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Impact of Renewable Energy Expansion to the Balancing Energy Demand of Differential Balancing Groups

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ABSTRACT

The research addresses the present situation on the German electricity market caused by variable renewable energy sources. The increasing number of households with photovoltaic and battery storage systems and their impacts require special attention. These systems change the traditional electricity customer from the sole electricity consumer to an electricity producer and consumer in one person. These so-called prosumers differ in their actual electricity demand from the initially estimated electricity demand with standard load profile. This discrepancy results in deviations within a differential balancing group. Thereby, the main finding of this research is a significant higher balancing energy demand with the expansion of photovoltaic and battery storage systems. Hence, the standard load profile is particularly not suitable for differential balancing groups with a high penetration of solar systems and still less suitable for groups with solar and battery storage systems.

KEYWORDS

Balancing energy, Balance responsible party, Electricity schedule registration, Variable renewable energy sources, Photovoltaic and battery storage systems, Prosumer, Standard load profile, Differential balancing group.

INTRODUCTION

Based on the transformation of the energy supply system into a system with a high share of renewable energy sources, the integration of fluctuating electricity generation becomes crucial. Renewable energy production is dependent on the load and the weather [1]. Consequently, the utilization of existing flexibility potentials has got to increase steadily [2], so that the security of supply and thus the acceptance of the energy transition among the population is still highly guaranteed [3].

The continuous spatial and temporal balancing of schedule deviations and as a result the balance between supply and demand is the foundation to ensure a secure electricity supply. Based on the fluctuating generation characteristics of wind energy and Photovoltaic (PV) systems and the accompanying uncertainty in production forecasts, it is not possible to accurately schedule their feed-in [4]. The increasing amount of Variable Renewable Energy Sources (VRES) at the consumer level leads to uncertainty in the demand forecasts [5]. Customer-sited electrical energy storage systems, e.g. PV battery storage systems, are mainly used to increase self-consumption of distributed VRES like PV systems, to reduce electricity withdrawal from the grid and in this regard to reduce demand charges [6]. On the balancing group level, this leads to schedule deviations compared to the day-ahead electricity schedule registration [7].

The balance responsible parties are obliged to keep their balancing groups balanced on a quarter-hour basis [8]. In addition, the Federal Ministry of Economics and Technology (BMWi) is calling to uphold balancing group commitments [9]. To adhere this demand forecast deviations can be traded on the day-ahead and intraday market and furthermore within the day after process. Remaining schedule deviations are offset within the framework of the settlement for balancing energy. As a result, input values to estimate balancing energy costs such as Transmission System Operator's (TSO) payments or proceeds for activated control energy are difficult to predict.

Market players need to expand their business area due to the increase of fluctuating electricity generation units at the balancing group level [10]. This is necessary to maintain balancing group commitments and thus the reduction of balancing energy costs and the resulting economic risk.

The German electricity market

The electricity market is changing from a static market to a flexible real-time market. Two causes motivate this change. The first trigger is the liberalization and creation of a single European electricity market, which enables the framework for free competition and free trade between producers and consumers. Second is the growing number of weather-dependent renewable energy sources, such as wind energy and PV systems. The integration of these fluctuating generation units requires short-term trading activities as well as short-term reactions to changes in grid state. Hereinafter, the structure of the European electricity market is going to be described. It provides a framework for production, consumption, trade and accounting. Based on this, the subject area of the balancing group management system is discussed, as well as their participants and the challenges arising from fluctuating production units.

The structure of the European electricity market follows a hierarchical order. This is shown in Figure 1 in accordance with [11, 12].

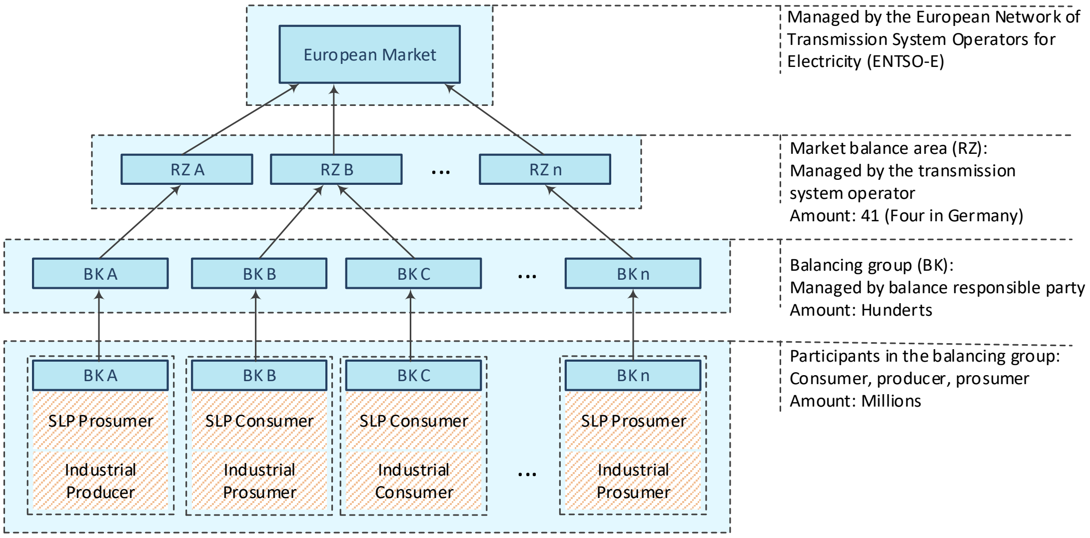


Figure 1. Structure of the European electricity market
(own illustration in accordance with [11, 12])

The top position of the structure is represented by the European electricity market. It is organized by the European Network of Transmission System Operators for

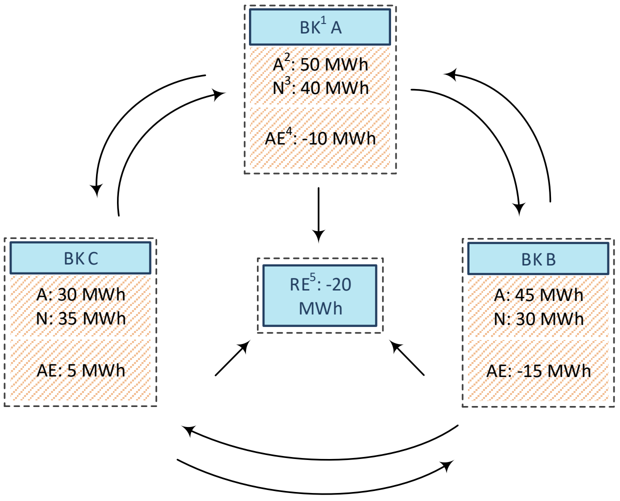
Electricity (ENTSO-E). The ENTSO-E is a network of 41 European TSOs from 34 countries. It organizes the operation of the European electricity market and divides it into control areas.

The associated TSO ensures the operation and the safety of the respective control area. In Germany there are four control areas, which are allocated to the TSOs Amprion, TenneT, 50Hertz and TransnetBW.

Within the control areas, balancing groups are formed. Market participants (producers, consumers and prosumers) are virtually divided into balancing groups. Each balancing group is organized by a balance responsible party. The balance responsible party is legally obliged towards the TSO to ensure the balance between the withdrawal and supply of electrical energy within the balancing group. This requirement is taken into account with purchase and delivery schedules, which are prepared by the balance responsible party on a forecast basis and transmitted to the TSO.

The last position in the structure of the European electricity market is taken by private customers that are accounted with the Standard Load Profile (SLP), industrial customers and industrial producers. Market participants with generation and consumption behaviours play a special role. This group of participants will be referred to as prosumers and will be discussed in detail later. In Germany, several million market participants are grouped into balancing groups and organized by balance responsible parties.

In addition to the organization of the balancing groups within their control area, the TSOs are responsible for ensuring the power system stability. This is considered by maintaining the balance between withdrawal and supply of electricity. Within each control area, the sum of all balancing group deviations must be compensated using control energy. For each quarter-hour within a control area the sum of balancing energy demand defines the control energy demand. This is provided by the TSO of the associated control area. Since balancing groups compensate each other physically the total amount of balancing energy within a control area can exceed the amount of control energy by many times. Consequently, control energy is used to balance the excess or shortage energy quantities in the electricity grid to maintain system stability. Figure 2 shows the interaction of three exemplary balancing groups within a control area, the distribution of the balancing energy quantities, and the resulting control energy demand.



[1] Balancing group (BK)
[2] Electrical energy supply (A)
[3] Electrical energy demand (N)
[4] Balancing energy (AE); AE = N – A
[5] Control energy (RE); Example: (-10 - 15 + 5) MWh = -20 MWh

Figure 2. Interaction between balancing groups with balancing energy and resulting control energy (in accordance with [13])

In Figure 2, three balancing groups with their electrical energy supply as well as electrical energy demand are shown. Balancing groups build the foundation to account all electricity trading activities of balance responsible parties within a control area. Each balance responsible party is legally obliged to deliver a balanced energy time series schedule for each quarter-hour of the year to its associated balance group coordinator for its balancing group. The role of the balance group coordinator in Germany is performed by the TSO of the associated control area. Because of inaccuracies in production and consumption, schedule deviations are inevitable. These are balanced with balancing energy and charged by the balancing group coordinator to the balance responsible party.

The difference between supply and demand describes the balancing energy demand of each balancing group. The sum of the balancing energy within a control area results in the amount of control energy. This is used within the system services by the TSO to maintain system stability. If positive or negative balancing group deviations occur in the individual balancing groups of a control area, the balancing groups compensate each other in a first step by exchanging balancing energy among themselves. Only the remaining positive or negative control area balance is compensated by the TSO with the physical provision of control energy. This is the amount of balancing energy that cannot be compensated by the interaction of balancing groups.

Figure 3 shows the components of a balancing group management system in chronological order with the allocation of trading options on the German electricity market. In addition, the schedule conditions for the schedule registration in Germany are presented using the ENTSO-E Scheduling System (ESS) [14].

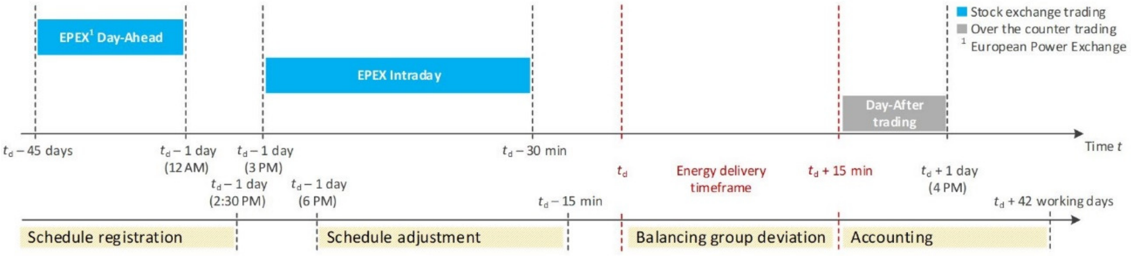


Figure 3. Balancing group management in chronological order with allocation of trading options on the German electricity market and the framework conditions for schedule registrations in Germany [14]

The energy time series schedule must contain only quarter-hour power values [14]. The schedule management of a balancing group is divided according to its schedule in before, during and after every ¼-h time interval. The start time of each ¼-h time interval is designated in Figure 3 and in the further course by t_d.

The modules of the schedule registration and adjustment serve to map each ¼-h time interval of the schedule management before the beginning t_d of the respective quarter-hour, considering the time specifications of the ESS [14]. The schedule registration is implemented with forward products and contracts for the day-ahead market. Schedule adjustments are made using intraday trading products.

The balancing group deviation module is used to represent each minute during each ¼-hour time interval. The balancing group total is determined based on the actual grid withdrawal and the data from the adjusted schedule registration. The balance of the balancing group represents the balancing energy demand to cover the schedule deviations of every quarter-hour. If deviations from the schedule adjustment are determined before the end of a ¼-hour time interval, these can be reduced within the ¼-hour time interval with flexibility units. This reduces the balancing energy procurement for the corresponding ¼-hour time interval.

The remaining schedule deviation which has not been balanced by trading activities or an active balancing group management is charged to the balance responsible party by the TSO. The accounting is carried out using the uniform balancing energy price for all control areas (reBAP). The reBAP is valid for each of the four German control areas. It is formed for each delivery interval (¼-h), based on the costs as well as quantities of the control energy used (secondary control and minute reserve energy) in all four control areas. The calculation of the reBAP has been extended to disable the balance responsible parties to optimize intraday trading activities using balancing energy payments. This is described in detail in [15]. In its presented form, the reBAP is intended to provide the balance responsible parties with an incentive for compliance of the balancing group commitment.

The balancing energy price will be published after the closure of the IntradayS trading window. The IntradayS is a kind of day-after market with guidelines according to the day after process from the ESS [14].

Therefore, it is not possible for the balance responsible party to calculate the prices for balancing energy within the intraday or day-after trading period. In accordance with the market rules for accounting balancing group grid billing (MaBiS), the TSO is obliged to notify the balance responsible party about the balancing energy prices for the delivery month up to the 20th working day after the end of the delivery month [16]. In addition, the TSO is obliged to submit the balancing group accounts to the balance responsible party until the 42nd working day after the end of the delivery month. This includes the invoiced balancing energy costs [16].

Balancing energy prices

The balancing energy costs represent a cost risk that is difficult to calculate for the balance responsible party. The balancing energy price data is published by the TSOs. Figure 4 shows the balancing energy prices for the year 2013 as heat map. On the ordinate the time is illustrated in the course of the day, on the abscissa the month and by colouring the surface the balancing energy prices are plotted. Yellow areas represent times with balancing energy prices in the range of 0 EUR/MWh. A colour change from orange over red to black shows intervals with positive reBAP. Black represents prices ≥ 200 EUR/MWh. A colour gradient from green over blue to purple illustrates negative balancing energy prices. A dark purple represents prices ≤ −200 EUR/MWh.

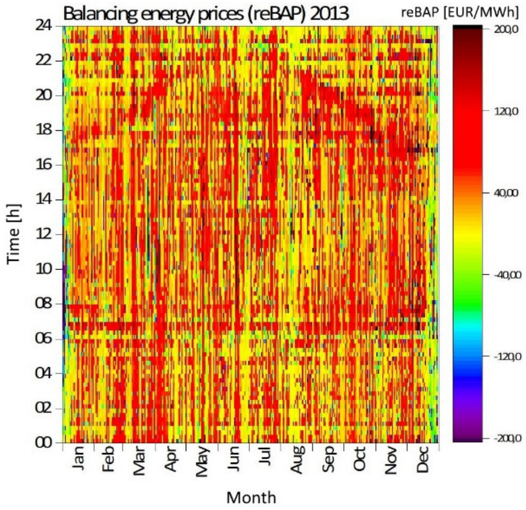


Figure 4. Balancing energy prices (reBAP) for the year 2013

Figure 4 shows the balancing energy prices for the year 2013. Over the entire year, a high level of balancing energy prices can be seen in the evening hours. These occur depending on the season between 5 and 10 PM. A similar behaviour of the balancing energy prices can be seen in the morning hours between 5 and 8 AM. The comparison between the evening and morning hours shows a stronger increase in the balancing energy prices in the evening hours. Possible relationships can be addressed in electricity generation as well as in electricity consumption. On the one hand, the electricity generation behaviour of PV systems, on the other hand, the electricity consumption in the evening hours depending on the season are possible reasons.

METHODS

The description of consumers within a balancing group is another aspect of the energy time series schedule management. In this context, SLP consumers take a special position in the balance of end consumers, especially those with electrical generation and consumption characteristics (prosumers).

Prosumers in balancing groups

According to section 12 para. 1 StromNZV [8], Distribution Network Operators (DNOs) in their role as balance responsible parties are obliged to recognize end consumers with an electricity withdrawal up to 100,000 kWh/a using SLP. The electricity withdrawal profile of end consumers differs from the SLP [17]. The reasons are manifold. The deviations can be caused by weather conditions and by the self-consumption of electrical energy from a PV system [18]. The expansion of a PV system with a battery storage system increases the deviations from the SLP [19]. The effects mentioned are not considered in the SLP adequately [20]. The SLP is not suitable for the accounting of prosumers [21].

Figure 5 shows possible components of an electricity feed-in and withdrawal profile from a SLP end consumer (prosumer). In accordance with section 12 para. 3 StromNZV [8], the DNO is obliged to create a differential balancing group if customers within their balancing group reach a number of 100,000. This sub-balancing group serves exclusively to record differences between the initially estimated electricity withdrawal and the real figures of all SLP end consumers in the associated distribution network [22].

Possible cause of the deviations from the SLP is the self-consumption of electricity from PV systems with or without battery storage. The results of the differences must be published annually. These differential balancing group deviations are offset by the TSO within the framework of the settlement for balancing energy with balancing energy prices. The balance responsible party is charged with the resulting balancing energy costs.

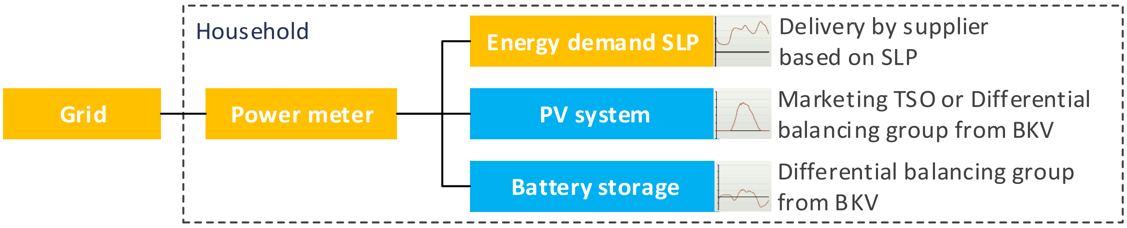


Figure 5. Components of an electrical feed-in and withdrawal profile from a standard load profile end consumer (in accordance with [19])

In Figure 6, the differential balancing group of a DNO with approx. 160,000 SLP end consumers is illustrated for the year 2015. On the ordinate, the time is plotted in the course of the day, on the abscissa of the month and by colouring the surface the load differences from the SLP. Yellow areas represent times with load differences in the range of 0 kW. A colour gradient from orange over red to black indicates intervals with positive load differences (underlap, SLP too low, load > SLP). Black is for values ≥ 10,000 kW. A colour change from green over blue to purple illustrates negative load differences (overlap, SLP too high, load < SLP). A dark purple represents load differences ≤ −10,000 kW.

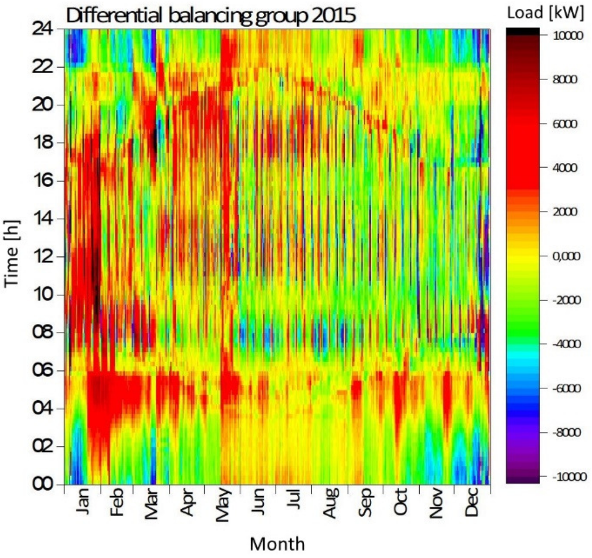


Figure 6. Differential balancing group of a distribution network operator with approx. 160,000 standard load profile end consumers for the year 2015 (data source: [23])

The illustration of the load differences in the differential balancing group for the year 2015 shows the weaknesses of forecasting electricity withdrawal with SLP for end consumers. Over the entire year 2015, a band of high load differences emerges in the evening and morning hours. High gradients of load differences occur between 5 PM and 10 PM depending on the time of the year. The load differences in the morning hours between 5 to 8 AM indicate a similar behaviour in a lesser degree. Furthermore, there are high load differences in the morning hours between 4 to 6 AM throughout the year. These are more pronounced during the winter months and the transitional period than in summer. High load differences in January 2015, in the time from 7 AM to 7 PM, can be attributed to the pronounced storm weather conditions with many rain clouds [24].

The self-consumption of electricity from PV systems with or without battery storage systems as well as the weather-related electricity withdrawal from the grid are not considered adequately in the SLP [20]. The illustrated differential balancing group confirms this statement. The same findings are shown by preliminary investigations that describe the changes in electricity withdrawal due to different PV systems in combination with battery storages for one household [25].

Modelling prosumers

In order to analyse prosumers electricity withdrawal from the grid a simulation model is created and described in the following subsection. It is divided into four parts:

- Load modelling;
- PV generation modelling;
- Battery storage modelling;
- System configuration modelling.

1st, data from the VDI 4655 [26] is used to model electricity demand characteristics. A load profile for a 4-person single-family house is created with demand values P_{Load}^{t} for every minute $t \in T \coloneqq [1{,}525600]$ of 2013.

2nd, solar radiation data from the German Weather Service (DWD) from January 1st to December 31th of 2013 for Stuttgart is utilized to perform the PV generation modelling with values for every minute. The DWD data offers values for the global solar radiation on the horizontal ($E^t_{\text{Glo,hor}}$) and the diffuse sky radiation on the horizontal ($E^t_{\text{Diff,hor}}$) for $\forall t \in T$ of 2013. To estimate the PV generation of a tilted solar panel, the data had to be converted into values for tilted surfaces.

The global solar radiation on a horizontal consists out of the direct radiation ($E^t_{\text{Dir,hor}}$) and the diffuse sky radiation ($E^t_{\text{Diff,hor}}$) on the horizontal. The relation is described with eq. (1):

$$E^t_{\text{Glo,hor}} = E^t_{\text{Dir,hor}} + E^t_{\text{Diff,hor}} \tag{1}$$

The global solar radiation on a tilted surface is calculated with eq. (2):

$$E^t_{\text{Glo,gen}} = E^t_{\text{Dir,gen}}(E^t_{\text{Dir,hor}}) + E^t_{\text{Diff,gen}}(E^t_{\text{Diff,hor}}) + E^t_{\text{Refl,gen}}(E^t_{\text{Glo,hor}}) \tag{2}$$

Different methods are utilized to estimate the three components:

- Direct radiation ($E^t_{\text{Dir,gen}}$);
- Diffuse sky radiation ($E^t_{\text{Diff,gen}}$);
- Reflected radiation ($E^t_{\text{Refl,gen}}$) to calculate global radiation on a tilted surface ($E^t_{\text{Glo,gen}}$) with eq. (2).

Based on Duffie and Beckmann [27] $E^t_{\text{Dir,gen}}$ is calculated with $E^t_{\text{Dir,hor}}$, its incidence angle and solar altitude angle. The radiation from ground reflection ($E^t_{\text{Refl,gen}}$) is estimated based on Perez [28] with an isotropic approach to global radiation on the horizontal ($E^t_{\text{Glo,hor}}$) and albedo values to consider diffuse reflection from the ground. The Perez model [29] is used to calculate $E^t_{\text{Diff,gen}}$. The model is based on an anisotropic approach that considers circumsolar and horizon brightness.

The PV generation P^t_{PV} $\forall t \in T$ is calculated for a PV system with an efficiency factor (η_{PV}) and a solar panel surface area (A) according to eq. (3):

$$P^t_{\text{PV}} = E^t_{\text{Glo,gen}} \times A \times \eta_{\text{PV}} \tag{3}$$

3rd, a battery storage system is implemented by modelling battery boundary conditions to estimate charge and discharge rate (P^t_{Batt}) and state of charge (SOC^t) $\forall t \in T$. Boundary conditions are maximum charge and discharge rate ($P^t_{\text{Batt,max}}$), maximum Depth of Discharge (DoD) to estimate the minimum state of charge (SOC_{min}) and the battery storage system efficiency rate (η_{Batt}).

In addition, eq. (4) is utilized to estimate P^t_{Batt}, grid withdrawal or feed-in (P^t_{Grid}) and curtailment losses ($P^t_{\text{Curtailment}}$) based on feed-in limitation:

$$0 = P^t_{\text{Load}} + P^t_{\text{Batt}} + P^t_{\text{Grid}} + P^t_{\text{Curtailment}} - P^t_{\text{PV}} \tag{4}$$

The boundary conditions to model a battery storage system eq. (5) and eq. (6) are used to estimate P^t_{Batt} [eq. (7)] and state of charge SOC^{t+1} [eq. (8)] for next timestep with $\Delta t = 1$ min.

$$P_{\text{Batt,discharge,max}} \leq P^t_{\text{Batt}} \leq P_{\text{Batt,charge,max}} \tag{5}$$

$$SOC_{\text{min}} \leq SOC^t \leq 100\% \tag{6}$$

$$P_{\text{Batt}}^{t} = P_{\text{PV}}^{t} - P_{\text{Load}}^{t} \quad \begin{cases} > 0 & \text{charge battery} \\ < 0 & \text{discharge battery} \end{cases} \tag{7}$$

$$SOC^{t+1} = SOC^{t} + P_{\text{Batt}}^{t} \times \eta_{\text{Batt}} \times \Delta t \tag{8}$$

4th, electrical withdrawal from the grid is modelled for various system configurations such as end consumer without a PV system (A), with a PV system (B), with a PV system and a battery storage system (C) as well as a PV system with a battery storage system that is promoted by the German Reconstruction and Development Bank (KfW) without (D) and with an algorithm to control battery charging behaviour (E).

The following subsection describes the utilization of eq. (4) with boundary conditions to model system configurations A-E.

- End consumers without a PV system:

$$0 = P_{\text{Load}}^{t} + P_{\text{Grid}}^{t} \tag{9}$$

$$P_{\text{Grid}}^{t} \quad \begin{cases} > 0 & \text{feed}-\text{in} \\ < 0 & \text{withdrawal} \end{cases} \tag{10}$$

- End consumers with a PV system. The boundary condition to fulfill grid feed-in limitation of 70 percent of installed PV capacity is based on the German Renewable Energy Sources Act [30]:

$$0 = P_{\text{Load}}^{t} + P_{\text{Grid}}^{t} + P_{\text{Curtailment}}^{t} - P_{\text{PV}}^{t} \tag{11}$$

$$P_{\text{Grid}}^{t} \leq P_{\text{PV,nominal}} \times 0.7 \tag{12}$$

- End consumers with a PV and battery storage system are modelled with eq. (4) and eq. (12);
- End consumers with a PV and battery storage system that is promoted by the KfW are modelled with eq. (4). The grid feed-in limitation changes to 50 percent of installed PV capacity [31]:

$$P_{\text{Grid}}^{t} \leq P_{\text{PV,nominal}} \times 0.5 \tag{13}$$

- Additional algorithm for the battery storage system to disable charging during morning hours and shift it to midday. The goal is to reduce curtailment losses based on grid feed-in limitation [31] based on ex post analysis of solar radiation data from the DWD between 2006 and 2015 [25].

The simulations for different system configurations A-E to estimate electricity withdrawal from the grid are implemented in MATLAB©. The parameters for PV system, battery storage system and feed-in limitation of installed PV capacity are shown in Table 1.

Table 1. Parameters for system configurations A-E

System	$P_{\text{PV,nominal}}$ [kW$_\text{P}$]	η_{PV} [-]	$C_{\text{Batt,nominal}}$ [kWh]	$P_{\text{Batt,(dis)charge,max}}$ [kW]	η_{Batt} [-]	Feed-in limitation[1] [-]
⬛ A	-	-	-	-	-	-
🟥 B	7.0	0.14	-	-	-	0.7
🟩 C	7.0	0.14	5.0	1.5	0.94	0.7
D	7.0	0.14	5.0	1.5	0.94	0.5
🟦 E	7.0	0.14	5.0	1.5	0.94	0.5

[1] Feed-in limitation relating to installed PV capacity $P_{\text{PV,nominal}}$

Modelling a differential balancing group

A differential balancing group with 74 end consumers that differ in their load profiles is modelled to analyse prosumers interaction at the balancing group level. The 15 min power values to describe the actual electricity demand of the differential balancing group are calculated with eq. (14):

$$W_{\text{Load,BK}}^{15\text{ min}} = \sum_{t=1}^{15} \sum_{n=1}^{74} P_{\text{Grid},n}^{t} \times \Delta t \tag{14}$$

The balancing energy demand ($AE_{\text{Load,BK}}^{15\text{ min},i}$) for every 15 min timeframe $i \in I \coloneqq [1{,}35040]$ of 2013 is calculated with eq. (15):

$$AE_{\text{Load,BK}}^{15\text{ min},i} = W_{\text{Load,BK}}^{15\text{ min},i} - W_{\text{SLP,BK}}^{15\text{ min},i} \quad \begin{cases} > 0 & \text{negative balancing energy} \\ < 0 & \text{positive balancing energy} \end{cases} \tag{15}$$

The total positive and negative balancing energy demands for 2013 are calculated separately with eq. (16):

$$AE_{\text{Load,BK}}^{1\text{ year}} = \sum_{i=1}^{35{,}040} W_{\text{Load,BK}}^{15\text{ min},i} - W_{\text{SLP,BK}}^{15\text{ min},i} \tag{16}$$

RESULTS

In order to demonstrate the characteristics of system configurations A-E, simulations for a 4-person single-family house with an electricity demand pattern according to VDI 4655 [26] were made.

Figure 7 shows the electrical energy demand pattern of a SLP end consumer with an annual electricity demand of 4,700 kWh/a. The course of the electrical energy fed-in and withdrawn from the grid is shown for various system configurations. An end consumer without a PV system (A), with a PV system (B), with a PV system and a battery storage system (C) as well as a PV system with a battery storage system that is promoted by the KfW (D and E) are discussed.

Compliance with a feed-in limitation at the grid connection point of 70% nominal power of the PV system is condition for the remuneration of the grid feed-in according to the EEG. This is considered in B and C. The program 275 of KfW promotes the purchase of solar energy storage by the Federal Government in the form of repayment grants for KfW loans [31]. The necessary condition is compliance with a feed-in limitation of 50% nominal power of the PV system at the grid connection point. This is considered in D and E. Moreover, an optimized charging variation of the battery storage system for the reduction of curtailment losses is shown in E.

Furthermore, the power generation profile of a PV system with 7 kW_p, the energy quantities for charging and discharging a battery storage system with 5 kWh nominal capacity as well as the electricity demand profile of a 4-person single-family house are illustrated. The generation profile of the PV system was calculated with data from the German Weather Service (DWD) for Stuttgart on Saturday, July 20, 2013. The electrical energy stored in the battery is used exclusively to cover the electrical energy demand. The excess power supply of the PV system is fed into the power grid, considering a feed-in limitation.

The amount of electrical energy to cover the electrical energy demand profile with a PV system is represented with dark grey areas. The electricity withdrawn from the grid to cover the remaining electrical energy demand is shown with light grey areas. The green areas illustrate the electrical energy from the PV system to charge the battery system. The pink areas describe the amount of electrical energy taken from the battery to cover the electrical energy demand before purchasing electricity from the grid. The yellow areas represent the excess power generation of the PV system. It is fed into the grid in compliance with the feed-in limitation of 70% (B and C) or 50% (D and E) nominal power of the PV system. The red areas describe the curtailment losses. Furthermore, the upper diagram area shows the battery State of Charge (SOC) over time.

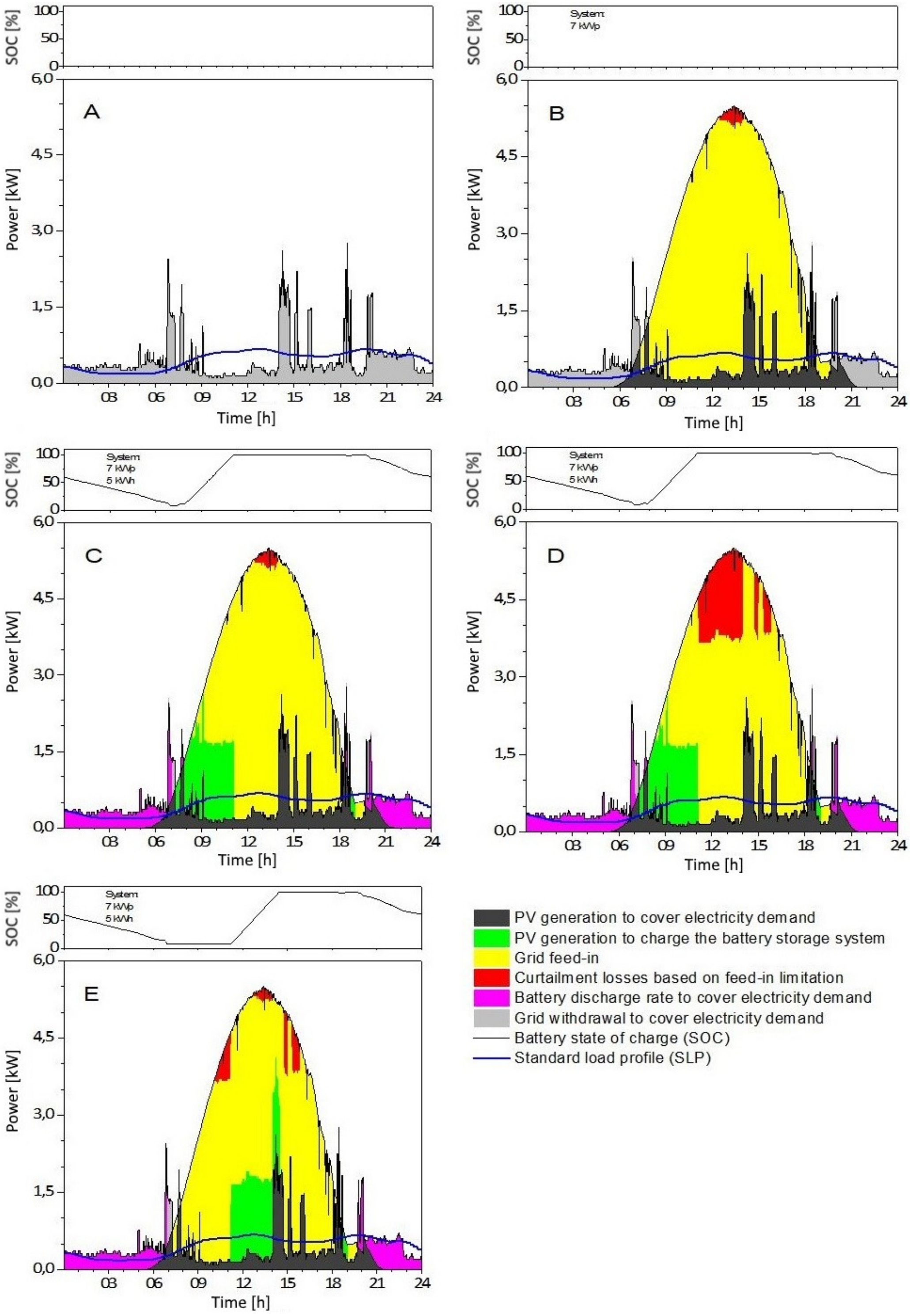


Figure 7. Course of the standard load profile and actual load profile of a 4-person single-family house for Stuttgart, on Saturday, July 20, 2013 with different system configurations

The area between the SLP (blue curve) and the abscissa shows the initially estimated electrical energy withdrawal from the grid for a SLP end consumer with a total of 4,700 kWh/a. The simulated electrical energy purchase is displayed as light grey area. In Figure 7 (E) the only electricity withdrawal from the grid takes place between 6 and 8 AM. Throughout the day, the SLP based purchase pattern is clearly projected too high. The differences between the initially estimated demand and the real figures are recorded in the differential balancing group.

Further simulations were made to get a more detailed view of the interactions between a variety of SLP end consumers with different electrical energy demand profiles. For this purpose, a balancing group with 74 single-family houses and different electrical energy demand profiles [32] was created. The 74 load profiles are based on two measurements. The first was carried out by the Institute for Future Energy Systems (IZES) between 2008 and 2011 with smart meter data from 497 households in a 15 min resolution. The second measurement was done by the DNO Energie AG Oberösterreich Netz GmbH during the “ADRES-Concept” project and covered 30 different households with a resolution of 1 second over one summer and one winter week. The households were in direct spatial proximity. 74 profiles were chosen from the first measurement and synthesized with data from the second measurement from a 15 min resolution to 1 min resolution.

Based on Figure 7, four of the five illustrated scenarios differ in their electrical energy withdrawal from the grid. These four scenarios cover the systems illustrated in Figure 7 A, B, C and E. Table 2 and Figure 8 compare the amount of balancing energy calculated with eqs. (16-18) and balancing energy costs for each scenario with different system configurations.

Table 2. Comparison of balancing energy and balancing energy costs between scenarios for 2013

System		Balancing energy [kWh]		Balancing energy costs [EUR]
		Negative	Positive	
⬛	A	38,967	38,967	270
🟥	B	26,755	135,507	−3,426
🟩	C	10,012	212,234	−6,862
🟦	E	10,235	209,526	−6,750

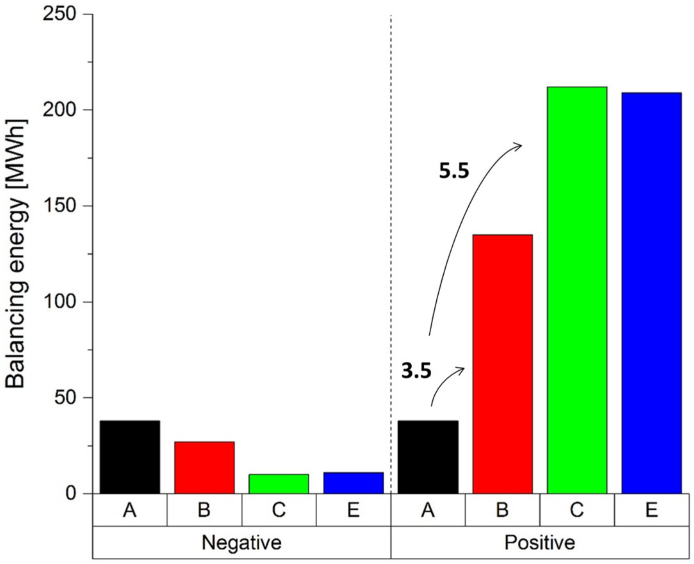


Figure 8. Comparison of balancing energy and balancing energy costs between scenarios for 2013

DISCUSSION

Scenario 1 (black) describes a balancing group with no renewable energy generation nor battery storage systems. With nearly the same amount of positive and negative balancing energy, the SLP is appropriate for balancing end consumers without PV systems nor battery storage systems. The small amount of balancing energy costs for the year 2013 with 270 EUR confirms this statement.

Scenario 2 (red) describes a balancing group with 7 kW_p PV systems in every household. The amount of positive balancing energy is 3.5 times higher compared to scenario 1. Based on self-consumption the electricity withdrawal from the grid decreases compared to scenario 1. This leads to an overlapping of the differential balancing group. Due to the interactions between balancing group participants the amount of negative balancing energy decreases too. Scenario 2 shows clearly the inappropriate balancing of electrical energy purchase for end consumers with PV systems. The resulting balancing energy costs are negative. Negative costs symbolize a payment to the balance responsible party. This payment of 3,426 EUR for the year 2013 is caused by positive balancing energy supplies to other balancing groups.

Scenario 3 (green) represents a balancing group with 7 kW_p PV systems and 5 kWh battery storage systems in every household. The battery storage systems increase the self-consumption and autarky quota. This results in fewer electricity withdrawal from the grid. Consequently, the deviations from the SLP increase. The amount of positive balancing energy is 5.5 times higher compared to scenario 1 and increases by 60% compared to scenario 2. Due to interactions between balancing group participants the amount of negative balancing energy decreases. These results show the inappropriate balancing of SLP prosumers even more. The amount of overlapping balancing energy leads to balancing energy payments for the balance responsible party of 6,862 EUR for 2013.

Scenario 4 (blue) deviates from scenario 3 in terms of time shifting to charge battery storage systems. The time shifting is realized by disabling the loading process during the morning hours. This results in lower self-consumption and autarky quota which lead to higher electricity withdrawal from the grid. Consequently, the amount of positive balancing energy decreases and the amount of negative balancing energy increases compared to scenario 3. Therefore, the balancing energy payments for the balance responsible party decrease to 6,750 EUR for 2013.

Simulation results for scenario 1-4 are based on load profile and weather data for a specific region and a specific timeframe. Hence, results are not directly transferable to other load profiles and weather conditions that differ spatially and temporally. Moreover, other uncertainties arise with different PV or battery storage system configurations such as installed PV capacity, battery storage capacity or battery (dis)charge rate. The relationship between these uncertainties and the autarky quota of prosumers result in different balancing energy demands of differential balancing groups. For example, a lower autarky quota based on less battery storage capacity or (dis)charge rate decreases the balancing energy demand.

CONCLUSIONS

The main finding of this research is a significant higher balancing energy demand with the expansion of PV and battery storage systems in the segment of SLP end consumers. The increasing autarky quota leads to increasing load differences in the differential balancing group. The SLP estimates prosumers electricity withdrawal from the grid too high, because self-consumption and resulting autarky quota are insufficiently mapped. Hence, the SLP is particularly not suitable for differential balancing groups with a high penetration of PV systems and still less suitable for groups with PV and battery storage systems. This results in SLP balanced energy time series forecast schedules being too high and therefore the amount of energy trading volumes too. The research proves this statement.

Due to the price formation mechanism of the reBAP energy trading before the actual energy delivery is always cheaper than afterwards through the reBAP. The recommendation is to reduce trading volumes and as a result trading costs based on knowledge about renewable energy generation and battery storage systems in the segment of SLP end consumers. A demand aggregation-based strategy to create differential balancing groups for end consumers depending on their system configuration or autarky quota is one option to minimize balancing energy and costs. Another option is the integration of Power to Heat units, such as systems with concrete core activation [33] or high temperature stone storage, into the differential balancing groups to reduce positive balancing energy. The reduction of balancing energy strengthens the balancing group commitment. Consequently, the requirement of reserve capacity and their costs which are passed with the grid usage fee to the end consumers decrease.

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NOMENCLATURE

A	surface	[m^2]
AE	balancing energy	[W min]
E	radiation energy	[W min/m^2]
P	power	[W]
t	time	[min]
W	electrical energy	[W min]

Greek letters

η	efficiency rate	[-]

Superscripts

i	time	[15 min]
n	household number	[-]

Abbreviations

Batt	Battery	
BK	Balancing Group	
Diff	Diffus	
Dir	Direct	
Gen	Tilted	
Glo	Global	
Hor	Horizontal	
SOC	State of Charge	[%]

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