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Flexibility Potential of Photovoltaic Power Plant and Biogas Plant Hybrid Systems in the Distribution Grid

The potential of combining biogas and photovoltaic (PV) power plants in hybrid systems in the German distribution grid is analyzed. The focus of the present research is on balancing the intermittent power supply from PV power plants with the controllable power production of combined heat and power (CHP) units of biogas plants within a period of seconds. To achieve an increase of the total energy feed-in of biogas and PV power plants to the electricity grid, a biogas plant energy management system is described. System parameters, such as the variable feed-in of PV power plants or power ramps of the start-up process of controllable biogas plant CHP unit, are described and adapted to the global installed capacity of PV power plant and biogas plants in the German distribution grid.

Keywords: Biogas, Combined heat and power units, Distribution grid, Flexible electricity production, Photovoltaic power plants

Received: January 17, 2020; *accepted:* April 29, 2020

DOI: 10.1002/ceat.202000025

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1 Flexibility Potential of the Energy System in Germany

In 2018, renewable power plants represented more than 50 % of the installed power plant capacity in Germany, with a net nominal capacity of all power plants of 215 583 MW_{el} [1]. According to the Renewable Energy Act, the amount of electricity generated from renewable energy sources in gross electricity consumption will be further increased to at least 80 % by 2050 [2]. Among the renewable power plants, photovoltaic (PV) and wind power plants, with an installed capacity of 97 770 578 kW_{el}, represent the main suppliers of the current and future energy system. The variable, weather-dependent nature of these plants causes a diversity of volatile energy states in the different regions and voltage levels of the electricity grid, which need to be managed. To avoid high planning and implementation costs and long planning time [3], current distribution grid studies [3, 4] suggest an increased utilization of flexible decentralized electric generators (DEGs) to reduce grid expansion costs by around 20 % [5]. Flexibility in this context is the ability to meet different electricity grid requirements in addition to a purely market-driven operation. Therefore, controllable DEGs will become more important [3], and new flexibility options to balance the difference between the resulting variable power production and consumption will be required in the future [2].

The electricity generation from biomass plants [6], especially from biogas plants (BPs), is independent from weather conditions, hence, allows a flexible [7] and demand-oriented energy supply for distribution systems [8]. Trommler et al. [9] demon-

strate that the flexible operation of biogas plants can lead to a decrease of the cost dynamics of electricity grid fees by minimizing the total system costs, thus representing a benefit for the economy as a whole. In addition, an increasing proportion of flexible biogas plants reduces the demand of conventional power plants, which are characterized by comparatively high marginal costs [10]. Therefore, the integration of flexible biogas plants as DEGs to stabilize the distribution grid is a sustainable and economic alternative.

Bioenergy plant operation as well as the optimum extension of bioenergy plants in interaction with other flexibility options like storage systems, demand management, and their flexible operation within hybrid systems have a positive impact on the energy supply system at a regional and national level [11]. Especially in regions dominated by weak loads and a high amount of renewable power plants, flexible biogas plants are particularly suitable at regional [7, 12–14] and national level [15] for stabilizing the distribution electricity grid. According to model simulations by Kneiske et al. [16], PV systems in combination with combined heat and power (CHP) units show promising results, i.e., an increased efficiency and reduction of primary energy consumption compared to conventional power generation. Hybrid systems consisting of PV power plants and

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biogas plants with the associated CHP units (PV-BP hybrid systems) are, therefore, analyzed as a promising step towards sustainable combined electrical and thermal power supply at distribution grid level.

2 Analysis of PV-BP Hybrid Systems in the German Electricity Grid

The German distribution grid is currently operated by 908 distribution system operators (DSOs) [17] and consists of the low-voltage level with 0.4 kV, medium-voltage level with 10–30 kV, and the high-voltage level with 110 kV as well as intermediate transformer levels [5]. To determine the number of DSOs with potential for PV-BP hybrid systems in the German electricity grid, the DSOs are divided in categories described by two letters (Fig. 1a). While the first letter repre-

sents the DSO's installed biogas capacity, the second letter describes their PV capacity (Fig. 1a).

Categories AA, BB, CC, and DD show the highest potential for the use of PV-BP hybrid systems as balancing instruments in a regional context since the biogas capacities are equivalent to the PV capacities within one distribution grid. The number of DSOs within each category in Germany is presented in Fig. 1b. At the low-voltage level, the limits of the categories are set to 150 kW_{el}, 500 kW_{el}, 8000 kW_{el}, and 207 855 kW_{el}. The highest potential within the low-voltage level is found within the categories AC (10 % of DSOs with installed PV or BP capacity) and BC (7 %) as well as AD (6 %), BD (8 %), and CD (11 %) (Fig. 1b). The categories AA (no DSOs), BB (2 DSOs), CC (34), and DD (0) are marginally represented on the low-voltage level.

The according category limits of the medium-voltage level are set to 1070 kW_{el}, 3300 kW_{el}, 10 000 kW_{el}, and 557 806 kW_{el} (Fig. 2a). With 27 % of the DSOs on the medium-voltage level

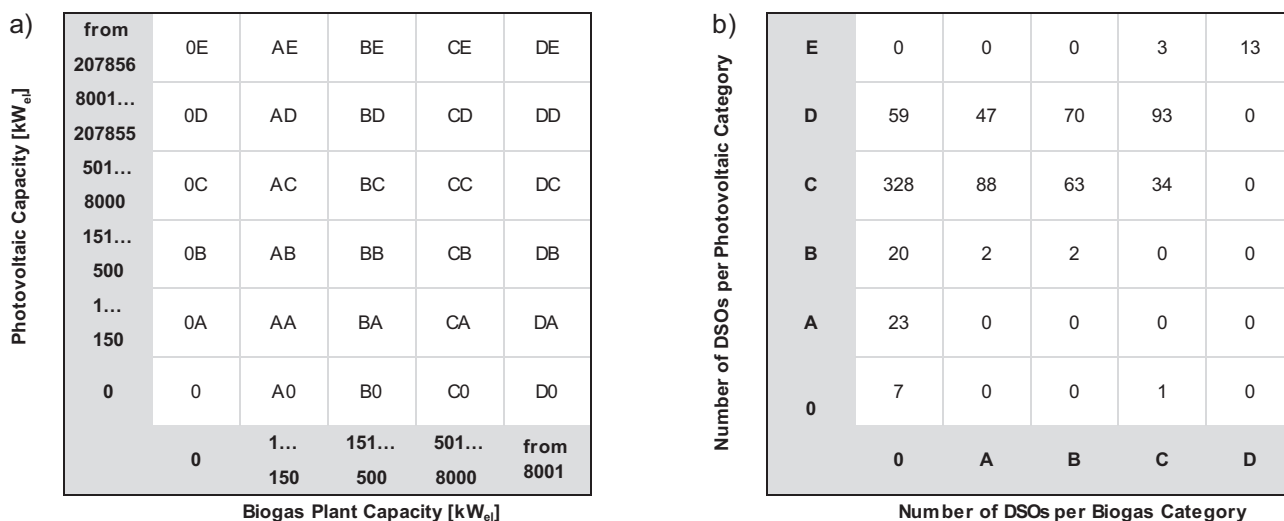


Figure 1. Number of PV-BP hybrid systems for DSOs in categories at low voltage level (based on data from [2, 18]).

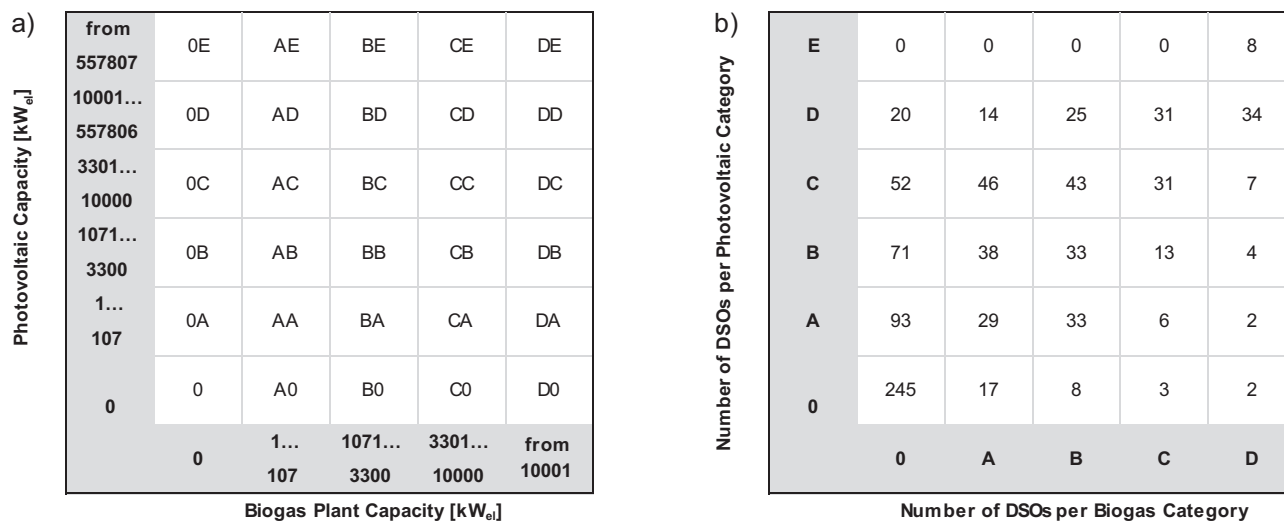


Figure 2. Number of PV-BP hybrid systems for DSOs in categories at medium voltage level (based on data from [2, 18]).

without a biogas or PV power plant, category 0 (Fig. 2b) includes more DSOs (Fig. 2b) than on the low-voltage level (Fig. 2b). Nevertheless, the categories well suited for balancing BB (5%), CC (5%), and DD (5%) are strongly represented with more than 30 DSOs each. Furthermore, there is a high potential for PV-BP hybrid systems, since 95 DSOs have more installed biogas capacity than PV capacity (A0, B0, BA, C0, CA, CB, D0, DA, DB, and DC). The highest number of DSOs with potential for PV-BP hybrid systems is represented in the categories AC (7%) and BC (6%).

As only a small number of 4% of the biogas plants and 6% of the PV power plant capacities installed in Germany are on high-voltage level, this level is not considerable for substantial contributions of PV-BP hybrid systems [17]. Hence, the analysis reveals significant potential with adequate biogas and PV power plant capacities for balancing on the medium-voltage level.

Since PV-BP hybrid systems are particularly common in German distribution grids, the number of DSOs within the different voltage levels, which have flexible biogas capacities in relation to the total installed biogas capacity, are analyzed. The number of DSOs with installed inflexible biogas plant capacities is 71% on the low-voltage level, 38% (102 DSOs) on the medium-voltage level, and 98% (266 DSOs) on the high-voltage level (Fig. 3) [18]. DSOs having flexible biogas plants are characterized by a relatively high share of flexible biogas plant capacity within. A minimum share of 76% is represented by 20 DSOs (7%) on low-voltage level, 46 DSOs (17%) on medium-voltage level, and 1 DSO (0.4%) on high-voltage level. Fully flexible biogas plant capacities (100%) are determined for 33 DSOs (12%) on low-voltage level, for 92 DSOs (34%) on medium-voltage level, and for 5 DSOs (2%) on high-voltage level (Fig. 3) [18].

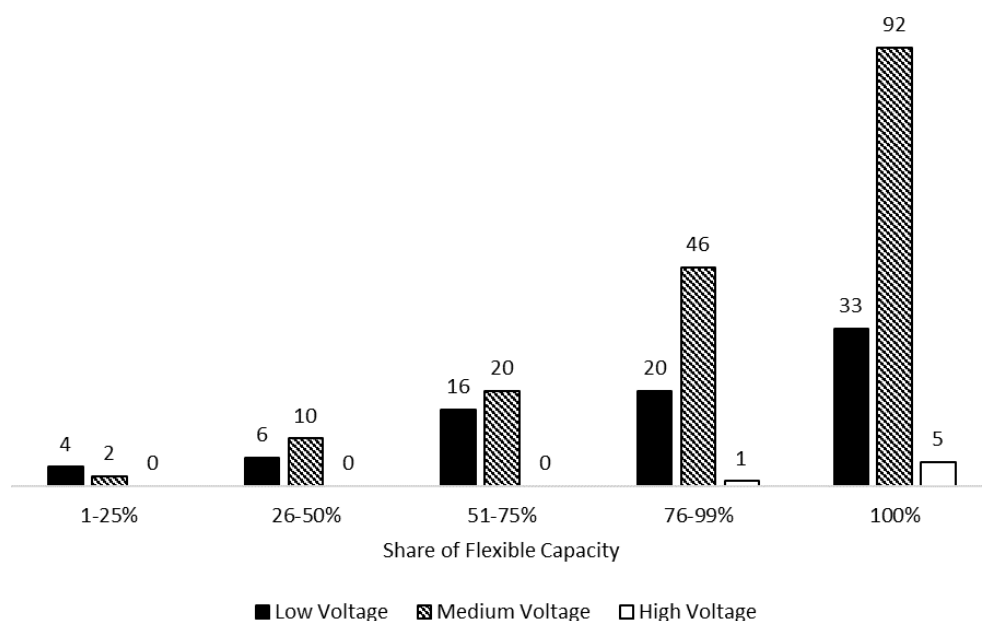


Figure 3. Number of DSOs with flexible biogas power capacity (in % of total installed biogas power) by voltage level [18].

3 Flexible Operation of Biogas Plants

One of the key factors for balancing within PV-BP hybrid systems is the power production of the CHP units within a specific reaction time t_{rt} in flexible operation of the biogas plant. Flexibility and reaction time are influenced by the following dimensions: (a) ramp (plant-specific load ramps; Sect. 3.1), (b) range (amplitude or control range between maximum and minimum system output; Sect. 3.2), and (c) start duration (duration of the start-up, beginning at standstill; Sect. 3.3) [19].

3.1 Ramp

The rate of change of power generation can be expressed by so-called ramps (Fig. 4). For biogas plants, these are limited by the technical specifications of the engine of the CHP unit, as this is the final conversion step from biogas to electricity. The positive ramp $m_{p+} = (P_{\max} - P_{\min})P_{\max}^{-1}\Delta t^{-1}$ and the negative ramp $m_{p-} = (P_{\min} - P_{\max})P_{\max}^{-1}\Delta t^{-1}$ represent the gradient between minimum and maximum power per second (in % of maximum power), respectively [8].

According to VDE-AR-N 4140 [20], the minimum gradient of positive and negative ramp has to be between 0.33 and 0.66 % s⁻¹.

3.2 Power Range

The power range $\Delta P = (P_{\max} - P_{\min})P_{\max}^{-1}$ depends on the total installed CHP unit capacity and the operation mode (Fig. 4). There are two different operating modes for systems with several CHP units. On the one hand, all CHP units can be operated synchronously, so that they are seen as one unit in full flexible operation (ffo). On the other hand, a partial flexible operation (pfo) resulting in smaller ΔP is possible, where one

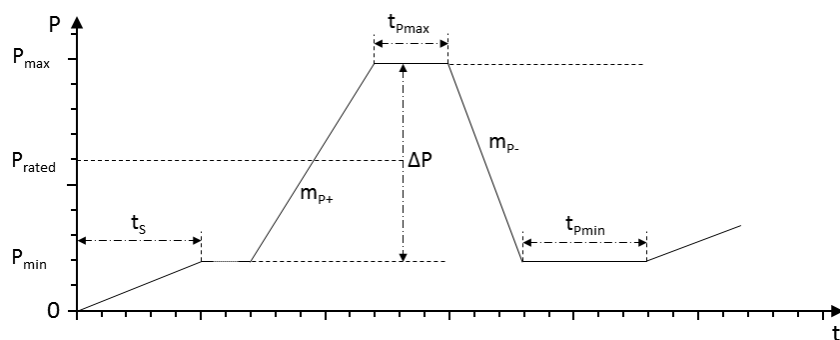


Figure 4. Measurable indicators for flexible electricity generation using CHP units [8].

part of the CHP units runs constantly, while the remaining capacities are operated flexibly [8].

3.3 Start Duration

The start-up (process) of a CHP unit ($0 - t_s$) (Fig. 5) up to full power production mainly includes six phases: warm-up (lb), start (i), rated speed (nr), synchronization with mains frequency (s), load absorption (lr), and rated power (nl), before electricity can be fed into the electricity grid.

According to the current state of the art, a modern CHP unit of a biogas plant takes up to 300 s for the start-up processes from standstill to full load operation ($0 - P_{max}$) [14]. In accordance to manufacturers data, the different phases of the start-up are set to 60 s (lb), 20 s (i) [21], 10 s (nr) [22], and the duration of the synchronization (s) to 20 s [21,23,24], summed up to 110 s ($0 - t_s$) until the electricity can be fed into the electricity grid. A shutdown to minimum power has no time delay and can be realized with the maximum gradient of $0.66\% s^{-1}$ [8].

4 Energy Management System of a PV-BP Hybrid System

For the flexible operation of the biogas plant, the difference between an ideal schedule (Fig. 6a) and the real operation (Fig. 6d) resulting from CHP unit operation (Sect. 2) has to be taken into account through a shift of the control action before the actual power demand. During load changes, the offset caused by the delayed reaction of the engine between power request and provision of electricity (t_s) has to be considered (Fig. 6b). In addition, the

ramps of the CHP unit (m_{p+} , m_{p-}) during load changes fluctuate around the developed ideal linear power specification of the optimization (Fig. 6c).

An efficient energy management system (EMS) [25] has to fulfil several steps [26] to find the best operational strategy for a PV-BP hybrid system [27] under uncertainty, and to adjust power flows to the requirements of the local electricity grid [6,28] at an expected time t (Fig. 7). For improved automatic control, the overall reaction time t_{ct} of the EMS to interface with the grid in real time is critical.

The first step of EMS control is to import the real time data of the solar irradiation (Solar Irradiation Data) and the distribution grid (Grid Data) from a monitoring system and forecast the future load of the electricity grid and solar radiation within

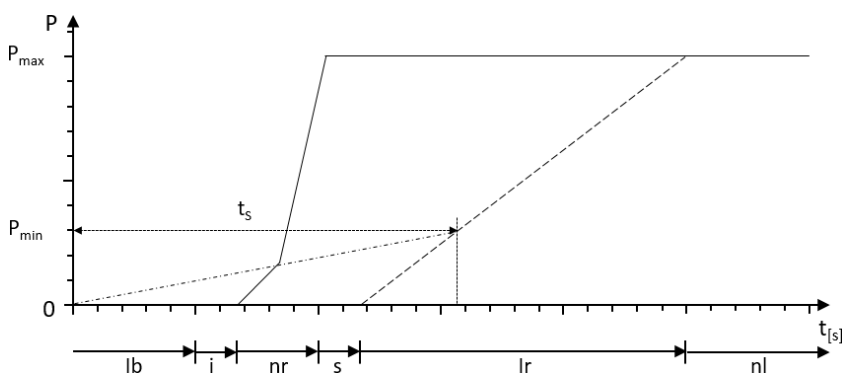


Figure 5. Phases of the CHP start-up process. Continuous line, rotational speed; dashed line, power; dash-dotted line, virtual ramp.

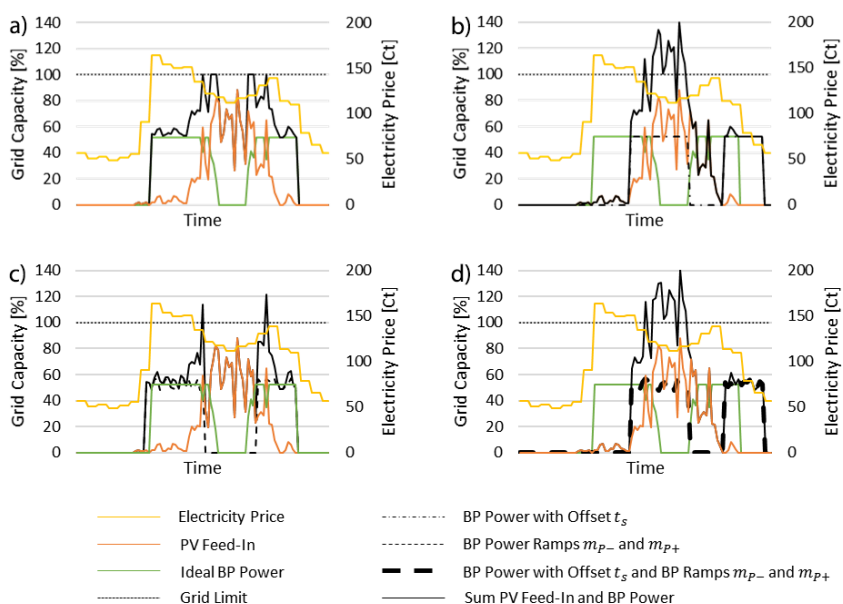


Figure 6. Balancing of PV feed-in with biogas plant CHP units within the electricity grid limit.

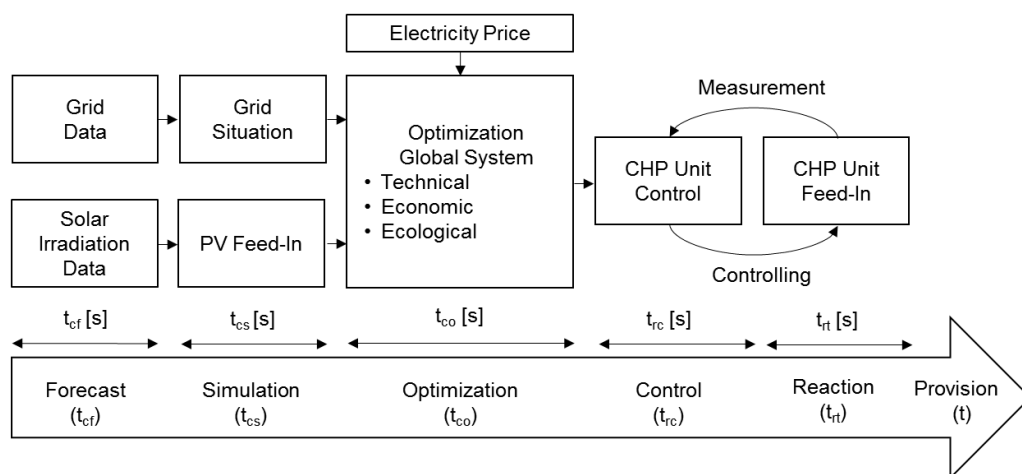


Figure 7. EMS process for PV-BP hybrid systems.

the time t_{cf} (Fig. 7). Subsequently, the data are used to simulate the future situation of the electricity grid (Grid Situation) and the PV power plant feed-in (PV Feed-In) within the computational time t_{cs} . The core of the ongoing project is the development, implementation, and verification of a mathematical optimization algorithm (Optimization Global System) to develop CHP unit schedules considering the electricity grid situation. As essential control signals the electricity prices of the European electricity exchange (EPEX SPOT SE) (Electricity Price) are implemented.

Within the optimization time t_{co} , a schedule leading to a maximization of the turnover of the plant operator simultaneously to flexible energy supply is calculated. The schedules are transmitted to the CHP unit control (CHP Unit Control), which regulates the feed-in of the CHP units in the period of time t_{rc} . At the same time, measured data from the CHP units (CHP unit Feed-In) and the biogas plant are returned to the

optimization unit. To ensure that the proposed PV-BP hybrid system is able to compensate for power shortages as fast as possible, the engine- and transformer-caused CHP unit reaction time t_{rt} has to be taken into account. The overall reaction time t_{ct} for the EMS process can, therefore, be defined as $t_{ct} = t_{cf} + t_{cs} + t_{co} + t_{rc} + t_{rt}$ (Fig. 7).

5 Reaction Times of PV-BP Hybrid Systems

A forward-looking operation considering the reaction time of the CHP unit t_{rt} is essential for an efficient EMS. Without consideration of the start-up time and assuming an ffo operation of the biogas plant capacities on the medium-voltage level of the electricity grid (Fig. 2), the corresponding CHP units within the defined categories of Sect. 2 can be switched on (Fig. 8a)

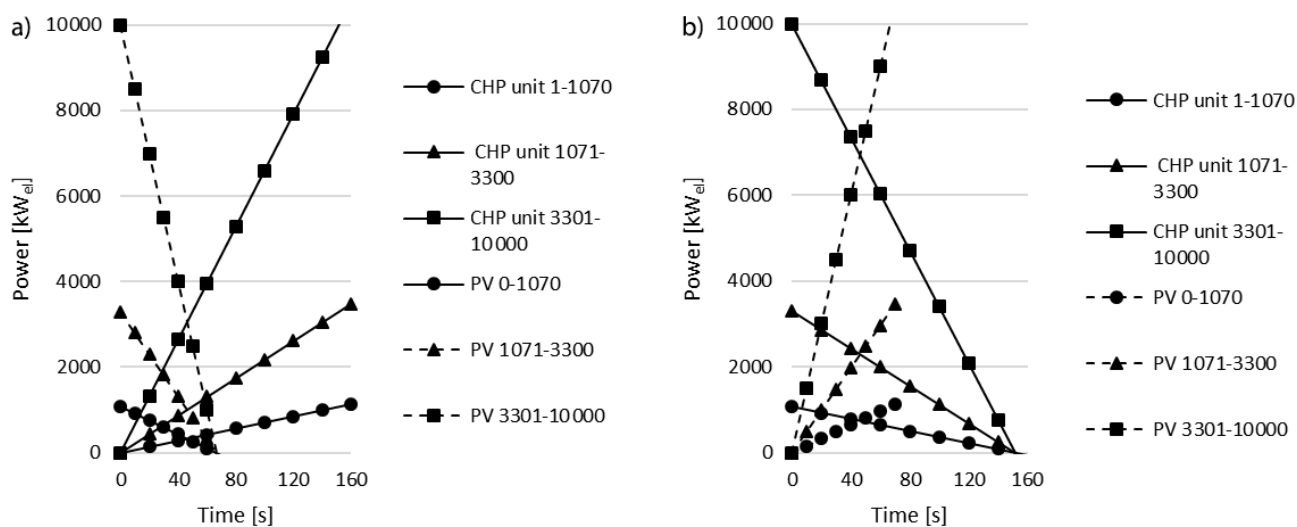


Figure 8. Maximum reaction time (ramp rates $0.66\% \text{ s}^{-1}$ of the biogas plant capacities) according to the DSO categories in the medium-voltage grid in seconds from (a) standstill to full load, (b) from full load to standstill for CHP units with opposed ramp rates of the PV power plant capacities.

and turned off (Fig. 8b) with the maximum ramp rate of $0.66\% \text{ s}^{-1}$ within 160 s and within 320 s with the minimum time ramp of $0.33\% \text{ s}^{-1}$. In contrast, the negative (Fig. 8a) and positive (Fig. 8b) feed-in from the according installed PV power plant capacity within one distribution grid (Sect. 2, Fig. 2) take 70 s.

To compensate an increase of the PV power feed-in with the available biogas plant capacity within the grid of a DSO, the corresponding time is about 46 s on the medium-voltage level and 55 s on the low-voltage level (intersection points Fig. 8). To ensure an adequate/sufficient reaction of the CHP unit (t_{rt}) at a given point in time t (Fig. 7), a time delay of approximately 156 s ($t_S + m_{p-}$, $t_S + m_{p+}$) on medium-voltage level and 165 s ($t_S + m_{p-}$, $t_S + m_{p+}$) on low-voltage level has to be considered.

6 Conclusion

Analyzing the installed capacities on the different voltage levels, the flexible biogas plant capacity on the low-voltage level is about 69 % (270 880 kW_{el}) and 87 % (4902 kW_{el}) on the high-voltage level of the electricity grid. The installed flexible biogas capacities of 1 770 981 kW_{el} and the inflexible capacities of 499 632 kW_{el} result in a flexible amount of 78 % biogas capacity on the medium-voltage level. Hence, biogas plants on medium-voltage level have the ability to provide adequate balancing capacities for the stabilization of the electricity grid within PV-BP hybrid systems.

The reaction time of the biogas plant in comparison to the feed-in of PV power plants, however, requires forward-looking controls considering the reaction time of the CHP unit as an essential element for an efficient energy management system. Further development of biogas plant controls as well as a better understanding and monitoring of PV-BP hybrid systems are necessary for the successful integration of bioenergy into the future power supply system within the next years.

Acknowledgment

The authors would like to express their gratitude to the Institute of new Energy Systems, Ingolstadt, Germany, for providing the working infrastructure. The German Federal Ministry of Food and Agriculture financially supported this work (grant number 22405217).

The authors have declared no conflict of interest.

Symbols used

i	[s]	start
lb	[s]	warm-up
lr	[s]	load absorption
m	[% s ⁻¹]	ramp
nl	[s]	rated power
nr	[s]	rated speed
ΔP	[%]	bandwidth
P	[kW _{el}]	power for electricity generation

s	[s]	synchronization with mains frequency
t	[s]	point in time/time

Subscripts

cf	forecast time
co	optimization time
cs	simulation time
ct	overall reaction time
max	maximum
min	minimum
P-	negative ramp
P+	positive ramp
rc	control time
rt	reaction time
S	start-up time

Abbreviations

BP	biogas plant
CHP	combined heat and power units
DEG	decentralized electric generators
DSO	distribution system operators
EMS	energy management system
ffo	full flexible operation
pfo	partial flexible operation
PV	photovoltaic
PV-BP	photovoltaic power plant and biogas plant hybrid system

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