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Performance of a photovoltaic plus battery home system with load profile scenarios changing over the system life

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Abstract

The ratio of self-consumed electricity to total electricity produced by a photovoltaic (PV) system depends on whether consumption and production match in time. A temporal mismatch can be partially overcome by buffering the energy produced by PV, e. g. in a battery. A key impact factor which affects the techno-economic performance of PV-battery systems is the household load profile, which may significantly change over the lifetime of the PV-battery system, but the effects of a changing load profile on e. g. the self-consumption ratio were not yet investigated. This paper shows on three different examples the possible changes over the 21 year lifetime of a typical PV-battery system. It is demonstrated that changes in the behavior patterns and the number of residents can cause the self-consumption to vary by more than a factor of 2 over the lifetime of the system. When dimensioning such a system e. g. for optimal return on investment over the lifetime or for a certain degree of autarky, not only changing energy prices, but also changing household structure and changing behavior of the household members should be taken into account.

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Keywords: photovoltaic; PV; battery; energy storage; household load profile

1. Introduction

The desire for increased self-consumption of electric power from rooftop photovoltaic (PV) systems and for higher autarky is one of the key drivers for the addition of batteries to PV systems [1]. The ratio of self-consumed to

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total electric energy production from a PV system increases, the better consumption and production match in time. A temporal mismatch can be partially overcome by buffering the energy, e. g. in a battery. Therefore the load profile of the household (HH) must be taken into account for the sizing of PV and battery systems. While the PV-battery system remains constant over the years of operation, the household's load profile can change significantly, but, to our knowledge, the effects of a changing load profile were not yet investigated. In this paper the effects of a changing HH load profile on the techno-economic parameters share of self-consumption and degree of autarky are shown for three examples.

Nomenclature

DWD	Deutscher Wetterdienst, Germany's National Meteorological Service
HH	household
LPG	LoadProfileGenerator
PV	photovoltaic
SCY	scenario year

Share of self-consumption: The share of electric energy produced by the PV system which is consumed by the household, either directly or after intermediate storage in the battery

Degree of autarky: The share of the electric energy consumed by the household which is supplied by the PV-battery system

In previous work, the performance of a PV-battery system for powering a household was examined [2, 3]. It was found that the performance highly depends on the assumed load profile and realistic results can be achieved only with an individual time series of the HH load, not with an averaged load profile. Also the step width must be short enough to appropriately model the short power peaks of typical HH appliances [4, 5].

Some publications use individual load profiles, too. E. g. [6] uses a HH load time series in 1 sec resolution from [7]. They note that the results depend "on the system configuration and the coincidence between the PV output and load demand". The time series from [7] are very good representations of the real world, but the HH type which a time series belongs to is not known, so it remains open which of the time series in this source would be appropriate to model the effect of changing HH members and their behavior.

There are many other publications on PV-battery system optimization, e. g. [4, 6, 8-10], but none of them investigated the influence of a household load profile changing over the years of system lifetime.

The question arises, how large is the effect of changes in the HH members and their behavior on the performance of the PV-battery system.

To answer this question, different load profiles are generated by a model which takes into account the household members and their behavior. The LoadProfileGenerator (LPG) developed in the thesis [11] and shortly described in section 2.1 was extended in this context for more easy modelling a series of years of a household with changing members and behavior.

2. Methodology and basis data

2.1. Short description of the LPG

Most load profile generators are based on a probability approach, which in the most simple form consist of rules such as "Between 7:00 and 8:00 there is an 80 % chance of running the coffee machine for breakfast". Since this simple approach yields unsatisfying results due to human behavior being much more complex than such simple rules, a lot of different models with various additions to the simple rules have been created. In [12] a good overview of the existing model approaches is provided. One of the approaches for improving the results is using activity probabilities instead of device probabilities, since e. g. by setting the rule that the TV and the set-top boxes are usually turned on together. Another one is modulating the activation probabilities by an occupancy profile to ensure that devices are only turned on when people are at home. A third approach is using Markov probability chains to model for example that the dryer will only be turned on after the washing machine has run. The biggest issue is always generating the appropriate probability profiles over the day, which requires large amounts of data to generate good results.

The LoadProfileGenerator (LPG) [11] which is applied in this paper avoids the issue by eschewing probability for a psychological behavior approach that models the occupants as independent agents which choose their next activity based on their current desire. This is supplemented in the model with various other elements needed to accurately describe residential energy use, such as time limits, vacations, illness, locations, autonomous devices such as refrigerators, variables to keep track of, for example, dirty laundry, joint activities and various other details. Due to the "intelligence" built into the model, much less data is required, and it becomes feasible to create representative households based on statistical data, domain knowledge and personal experience without a large measuring campaign. This feature has been used in this paper to simulate the change in energy consumption and the load profile over the lifetime of a PV-Battery system for three different scenarios. The LPG is implemented as a C# Windows program and is available for download at www.loadprofilegenerator.de.

2.2. Short description of the BaPSi model

The BaPSi (Battery-Photovoltaic-Simulation) model [3] is a tool for the techno-economic analysis of battery-supported PV systems. With this simulation model it is possible either to calculate a fixed system configuration with defined PV system size and battery capacity, or to conduct an iterative parameter variation to determine the cost-optimized combination of the PV system size (power rating) and the nominal capacity of the battery. The direct self-consumption of PV electricity is always prioritized over storage in the battery and feed-in to the electric grid. The energy balance is calculated for every time step. The required input parameters for the calculations presented here are PV electricity generation time series, household load time series, and PV-battery system size and efficiency rates. For the calculations a linear degradation per time step is assumed for the PV modules of 0.5 % / a and for the battery of 1 % / a.

2.3. Scenario development

Before generating the load profiles, the households have to be defined, i. e. the members and their behavior. Other factors, like house type and the electrical devices used in the HH, are kept constant as far as possible. The house and water heating is provided by natural gas. The PV-battery system was not optimized for the HH but was assigned a fixed PV power rating of 4 kWp, a battery capacity of 4 kWh with a maximum depth of discharge of 80 % (resulting in a usable capacity of 3.2 kWh) and a maximum battery charging/ discharging power of 4 kW for all modelled HH. A fixed system configuration has been chosen in order to make the results from the different scenarios comparable to each other.

We define three scenarios, each describing a HH in the course of 21 successive years. The HH members and their behavior change between scenario years (SCY), but within a SCY they are kept constant. The solar irradiation and the outdoor temperature time series are taken from the values measured in 2007 at the DWD station Lindenberg [13], providing consistent conditions for PV production and externally triggered HH load (especially lighting). The resulting electricity production for a PV system with south orientation and a tilt angle of 30° is calculated based on the approach from [14]. For each SCY the same solar and temperature time series is used, so that the difference between SCYs only depends on the HH members and their behavior.

For scenario 1 we modify the modular household "CHR15 Multigenerational Home: working couple, 2 children, 2 seniors", which is predefined in the LPG, so that in scenario year 1 to 3 the HH consist of the working couple only. In SCY 4 the first child is born, and the mother suspends her job for this and the next year. With SCY 6 the first child goes to kindergarten and the mother resumes work. In SCY 7 the second child is born, and the mother suspends her job again until SCY 9. In SCY 10 the first child starts school, the second starts kindergarten, and the mother resumes work. In SCY 16 the grandparents join the household. This last constellation remains until the end of the scenario (SCY 21).

Scenario 2 starts with a family with 3 children (6, 9, and 13 years old) with both parents employed. In SCY 8 the first child leaves the HH, in SCY 12 the second child leaves, in SCY 15 the third child leaves. In SCY 20 a senior joins the HH.

Scenario 3 starts with a HH consisting of a working couple with 2 children, and 2 seniors. In SCY 6 both children and one senior leave the HH. In SCY 12 the couple retire and the other senior leaves the HH. In SCY 19 the wife leaves the HH.

3. Results and discussion

3.1. Characteristics of generated scenarios

The summarized characteristics of the household load time series show that the LPG model yields reasonable results. The electric energy consumption per year (Fig. 1) is an increasing function of the number of people belonging to the HH. When people stay at home most of the day (toddlers, seniors), the energy consumption is higher than when people are not at home for a significant part of the day (working people, children at school).

But an even higher difference between the scenario years can be seen in the average daily load profiles, generated by averaging the electric energy consumption for each quarter hour of a weekday over all same weekdays of a year. Fig. 2a, representing SCY 1 of scenario 1 (working couple only), shows that the peak load on workdays is at evening hours, respectively at noon on weekends, while in SCY 4 (mother and toddler at home) the peak load is at noon also on workdays (Fig. 2b).

3.2. Results for self-consumption and autarky

In comparison to the year of system commissioning, the load profile as well as the share of self-consumption and degree of autarky change significantly over the years.

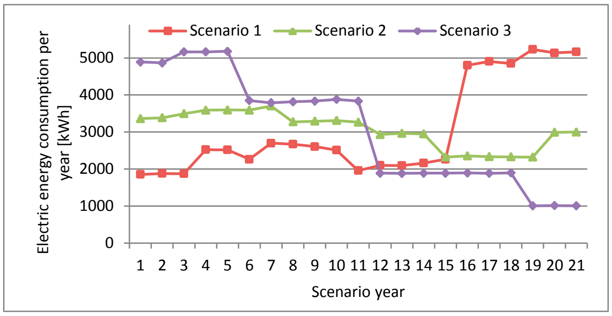

Fig. 1. Electric energy consumption of the households per scenario year

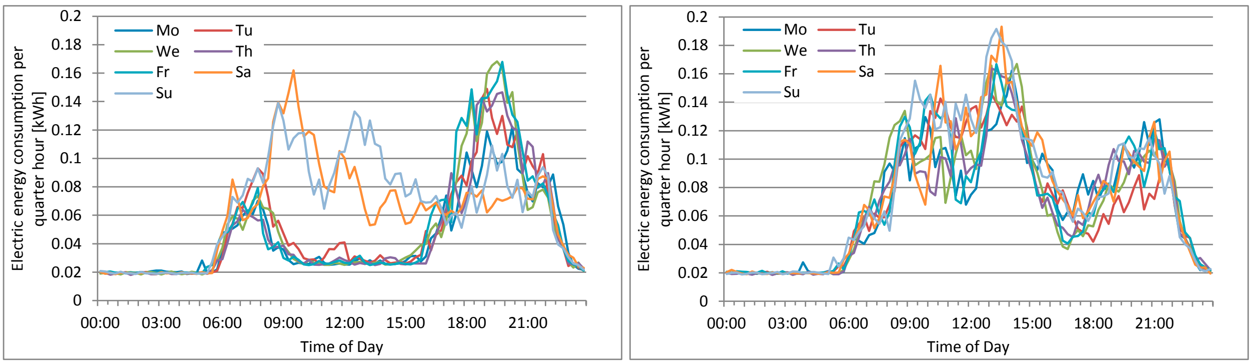

Fig. 2. Examples of average daily load profiles, scenario 1: (a) scenario year 1; (b) scenario year 4

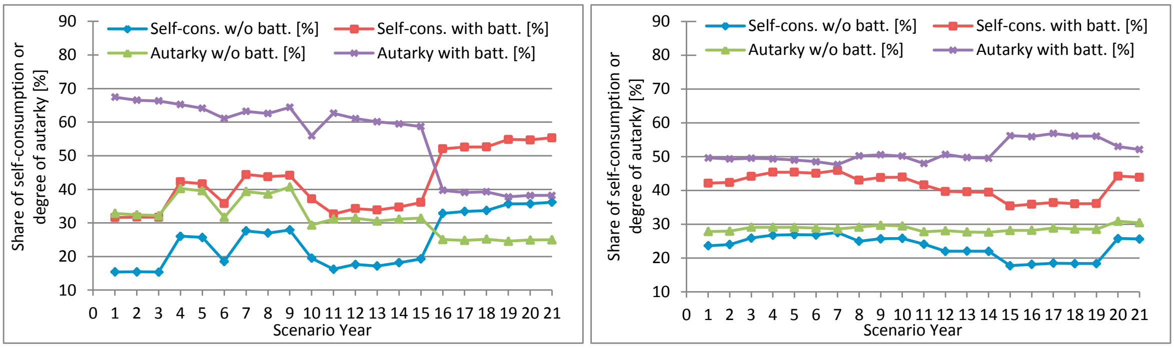

Fig. 3. Share of self-consumption and degree of autarky, (a) scenario 1; (b) scenario 2

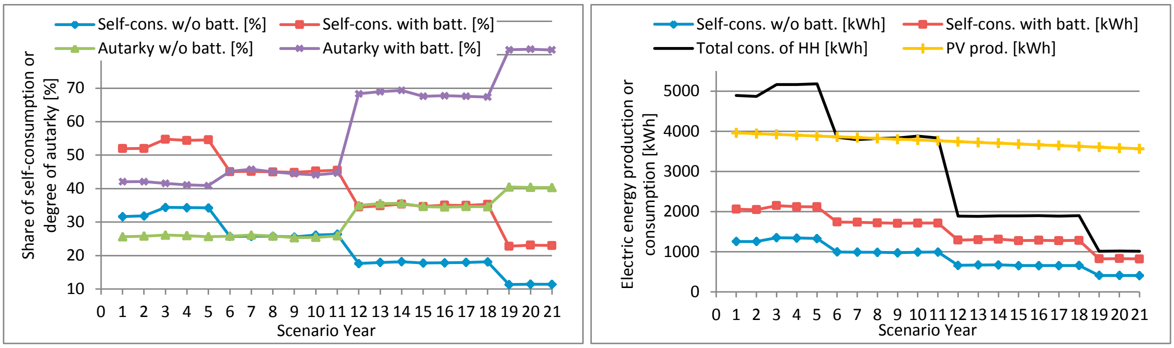

Fig. 4. Scenario 3: yearly HH electr. energy consumption, PV production, share of self-cons. and degree of autarky: (a) ratios; (b) abs. values

Fig. 3 and 4 show the effects of the changes in the households on self-consumption and autarky.

The main effect can be attributed to the yearly electric energy consumption of the HH. If this is low compared to the PV production, the degree of autarky is high (Fig. 4a), i. e. most of the HH electric energy demand can be supplied by PV, but on the other hand a major part of PV energy must be fed to the grid or remains unused (Fig. 4b). This applies to a PV system without battery as well as with battery.

By using a battery, the share of self-consumption and degree of autarky are both increased. Qualitatively this holds for all scenarios and years. Quantitatively the relative gain by using a battery is high (factor 2) when the peak load is in the evening (e. g. working couple, scenario 1 SCY 1); it is lower (factor 1.6) when the peak load is at noon (e. g. family with toddler, scenario 1 SCY 4). However the absolute gain by the battery strongly depends on the yearly energy consumption of the HH.

Table 1 shows that the share of self-consumption can vary over the lifetime of the system by more than a factor of three without battery and more than a factor of two with battery. The average share of self-consumption over the lifetime may be about 30 % higher or lower than in the year of commissioning.

Table 1. Calculated shares of self-consumption and degrees of autarky

Scenario	Parameter	In year of commissioning	Minimum over the lifetime	Average over the lifetime	Maximum over the lifetime
1	Share of self-consumption without / with battery	15% / 32%	15% / 32%	25% / 42%	36% / 55%
2	Share of self-consumption without / with battery	24% / 42%	18% / 35%	23% / 41%	28% / 46%
3	Share of self-consumption without / with battery	32% / 52%	11% / 23%	23% / 41%	34% / 55%
1	Degree of autarky without / with battery	33% / 67%	25% / 38%	32% / 56%	41% / 67%
2	Degree of autarky without / with battery	28% / 50%	28% / 48%	29% / 51%	31% / 57%
3	Degree of autarky without / with battery	26% / 42%	25% / 41%	31% / 57%	40% / 82%

4. Conclusions and outlook

The calculations show that the energy consumption of a household and its time profile may change significantly over the years, and this has strong effects on how much of the energy produced by a PV system without or with battery can be self-consumed by the household as well as on the achievable degree of autarky. For example in Scenario 1 the self-consumption without a battery varies over the years between 15 % and 36 %. The financial effects of these changes in self-consumption depend on the prices for electric energy fed to and drawn from the grid and retail electricity prices for electricity supply from the grid as well as on related regulations, governmental support programs and aspects of taxation. So when dimensioning the PV-battery system for optimal return on investment over the lifetime, not only changing electricity prices but also changing household behavior should be taken into account. An interesting trend in this context is the appearance of PV-battery systems as commercially available systems with modular storage capacities. These systems allow an easy adoption of the available storage capacity to changes of the HH electricity demand by adding or removing battery modules. A techno-economic evaluation of such systems could be subject to future research.

Possible future changes in HH electric energy consumption due to new consumers (e.g. electric vehicles), new devices, new energy supply concepts (e.g. integration of power-to-heat) or fundamental behavior changes of household members (e.g. breakthrough of virtual-reality) are not reflected by the presented approach. Nevertheless, it is expected that these aspects will have a significant impact on the future HH electric energy consumption. Future work should therefore try to quantify these trends and to integrate them in the analysis.

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