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A plant-specific model approach to assess effects of repowering measures on existing biogas plants: The case of Baden-Wuerttemberg

Joshua Güsewell | Marlies Härdtlein | Ludger Eltrop

Department System Analysis and Renewable Energy, Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Stuttgart, Germany

Correspondence
Joshua Güsewell, Department System Analysis and Renewable Energy, Institute of Energy Economics and Rational Energy Use, University of Stuttgart, Stuttgart, Germany.
Email: joshua.guesewell@ier.uni-stuttgart.de

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Abstract

Up to the latest versions of the German renewable energy act (EEG), there had been a constant growth of new biogas plants (BGPs). After reaching a stagnation in the last years, today the focus has shifted to improving the existing BGPs. Assuming that most plants have not reached the technical end of life, the question arises on how an operation can be realized beyond the initial EEG support period of 20 years. In addition, new legal and economic conditions require the implementation of adjustments, that is, "repowering measures." Based on a method review, a plant-specific model approach is presented to assess repowering measures for a wide range of BGPs differing in capacity, substrate mixture and agricultural structures. The techno-economic model includes different performance indicators like levelized cost of electricity (LCOE) and temporal aspects like technical progress. Using a data set for BGPs in the state of Baden-Wuerttemberg (Germany), results are illustrated for the different model modules and three repowering scenarios of an extended operation period of ten years. The scenarios regard different options to meet the requirements of the current EEG, namely the flexibilization and restrictions on energy crops, in comparison with a reference case. While in repowering scenarios, the number of plants decreases between 54% and 69% and the overall power capacity changes between −48% and 13% until 2035. The results further show a reduction potential in the specific area demand and GHG emission up to 12% and 24%, respectively. Technical progress, additional revenues and capacity premiums are shown to be an important factor for efficient substrate utilization, low LCOE and thereby the enabling of an extended operation period. The scenario results indicate that the agricultural areas for energy crop cultivation and the amount of manure used in BGPs will be reduced considerably, inducing new chances and challenges in the future.

KEYWORDS

biogas plants, energy efficiency, flexibilization, GHG emissions, levelized cost of electricity, mass and energy balance, plant-specific model approach, repowering

1 | INTRODUCTION

In the year 2000, the renewable energy act (EEG) was introduced in Germany to promote renewable energy technologies and climate protection. Since then, the initial support scheme of the EEG, the feed-in tariffs for electricity, has ensured 20 years of operation and induced a steady, sometimes steep growth of newly installed biogas plants (BGPs). Today around 9,200 BGPs with an electric capacity of 4,240 MW exist in Germany (FvB, 2017).

With new regulations in the latest versions of the EEG (2017), the installation of new BGPs is now stagnating, showing only a negligible growth. Due to this development, the biogas sector is shifting from building new to improving the existing BGPs.

Beginning in 2020, the first BGPs will reach the end of their initial EEG promotion period. Questions arise on how the development over the next 10–20 years will look like, if operators continue the operation beyond the 20 years' EEG period or if a large share of BGPs, forced by the economic frame conditions, will shut down. Assuming that from a technical viewpoint, the capital-intensive components, like digesters and digestate storage tanks, can operate longer than 20 years, and the major issue is the unclear economic long-term perspective. The future perspective of BGPs is mainly determined by the following aspects:

- Existing BGPs continue to show high levelized cost of electricity (LCOE) even after the depreciation of major components. This is due to continuous high capital cost for the replacement of technical components, which do not underlie the same cost reduction due to economy of scales and learning rates as, for example, the production of photovoltaic cells (Nemet, 2006).
- High biogas production costs caused by the cultivation of energy crops. A considerable cost reduction seems unlikely due to the competition in the use of biomass in different sectors and increasing means of production.
- A constant need for adjustments and modifications of BGPs are caused by new functions like flexible power generation (flexibilization) to balance rising shares of fluctuating renewable electricity (Szarka et al., 2013) and the implementation of new legal requirements in the agricultural sector like the fertilization ordinance (DüV, 2017).
- Continuous replacements and optimization measures are required by the breakdown, the projected end of life and the technical progress of BGP components.

These adjustments and measures may be considered under the term "repowering." In traditional energy economics, the expression "repowering"—synonymously used to the term retrofitting—is according to Walters (1995) defined as replacing old power plants or central components like steam generators or turbines to increase either the efficiency rate or the capacity of the plant as well as to reduce emissions. In the same sense, the term "repowering" is also broadly used in the wind energy sector and refers to replacing wind turbines with new ones and thereby increasing the capacity and full load hours (FLH), sometimes also decreasing the number of turbines in wind power farm (Lantz, Leventhal, & Baring-Gould, 2013). In the biogas sector, the term "repowering" is widely used but there is no consistent definition (Effenberger & Lebhun, 2011; Fischer, Postel, & Ehrendreich, 2015; FNR, 2016).

To define the term repowering more clearly and distinguish between different types of repowering measures, a categorization is proposed. Figure 1 contains an overview of possible technical measures for adjustments and modifications of existing BGPs. Two major categories were defined, each with subgroups. In category I, compulsory measures are grouped that maintain the operation of the plant (a) and enable the continued operational ability (b). In category II, specific measures are summarized that have the aim to improve the economic or the energy efficiency of the plant and allow the extension of operation. The subgroups are distinguished by the scale of the modified plant configuration. While some measures in category II only change operating and process parameters of the plant (c), other measures integrate minor new components to increase efficiency or enable the plant to participate in new submarkets (e.g., reserve control market) and generate new revenues with the main product (d). Others measures drastically alter the plant concept by introducing or adding components that may enable the plant to produce new main products (e).

To narrow down the range of repowering and differentiate repowering from other technical measures, the authors propose the following definition: Repowering for BGPs describes the replacement, adjustments or addition of components that have the aim to maintain or extend the operation and/or improve the energy as well as economic efficiency. Using this definition, the measures of the groups (a), (c) and (d) are considered as "repowering.".

Against this background, the objectives of the study are twofold. Firstly, a new model approach is introduced to analyse and assess repowering measures and to answer the question if BGPs can sustain a cost-covering operation or must shut down. Secondly, four scenarios are analysed representing development paths of the existing, agricultural BGPs in the state of Baden-Wuerttemberg (BW) under the current EEG 2017. The scenarios regard the mandatory requirements to supply demand-orientated power production by the BGPs and include technical options like flexible feed management, the addition of CHP units and gas storage capacity.

In order to identify research gaps and to classify the new model approach, a broad review is given. It contains and categorizes studies analysing the biogas process chain and assessments methods that can be applied for BGPs and their repowering. The developed biogas plant design and balance model with its three specific modules and the methods used are described in detail. The assessment regarding energy-, economic- and climate-related aspects is done using key performance indicators (KPI).

Due to the integration into the agriculture sector and the installation under different EEG versions, BGPs differ in capacity, substrate mixture, agricultural and operational structures. Hence, the analysis is conducted from the viewpoint of a plant operator. It covers the heterogeneity of the existing plants and enables the identification of plant-specific effects. In the model, a gate-to-gate approach is pursued and all major parts in the biogas process chain are included (also see Figure 4). The time scale of the analysis is 10 years of continued operation after the original promotion period of the EEG of 20 years. Aggregating the results for the complete data set, forecasts on the development of all BGPs in BW are then given.

2 | MATERIALS AND METHODS

2.1 | Review on existing methods, models and studies

Table 1 gives an overview on studies analysing and assessing, single biogas processes, the complete plant process chain, optimization measures and different utilization pathways of BGPs. The overview is grouped according to the analysis type and categorizes them according to the addressed issues and objectives, methods, scope and type of data used. In the following, each group is explained shortly. Concluding relevant research gaps are pointed out, and the suitability is compared with the objective of this study.

Studies in the group of experiments and process simulation comprise biological models which focus on the understanding and describing of the biochemical processes of anaerobic digestion (AD) (Batstone et al., 2002), the biogas yield optimization (Garcia-Gen, Rodriguez, & Lema, 2014) or the feasibility of flexible gas production by adjusting the feeding regime (Mauky et al., 2017). By determining the main influencing factors in AD, monitoring and control systems are enabled (Gaida et al., 2011; Mauky et al., 2016). The system boundary is usually limited to the digester. Experiments are either used to gain insight into indicators for the AD efficiency (Schievano, D'Imporzano, Orzi, & Adani, 2011) or are linked with mathematical models to provide necessary parameters for the calibration of AD simulation. In these, often modifications (Lübken, Wichern, Schlattmann, Gronauer, & Horn, 2007) or simplifications (Biernacki, Steinigeweg, Borchert, Uhlenhut, & Brehm, 2013; Weinrich & Nelles, 2015) of the anaerobic digestion model no. 1 (ADM1) are used. Grim, Nilsson,

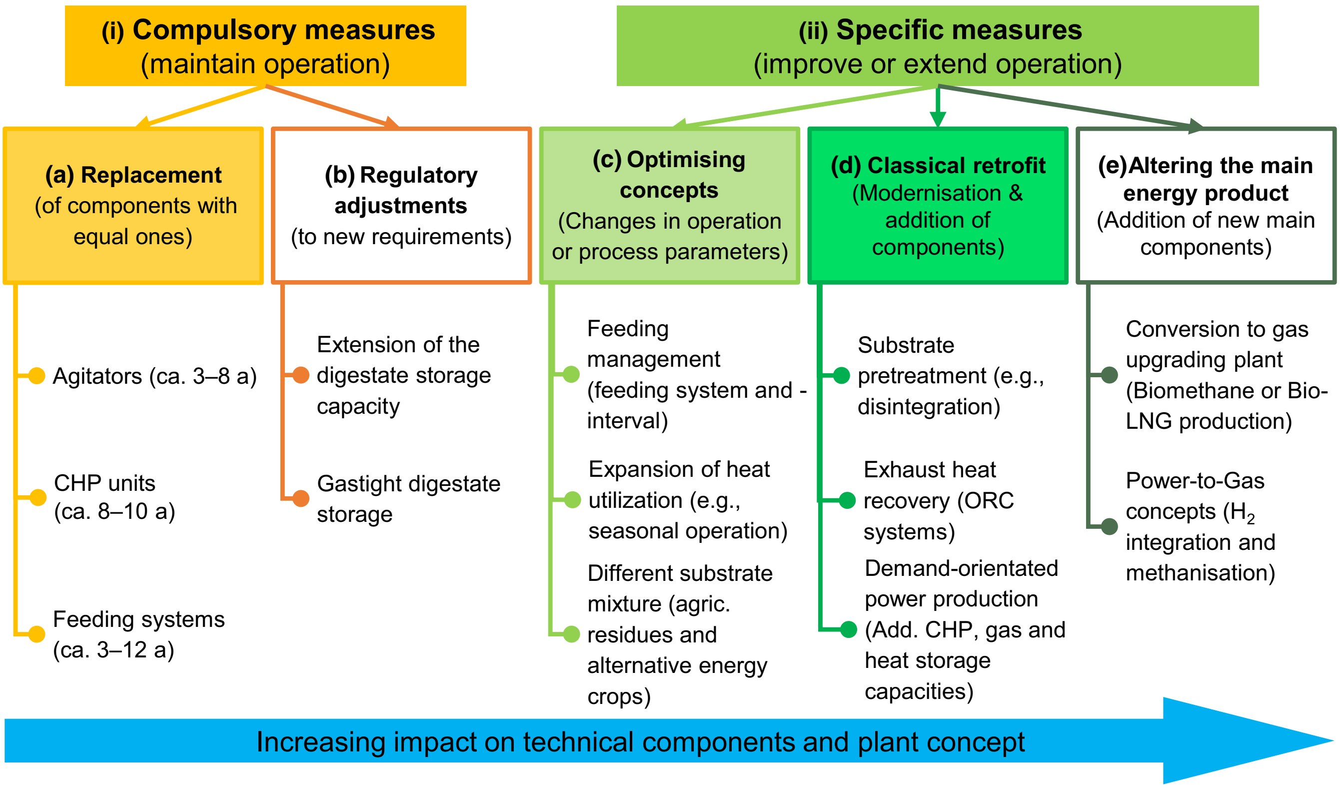

FIGURE 1 Overview and categorization of different technical measures to adjust, modify or improve the operation and concept of BGPs. Repowering measures in the understanding of the current article are marked by a coloured background

TABLE 1 Overview on methods and models for the analysis of biogas plants. Note, that some studies can be assigned to more than one group

Group	Type of analysis	Number of studies	Topics and objectives (problem statement)	Methods or model types	System boundary/process chain (scope)	Type of data basis/sources
1	Experimental studies and process simulation	29	• Describe AD process • Optimization of biogas yield (e.g., by adjusting process parameters or change in substrate mixture • Improve process stability • Enable flexible gas production • Feasibility analysis (e.g., pretreatment technology)	• Experiments and statistical evaluation (e.g., BMP test or measurement of process parameters like pH) • Kinetic biological degradation models like ADM1 or prediction by artificial neural networks • (Non)Linear programming	• Process of anaerobic digestion (digester), • sometimes with substrate provision, • few gate-to-gate	• Laboratory measure-ments • Pilot/ full-scale plant measure-ments • Literature
2	Energy balance and plant monitoring	23	• Determine critical/weak points • Improve efficiency rates • Compare technologies/ utilization paths • Determine/compare plant performance • Develop benchmark systems	• Measurements and surveys • Mass, energy and exergy balances • Energy efficiency and utilization rates • (key) performance indicator systems	• Mostly gate-to-gate, • sometimes cradle-to-grave	• Measured data from full-scale plants • Survey data from full-scale plants
3	Economic analyses	15	• Optimization of substrate mixture • Compare different flexible operation modes/options • Optimize CHP dispatch • Optimize heat storage for CHP units • Reduce/optimize operation costs • Compare technologies/ utilization paths	• Investment appraisal (Net present value or equiva-lent annuity method) • (Mixed-integer) Linear programming	• Often gate-to-gate, • some cradle-to-grave and • some focus on gas utilization	• Literature • Data from full-scale plants
4	Environmental analyses	23	• Identify majors impact factors • Compare regional factors • Compare substrate mixtures • Compare technologies/ utilization paths like demand-oriented gas production/plant operation	• Life cycle assessments • GHG emission balancing	• Mostly cradle-to-grave	• Literature • Data from full-scale plants • Survey data

(Continues)

TABLE 1 (Continued)

Group	Type of analysis	Number of studies	Topics and objectives (problem statement)	Methods or model types	System boundary/process chain (scope)	Type of data basis/sources
5	Holistic and integral analyses	16	• Compare biomass utilization paths/technologies • Optimization of process and combined production	• Combination of analysis (e.g., economic +ecologic Analysis) • Exergo-economic methods	• Mostly cradle-to-grave, • some gate-to-gate	• Literature • Data from full-scale plants • Survey data
-	Integral plant-specific analysis (current study)	-	• Identify and assess plant-specific repowering measures • Assess effects of changes in the framework conditions, temporal and regional differences	Integrated combination of: • Mass, energy and GHG balances • Mixed-integer linear programming (dispatch simulation) • NPV method for LCOE determination	• Gate-to-gate (with extensions to cover up/downstream effects)	• Literature • Statistical data • Survey data

Hansson, and Nordberg (2015) connected ADM1 to a dynamic model simulating the combined heat and power (CHP) plant dispatch to analyse the effects of the demand-oriented electricity production with different gas storage sizes and feeding intervals on the net present value (NPV).

Energy balance and plant monitoring studies mainly deal with the performance evaluation of BGPs, certain parts of the process chain or single components like the CHP unit. Different plants, technologies and substrates mixtures are compared and ranked based on efficiency aspects, performance indicators and benchmark systems (Besgen, Kempkens, & Lammers, 2007; Djatkov, Effenberger, & Martinov, 2014; Madlener, Antunes, & Dias, 2009; Schöftner et al., 2006). Additionally, weak points are identified and measures for improvement proposed (Pfeifer & Oberberger, 2007). The system boundary often covers a gate-to-gate and sometimes cradle-to-cradle approach. Mass and energy balances are based on thermodynamic conservation laws and are often based on measurements or survey data of full-scale plants. The assessment of the energy efficiency can vary considerably depending on the system boundary, the analysed energy type and the chosen reference value for the substrate energy content (Havukainen, Uusitalo, Niskanen, Kapustina, & Horttanainen, 2014). For the determination of the latter, there is no explicit method, since the lower or higher heating value (LHV, HHV) of a substrate can be based on different references like the total solids content (TS). Because hardly degradable components like lignin limit the turnover, and energy is needed to sustain the involved microorganisms, Fischer, Postel, Ehrendreich, and Nelles (2016) propose to use the mean fuel efficiency based on the HHV of the fermentable organic dry matter (FoDM) by introducing an adjustment factor.

Economic analyses focus on the assessment of key figures like LCOE or the profitability and often compare different technologies and utilization paths. Standard methods refer to the investment appraisal, for example, based on the NPV or the equivalent annuity (VDI, 2012). Often an optimization approach is used to find an optimal solution for a constrained problem. The system boundary is often gate-to-gate but can also be cradle-to-grave or just focus on the gas utilization. Lantz (2012) determines the break-even costs of CHP technologies and scales and assesses the influence of the heat utilization. Different concepts enabling demand-oriented biogas production were analysed by Hahn, Ganagin, Hartmann, and Wachendorf (2014). Analysing different sizes of a CHP unit is done by Hochloff and Braun (2014) by optimizing the concurrent dispatch in the reserve control market and day-ahead electricity spot market. A nonlinear programming model has been developed by Willeghems and Buysse (2016) to optimize profits by adjusting the feeding regime and regarding a first-order kinetic biogas yield function, the organic loading rate (OLR) as well as nutrient restrictions. Gebrezgabher, Meuwissen, Prins, and Lansink (2010) optimize the sales of electricity under digestate application restrictions and analysis the influence of digestate treatment technologies.

Environmental analyses assess the environmental impacts of the biogas production and utilization chain, the major influencing factors and ways to reduce them (Lijó et al., 2017; Poeschl, Ward, & Owende, 2012a, 2012b). The main method is to conduct life-cycle assessments (LCA), for example, according to (ISO, 2006) with a strong focus on the impact category of greenhouse gas emissions. Therefore, the system boundary is usually cradle-to-grave. Many studies have been done varying on the life cycle impact assessment (LCIA) methodology, substrate mixture (Bacenetti, Sala, Fusi, & Fiala, 2016; Hijazi, Munro, Zerhusen, & Effenberger, 2016) and regional factors like soil qualities and crop yields (Dressler, Loewen, & Nelles, 2012). As in the case of economic analysis, the topic of demand-oriented biogas production and electricity generation has also been analysed using LCA approaches. Hahn, Hartmann, Bühle, and Wachendorf (2015) compared different utilization pathways and showed that the flexible gas production increases the net GHG emissions; however, possible efficiency gains of a bigger CHP unit are not regarded.

Holistic and integral analyses combine two or more of the analysis types mentioned so far and often extend them with other factors like temporal or regional aspects. A common approach is to combine energy, economic and ecological analysis with the focus on LCOE and GHG a balance, for example, to determine GHG abatement costs. The system boundary is usually cradle-to-grave. Lauer et al. (2017), for example, compare different flexible power generation scenarios for two plants and show that there is no correlation between GHG emissions and the average annual gain, since the chosen scenarios are not optimizing both dimensions simultaneously. Koch (2009) formulates several environmental objectives functions and implements the results of an economic optimization as a restriction to determine the optimal location of several BGP types. Auburger, Jacobs, Märländer, and Bahrs (2016) optimize regional feedstock production costs throughout Germany using linear programming and assess the introduction of sugar beet in the feedstock on the GHG balance. In the same way, the opportunity costs for energy crops, risk factors for indirect land use changes (iLUC) and a fixed GHG mitigation potential on the competitiveness of grassland are assessed (Auburger, Petig, & Bahrs, 2017).

While studies in Group 1 in general consist of a very detailed analysis of the AD process, the integration into the whole plant and the wider context including energy and agricultural framework conditions is usually neglected. In Group 2 and 4, the system boundary is usually broader and covers gate-to-gate until cradle-to-grave approaches. Thereby, the identification of energy efficient and environmental friendly technologies and processes is possible. However, usually the most efficient and environmental friendliest technology is not the most cost-effective. Therefore, studies of Group 5 incorporate more dimensions to overcome these gaps but only few examine existing biogas installations or the long-term effects of introducing technical and operational changes regarding technical progress. Additionally, the replacement of components and their technical progress usually plays a minor role if regarded at all. Finally, repowering measures to extend the operation beyond the original intended 20 years of operation have not been analysed so far using an integral approach, which combines mass, energy and GHG balances with a detailed economic evaluation and includes a CHP dispatch optimization. To conclude, there is a need for an integral assessment through a consistent method for the existing BGP regarding their wide heterogeneity.

2.2 | The biogas plant design and balance model

To meet the heterogeneity of BGPs, the assessment of repowering is conducted on a plant-specific level. The model, implemented in MATLAB and Statistics Toolbox (2017), has been developed with the goal to process different data sets, for example, for a certain region or state. Thereby, any number of plants, depending on the size of the primary input data, can be handled. An overview on the developed approach, the input data, used methods and model modules and output gives Figure 2. The first two modules of the model, the substrate analysis and the design of the existing BGPs, are conducted consecutively and determine the reference state of each BGP. All other parts, namely, the repowering implementation, the detailed mass, energy, and GHG emission balances, the CHP dispatch optimization and economic evaluation based on NPV method, are conducted for each year based on average daily values and integrated over the defined period of review (Module 3). Thus, changes within the period of review like the deterioration of the CHP efficiency rate due to ageing (–0.05%–points per 10,000 hr of operation derived from Aschmann and Effenberger (2012)) are also regarded. The effects of the implemented measures and scenarios are then assessed using KPI (Table 2). With the aggregation over all plants according to their initial year of operation and performance for each operation year, detailed forecasts for the future development and possible qualitative effects on the energy or agricultural system level are drawn. In the following, the core elements of the different modules are explained.

2.2.1 | Substrate analysis module (M1)

The substrate analysis module uses the matched EEG plant master and transaction data released by the German transmission system operators (TSO, 2017; Figure 2). While the reference data contain parameters like the installed capacity, the initial year of commissioning and the location of the plant, the transaction data give details on the feed-in electricity and remuneration categories. With the latter additional information on the type of biomass plant, the general substrate mixture limitations as seen in Table 3 and further technical details like an existing heat utilization are derived. The TSO BGP data in this study are dated to the year 2013.

Based on the TSO BGP data, the annual substrate mixture meaning the specific amount and composition is determined for each plant. Since the actual substrate mixtures for each plant is not known, only a theoretical solution is found. To provide more details on the substrate mixture, the TSO BGP data are combined with data of regional operator surveys (Härdtlein, Eltrop, Messner, & Dederer, 2013), data for the substrate properties (Table 4) and data on the efficiency rate of CHP units (see flow chart of Figure 3). The regional data contain the average substrate mixture and the related specific methane yield (SMY) for each power class (Supporting Information Table S1). The main module function "substrate solve" minimizes for all plants in a power class the difference between the actual SMY including plant-specific substrate limitations and the average SMY for the substrate mixture of the power class in a region. The variables are the shares of manure and grass substrates in each substrate category and thereby underlie the substrate limitations as seen in Table 3. The ratio within each substrate type (energy crops, manure and grass) according to the average substrate mixture of the regional data is not changed. Also, more than one solution is possible and a certain amount of plants in a class with different substrate categories are needed to find a good solution. In reality, it is more likely that certain plants use only specific substrates and their ratio differs from the average mix.

In addition, the module determines the main plant configuration based on statistical distributions taken from the regional data. This includes the process type of the plant, which can be single- or two-staged, the digesters types as well as their roof types and types of agitators. For details on the included technologies, see Supporting Information Table S6, and for details on the distributions, see Supporting Information Table S2, S3 and S5.

2.2.2 | Design and dimensioning of existing BGPs module (M2)

For the design and dimensioning of the existing BGPs, the output data from the substrate analysis module are used as the main input. The objective of the module is to determine all major components and their technical parameters necessary for the later balances and economic evaluations. The derived plant configuration also sets the reference state for the integration of repowering and changes due to regulations. An overview of the five main sections of the process chain from the substrate provision up to the gas utilization is given in Figure 4. The model boundaries are the substrates supplied to the plant and the energy supplied to the grid. Each section consists of several components, which includes various technologies. For example, the substrate provision section consists of the

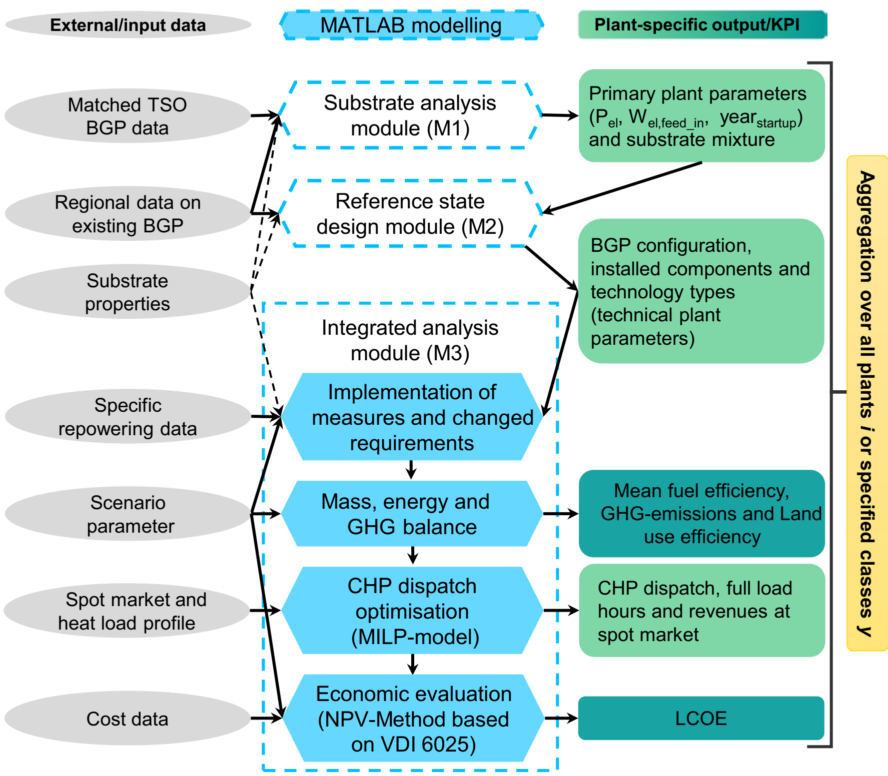

FIGURE 2 Overview on methods and the plant-specific model approach

TABLE 2 Key performance indicators (KPI) for the assessment of repowering

Dimension	Parameter	Unit	*Description*
Energy-related	Gross/net mean fuel efficiency	$kWh_{el/th}/kWh_{HHV}$	Supplied energy to the system in relation to theoretical energy content in the substrate (Based on HHV of TS)
Economical	LCOE	€ct/kWh	
Environmental	GHG emissions	gCO_2eq/kWh	Specific GHG emission per unit of electricity
	Land use efficiency	m^2/kWh_{el}	Area demand per unit of electricity

TABLE 3 BGP classification according to size and substrate categories derived from TSO BGP data (TSO, 2015)

Power classes *[kW el, rated]*	Substrate categories
≤150	≥30 wt% manure
>150 & ≤325	≥80 wt% manure
>325 & ≤500	<30 wt% manure
>500	≥50 wt% grass
	≥50 wt% grass + ≥30 wt% manure

components bunker silo, the manure pretank, the solid feed and an optional liquid feed. All modelled sections, components, technologies, objective of each component function and the main output parameter are listed in Supporting Information Table S6. The level of detail can vary for the different components and is more extensive for main components like the digesters. In addition, the general layout of the plant can also differ with several optional components. For example, the feeding of solid substrate can either occur via the solid feed and screw conveyors, a sequential liquid feed, or directly into the pretank and from there by pump into the digester.

2.2.3 | Integrated analysis module (M3)

Based on the design and dimensioning of the existing plant, module M3 integrates the repowering implementation and changing scenario parameters, the simultaneous execution of energy, mass and GHG balances with the CHP dispatch optimization and the economic evaluation. It conducts balances for each year in the period of review.

The following explanation of the balance focuses on the digester, as it is one of the core components and the most complex next to the CHP unit. Figure 5 displays the digester with all its modelled mass and energy flows across the component system boundary. Regarding the mass balance, the model distinguishes between two phases, the substrate phase and the gas phase. The latter is only modelled from the digester onwards. In the substrate phase next to the total mass, the dry mass, organic dry mass and ash mass are balanced. The formed mass of biogas is subtracted from the organic dry mass (85%) and the water content (15%) in the substrate mass (Reinhold, 2005). For the biogas formation, standard methane yields and contents according to KTBL (2013) are used. The gas phase and its components (CH_4, CO_2, H_2O, N_2, O_2, H_2S) are regarded as an ideal gas mixture according to the ideal gas law and balances are based on the molar amount. For the calculation of biogas losses, see Table 5. The energy balance considers thermal, chemical and electric energy and neglects kinetic and potential energy. The energy transported via mass consists of the enthalpy flow according to Equation (1). The $c_{p,i}$ for the substrates and digestate are calculated depending on the TS content and for the gas phase the molar heat capacity for each gas component (Gerber, 2009).

$$\dot{H}_i = \dot{m}_i \times (\text{HHV}_i + c_{p,i} \times \Delta T) \quad (1)$$

with: HHV_i = higher heating value of component i (see Table 4)

$c_{p,i}$ = specific heat capacity at constant pressure for component i

ΔT = temperature difference between component i and standard temperature T_0

In contrast to the mass balance, the heat balance is conducted monthly to include seasonal fluctuations regarding the process heat demand. While the process temperature of the digester for the substrate and biogas phase is set stationary over the year, for the silage, the liquid manure, the ambient soil and air temperature monthly average values are taken. With the digester dimensions from the design module M2 and heat transfer coefficient based on the material properties, (thickness and thermal conductivity) the heat loss via the different surfaces is determined. In addition, due to the biological activity, a certain self-heating rate depending on the substrate category of the plant in relation to HHV of the formed biogas is assumed (Lindorfer, Braun, & Kirchmayr, 2006). Next to the mass transported energy flow, there is heat supplied by solar radiation, the heating system and the dissipative energy caused by the agitator propulsion. Finally, the heat demand of the process can be derived from Equation (2).

$$\dot{Q}_{\text{heating}} = \dot{Q}_{A,\text{loss}} + \sum_{i=1}^{n} \dot{H}_{i,\text{out}} - \dot{Q}_{\text{solar}} + \sum_{i=1}^{n} \dot{H}_{i,\text{in}} - W_{\text{el,diss.}} \quad (2)$$

TABLE 4 Properties, specific GHG emission factors, yields and cost of substrates implemented in the model

Substrate type	TS	VS	CH_4 content	Density	SMY	Storage loss	HHV	Bulk density	GHG factors	Substrate costs	Yield
	TS/FM	VS/FM	%	tFM/m^3	m^3CH_4/tFM	%	kWh/tTS	tTS/m^3	$kgCO_2eq/kgFM$	€/tFM	tFM/ha
Cow liquid manure[1]	0.10	0.08	0.55	1.00	16.7	0.00	4,782	0.10	−0.068	1.23	0
Pig liquid manure[1]	0.06	0.05	0.60	1.00	12.1	0.00	4,724	0.06	−0.073	1.53	0
Cow solid manure[1]	0.25	0.21	0.55	0.83	52.6	0.02	4,724	0.21	−0.111	6.59	0
Pig solid manure[1]	0.25	0.20	0.60	0.91	52.8	0.02	4,724	0.23	−0.223	1.11	0
Maize silage[2]	0.35	0.33	0.52	0.70	112.4	0.12	5,068	0.29	0.150	36.01[a]	43[a]
Whole crop silage[2]	0.35	0.33	0.53	0.55	109.3	0.12	5,044	0.23	0.090	37.21	33[a]
Grains[2]	0.87	0.84	0.52	0.70	320.3	0.01	5,338	0.66	0.500	186.05	7.5
Grass silage[3]	0.35	0.32	0.53	0.55	100.2	0.10	5,064	0.20	0.130	28.88	20[a]
Forage grass[3]	0.22	0.20	0.55	0.70	65.2	0.12	4,951	0.18	0.130	35.19	23

Note. 1 = manure, 2 = energy crops, 3 = grasses; TS = total solid, VS = volatile solid.
Data based on (B. Amon, Kryvoruchko, Amon, & Zechmeister-Boltenstern, 2006; Clemens, Trimborn, Weiland, & Amon, 2006; Dressler et al., 2012; Fischer et al., 2016; Haenel et al., 2016; Härdtlein et al., 2013; KTBL, 2013; Schmehl, Hesse, & Geldermann, 2012; Statistisches Landesamt Baden-Württemberg, 2017; Stenull, Brellochs, Härdtlein, & Eltrop, 2014; Wernet et al., 2016)
[a]Actual values differ according to eight subregions in BW, average values from regional data are shown.

For the determination of specific GHG emissions and emission changes due to repowering, all relevant GHG emitted on site are covered. All direct, on-site GHG emission sources and their calculation methods are explained in Table 5. They are combined with specific GHG emission factors linked to the upstream substrate production (Table 4) and downstream changes in the digestate application. The specific emission factors also include credits for the gastight storage of manure, which reduces GHG emissions (negative GHG factors of Table 4). Changes over the period of review like the gas tight coverage of a digestate storage or a reduced methane slip at the CHP are also modelled. The GHG emissions are calculated as CO_2-equivalents (global warming potential 100-year according to IPCC, 2013).

The CHP unit dispatch optimization assesses the changes in FLH of the CHP units and the additional revenues caused by the demand-oriented operation. The model uses historical hourly spot price data for the day-ahead market (EPEX Spot SE, 2018). The determined FLH of the CHP unit influences the lifetime of the unit which underlies maximal operating hours of 80,000 hr and 40,000 hr for a spark-ignited gas engine and ignition oil engine, respectively. The optimization is implemented as a mixed-integer linear programming model and based on Hochloff and Braun (2014) but without the integration of supplying control reserve. The objective of the optimization is to maximize the revenues at the spot markets under keeping the constraints imposed by the heat demand and the capacity of the gas and heat storage. The heat demand is constructed with a synthetic head load profile based on Hellwig (2003), adjusted to the heat utilization rate of each plant and can also be met with an additional peak load boiler. In addition, a higher gas consumption due to start-up, a heat demand due to keep the engine warm and an aligned own power consumption of the CHP in relation to emergency cooling demand are also implemented. The optimization time frame is set to 72 hr and uses rolling planning with an overlap of one day. The optimization is solved with Gurobi Optimizer (2018). For an exemplary result of one optimization time step see Supporting Information Figure S1.

For the economic evaluation, the costs are distinguished in capital-related, demand-related, operation-related and other costs according to VDI (2012). The interest rate for capital is set to 5% in all scenarios (for other financial parameters like price rates see Supporting Information Table S7). The capital-related cost consists of investment cost for the installation of new components and the replacement during the period of review. It also includes costs for residual values for mobile components like pumps or CHP units which still have a remaining operation lifetime at the end of the first

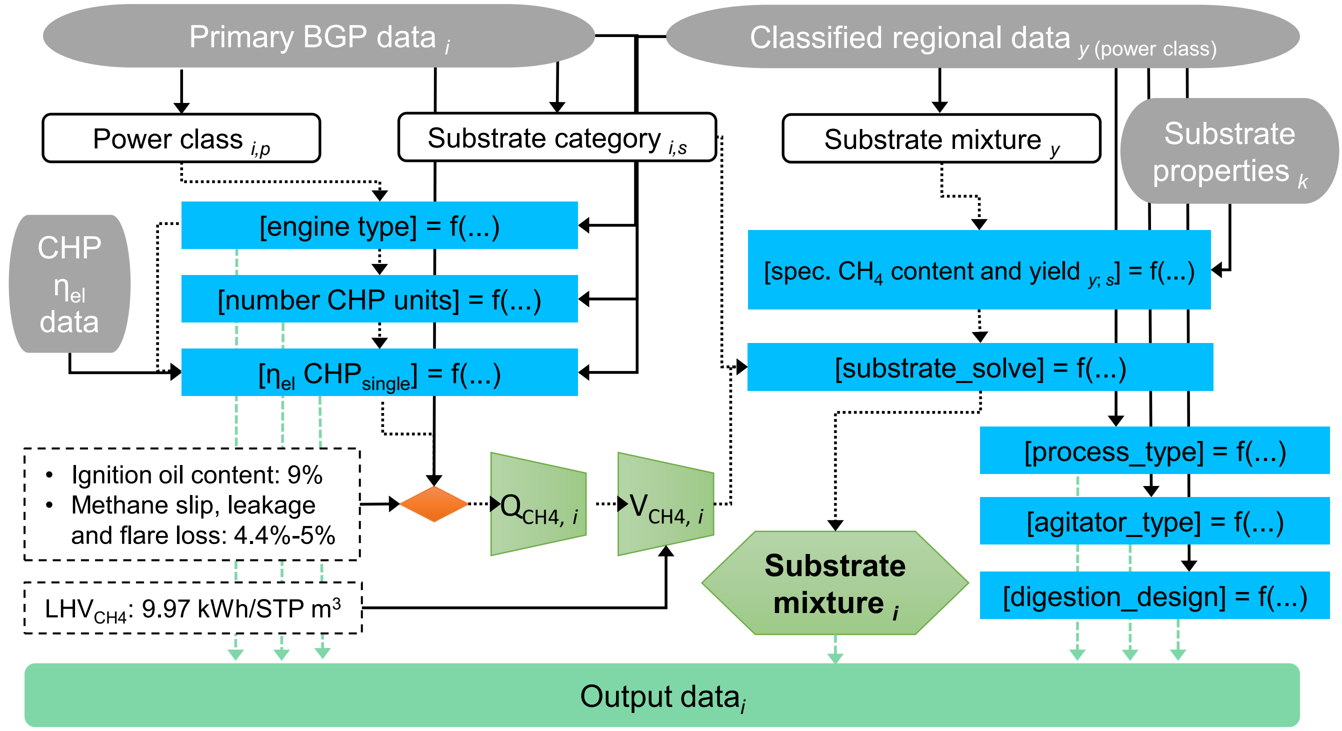

FIGURE 3 Flow chart for the substrate analysis module

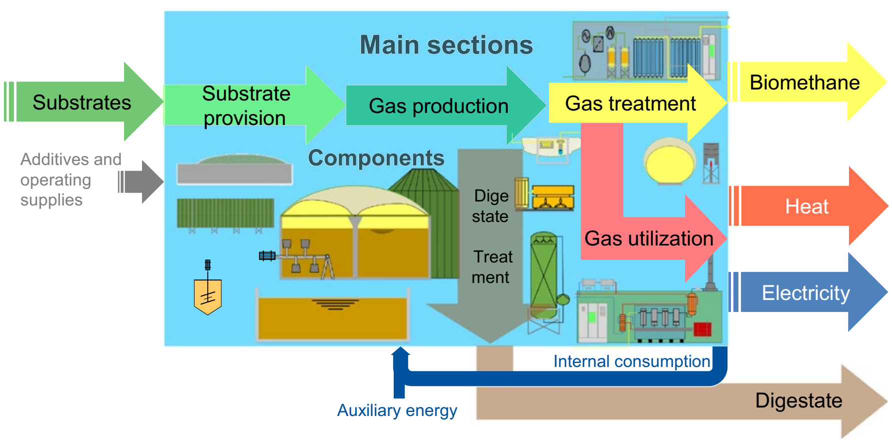

FIGURE 4 Overview of model boundaries and BGP process chain

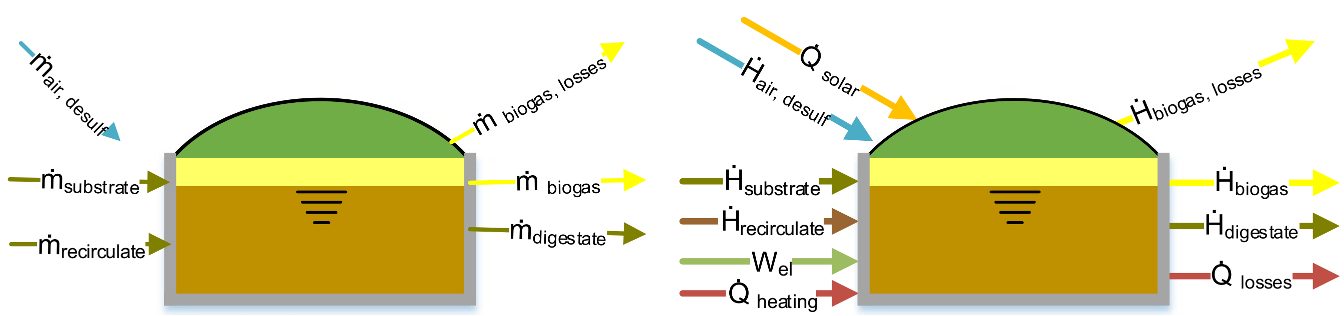

FIGURE 5 Main mass (left) and energy (right) flows for a digester

EEG period and would be saleable in a decommissioning. The residual values result from a linear depreciation from the acquisition to the start and end of the continued operation. In addition, a renovation rate of 5% of the original investment is assumed for components with a lifetime longer than 20 years. The investment costs, lifetimes, factors for maintenance, repair, insurance and planning are determined by specific cost functions. For each component, the investment costs are calculated with regression functions in relation to a specific design parameter, for example, for the gas storage the storage volume in cubic meter.

The demand-related costs mainly consist of the substrate costs and the costs for electricity consumption in the plant but also costs for ignition oil and AD supplies. Maintenance and personnel costs are assigned to the operation-related costs. The latter is calculated in relation to the size of the plant. Other costs are made up of insurance costs and overhead costs. Next to the different cost categories also revenues for heat sales and flexible operation as determined by the dispatch optimization are considered.

Conclusively, the model cumulates all results for each year in form of several KPI in different impact dimensions as stated in Table 2.

2.3 | Repowering measures and scenarios

Depending on the measure, new components or changes in components are switched on, resulting in changes in the balances but also adding new costs. Table 6 gives an overview over the repowering measures assessed in this study, their main parameters and effected components. The scenarios represent the new requirements and bidding process of the current EEG version (EEG, 2017). The current maximum bid size of 16.9 €ct/kWh serves as the criterion to determine the future of each BGP. If the LCOE is equal or smaller than the bidding limit, the BGP will continue to operate for 10 more years, otherwise shut down. It is assumed that there are no changes in the existing BGPs until the start of the 2nd EEG period and that no new plants are built. Also, it is considered that the bidding process is not changed and stays available after 2022 which is currently the latest year

TABLE 5 GHG emission analysis (gate-to-gate): used calculation methods and assumptions

Emission source	GHG	Calculation method	Value	Sources
Transport on site (diesel consumption)	CO_2	Based on specific diesel consumption and volume of loading/handling machine plus the distance silo - digester distance	See Supporting Information Table S4 for specific diesel consumption	KTBL (2014)
Pretank/solid/liquid feed	CH_4	Fixed percentage rate in relation to produced methane	0.097%	Liebetrau et al. (2011)
Digester internal fittings	CH_4	Fixed percentage rate in relation to produced methane	See technical regression functions (Supporting Information Excel file)	Bachmaier, (2012) and Liebetrau et al. (2011)
Gas membrane	CH_4	Losses via membrane permeation based on diffusion rates (distinction for single- and double-layer membranes), surface area and gas pressure, no losses for concrete roofs	See technical regression functions (Supporting Information Excel file)	DLG e. V. (2009)
Separator	CH_4	Fixed percentage rate in relation to produced methane	0.008%	Liebetrau et al. (2011)
Digestate storage (open and gas tight)	CH_4	Residual biogas potential in relation to: • substrate mixture • HRT • coverage	2.65 gCH_4/kgTS silage See technical regression functions (Supporting Information Excel file) Open: 1.58%, Gas tight: 5.73%	Haenel et al. (2016) Reinhold (2009) Ebertsch et al. (2012)
	N_2O	Fixed rate for nitrous oxide in relation to digestate amount	0.04 $kgNO_2$/tFM	Clemens et al. (2006) and Vazquez-Rowe et al. (2015)
Digestate spreading	CO_2, CH_4, N_2O	Specific emissions factors for liquid and solid digestate per kg digestate plus diesel consumption for transportation and spreading	12.46 gCO_2eq/kg liquid digestate 14.75 gCO_2eq/kg liquid digestate	KTBL (2016), Liebetrau et al. (2011) and Vazquez-Rowe et al. (2015)
CHP	CH_4	Fixed percentage rate in relation to entering methane	1.3%	Liebetrau et al. (2011), Tappen, Aschmann, and Effenberger (2016)

with a set bidding volume. In the reference scenario (REF), no changes to the plants, except an adjustment of the CHP unit at the end of its lifetime, and no extension of operation within the EEG 2017 are regarded. The business as usual (BAU) scenario regards all major requirements for a switch to a flexible operation and a maximum input of energy crop of 50 wt% as required by the EEG 2017 (Table 7). In TECH+ scenario, technical progress for the CHP unit and flexible gas production is included. The difference in the POWER- scenario is the compliance with the energy crop cap. Here, only a reduction in energy crops is assumed leading to a decreased rated gas and power capacity. In average, the reduction for plants underlying changes due to crop cap is 28% in the POWER- scenario.

3 | RESULTS

The plant-specific results are shown for exemplary and selected plants, and the aggregated results are either grouped according to the power classes Table 3 or summarized for the complete data set of BW.

3.1 | Plant-specific results

To illustrate the model calculations and intermediate results, Figure 6 (Output module 2) and Figure 7 (Energy balance of module 3) show the component configuration and the energy flow of an exemplary plant in the reference state. The main substrates of the plant are energy crops, and the installed capacity is 250 kW_{el} (see Table 8). As seen in Figure 6, the process type is two-staged with a concrete roof digester, a double-layer membrane secondary digester and open digestate storage. Around 42 wt% of the separated liquid digestate is used for recirculation while 24 wt% of the substrates is transformed into biogas.

Figure 7 shows that—although 15 wt% manure is used—the relevant energy flow is only minor. The main losses occur in the silo (storage loss due to biological degradation), the CHP unit, the theoretically remaining energy in digestate (due to the limited degradation of AD) and the auxiliary energy demand for the plant. The latter reduces the gross fuel efficiency of the plant from 42.17% down to the net fuel efficiency of 37.48%

TABLE 6 Repowering measures (RM) on flexibilization and their relevant, components and parameters

Flexibilization measures	Affected[a]/additional[b] components	New/changed parameters
• Replacement of existing CHP (RM1) • Unchanged existing CHP and installation of additional CHP (RM2) • Integration of demand-oriented gas production; gas production can vary between 50% and 130% of average rated gas capacity (RM3)	• Gas dryer[a] • Existing CHP unit[a] • Additional CHP unit[b] • External gas storage[a] • Heat storage[b] • Transformer[a] • ICT system[b]	• $W_{el, gas cooling}$ [kWh/day] • Additional gas storage capacity [m^3] • $P_{el,transformer}$ [kW] • Additional CHP parameters (same details as existing CHP, see Supporting Information Table S6) • Volume heat storage [m^3]

TABLE 7 Overview on main parameters in the four scenarios

Parameter	REF	BAU	TECH+	POWER-
2nd EEG Period	None	Existent		
Min. gastight HRT	–	150 days		
Degree of flexibilization	1.1 (≙ 8,000 FLH)	2		
Capacity premium	–	40 €/$kW_{el,inst}$		
Flex revenues	–	According to CHP dispatch optimization for the year 2013		
Type of flexibilization	None, base load operation	Replacement of existing CHP (RM1)	Replacement of existing CHP (RM1) + flexible gas production (RM3)	
Energy crop cap	–	Energy crops restricted to a maximum of 50 wt%		
Substrate mixture	Unchanged compared to 1. EEG period	Energy crops ↓ Manure and grass ↑		Energy crop ↓ Manure and grass →
Rated gas capacity		→		↓
Technical progress for CHP	–		Increase in electric efficiency of 0.2%-points per a and reduction in CHP investment cost of 2% per a	

In Table 9, the KPI all repowering measures and combinations of Table 6 with the parameters of the TECH+ scenario in comparison with the reference state is given for selected BGP. Five different plants have been chosen, differentiating between EEG versions, capacities, substrate mixtures, heat usages and digestate storage coverage. Due to the scenario requirement of 150 days mandatory HRT in the gas-tight system (plant No. 1, 2 and 4), all open digestate storages are covered. The manure share remains constant for all plants compared to the reference state except for plant No. 4 with energy crops as main input. Here, the manure share raises from 18 to 27 wt%. The gross and net fuel efficiency increases for all plants in the range between 0.28% and 2.31%-points. The highest gains are obtained in the case of the gas-tight coverage of the digestate storage due the capturing of the residual gas. Likewise, the LCOE is changed between 2.4 and −3 €ct/kWh_{el}. Measures which directly replace the existing CHP (RM1) are more effective at reducing the LCOE than measures using the existing CHP until the end of life (RM2). Due to the higher specific investment costs for two smaller units, it even can lead to an increase in LCOE (see plant No. 1, 4 and 5). Another reason is the lower efficiency rates, which also leads to slightly smaller reduction in GHG emissions and area demand.

For all plants except the small manure plant, these are reduced between −43 and −192 gCO_2eq/kWh_{el}, and −0.003 and −0.013 m^2/kWh_{el}, respectively. The increase in the manure plant can be explained with way of calculating the specific GHG emissions. While the produced electricity is increasing due to efficiency gains, the absolute negative emissions are not changing.

The reduction in LCOE and GHG emissions contrasts with the fuel efficiency gains, which are highest for RM2 and RM2/3, because the overall CHP efficiency including thermal efficiency is higher for smaller units. However, since only the theoretical heat production is increasing and not the heat usage rate, this has no influence on the LCOE. Another influencing factor is the FLH in the reference state, the higher the FLH and thereby rated power output the higher the new installed capacity. Hence, the relative strong change in specific investment costs and efficiency rates leads to a stronger reduction in the LCOE.

3.2 | Aggregation according to power class and scenario developments

The same trend for the LCOE can also be observed when aggregating the results for all plants in BW. Figure 8 shows the results aggregated over the four power classes for the TECH+ scenario in comparison with the reference case. The results are grouped according to the different cost and credit types. The main cost share composes of demand-related costs ranging from 47% to 66% in the reference case and 34% to 63% in the TECH+ scenario. The demand-related cost share increases with the power class and is lower in the TECH+ scenario due to efficiency gains, changes in the substrate mixture and rising share of capital costs. Even though the capital-related costs are increasing, the LCOE (without credits) is lower for the classes ≥325 kW_{el}. The increase is higher for smaller plants due to the higher specific investment costs for the adjustments of the CHP capacity and the gas-tight cover of the digestate storage.

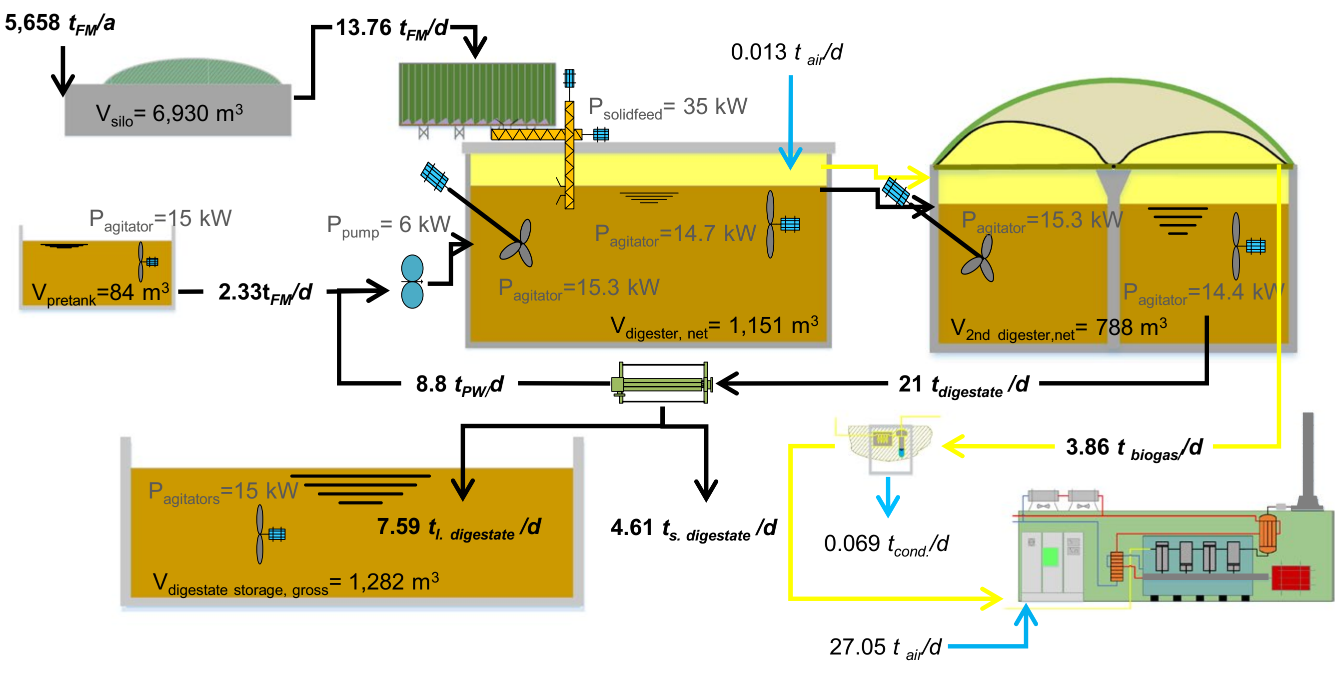

FIGURE 6 Reference configuration and main mass flows for the exemplary biogas plant (biogas losses are not shown)

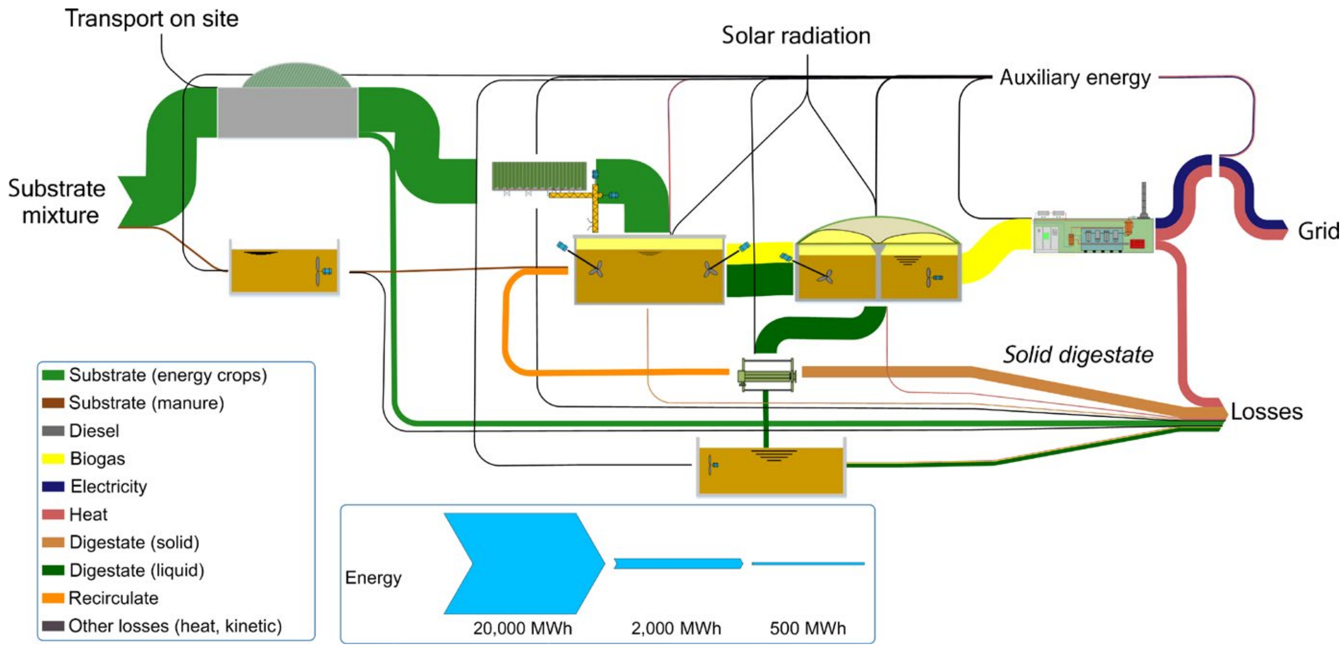

FIGURE 7 Energy flow for the exemplary plant divided by energy carrier (Note: due to visibility small flows are drawn with a black border line and appear bigger than they are)

Factors reducing the capital-related costs are the technical progress and the reduced CHP replacement demand due to higher lifetime resulting from lower FLH per year. In combination with additional revenues from the flexible operation and the flex premium, the LCOE is reduced considerably, resulting in a significant higher share (51%) of plants with a LCOE below the bid limit of 16.9 €ct/kWh$_{el}$ of the EEG 2017 in comparison with the reference (21%). The average rated power output of these plants is 390 kW$_{el}$ compared to 249 kW$_{el}$ of all plants of the data set currently in operation. Therefore, the TECH+ scenario leads to less but in average larger plants and follows the capacity development as seen in Figure 9. While the number of plants steadily decreases until the year 2035 in all scenarios, the total capacity undergoes different phases which follow the initial installations under the different EEG versions in the years 2000–2013. Until 2024, only few plants drop out of the EEG in each scenario. From 2024, the capacity decreases strongly in the reference scenario with no plants left in 2034 and less strong in the BAU scenario where less than a third is still in operation in 2035. In the TECH+ and POWER−, the decrease of plants is only down to less than half, resulting in an increase of installed capacity until 2031 due to flexibilization of the plants which continue their operation.

Afterwards, the capacity is decreasing again and resulting in almost the same capacity as in 2020, because the shutdown of more plants and loss of capacity cannot be compensated by flexibilization anymore. The two scenarios differ in a higher total capacity of 39 MW$_{el}$ and number of plants of 24 for the TECH+ scenario, because the, in general, lower rated power as the baseline for the installed capacity and slightly higher LCOE leading to less plants being able to continue their operation.

In Figure 10, the development of the electricity and biogas generation for the same period is shown. An axis with a percentage change is chosen to clarify the decoupling of electricity from gas generation which starts to show in the late 20 s and is similar in all scenarios except the reference one. Reasons for the decoupling are higher efficiency rates of new and larger CHPs units and the technical progress. In total, the electricity generation until 2035 is reduced to 57%, 76% and 66% and the biogas production down to 50%, 68% and 60% in the BAU, TECH+ and POWER- scenario, respectively.

With the increase in the efficiency rates, the specific GHG emissions also improve. As shown in Figure 11, the average specific GHG emissions for the plants in BW are reduced from 423 gCO_2eq/kWh$_{el}$ in 2020 to 372, 343 and 324 gCO_2eq/kWh$_{el}$ in 2035 for the BAU, TECH+ and POWER− scenario. In comparison with the capacity and electricity generation, the difference for the development of GHG emissions and area demand is stronger because the substrate mixture is one of the main influencing factors. This becomes apparent when looking at the REF scenario where the emissions sink down to 87 (2033) and −472 (2034) gCO_2eq/kWh$_{el}$. Here, the last plants shutting down are small plants with high manure shares, which started their operation from 2012 onwards. In contrast, in the BAU scenario, few larger plants with a high energy crop share remain in 2035, increasing in the average specific emissions from 2032 onwards. Thereby, the positive

TABLE 8 Main parameters of the exemplary BGP

Parameter	Unit	Value
Installed capacity	kW_{el}	250
Rated capacity	kW_{el}	236
Substrate mixture	%	Energy crops (manure <30 wt%)
Start of operation	year	2005
Subregion in BW	–	Unterland/Gäue
$OLR_{digester}$	kg VS/m^3/day	4
$HRT_{digester}$	d	72
Total energy input		
(HHV of dry biomass)	MWh/a	10,345
$\eta_{fuel,\ gross}$	%	42.17
$\eta_{fuel,\ net}$	%	37.48

effects of the AD treatment and storage of manure reducing GHG emissions are no more affecting the electricity production from biogas. This is also the case in the TECH+ and POWER− scenario, though to a lesser degree. The specific area demand follows the same trend as the GHG emissions.

4 | DISCUSSION

4.1 | Strengths and limitations of the model approach

The model focuses on a high level of detail regarding the component variations, mass and energy flows throughout the plant. It thereby allows to identify weak points (Figure 7) and assess repowering and changes in the framework (Figures 9–11) for individual and wide bandwidth of plants at the same time (Table 9). From changes in the substrate mixture to new requirements like minimal HRT, extended digestate storage capacities and different flexibilization modes, the model structure allows to apply the same approach easily to different data sets and assess each measure separately or in combination. Another strength is that each year in the period of review is regarded individually considering the implementation of temporal changes, which has not been done so far in other studies. The model also allows to assess plants from different construction periods. In the analysis of effects on whole bandwidth of existing plants, this is essential, since the same issues and investment decisions concern them at varying points in time, each with their own specific framework condition. This becomes apparent when looking at the forecast of the scenarios where different phases, for example, in the capacity development, could be identified.

In reality, the future development will likely occur in a more diverse way. For example, the degree of flexibilization will occur according to plant-specific constraints and likely long before the end of the first EEG period and not as a fix degree for each plant as assumed in the scenarios.

In the model, the AD process is regarded as a “black box.” Since no integration of degradation kinetics or other influence of parameters on the biogas yield is regarded, the AD performance of each plant is calculated to be constant. However, parameters like HRT (Ruile, Schmitz, Mönch-Tegeder, & Oechsner, 2015) and energy crop content (Linke, Muha, Wittum, & Plogsties, 2013) have strong influence on the SMY. This shortfall of the model has also to be considered in the case of flexible biogas production. Even though limitations to variable gas productions have been considered in the dispatch model according to Mauky et al. (2017) and Laperrière et al. (2017), constraints for gradients and temporally high OLR are not modelled and might therefore overestimate the potential of flexible gas production.

Although several substrates are regarded, another limitation of the model is the homogeneous implementation of the single substrate properties. However, parameters like the TS content vary throughout different regions and have strong influence on the AD process, the SMY and thereby also KPI like LCOE. In the same way cost, area yield and GHG emissions of crop production vary considerable for different regions as shown by Auburger et al. (2016) and have a large impact if iLUC are regarded (Auburger et al., 2017). Especially if the number of plants and the study area are increasing, this has to be taken into account and the model has to be adapted to a more differentiated data base.

4.2 | Comparison of plant-specific KPI and forecasts

In comparison with other studies, our model tends to show a smaller spread regarding gross fuel efficiencies rates and a higher spread regarding net fuel efficiency rates. The calculated gross (net) fuel efficiencies of all plants lie between 32.56% (11.88%) and 46.11% (42.86%) with a mean of 41.19% (35.74%) in the REF scenario. Fischer et al. (2016) determine gross values of 29.6%–48.6% and net values of 24.9%–37.9% for four BGPs. As in the current study, there is a much larger BGP basis, which includes many small plants, and the spread for the net fuel efficiency is much bigger. The low values of many small plants for the net fuel efficiency might be explained by an overestimation of the auxiliary energy and losses in the model.

Regarding the LCOE, the model results show higher values in comparison with other studies. The average LCOE according to the four power classes lie between 16.65 and 33.24 €ct/kWh_{el} without heat credits and 14.06–31.38 €ct/kWh_{el} including heat credits in the TECH+ scenario. In Kost, Shammugam, Jülch, Nguyen, and Schlegl (2018), LCOE is stated without regarding heat credits for new plants (500 kW_{el}) in a range of 10.14–14.47 €ct/kWh_{el} for

TABLE 9 KPI of different repowering measures in the TECH+ scenario for selected BGPs in BW

BGP No.	Start of operation	Heat usage	Scenario and RM	$P_{el,inst}$	Digestate storage cover	Manure share	$\eta_{fuel, gross}$	$\eta_{fuel, net}$	LCOE	GHG emissions	area demand	FLH existing CHP
-	year	-	-	kW_{el}	-	%	%	%	€ct/kWh_{el}	gCO_2eq/kWh_{el}	m^2/kWh_{el}	h/a
1	2004	no	Ref. & No RM	155	open	54	41.58	33.07	22.74	469	0.073	6,464
			TECH+ & RM1	264	gas-tight		43.50	34.94	22.48	318	0.063	4,515
			TECH+ & RM2	264			43.89	35.28	25.03	328	0.065	5,052
			TECH+ & RM1/3	264			43.67	35.11	22.28	317	0.063	4,532
			TECH+ & RM2/3	264			43.86	35.25	25.10	328	0.065	5,346
2	2009	yes	Ref. & No RM	340	open	48	39.72	34.68	18.60	564	0.069	7,160
			TECH+ & RM1	632	gas-tight		41.51	36.42	15.61	373	0.056	4,755
			TECH+ & RM2	632			41.91	36.81	17.84	392	0.059	3,743
			TECH+ & RM1/3	632			41.56	36.47	15.62	372	0.056	4,761
			TECH+ & RM2/3	632			41.90	36.79	17.72	392	0.059	3,389
3	2010	yes	Ref. & No RM	530	gas-tight	40	42.23	37.26	16.27	346	0.060	8,429
			TECH+ & RM1	1,054			42.84	37.84	13.95	301	0.052	5,110
			TECH+ & RM2	1,054			43.05	38.03	14.78	303	0.052	4,290
			TECH+ & RM1/3	1,054			42.86	37.85	13.90	301	0.052	5,112
			TECH+ & RM2/3	1,054			43.04	38.02	14.92	302	0.052	4,000
4	2005	yes	Ref. & No RM	370	open	18	42.06	37.67	17.25	525	0.058	7,016
			TECH+ & RM1	597	gas-tight	27	43.16	38.47	15.51	368	0.052	4,632
			TECH+ & RM2	597			43.53	38.82	17.90	391	0.055	5,384
			TECH+ & RM1/3	597			43.26	38.56	15.51	368	0.052	4,642
			TECH+ & RM2/3	597			43.50	38.78	17.82	388	0.055	5,715
5	2012	no	Ref. & No RM	75	gas-tight	94	34.99	21.25	25.01	−642	0.030	7,924
			TECH+ & RM1	154			35.31	21.53	22.95	−516	0.024	5,023
			TECH+ & RM2	154			35.68	21.84	26.63	−556	0.026	4,450
			TECH+ & RM1/3	154			35.31	21.53	22.94	−516	0.024	5,023
			TECH+ & RM2/3	154			35.68	21.84	26.60	−556	0.026	4,478

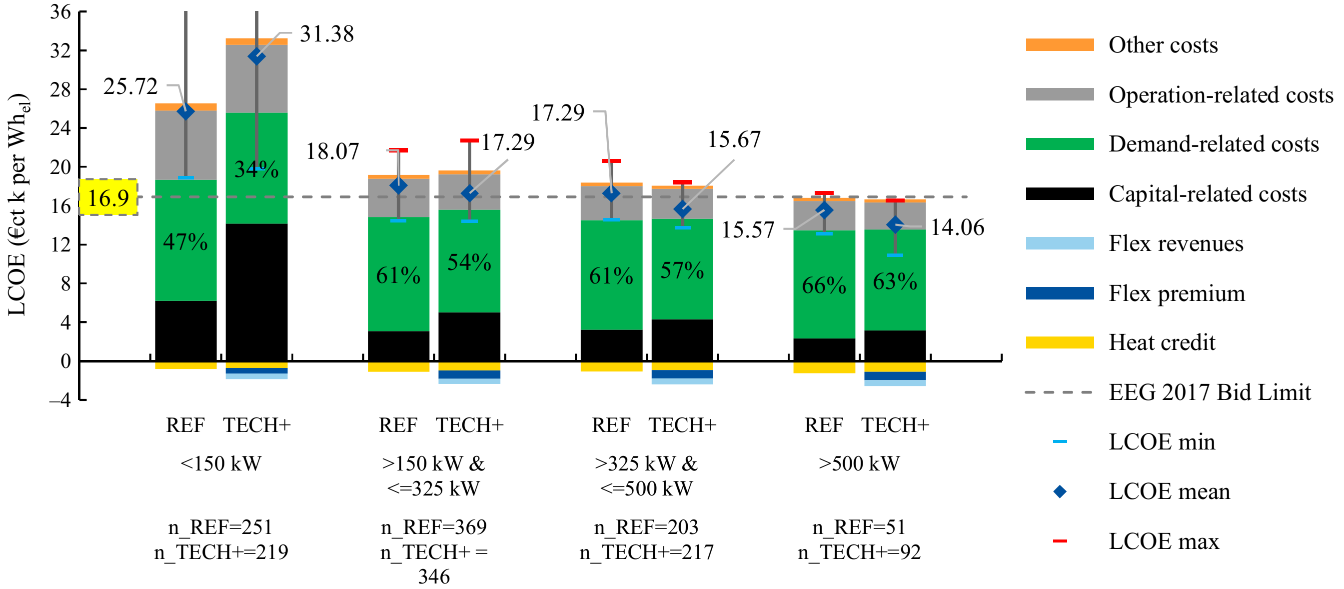

FIGURE 8 Comparison of aggregated LCOE for REF and TECH+ scenario over different power classes according to electric, rated power output and stated number of plants for each power class

7,000 FLH and 5,000 FLH, respectively, and no reduction potential is assumed until 2035. However, in their study, the period of review is much higher (30 years instead of 10 years as assumed for the current study) and no altering of efficiency rate (ageing) is assumed. It is also possible that they underestimated the replacement investments, which are high for BGPs considering capital-related costs of 3.1–14.16 €ct/kWh$_{el}$ for an extended operation of the current study. The high LCOE in the current study is again explained with the range of the data set with an average rated power of 249 kW$_{el}$ and 219 plants in the class below 150 kW$_{el}$. Especially for these small BGPs, a flexibilization leads to a strong increase in LCOE and is therefore not a viable option for an extended operation. The increase itself results mainly from capital-related cost due to the additional requirements and capacity increase (Figure 8). Similar increases are shown by Holzhammer et al. (2014) for very flexible operation modes with FLH in the range of 5,500–1,500 hr. At the same time, the TECH+ and POWER− scenario show that there is also a reduction potential due to factors like the technical progress and changes in the substrate mixture.

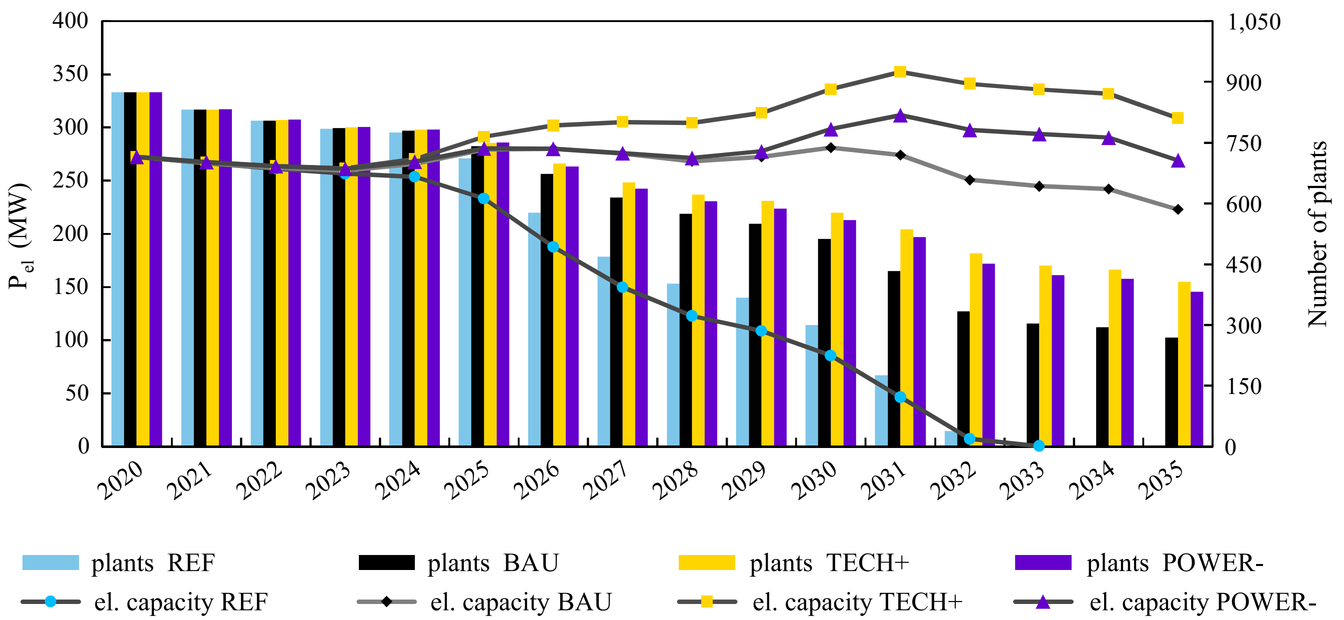

FIGURE 9 Scenario development for the capacity and number of plants for the period from 2020 to 2035

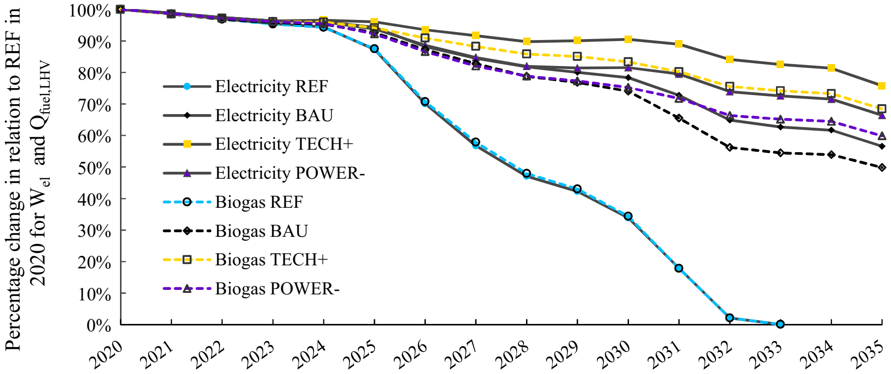

FIGURE 10 Scenario development of the total electricity and biogas generation for the period from 2020 to 2035, 100% = 1,905 GWh_{el}, and 5,424 $GWh_{fuel,HHV}$

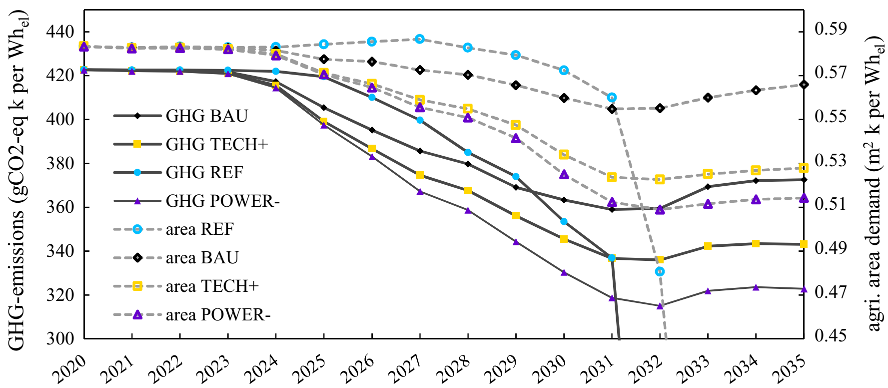

FIGURE 11 Scenario development of the average specific GHG emissions and area demand for the BGPs in BW for the period from 2020 to 2035; Note that y-axis have been edited to highlight the difference between the scenarios, and extreme values of the REF scenario are cut-off: GHG REF 86 (2032) and −472 (2033) gCO_2eq/kWh_{el}; area REF 0.24 (2033) m^2/kWh_{el}

The specific GHG emissions are within the results of other studies. However, considering the relative high shares of manure in BW, the model output is comparable high. In the TECH+ scenario, the specific GHG emissions range from 729 to −843 gCO_2eq/kWh_{el} regarding heat credits with an average of 337 gCO_2eq/kWh_{el}. Bacenetti et al. (2016) state in their review that there is wide range between 550 and –1,720 gCO_2eq/kWh_{el}. The reason for the averagely high emissions is the fix emission factors for the substrates taken from literature (Table 4). They contribute in average 62% to the GHG emissions, followed by emissions from the digestion system and CHP methane slip with 17% and 18%. Yet, the TECH+ and POWER− scenarios show a considerable GHG reduction potential of −12% to −34% for the plants in Table 9. Similar findings for flexibilization of BGPs are stated by the studies of Ertem, Martínez-Blanco, Finkbeiner, Neubauer, and Junne (2016) and Lauer et al. (2017). The reasons stated for the reduction in the GHG are different loading rates due to feed management and the increase in the efficiency rate of bigger CHP units, respectively.

A comparison of the scenario development with other findings is difficult since similar studies choose different approaches and assumptions. In Dotzauer et al. (2016), the scenarios are similar to the REF scenario. The study is not regarding an extended operation but instead a gross capacity addition (for all biomass plants in Germany) mainly due to small manure plants and a flexibilization during the first EEG period. After a capacity increase up to 2020, there is a strong reduction until 2035 leaving only small manure plants operational. In Lauer and Thrän (2017), the capacity development in the scenario is preset with three different development paths. A biogas increase out which is congruent with the REF scenario, a biogas back up scenario similar to the BAU scenario and a biogas increases path which is not comparable with the scenarios of the current study. It may be concluded that with the current plant-specific approach and the outlook to more detailed scenario analyses, more versatile development paths for the existing BGPs can be drawn, while simultaneously assessing the effects on wide range of impact categories.

4.3 | Scenario assumptions and implications

Regarding the forecasts, it needs to be stated that these represent best case scenarios. This is due to the fact that bidding process is not considered. In this process, the plants within BW are competing with each other but also with BGPs from other states that likely have different LCOE structures. As the first auction of the EEG has shown, bids can be much lower than the current maximum bid size (BNetzA, 2017). Since only the lowest bids within the bidding volume will get an acceptance, this situation will aggravate when many biogas plants drop out of the EEG starting around 2024.

Despite these uncertainties, the flexibilization in combination with subsidies like the flex premium and a continued support by the EEG offers chances for many biogas plants. At the same time, for most small plants with high manure shares, this will not be enough. With their shutdown, the AD treatment and gas-tight storage of manure ceases and more GHG emission might be emitted again. This development will be contrary to the goals of the German climate protection plan for the agricultural sector (BMUB, 2016). Nevertheless, the shutdown of BGPs is also releasing large agricultural areas which will then again be available for food and feed production, set-aside or new utilization pathways of the bio economy.

If a wide shutdown of BGPs is to be averted and the established capital-stock is to be retained to support the attainment of climate targets, this requires adjustments of the EEG policy regarding small manure plants. For example, introducing a special bidding process for plants up to a rated power output of 150 kW_{el} and high manure shares in the range of 65%–80% without a mandatory flexibilization but with a higher bid limit may enable more plants to stay operative. At the same time, the flexibilization of larger plants should further be pursued not only regarding the positive effects of higher efficiency rates of bigger and future CHP units on plant-specific KPIs but also the value of flexible BGPs in the interaction with fluctuating renewable energy sources.

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ORCID

Joshua Güsewell https://orcid.org/0000-0003-3062-9574
Ludger Eltrop https://orcid.org/0000-0002-1721-7607

REFERENCES

Amon, B., Kryvoruchko, V., Amon, T., & Zechmeister-Boltenstern, S. (2006). Methane, nitrous oxide and ammonia emissions during storage and after application of dairy cattle slurry and influence of slurry treatment. *Agriculture, Ecosystems & Environment*, *112*(2–3), 153–162. https://doi.org/10.1016/j.agee.2005.08.030

Aschmann, V., & Effenberger, M. (2012). Elektrische Wirkungsgrade von biogasbetriebenen BHKW. *Landtechnik - Agricultural Engineering*, *67*, 118–121.

Auburger, S., Jacobs, A., Märländer, B., & Bahrs, E. (2016). Economic optimization of feedstock mix for energy production with biogas technology in Germany with a special focus on sugar beets – Effects on greenhouse gas emissions and energy balances. *Renewable Energy*, *89*, 1–11. https://doi.org/10.1016/j.renene.2015.11.042

Auburger, S., Petig, E., & Bahrs, E. (2017). Assessment of grassland as biogas feedstock in terms of production costs and greenhouse gas emissions in exemplary federal states of Germany. *Biomass and Bioenergy*, *101*, 44–52. https://doi.org/10.1016/j.biombioe.2017.03.008

Bacenetti, J., Sala, C., Fusi, A., & Fiala, M. (2016). Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable. *Applied Energy*, *179*, 669–686. https://doi.org/10.1016/j.apenergy.2016.07.029

Bachmaier, J. (2012). Treibhausgasemissionen und fossiler Energieverbrauch landwirtschaftlicher Biogasanlagen: Eine Bewertung auf Basis von Messdaten mit Evaluierung der Ergebnisunsicherheit mittels Monte-Carlo-Simulation (Dissertation). Universität für Bodenkultur Wien, Wien.

Batstone, D. J., Keller, J., Angelidaki, I., Kalyuzhnyi, S. V., Pavlostathis, S. G., Rozzi, A., … Vavilin, V. A. (2002). The IWA anaerobic digestion model no 1 (ADM1). *Water Science and Technology*, *45*(10), 65–73. https://doi.org/10.2166/wst.2002.0292

Besgen, S., Kempkens, K., & Lammers, P. S. (2007). Energieumsetzung in Biogasanlagen: Ergebnisse messtechnischer Untersuchungen an landwirtschaftlichen Biogasanlagen. *Agricultural Engineering Research*, *13*, 57–66.

Biernacki, P., Steinigeweg, S., Borchert, A., Uhlenhut, F., & Brehm, A. (2013). Application of anaerobic digestion model no. 1 for describing an existing biogas power plant. *Biomass and Bioenergy*, *59*, 441–447. https://doi.org/10.1016/j.biombioe.2013.08.034

Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit (BMUB) (2016). *Klimaschutzplan 2050 - Klimaschutzpolitische Grundsätze und Ziele der Bundesregierung*. Retrieved from www.bmub.bund.de

Bundesnetzagentur für Elektrizität, Gas Telekommunikation, Post und Eisenbahnen (BNetzA) (2017). *Ergebnisse der ersten Ausschreibung für Biomasse*. Retrieved from https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/2017/18092017_Biomasse.html?nn=265778

Clemens, J., Trimborn, M., Weiland, P., & Amon, B. (2006). Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture, Ecosystems & Environment*, *112*(2–3), 171–177. https://doi.org/10.1016/j.agee.2005.08.016

Djatkov, D., Effenberger, M., & Martinov, M. (2014). Method for assessing and improving the efficiency of agricultural biogas plants based on fuzzy logic and expert systems. *Applied Energy*, *134*, 163–175. https://doi.org/10.1016/j.apenergy.2014.08.021

DLG e. V. (2009). *Biogasspeichermembranen (Elastomer): Mehtandurchlässigkeit/Reißfestigkeit*. DLG-Prüfbericht 5891F. Groß-Umstadt, Germany: DLG e.V.

Dotzauer, M., Hennig, C., Lenz, V., Brosowski, A., Trommler, M., Barchmann, T., … Stinner, W. (2016). Kurzstudie: Entwicklung der Biomasseverstromung bei Fortschreibung der aktuellen EEG-Vergütung (EBFE).

Dressler, D., Loewen, A., & Nelles, M. (2012). Life cycle assessment of the supply and use of bioenergy: Impact of regional factors on biogas production. *The International Journal of Life Cycle Assessment*, *17*(9), 1104–1115. https://doi.org/10.1007/s11367-012-0424-9

DüV (2017). Verordnung über die Anwendung von Düngemitteln, Bodenhilfsstoffen, Kultursubstraten und Pflanzenhilfsmitteln nach den Grundsätzen der guten fachlichen Praxis beim Düngen

(Düngeverordnung - DüV), 26.05.2017. Bonn, Germany: Bundesministerium für Ernährung und Landwirtschaft (BMEL).

Ebertsch, G., Kissel, R., Lehner, A., Gracia, E. R., Bachmaier, H., & Effenberger, M. (2012). *Monitoring und Dokumentation von Praxis-Biogasanlagen* (Schriftenreihe der Bayerischen Landesanstalt für Landwirtschaft No. 8).

EEG (2017). *Gesetz für den Ausbau erneuerbarer Energien (Erneuerbare-Energien-Gesetz - EEG 2017)*. Berlin, Germany: Deutscher Bundestag.

Effenberger, M., & Lebhun, M. (2011). Repowering von Biogasanlagen zur Steigerung der Prozesseffizienz. In Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (Ed.), KTBL-Schrift, Biogas in der Landwirtschaft: Stand und Perspektiven. Darmstadt, Germany: Kuratorium für Technik und Bauwesen in der Landwirtschaft.

EPEX Spot SE (2018). *Market data day-ahead auction*. Retrieved from https://www.epexspot.com/en/market-data/dayaheadauction/auction-table/2013-01-01/DE

Ertem, F. C., Martínez-Blanco, J., Finkbeiner, M., Neubauer, P., & Junne, S. (2016). Life cycle assessment of flexibly fed biogas processes for an improved demand-oriented biogas supply. *Bioresource Technology*, *219*, 536–544. https://doi.org/10.1016/j.biortech.2016.07.123

Fachagentur Nachwachsende Rohstoffe e.V. (FNR) (2016). *Repowering*. Retrieved from https://biogas.fnr.de/gewinnung/repowering/

Fachverband Biogas e.V. (FvB) (2017). *Branchenzahlen 2016 und Prognose der Branchenentwicklung 2017: Stand: Oktober 2017*. Freising, Germany: Fachverband Biogas e.V. (FvB).

Fischer, E., Postel, J., & Ehrendreich, F. (2015). Repowering im Biogasanlagenbestand - Einführung des Nutzungsgrades zur Bewertung von effizienzsteigernden Maßnahmen. In Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) (Ed.), *KTBL-Schrift, Biogas in der Landwirtschaft - Stand und Perspektiven* (pp. 162–171). Darmstadt, Germany: Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL). Retrieved from https://www.ktbl.de/shop/produktkatalog/show/Product/11508/

Fischer, E., Postel, J., Ehrendreich, F., & Nelles, M. (2016). Using the mean fuel efficiency to energetically assess agricultural biogas plants. Landtechnik - Agricultural Engineering, *71*(4), 139–154. https://doi.org/10.15150/lt.2016.3132.

Gaida, D., Sousa Brito, A. L., Wolf, C., Bäck, T., Bongards, M., & McLoone, S. (2011). Optimal control of biogas plants using nonlinear model predictive control. In IET (Ed.), 22nd IET Irish Signals and Systems Conference (ISSC), Dublin, Ireland.

Garcia-Gen, S., Rodriguez, J., & Lema, J. M. (2014). Optimisation of substrate blends in anaerobic co-digestion using adaptive linear programming. *Bioresource Technology*, *173*, 159–167. https://doi.org/10.1016/j.biortech.2014.09.089

Gebrezgabher, S. A., Meuwissen, M. P. M., Prins, B. A. M., & Lansink, A. G. J. M. O. (2010). Economic analysis of anaerobic digestion—A case of Green power biogas plant in The Netherlands. *NJAS – Wageningen Journal of Life Sciences*, *57*(2), 109–115. https://doi.org/10.1016/j.njas.2009.07.006

Gerber, M. (2009). *Ganzheitliche stoffliche und energetische Modellierung des Biogasbildungsprozesses* (Dissertation). Ruhr-Universität Bochum, Bochum.

Grim, J., Nilsson, D., Hansson, P.-A., & Nordberg, Å. (2015). Demand-orientated power production from biogas: Modeling and simulations under Swedish conditions. *Energy & Fuels*, *29*(7), 4066–4075. https://doi.org/10.1021/ef502778u

Gurobi Optimizer (2018). *Gurobi Optimizer: Gurobi Optimization, Inc. (Gurobi)*. Retrieved from https://www.gurobi.com

Haenel, H.-D., Rösemann, C., Dämmgen, U., Freibauer, A., Döring, U., Wulf, S., … Osterburg, B. (2016). *Calculations of gaseous and particulate emissions from German agriculture 1990–2014: Report on methods and data (RMD) submission 2016*. Thünen Report: Vol. 39. Braunschweig: Johann Heinrich von Thünen-Institut. Retrieved from https://hdl.handle.net/10419/130598

Hahn, H., Ganagin, W., Hartmann, K., & Wachendorf, M. (2014). Cost analysis of concepts for a demand oriented biogas supply for flexible power generation. *Bioresource Technology*, *170*, 211–220. https://doi.org/10.1016/j.biortech.2014.07.085

Hahn, H., Hartmann, K., Bühle, L., & Wachendorf, M. (2015). Comparative life cycle assessment of biogas plant configurations for a demand oriented biogas supply for flexible power generation. *Bioresource Technology*, *179*, 348–358. https://doi.org/10.1016/j.biortech.2014.12.007

Härdtlein, M., Eltrop, L., Messner, J., & Dederer, M. (2013). *Schwachstellen-Identifikation und Optimierungspotenziale von Biogasanlagen in Baden-Württemberg. Eine technisch-ökonomische Analyse auf der Basis einer Befragung von Biogasanlagenbetreibern*. Stuttgart, Germnay: Endbericht.

Havukainen, J., Uusitalo, V., Niskanen, A., Kapustina, V., & Horttanainen, M. (2014). Evaluation of methods for estimating energy performance of biogas production. *Renewable Energy*, *66*, 232–240. https://doi.org/10.1016/j.renene.2013.12.011

Hellwig, M. (2003).*Entwicklung und Anwendung parametrisierter Standard-Lastprofile* (Dissertation). Technische Universität München, München.

Hijazi, O., Munro, S., Zerhusen, B., & Effenberger, M. (2016). Review of life cycle assessment for biogas production in Europe. *Renewable and Sustainable Energy Reviews*, *54*, 1291–1300. https://doi.org/10.1016/j.rser.2015.10.013

Hochloff, P., & Braun, M. (2014). Optimizing biogas plants with excess power unit and storage capacity in electricity and control reserve markets. *Biomass and Bioenergy*, *65*, 125–135. https://doi.org/10.1016/j.biombioe.2013.12.012

Holzhammer, U., Krautkremer, B., Stelzer, M., Jentsch, M., van Oehsen, A., Kirchner, D., …Doderer, H. (2014).*Optimale Konzepte für eine steuerbare und bedarfsorientierte Stromerzeugung aus Biogas und Biomethan (OptiKobi2)*. Kassel, Germany: Fraunhofer-Institut für Windenergie und Energiesystemtechnik (Fraunhofer IWES).

Intergovernmental Panel on Climate Change (IPCC) (Ed.) (2013). *Climate change 2013: The physical science basis : Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change*. Cambridge, UK: Cambridge University Press. Retrieved from https://www.climatechange2013.org/images/report/WG1AR5_ALL_FINAL.pdf

ISO (2006). *Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen*. (ISO, 14040). Geneva, Switzerland: Beuth Verlag GmbH.

Koch, M. (2009). *Ökologische und ökonomische Bewertung von Co-Vergärungsanlagen und deren Standortwahl*. Dissertation, Universitätsverlag Karlsruhe, Karlsruhe.

Kost, C., Shammugam, S., Jülch, V., Nguyen, H.-T., & Schlegl, T. (2018). *Stromgestehungskosten erneuerbare Energien: März 2018*.

Freiburg, Germany: Fraunhofer-Institut für Solare Energiesysteme (ISE).

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) (Ed.) (2013). *Faustzahlen Biogas* (3. Ausg). Darmstadt, Germany: Kuratorium fur Technik und Bauwesen in der Landwirtschaft e.V. (KTBL).

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) (Ed.) (2014). *Betriebsplanung Landwirtschaft: 2014/15* (24th ed.). Darmstadt, Germany: Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL).

Kuratorium für Technik und Bauwesen in der Landwirtschaft e.V. (KTBL) (2016). *KTBL Feldarbeitsrechner*. Retrieved from https://daten.ktbl.de/feldarbeit/home.html

Lantz, M. (2012). The economic performance of combined heat and power from biogas produced from manure in Sweden – A comparison of different CHP technologies. *Applied Energy*, *98*, 502–511. https://doi.org/10.1016/j.apenergy.2012.04.015

Lantz, E., Leventhal, M., & Baring-Gould, I. (2013). *Wind power project repowering: Financial feasibility, decision drivers, and supply chain effects* Denver, CO: National Renewable Energy Laboratory.

Laperrière, W., Barry, B., Torrijos, M., Pechiné, B., Bernet, N., & Steyer, J. P. (2017). Optimal conditions for flexible methane production in a demand-based operation of biogas plants. *Bioresource Technology*, *245*(Pt A), 698–705. https://doi.org/10.1016/j.biortech.2017.09.013

Lauer, M., Dotzauer, M., Hennig, C., Lehmann, M., Nebel, E., Postel, J., … Thrän, D. (2017). Flexible power generation scenarios for biogas plants operated in Germany: Impacts on economic viability and GHG emissions. *International Journal of Energy Research*, *41*(1), 63–80. https://doi.org/10.1002/er.3592

Lauer, M., & Thrän, D. (2017). Biogas plants and surplus generation: Cost driver or reducer in the future German electricity system? *Energy Policy*, *109*, 324–336. https://doi.org/10.1016/j.enpol.2017.07.016

Liebetrau, J., Daniel-Gromke, J., Oehmichen, K., Friehe, J., Clemens, J., & Hafermann, C. (2011). *Emissionsanalyse und Quantifizierung von Stoffflüssen durch Biogasanlagen im Hinblick auf die ökologische Bewertung der landwirtschaftlichen Biogasgewinnung und Inventarisierung der deutschen Landwirtschaft: (FKZ: 22023606)*. eipzig, Germany: Deutsches BiomasseForschungsZentrum (DBFZ).

Lijó, L., Lorenzo-Toja, Y., González-García, S., Bacenetti, J., Negri, M., & Moreira, M. T. (2017). Eco-efficiency assessment of farm-scaled biogas plants. *Bioresource Technology*, *237*, 146–155. https://doi.org/10.1016/j.biortech.2017.01.055

Lindorfer, H., Braun, R., & Kirchmayr, R. (2006). Self-heating of anaerobic digesters using energy crops. *Water Science and Technology*, *53*(8), 159–166. https://doi.org/10.2166/wst.2006.246

Linke, B., Muha, I., Wittum, G., & Plogsties, V. (2013). Mesophilic anaerobic co-digestion of cow manure and biogas crops in full scale German biogas plants: A model for calculating the effect of hydraulic retention time and VS crop proportion in the mixture on methane yield from digester and from digestate storage at different temperatures. *Bioresource Technology*, *130*, 689–695. https://doi.org/10.1016/j.biortech.2012.11.137

Lübken, M., Wichern, M., Schlattmann, M., Gronauer, A., & Horn, H. (2007). Modelling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. *Water Research*, *41*(18), 4085–4096. https://doi.org/10.1016/j.watres.2007.05.061

Madlener, R., Antunes, C. H., & Dias, L. C. (2009). Assessing the performance of biogas plants with multi-criteria and data envelopment analysis. *European Journal of Operational Research*, *197*(3), 1084–1094. https://doi.org/10.1016/j.ejor.2007.12.051

MATLAB and Statistics Toolbox (2017). *The MathWorks, Inc*. Natick, MA: Mathworks.

Mauky, E., Weinrich, S., Jacobi, H.-F., Nägele, H.-J., Liebetrau, J., & Nelles, M. (2017). Demand-driven biogas production by flexible feeding in full-scale - Process stability and flexibility potentials. *Anaerobe*, *46*, 86–95. https://doi.org/10.1016/j.anaerobe.2017.03.010

Mauky, E., Weinrich, S., Nägele, H.-J., Jacobi, H. F., Liebetrau, J., & Nelles, M. (2016). Model predictive control for demand-driven biogas production in full scale. *Chemical Engineering & Technology*, *39*(4), 652–664. https://doi.org/10.1002/ceat.201500412

Nemet, G. F. (2006). Beyond the learning curve: Factors influencing cost reductions in photovoltaics. *Energy Policy*, *34*(17), 3218–3232. https://doi.org/10.1016/j.enpol.2005.06.020

Pfeifer, J., & Oberberger, I. (2007). Technological evaluation of an agricultural biogas chp plant as well as definition of guiding values for the improved design and operation. In *15th European Biomass Conference & Exibition* (pp. 1864–1868).

Poeschl, M., Ward, S., & Owende, P. (2012a). Environmental impacts of biogas deployment – Part I: Life cycle inventory for evaluation of production process emissions to air. *Journal of Cleaner Production*, *24*, 168–183. https://doi.org/10.1016/j.jclepro.2011.10.039

Poeschl, M., Ward, S., & Owende, P. (2012b). Environmental impacts of biogas deployment – Part II: Life cycle assessment of multiple production and utilization pathways. *Journal of Cleaner Production*, *24*, 184–201. https://doi.org/10.1016/j.jclepro.2011.10.030

Reinhold, G. (2005). *Masse- und Trockensubstanzbilanz in landwirtschaftlichen Biogasanlagen*. Jena, Germany: Thüringer Landesanstalt für Landwirtschaft (TLL).

Reinhold, G. (2009). Einfluss der Biogaserzeugung auf das Restgaspotenzial und Eigenschaften der Gärreste sowie die Anforderungen an Gärrestlager. In *Internationale Bio- und Deponiegas Fachtagung "Synergien nutzen und voneinander lernen III"* (pp. 179–197).

Ruile, S., Schmitz, S., Mönch-Tegeder, M., & Oechsner, H. (2015). Degradation efficiency of agricultural biogas plants–a full-scale study. *Bioresource Technology*, *178*, 341–349. https://doi.org/10.1016/j.biortech.2014.10.053

Schievano, A., D'Imporzano, G., Orzi, V., & Adani, F. (2011). On-field study of anaerobic digestion full-scale plants (Part II): New approaches in monitoring and evaluating process efficiency. *Bioresource Technology*, *102*(19), 8814–8819. https://doi.org/10.1016/j.biortech.2011.07.012

Schmehl, M., Hesse, M., & Geldermann, J. (2012). Ökobilanzielle Bewertung von Biogasanlagen unter Berücksichtigung der niedersächsischen Verhältnisse (Research Paper No. 11). Göttingen, Germany: Schwerpunkt Unternehmensführung Wirtschaftswissenschaftliche Fakultät Georg-August-Universität Göttingen.

Schöftner, R., Klaus, V., Schmiedinger, B., Trogisch, S., Haberbauer, M., Katzlinger, K., … Weran, N. (2006). Best Biogas Practise: Monitoring und Benchmarks zur Etablierung eines Qualitätsstandards für die Verbesserung des Betriebs von Biogasanlagen und Aufbau eines österreichweiten Biogasnetzwerks (Berichte aus Energie- und Umweltforschung No. 45/2007). Steyr.

Statistisches Landesamt Baden-Württemberg (2017). *Regional Daten: Land und Forstwirtschaft*. Retrieved from https://www.statistik-bw.de/SRDB/?E=GS

Stenull, M., Brellochs, J., Härdtlein, M., & Eltrop, L. (2014). *Upgrading' der Biomassepotenziale Strom aus erneuerbaren Energien: Eine Perspektive zur effizienten Nutzung von Biomasse - Techniken und Kosten*. Stuttgart, Germany: Zentrum für Energieforschung e.V. (ZfES).

Szarka, N., Scholwin, F., Trommler, M., Jacobi, H. F., Eichhorn, M., Ortwein, A., & Thrän, D. (2013). A novel role for bioenergy: A flexible, demand-oriented power supply. *Energy*, *61*, 18–26. https://doi.org/10.1016/j.energy.2012.12.053

Tappen, S., Aschmann, V., & Effenberger, M. (2016). *Energetische Effizienz und Emissionen der Biogasverwertung*. Abschlussbericht.

Transmission system operators (TSO) (2017). *EEG-Anlagenstammdaten*. Retrieved from https://www.netztransparenz.de/EEG/Anlagenstammdaten

Vazquez-Rowe, I., Golkowska, K., Lebuf, V., Vaneeckhaute, C., Michels, E., Meers, E., … Koster, D. (2015). Environmental assessment of digestate treatment technologies using LCA methodology. *Waste Management*, *43*, 442–459. https://doi.org/10.1016/j.wasman.2015.05.007

VDI (2012). *Betriebswirtschaftliche Berechnungen für Investitionsgüter und Anlagen*. (VDI-Richtlinie, 6025). Düsseldorf.

Walters, A. B. (1995). *Power plant topping cycle repowering*. Retrieved from https://www.osti.gov/biblio/160794-power-plant-topping-cycle-repowering.

Weinrich, S., & Nelles, M. (2015). Critical comparison of different model structures for the applied simulation of the anaerobic digestion of agricultural energy crops. *Bioresource Technology*, *178*, 306–312. https://doi.org/10.1016/j.biortech.2014.10.138

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., & Weidema, B. (2016). The ecoinvent database version 3 (part I): Overview and methodology. *The International Journal of Life Cycle Assessment*, *21*(9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Willeghems, G., & Buysse, J. (2016). Changing old habits: The case of feeding patterns in anaerobic digesters. *Renewable Energy*, *92*, 212–221. https://doi.org/10.1016/j.renene.2016.01.081

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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