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District Battery for Optimized Use of Photovoltaic Energy

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***Abstract*—The aim of this work is the comparison of a common storage to individual batteries for an improved use of generated photovoltaic (PV) generation for a planned residential area of 22 houses. 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 significant increase of the grade of autarky and self-consumption compared to the concept without a battery. In addition, a method to point out the benefits of an integration of a storage technology into a neighborhood has been determined. This enables an evaluation whether 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.

Germany has 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 the 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 significant 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.

Certainly, there is no legal definition of a residential area and it is not defined in the German Renewable Energies Act (EEG) [3]. For this reason an extensive research has been carried out on this specific subject “common storage” as part of the research project of the Cologne University of Applied Science. A database has been set up. This contains 318 publications and information on varying neighbourhoods and projects in Germany and surroundings. One result of the research is that the size of the area varies greatly in the number of inhabitants and households. Additionally, an overview of 15 areas with a shared storage system has been created. These are pilot projects or real laboratories. The present research indicates that the capacity of a commonly used storage can be reduced, required to the storage capacity of the installed batteries in the households. Furthermore, the investment costs can be reduced while maintaining the same benefits. This depends in various factors, for example the business model and future legal development [4]. To support these statements and to show the advantages of a shared storage to an individual battery design, these storage systems are compared.

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

II. Proceedings

A. Households

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

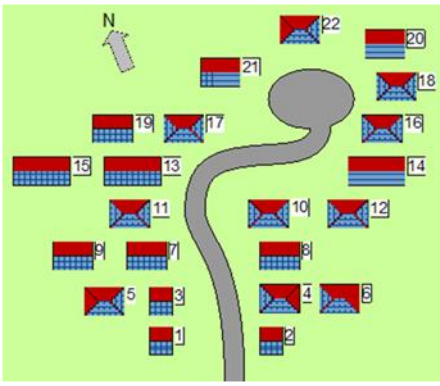

Fig. 1. Assumed arrangement for 22 households

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 [5]. 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.

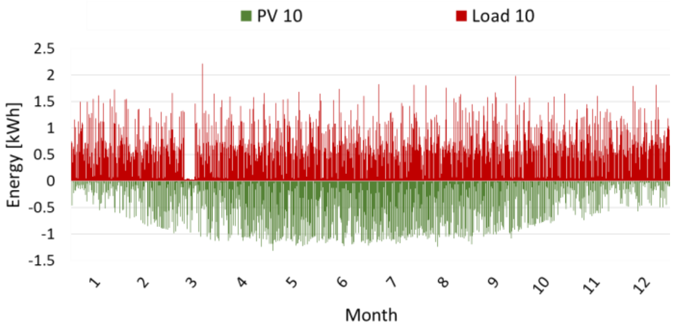

Fig. 2. Load and PV profiles of household number 10

The figure shows the energy flow in terms of consumption and generation. When a load is connected, the energy is taken from the public grid. Accordingly, the consumption of the household is given as a positive value and shown by the red graph. In contrast, the energy generation by a photovoltaic system is fed into the grid and indicated as a negative value. It is represented by the green graph.
The consumption in March shows a clear difference compared to the usual load. Only the base load, which is applied to the house, is covered. This suggests that the resident has not entered the house for a long time slot. This could be due to a holiday or hospital stay.

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.

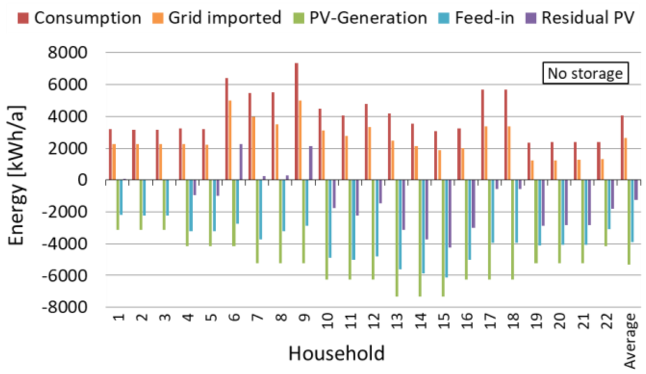

Fig. 3. Load, PV profiles and the summed energy flow

The annual energy flow for the households and their average are 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 consumed energy 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 can be advantaged to store the surplus in a storage.

B. Simulation Tool

The simulation tool is implemented in Excel [6]. A class of electrical storages was developed. This class is used to construct a lithium-ion storage and to define its characteristics, like capacity or state of charge. The data basis of the program are the generated load and PV profiles of each household. The residual load of the profiles are calculated. The assumed algorithm for the usage of the battery is optimized for the self-consumption of the generated PV power. Self-consumption of generated PV energy has top priority. Excess energy 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 of the household, first the battery is used for the supply. If the battery is fully discharged, the needed power demand is covered from the public power grid.

III. EVALUATION

In order to constitute the effects of the various storage concepts, the evaluation of the benchmark regards 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.

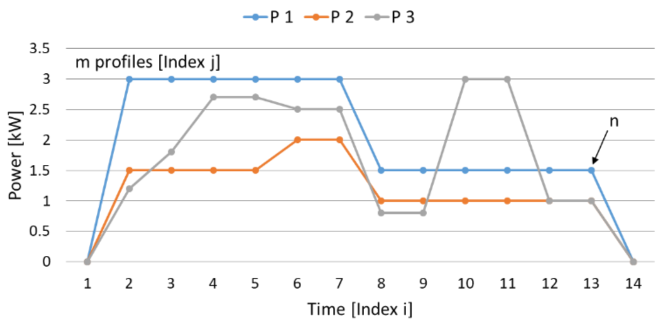

Fig. 4. Examplary profiles

Exemplary profiles can be seen. The indexes 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:

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

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

$$W_{use} = \Delta t \cdot \sum_{i=1}^{n} \min(P_{PV}(i); P_{con}(i)) \quad (3)$$

A. Terminology

- Grade of autonomy

The grade of autonomy g_{auto} does not follow a fixed definition, but contains core criteria that can be transferred to different applications. Basically, the term autonomy describes the self-determination or self-legislation. Autonomy is given if the individual can act without restriction. In the case of a PV and storage system the grade of autonomy describes the autonomous or independent supply of a system per year [7]. This term has to be distinguished from the grade of autarky.

$$autonomy = \frac{PV\ energy\ consumption\ per\ year}{energy\ consumption\ per\ year} \quad (4)$$

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

$$g_{auto} = \min\left(\frac{W_{PV}}{W_{con}}\,;1\right) = min\,\left(\frac{\sum_{i=1}^{n} P_{PV}(i)}{\sum_{i=1}^{n} P_{con}(i)};1\right) \quad (5)$$

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 [8].

$$autarky = \frac{internal\ consumption\ of\ PV\ power}{total\ electric\ power\ consumption} \quad (6)$$

$$g_{autark} = \min\left(\frac{W_{use}}{W_{con}}\,;1\right) = \frac{\sum_{i=1}^{n} \min(P_{PV}(i);P_{con}(i))}{\sum_{i=1}^{n} P_{con}(i)} \quad (7)$$

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 internally consumed solar electricity by total generated solar electricity [8]. 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.

$$self\text{-}consumption = \frac{internal\ consumption\ \ of\ PV\ power}{total\ generated\ PV\ power} \quad (8)$$

B. 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 34.5 % and the average value of the grade of self-consumption is 26.3 %. The following Figure 5 presents the grade of autarky and self-consumption for the 22 households with battery storage concepts. 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 provides information about the capacity and the potential of the storage.

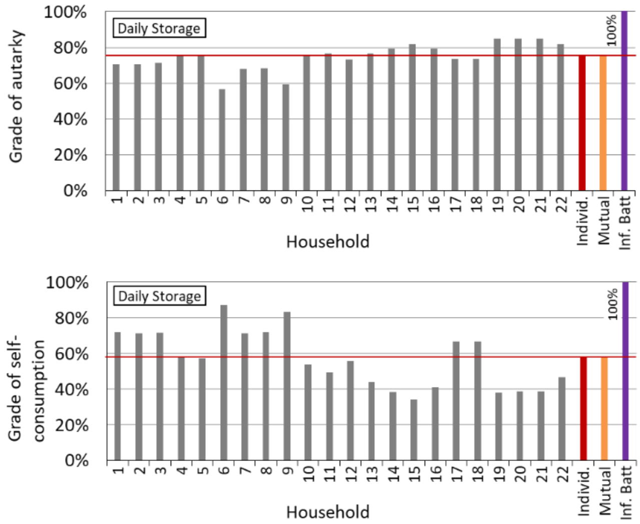

Fig. 5. Daily storage apropos of grade of autarky and self-consumption

The average value of the grade of autarky raised up to 75.8 % and the average value of the grade of self-consumption increased up to 57.64 %. These values increase remarkably. It is obvious that not all households exceed the average of the batteries with their individual values. A common solution could become an improvement for some of the 22 households, while others cannot compete. This shows that the use of the electricity production in the households can be increased by 35 % points with an installed storage system. This offers the advantage of lower electricity consumption from the public grid. This saves costs that refinance the technologies. Furthermore, the household becomes more independent of the public power grid. In order to make an exact statement on the relation between investment and economic benefit, an economic balance sheet should be drawn up in the further course. Moreover, since the current rate of remuneration per generated kWh has fallen below the commercial electricity purchase price, it is more profitable to use the generated solar electricity for self-consumption [9].

As depicted, the grade of autarky for both storage concepts has been calculated for the entire settlement. This is followed by the differentiation between individual and common storage systems. The difference is pointed out by the grade of autarky. The direct comparison of the storage technologies for different battery sizes and the energy use is shown in the following Figure 6.

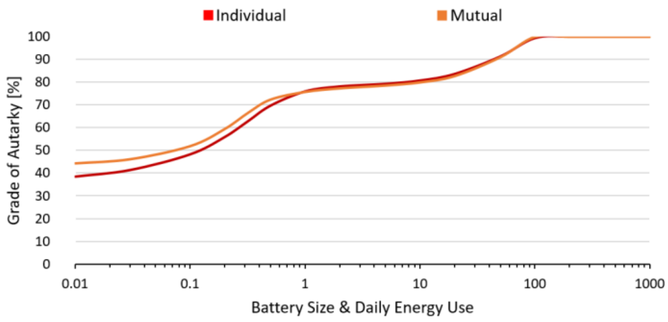

Fig. 6. Comparison of the battery concepts for different battery sizes and energy use

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 comparison, the community concept exhibits only one storage. The grade of autarky for this concept is indicated by the orange graph.

The diagram describes the grade 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 peak is reached when the storage covers the daily needed energy use. The second peak 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.
Both curves have a comparable course. The mutually used battery is showing a slightly better performance of the grade of autarky. 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.

C. *Figure of Merit*

In the area of the use of common storages, many pilot projects or real laboratories have been developed. These are intended to provide information on the technical possibilities and their areas of application on the German electricity market. There are no regulations, for example, the operation of the storage facility and the shifting of energy to the producer or defining the operators and owners. Furthermore, the basic concept of using a storage as a community is relatively new, even if the annually increasing growth of fluctuating renewable energies and the expansion targets up to the year 2050 are taken into account [3]. There is a lack of experience and legislation to draw up a meaningful analysis of the benefits of cooperating storage systems for individual projects.

Here the developed Figure of Merit – Method (FOM) is used. These allow an assessment of the potential of using a storage system in the neighbourhood. Load and PV profiles are the data basis and are calculated against each other. The FOM Method is formed by the ratio of the grade of autarky g_{autark} and the grade of autonomy g_{auto}.

$$\text{FOM} = \frac{g_{autark}}{g_{auto}} \tag{9}$$

The grade of autonomy is determined for the entire settlement and the use of an infinitely large battery. For the further procedure, two scenarios are assumed, the use of a co-operating community to a standard settlement without community use.

The first concept is based on the assumption that individual households act individually. There is no exchange between them. This is intended to identify potentials, how well the load and PV profiles harmonise and offers the initial value. For example, if a 100 % generation at almost 100 % consumption is already available without a storage, the integration of a battery system is unnecessary. If a lower FOM value is found, the analysis can be continued with a cooperating storage to increase the potential. This is described by the second scenario. The individual households can cooperate with each other. They complement each other in terms of the consumed and produced energy.

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

- Scenario 1 (individual storages)

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

- Scenario 2 (common storage)

$$g_{autark} = \frac{\sum_{i=1}^{n} \min(\sum_{j=1}^{m} (P_{PV,j}(i); \sum_{j=1}^{m} P_{con,j}(i))}{\sum_{i=1}^{n}\sum_{j=1}^{m} P_{con,j}(i)} \tag{12}$$

The FOM is applied on the basis of the load and PV profiles and results of the calculation. The value of the first scenario is about 26.7 %. The calculation for cooperative storage results in a value of 57.3 %. The results imply an increase in performance of about 30 % points. If the previously calculated results of the efficiency increase are used and compared with the FOM, they differ by only 5 %.

IV. Conclusion

In this work different usage concepts of lithium-ion battery 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 76 %. The implementation of a storage system yields an increase of the grade of self-consumption 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 concept of the individual storages integrates one storage in each household, while all generation in the concept of mutual storage feed into a common storage unit. The investigation of both concepts indicates that a common storage is only advantageous if the storage is smaller than the daily needed energy. In addition, a method has been developed to evaluate the use of a cooperating storage technology in a planned concept. The calculated results compared to the FOM differ by 5 %.

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