District battery for optimized use of phtovoltaic energy

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***Abstract*—The aim of this work is the comparison of a common storage for a planned residential area of 22 houses to individual batteries for an improved use of generated photovoltaic (PV) generation. For this purpose, a simulation tool has been developed. It compares the storage concepts regarding grade of autarky and self-consumption. The combination of PV system and storage shows a high increase of the grade of autarky and self-consumption compared to the concept without a battery. In addition, a method has been determined using load and PV profiles. This enables an evaluation if a battery technology should be used in the supply concept.**

Keywords—photovoltaic generation, lithium-ion storage, comparison of load and photovoltaic profiles, comparison of storage concepts

I. Introduction

In the course of the energy transition, new and existing technologies are developed and further extended. Due to deactivation of conventional power plants, power supply by fluctuating renewable energies is unavoidable.
In Germany is a great potential in the field of photovoltaic (PV). This is confirmed by the steadily growing installed PV capacity in Germany since 2008. However, this energy source is intermittent [1]. In order to increase this house integrated power generation, a combination with a storage system is essential. Due to the versatile application possibilities of the lithium-ion battery and the expected strong cost reduction per installed kWh until 2030, concepts of PV systems and lithium-ion storages are presented in this paper [2]. Here, a common storage for a planned residential area of 22 households is compared to individual batteries in the houses for improved use of generated photovoltaic generation. Despite the time lag between generation and consumption, the storage unit can ensure the energy supply. The storage units are able to store the energy at times of high energy production and release it during slack periods or at night. This ensures a constant energy supply.

In the following, the generation of the load and PV profiles are described, as well as the developed simulation tool. The evaluation of the results is based on the grade of autarky and self-consumption. In addition, a method to compare residual load profiles is presented.

II. Proceedings

A. Households

The assumed residential area in Germany serves as a data basis. Figure 1 points out the arrangement of the 22 households.

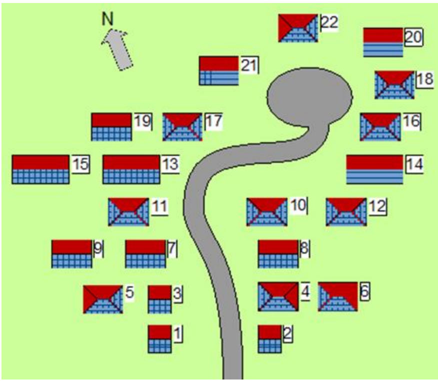

Fig. 1. Assumed arrangement for 22 households

The households differ in construction and PV system size. This implies variable load and PV profiles. The load profiles are created by the *LoadProfileGenerator* for singles, couples, families, workers and pensioners [3]. For all houses a profile of a real existing PV system in Köln Porz from 2018 is attributed and scaled to an assumed size. The load and PV profile of one household is given as an example. In Figure 2 the profiles are shown in high resolution of 15 minute values of the year 2018.

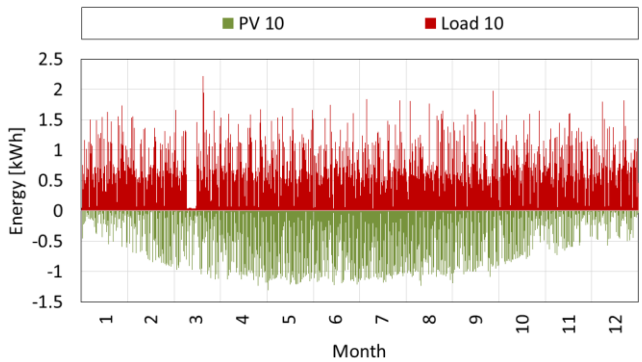

Fig. 2. Load and PV profiles of the one household

The energy generated by the photovoltaic system is indicated as a negative value and represented as the green graph. The consumption is given as a positive value and shown as the red graph.

The annually consumption of load and PV profiles of each house is shown in Figure 3. For each time step feed-in energy or grid-imported energy are calculated and summed up.

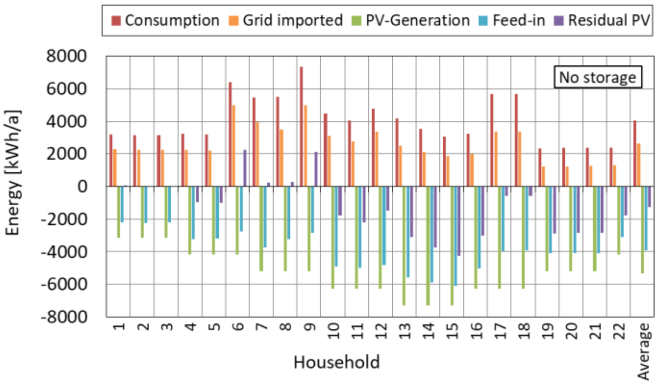

Fig. 3. Load, PV profiles and the summed energy flow

The annual energy flow for the households and their average is depicted. The consumption as well as the grid imported energy are shown as positive values. In contrast the PV generation and the feed-in energy are marked as negative values. As depicted the average of the generated PV energy, which is fed into the public grid, is greater than the average of the consumption that has to be imported from the grid. Here the average of the feed-in energy is -4000 kWh/a and the average of the grid imported energy is 2800 kWh/a. In order to relieve the power grid or to increase the grade of autarky, it is recommended to store the surplus in a storage.

B. *Simulation Tool*

The simulation tool is executed using the program *Excel* [4]. A class of electrical storages was developed. This class is used to construct a lithium-ion storage and to define its characteristics, like capacity. The data basis of the program are the generated load and PV profiles of each household. The residual load of the profiles are calculated and the capacity of the storage is interpreted.

The assumed algorithm for the usage of the battery is optimized for the self-consumption of the generated PV power. Generated power is first used. Excess is stored in the battery. If the battery is fully charged, the remaining PV power is fed into the power gird. If the PV power doesn't meet the demand, first the battery is used for the supply. If the battery is fully discharged, the needed power is retrieved from the public power grid.

III. Evaluation

In order to constitute the effects of the various storage concepts, the evaluation is carried out by grade of autonomy, grade of autarky and grade of self-consumption. First, these factors are defined. Then the calculated values are examined and interpreted.

Different indexes have been created to track the derived formulas. These are shown in figure 4.

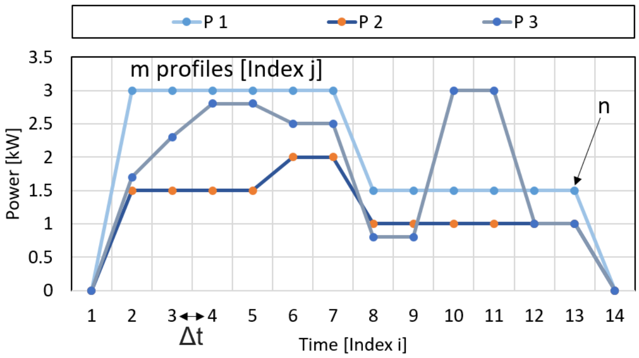

Fig. 4. Examplary profiles

Exemplary profiles can be seen. The indices describe a scalable size. The number of households is described by *m* with index *j*. The index *i* defines each individual time step. The number of time steps is defined by *n*. The key values are also defined.

- $P_{PV}(i)$ generated PV profiles
- $P_{con}(i)$ profile of consumption
- W_{PV} total generated energy per year
- W_{con} total consumed energy per year
- W_{use} total used PV energy per year

W_{PV} and W_{con} are defined as:

$$W_{PV} = \sum_{i=1}^{n} P_{PV}(i) * \Delta t(i) = \Delta t * \sum_{i=1}^{n} P_{PV}(i) \quad (1)$$

$$W_{con} = \sum_{i=1}^{n} P_{con}(i) * \Delta t(i) = \Delta t * \sum_{i=1}^{n} P_{con}(i) \quad (2)$$

A. *Terminology*

- Grade of autonomy

The grade of autonomy g_{auto} describes the autonomous or independent supply of a system per year [5]. This term has to be distinguished from the grade of autarky.

$$autonomy = \frac{generated\ solar\ energy\ per\ year}{energy\ consumption\ per\ year} \quad (3)$$

In order to calculate the grade of autonomy, first the total used PV energy and the total consumed energy per year must be determined.

$$g_{auto} = \min\left(\frac{W_{PV}}{W_{con}};1\right) = min\left(\frac{\sum_{i=1}^{n} P_{PV}(i)}{\sum_{i=1}^{n} P_{con}(i)};1\right) \quad (4)$$

The ratio describes the generated PV energy to consumed energy, set to 1.

- Grade of autarky

The grade of autarky g_{autark} indicates the proportion of electricity consumption that is supplied by the photovoltaic storage system. Here, either the simultaneous direct consumption of the generated solar power or the discharge of the battery storage contributes. The greater the grade of autarky, the less energy is drawn from the public power grid [6].

$$autarky = \frac{internal\ consumption\ of\ solar\ electricity}{total\ electric\ power\ consumption} \quad (5)$$

$$g_{autark} = \min\left(\frac{W_{use}}{W_{con}};1\right) = \frac{\sum_{i=1}^{n}\min(P_{PV}(i);P_{con}(i))}{\sum_{i=1}^{n}P_{con}(i)} \quad (6)$$

The ratio describes the used PV energy to consumed energy, set to 1.

- Grade of self-consumption

The grade of self-consumption describes the ratio of internal consumption solar electricity by total generated solar electricity [6]. The electricity is either used simultaneously by the electricity consumers or to charge the battery storage. The greater the ratio of the grade of self-consumption, the less solar power is fed into the public power grid.

$$\textit{self-consumption} = \frac{\textit{internal consumption of solar electricity}}{\textit{total generated solar electricity}} \quad (7)$$

B. *Figure of Merit*

The Figure of Merit (FOM) is developed to evaluate the distribution and capacity of renewable energies in various areas. The utilization of the profiles indicates whether the installation of electricity storage is recommended.

$$\mathrm{FOM} = \frac{g_{autark}}{g_{auto}} = \frac{\frac{W_{use}}{W_{con}}}{\min(\frac{W_{PV}}{W_{con}};1)} \quad (8)$$

The grade of autonomy is determined for the entire settlement and the use of an infinite large battery. Furthermore, the grade of autarky is calculated without a storage concept. However, in the first case the households can cooperate with each other, in the second case this is not possible.

$$g_{auto} = min(\frac{\sum_{j=1}^{m}W_{PV,j}}{\sum_{j=1}^{m}W_{con,j}}) = \min(\frac{\sum_{i=1}^{n}\sum_{j=1}^{m}P_{PV,j}(i)}{\sum_{i=1}^{n}\sum_{j=1}^{m}P_{con,j}(i)};1) \quad (9)$$

$$g_{autark} = \frac{\sum_{i=1}^{n}\min(\sum_{j=1}^{m}P_{PV,j}(i);\sum_{j=1}^{m}P_{con,j}(i))}{\sum_{i=1}^{n}\sum_{j=1}^{m}P_{con,j}(i)} \quad (10)$$

$$g_{autark} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m}\min(P_{PV,j}(i);P_{con,j}(i))}{\sum_{i=1}^{n}\sum_{j=1}^{m}P_{con,j}(i)} \quad (11)$$

C. *Grade of autarky and self-consumption*

Different loads and PV profiles imply different values of the grade of autarky and self-consumption for each individual household. If this factors are calculated without a battery storage concept, the average value of the grade of autarky is 35 % and the average value of the grade of self-consumption is 25 %.

The following Figure 4 presents the grade of autarky and self-consumption for the 22 households with battery storage concepts. A comparison will be made between a common storage and many individual household storages for a daily use. The grey bars show the individual grade of autarky or self-consumption for each household. The red bar describes the individual and the orange bar the mutual storage. The red line shows the average value of the grade of autarky or grade of self-consumption of the storages. Furthermore, the purple bar indicates an infinitely large battery. This provide information about the capacity and the potential of the storage.

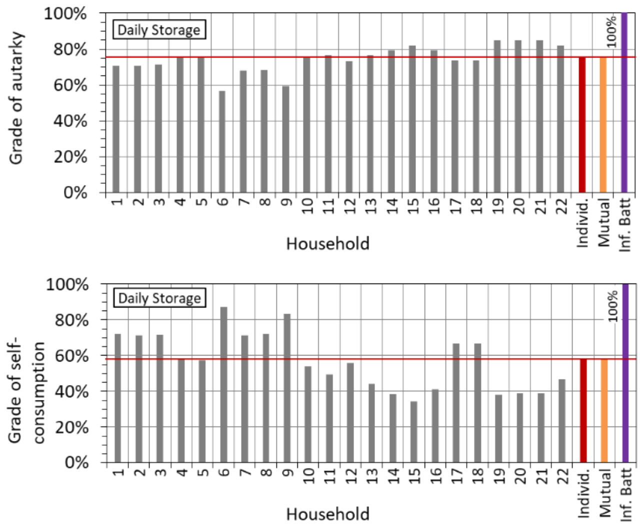

Fig. 5. Daily storage apropos of grade of autarky and self-consumption

The average value of the grade of autarky raised up to 75 % and the average value of the grade of self-consumption increased up to 60 %. A significant increase of these values is to identify. It is obvious that not all households exceed the average with their individual values. A common solution could become an improvement for some of the 22 households, while others cannot compete.

As depicted, the grade of autarky for both storage concepts has been calculated for the entire settlement. This direct comparison of the storage technologies for different battery sizes and the energy use is shown in the following figure. In addition, the differences between a cooperating storage concept and the individual solution, as described by the FOM, can be seen.

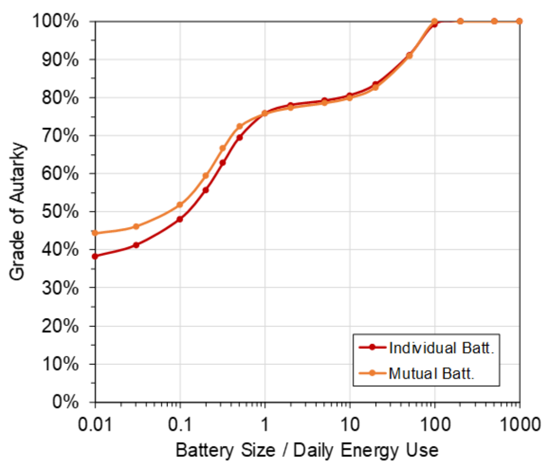

Fig. 6. Comparison of the battery concepts for different battery sizes and energy use

The red graph describes the grade of autarky for the individual concept. In addition to the installed PV system, every household has its own house integrated electricity storage. In contrast, the community concept exhibits only one storage. The grade of autarky for this concept is indicated by the orange graph.

The diagram describes the degree of autarky in relation to the size of the storage concepts. The x-axis is normalized to a daily storage. This is defined as the average consumption of the considered participants for one day. The axis describes the growth of the storage capacity from a daily to a seasonal or annual storage. The curves have two peaks. The first point is reached when the memory should be larger than the daily energy use. The second point describes the transition to a seasonal storage. Between the start value and the first peak as well as the first and second peak the graphs do not run continuously but fluctuate. These variations can be explained by daily and annual oscillations.

Both curves have a comparable course. They differ in the initial value. The figure shows that the larger the storage concept is, the more similar the graphs become. The graphs approach when the storage size for the generated energy exceeds one day. As a result, it is possible to install a smaller common storage (Mutual Battery) and still achieve the same grade of autarky as long as the storage does not exceed a daily consumption. In return, no difference results if a storage concept is required for seasonal use.

IV. Conclusion

In this work different lithium-ion battery concepts are investigated. The value of the grade of autarky and self-consumption indicate a great increase by using a storage technology. The value of the grade of autarky rises from 35 % up to 75 %. The value of the grade of self-consumption yields from 25 % to 60 %. Furthermore, the grade of autarky is compared for the different battery concepts. The systems differ in the number of installed battery units. The individual concept integrates one storage in each household, while all generation in the mutual concept feed into a common storage unit. The investigation of both concepts indicates that a common storage gives improvements only, if the storage is smaller than the daily needed energy. In addition, a method has been developed to evaluate the use of a storage technology in a planned concept.

Acknowledgment

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