are given in table V as a worst case estimate.

TABLE V. MAXIMUM ABSOLUTE ERROR BY RECORDING LENGTH

Recording length	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
1 week	21.26 %	20.98 %	21.15 %
2 weeks	20.45 %	19.78 %	18.76 %
3 weeks	18.67 %	18.13 %	17.70 %
4 weeks	17.58 %	17.69 %	17.88 %

These errors are also higher than for coarse resolutions. This shows that the length of recording period is critical to achieve reliable results on on-site consumption.

2) Season of recording period

Due to varying requirements with regard to heating, cooling and lighting, residential load in summer differs from the residential load in winter. Therefore the choice of season to record energy consumption can also affect the quality of the result. To examine this, the starting points for recording the data are set at the beginning of each month. Consequently twelve different parts of the whole year are extracted. Since the previous section shows that longer recording times yield better results, 4 weeks are used in this case.

Table VI and table VII show mean and maximum absolute error, respectively.

TABLE VI. MEAN ABSOLUTE ERROR BY MONTH

Recording month	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
Jan	4.58 %	4.71 %	5.07 %
Feb	4.13 %	4.28 %	4.49 %
Mar	2.87 %	3.00 %	3.35 %
Apr	2.25 %	2.48 %	2.59 %
May	2.21 %	2.31 %	2.38 %
Jun	2.46 %	2.63 %	2.66 %
Jul	3.85 %	3.94 %	4.05 %
Aug	3.43 %	3.58 %	3.78 %
Sep	2.58 %	2.71 %	2.71 %
Oct	3.62 %	3.66 %	3.80 %
Nov	4.11 %	4.22 %	4.41 %
Dec	4.72 %	4.89 %	5.13 %

Winter months evince large errors, whereas recording in spring or fall yields more accurate results. One possible explanation for the latter is that consumption in winter has different characteristics than the months with a majority of photovoltaic production. Except for July, most summer months also perform well. A possible reason for this is school vacation in this month. Therefore the consumption behavior in these months can be considered approximately representative for the entire year.

TABLE VII. MAXIMUM ABSOLUTE ERROR BY MONTH

Recording month	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
Jan	29.68 %	29.06 %	27.40 %
Feb	18.64 %	20.26 %	19.58 %
Mar	15.16 %	15.03 %	14.81 %
Apr	13.97 %	13.00 %	11.26 %
May	7.34 %	8.29 %	9.87 %
Jun	10.78 %	10.96 %	11.28 %
Jul	14.26 %	15.61 %	19.07 %
Aug	16.71 %	17.60 %	21.95 %
Sep	16.35 %	16.99 %	18.07 %
Oct	28.77 %	25.50 %	20.29 %
Nov	17.13 %	17.33 %	18.67 %
Dec	22.18 %	22.60 %	22.37 %

The extrapolation of the extracted four weeks to a whole year is performed by simply repeating the recorded data. This does not model seasonal behavior, which might be a reason that summer and winter months show larger errors. As an approach to overcome this, the dynamic factors defined in Germany’s standard load profile for households are applied to scale the resulting year profile. The resulting mean absolute errors are shown in table VII.

TABLE VIII. MEAN ABSOLUTE ERROR BY RECORDING LENGTH

Recording month	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
Jan	4.47 %	4.91 %	5.01 %
Feb	4.33 %	4.69 %	4.84 %
Mar	3.40 %	3.65 %	3.61 %
Apr	2.32 %	2.40 %	2.44 %
May	2.45 %	2.54 %	2.50 %
Jun	3.00 %	3.12 %	3.10 %
Jul	3.78 %	3.83 %	3.81 %
Aug	3.52 %	3.66 %	3.71 %
Sep	2.79 %	2.89 %	2.88 %
Oct	3.45 %	3.47 %	3.52 %
Nov	3.06 %	3.17 %	3.30 %
Dec	4.16 %	4.42 %	4.49 %

The comparison to table VI shows that the minimal errors which could be achieved by optimal choice of recording month can only be reduced slightly, but the results for months that yield unusable results in the simple case can be improved by application of these scaling factors.

C. Standard load profiles

Table IX shows the results for the simulation of on-site consumption using standard load profiles [5]. Since these are defined in a resolution of 15 minutes, the simulation uses this interval. Large errors can be observed, which confirms that real measurements of the respective household are critical for reliable results. Even short recording periods lead to significantly better approximations of the percentage of on-site consumption.

TABLE IX. MEAN ABSOLUTE ERROR WITH STANDARD LOAD PROFILE

Standard load profile	Absolute error of on-site consumption		
	no battery	*2.5 kWh battery*	*5 kWh battery*
H0	14.00 %	13.41 %	13.75 %

IV. CONCLUSION

A simulation model that describes the interaction between a residential photovoltaic plant and a combined battery system can be used to rate the profitability of potential plants. If smart meter data is not available for at least one year, approximations can be deduced from recorded data over periods of some weeks. First of all just using the standard load profile due to missing real data of the respective households can lead to large errors of the calculated on-site consumption. Even short recording periods lead to significantly better approximations but as expected, longer recording periods yield better results. Recording periods of at least one month are recommended. However, more important is the right choice of the season for recording. Data from winter or summer months are not representative for a whole year and lead to results of poor quality. To some extent, this can be overcome by applying the scaling function known from standard load profiles, but months in spring or fall are still preferable in general. The influence of time resolution is smaller in comparison, but can also be a significant source of error, specifically for plants without battery. The investigations recommend recording the electric consumption with at least a resolution of 5 minutes. Best results can be achieved with data in 1 minute resolution for at least one year.

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