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A FULL-SCALE STUDY ON EFFICIENCY AND EMISSIONS OF AN AGRICULTURAL BIOGAS PLANT

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Contents

Abbreviations

BGP	biogas plant
CAP	common agricultural policy
CH_4	methane
CHP	combined heat and power
CO	carbon monoxides
CO_2	carbon dioxide
CPC	central plant control
DM	dry matter
EEG	German renewable energy act
el.	electrical
FBTB	fixed-bed trickling bioreactor
GHG	greenhouse gases
H_2S	hydrogen sulfide
kW	kilowatt
kWh	kilowatt hours
MW	megawatt
NIRS	near infrared spectroscopy
NO_x	nitrogen oxides
O_2	oxygen
oDM	organic dry matter
OLR	organic loading rate
RE	removal efficiency
SNG	substitute natural gas
TWh	terrawatt hours
VFA	volatile fatty acids
LCA	life cycle assessment
HBT	Hohenheimer biogas yield test

1. General introduction

Energy and renewable energy in Germany

The excessive use of fossil fuels as our main energy source has tremendous impacts on mankind and has been extensively debated worldwide, concerning social, ecological and economic issues. In 2010 more than half (54.1%) of the EU-27's gross inland energy consumption came from imported sources [1]. Germany is the 7th largest consumer of primary energy in the world, importing about 60% of this source for its gross national energy consumption [2].

The term "Energy Transition" describes the German political agenda to move away from the use of fossil fuels for energy generation in order to contribute to climate protection and to secure a domestic energy supply from diversified energy sources [3]. The "Energy Concept," released in 2010, sets the long-term strategic key objectives of energy and climate policy, and includes a wide range of measures [4]. Using the greenhouse gas emissions of 1990 as reference, the goal is to reduce emissions by 40% by 2020, 55% by 2030, 70% by 2040 and 80-95% by 2050. The share of renewables in total final energy consumption is targeted to reach 18% by 2020, and then gradually increases to 30% by 2030 and 60% by 2050. The share of renewables in electricity production is expected to be 80% by 2050 [5]. Energy efficiency will be a major part of the strategy to reduce primary energy consumption by 20% by 2020 and 50% by 2050 compared with the consumption in 2008 [5]. This plan seems challenging, as the previous energy networks are inefficient, disconnected, ageing and centralized, which must be changed into modern, efficient, connected, distributed and decentralized energy networks [6].

Even before "Concept 2050" was developed, a powerful instrument known as the "German Renewable Energy Act" (EEG) was established to support the electricity generation from renewable energy sources such as solar radiation, wind power, geothermal power, hydropower and energy production from biomass to reach the political goals. Since 1991, when the forerunner of the EEG became law, and especially from 2001 on, when the German parliament implemented the EEG, renewable energies have become increasingly important [7]. In 2011, 20% (123.2 TWh) of the German electricity supply was generated from alternative resources and a share of 12.5% (300.9 TWh) of total final energy consumption (2,415 TWh) was achieved by renewable energies, reducing total greenhouse gas emissions by approximately 129 million t CO_2 equivalent [8]. Also in 2011, the production of biogas contributed to 14.2% (17.5 TWh) of electric energy and to 11.8% (17 TWh) of heat energy produced from renewable sources, thus avoiding ~12.5 million tons of CO_2 equivalent in total [9].

Status quo of agriculture and agricultural biogas production in Germany

Since 1950, agricultural production has been supported by market protection in Germany. In combination with the expansion of agricultural area and a massive increase in productivity, especially in the 1960s and 1970s, a massive surplus of food was produced. This led to low agricultural incomes, rising costs for government policies, environmental concerns and competition distortion, especially for third world countries [3]. Since this policy changed in 2005 (CAP reform), farmers are facing world market prices, and an overdue structural change of the sector began. At the time the CAP reforms came into power, the Renewable Energy Act offered an opportunity to secure farmers' income. As a consequence, farmers adopted the biogas technique, as wastes from animal husbandry, as well as energy crops, are suitable for biogas production and thus led to a rapid and massive growth of the biogas sector in Germany. By 2011, 7,320 biogas plants were in operation, supplying the electricity grid with 2,997 MW electrical power [10]. Agricultural biogas production can contribute to energy security, environmental and climate protection, as well as provide socio-economic benefits. In addition, it promotes the development of rural areas [11] and creates new jobs (58,400 in 2010 [10]). There is also a benefit for operators of agricultural biogas plants, as the digested manure shows improved fertilizing effect, so the amount of synthetic fertilizer purchased can be reduced. Additionally, a substantial reduction of odor can be expected while applying the fermentation residue as fertilizer [11]. Furthermore, anaerobic digestion was found to be very effective in reducing Greenhouse Gas (GHG) emissions from undigested animal manure [12].

In agricultural biogas production, biomass from organic waste and/or energy crops is fermented in a complex process under anaerobic conditions in four phases, resulting in a gas mixture consisting of methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S) and traces of other gases like nitrogen (N_2), oxygen (O_2), hydrogen (H_2), ammonia (NH_3) and additional trace gases. The composition of biogas depends on the organic material, as well as on the conversion technology, varying between 50%-75% CH_4, 25%-45% CO_2 and 0-20,000 ppm H_2S [13, 14].

For biogas production and conversion, different concepts and operation modes are used and a wide range of technical equipment is available on the market. Primarily driven by the amendments of the EEG, the concepts and layout of biogas plants are changing. The implementation of a bonus for renewable energy crops, a technology bonus for dry fermentation techniques and a bonus for heat and power coupling in the amended EEG 2004 led to a growth in digester sizes, novel agitation designs and solid substrate feeding systems. The technical and operational complexity of biogas plants increased.

The largest nationwide study of the agricultural biogas sector in Germany in 2009, called "Biogas-Messprogramm II (BMP II)" [15], covered 413 biogas plants of which 61 were presented in detail. The results showed that a proportion of 37% of the feed was covered by solid and liquid manure from animal husbandry and 63% from renewable energy crops. Maize silage was the predominant crop used for biogas production in percentage of mass and relative frequency. 88% of the biogas plants were operated in wet and 12% (including batch systems) in dry fermentation mode.

The majority of digesters (90%) were built as vertical reactors, 2% as horizontal reactors and 4% being a combination of both. One-stage plants, consisting of one digester, were found in 30% of the biogas plants, 62% were two-stage plants fitted with a digester and a secondary digester and only 8% were multi-stage plants. About 86% of the biogas plants were operated at mesophilic conditions and only 6% under thermophilic conditions. Another 4% of the plants were using a combination of thermophilic digestion in the first stage and mesophilic digestion in the second stage. The digester size is based on the amount of feed supplied, but can vary heavily among biogas plants fed with the same amount of substrate due to different technique and operation mode. The digester volume ranged, depending on plant size, between 350 and 9,200 m^3 at an average of 3,000 m^3 with a majority of 26% between 2,000 and 3,000 m^3. A tendency towards larger digester volumes was found with 42% of all plants showing volumes >3,000 m^3.

Most of the biogas plants (84%) used screw-systems to feed solid substrate into the digesters at a frequency of 20 times a day on average. Liquid manure was supplied six times a day on average. 47% of the anaerobic digesters were equipped with fast rotating submersible mixers. Due to changing input substrates with a tendency of high proportions of renewable energy crops in the feed, slow rotating agitators such as incline shaft agitators (12.9%), paddle agitators (7.4%), central agitators (6.0%) and reel agitators (0.8%) were used to an increasing extent. Furthermore, a combination of slow and fast rotating agitators was found in 16% of the BGP.

In 70% of the biogas plants, the biogas was stored in the headspace of the digester or in fermented substrate storage under foil roofs. The remaining 30% used external gas storage.

Among the majority of recorded biogas plants, the biogas was utilized by Combined Heat and Power (CHP) units. Regarding the total installed electrical capacity, the results showed that 45% of the biogas plants were operated in a power range up to 250 $kW_{el.}$. Only 12% of the biogas plants had a capacity of more than 500 $kW_{el.}$. 57% of the biogas plants with more than 500 $kW_{el.}$ used Gas-Otto engines, more than 30% Dual-fuel engines and the rest a combination of both. In 64% of the biogas plants, only one CHP unit was used to combust the biogas, and in more than 30% of the plants, two engines were registered. Less than 5% of the biogas plants used three CHP units [15]. Regarding the 63 biogas plants measured in detail, the results for electric load showed that 17% achieved 95% load but 10% of the biogas plants showed an electric load less than 60%. A proportion of 9% of the biogas plants (BGP) used the heat from the CHP unit only for the biogas plant and 72% of the BGP used the heat on the farm site. A share of 25% of the plants supplied a heat distribution network and 15% used the heat for other farm site applications. A novel way of gas utilization was applied by 79 [16] biogas plants (1.08% of the total biogas plants in operation in 2011) by using biogas upgrading systems for methane injection into the gas grid [10].

The study showed that only a minority of BGP applied measurement techniques to monitor the production process. Therefore, a selection of 61 BGP equipped with basic measurement technique was chosen for the intensive study. Almost all of them measured the electricity produced by the CHP unit. More than 70% of the biogas plants used electricity meters to record the electric energy consumption of the process. A proportion of 50% of the biogas plants used measurement equipment to record the amount of liquid manure supplied to the digester, whereas 80% of the solid substrates supplied were measured. Gas quality and quantity of the biogas plants is measured at 70% and 60%, respectively. The study showed that 46 out of 61 BGP could measure auxiliary electric energy demand but none of them could measure CHP heat production [15].

According to a study carried out in the German Federal State of Baden-Württemberg, a number of 612 biogas plants have been in operation in 2009. The total electric capacity has increased six-fold and the average electric capacity has tripled since 2005. In comparison to the BMP II study, a rising input of manure was found. The influence of the EEG 2009 is clearly visible in this regard as manure is subsidized by a bonus when fed at a minimum of 30% of the total substrate input. An increase in digester volume was also found. No other fundamental changes are found in comparison to the BMP II measurement program. On average, 88% of the biogas plants were operated at full load and one third achieved a load of 90%. Only about 10% of the biogas plants achieved a load of less than 80%. Not more than 30% of the biogas plants supplied the heat provided by the CHP unit to external consumers

[17]. The study showed how politics had a fast and direct impact on biogas plant design and development of the sector.

Critical issues of agricultural biogas production

Despite the technological, environmental and economic opportunities of biogas production as well as a positive public image of bioenergy in general - agricultural biogas production is not generally regarded as a positive development, and has been controversially debated recently. One criticism is that biogas may cause lower biodiversity due to the large increase of maize grown for biogas plants and the negative effects of this crop on the environment. Furthermore, there is a doubt that biogas production contributes to a reduction of greenhouse gases. There is debate that due to limited agricultural land in Germany and an increase in demand for energy crop production, the lease prices for agricultural land have risen drastically, thus intensifying competition over land use [5]. An important issue has been the concerns about the competition between fuel and food. At a global scale, land available for food production is limited and production growth must come from an increase in productivity of the land already in use. The growth in food supply will not keep pace with the growth in global demand [3]. The study "bioenergy – changes and limits" published by the Leopoldina in 2012 [18] provoked sharp criticism on the current state of legal governance of bioenergy production as it leads to a misallocation of resources. "Promotion of bioenergy should be limited to those forms of bioenergy that: (a) do not reduce food availability or spur food-price increases due to competition for limited resources such as land or water; (b) do not have large adverse impacts on ecosystems and biodiversity; and (c) have a substantially (>60 –70 per cent) better GHG balance than the energy carriers they replace" [18]. The researchers believe that animal manures and energy captured from biogenic wastes or residues, combining food and bioenergy production are promising for bioenergy production. Furthermore, the authors recommend further research in the fields of land-use related to GHG emissions and on consequential comprehensive GHG life-cycle assessments of different production systems for agriculture, food and bioenergy [18]. The rising prices of electric energy in Germany have been debated intensively in the context of the fast growing renewable energy provision over the last time and led to political considerations about measures to keep prices down [19].

The success of biogas is, in respect to other bioenergy sources, based on its flexibility as it is balanceable, capable for base and peak load, as well as storable. These advantages are so essential that the "Energy Transition" in Germany will not be successful without biogas [20].

Thus, biogas technology can be expected to gain further efficiency and importance in the future as continuous innovations are underway.

To address current criticism, energy production based on agricultural resources needs to be improved in efficiency - in terms of technical and environmental aspects. This is essential to deescalate the mentioned conflicts and mitigate conflicts in future. The rapid dissemination of biogas technology over the last years and the upcoming critical debates lead to an increasing demand for research.

History of research on biogas

Today, biogas is well established, but it is often forgotten that it has been used for many centuries. Since 1900, biogas technology has been used in technical applications, for the treatment of wastewater, solid organic wastes and energy crops [21]. Nevertheless, only a little information is found that reports about biogas research. Research on agricultural biogas production has a 60-year-old tradition at the University of Hohenheim and at the Bayerische Landesanstalt für Landtechnik. At Hohenheim, research began with small scale biogas plants for 10 livestock units, but the need for further research was recognized and a biogas laboratory with 22 horizontal stirred and heated digesters was built in 1979/80, at the institute of agricultural engineering. Six pioneer, full-scale biogas plants built after 1981, with governmental funding, have been advised, monitored and evaluated by the state institute of farm machinery and farm structures. Low oil prices in the 1980s prevented further development, until in 1990 the electricity feed act was signed, leading to a new impetus in biogas research. Even before the Electricity Feed-in Act came into force in 1990, numerous institutes such as the Leibniz-Institut für Agrartechnik Potsdam-Bornim e.V. (ATB), Bayerische Landesanstalt für Landwirtschaft (LFL) and Forschungsanstalt für Landwirtschaft (FAL) started to intensify biogas research. The rapid development of the agricultural biogas sector led to a rapid growth of research, and nowadays a vast number of research institutes can be found all over Germany. In recognition of the increasing importance of bioenergy research, the Deutsches Biomasseforschungszentrum (DBFZ) was founded in 2008 as a non-profit LLC by the Federal German Government, represented by the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) as the sole shareholder of the DBFZ. At the University of Hohenheim, a new biogas laboratory came into operation in 2004, allowing research on liquid and solid material digestion, including automatic measurements of gas quality and quantity [22]. In addition to the research capacities on a laboratory scale, the first

European full-scale research biogas plant was established in 2008 at the agricultural research station “Unterer Lindenhof.”

Research on agricultural biogas production

Weiland [23] provides a comprehensive overview on the current state and perspectives of biogas research, in combination with the practical point of view. He describes the technical status and developments by selecting the categories:

- biochemical parameters
- feedstock
- process technology
- biogas utilization
- digestate utilization.

Since this review was published, biogas technology and biogas research continued developing, but Weiland’s classification is still valid. Current research on biochemical parameters is focusing on microbiology and methanogenic germs [24-27], micronutrient supply for methanogenic bacteria [28, 29] and online monitoring of the process stability [30]. Research on feedstock for biogas production increased strongly in the fields of plant breeding [31, 32], crop production [33], feedstock potential analyses [31, 34] and substrate pre-treatment [35, 36]. In process technology, the separation of digestion processes [37], fermentation under high pressure [38-40] and a novel digester design [41] are state-of-the-art research. Current research in biogas utilization is carried out on the subjects of CHP efficiency and emissions [42], and upgrading of biogas to SNG quality with membrane or washing technology [43, 44]. The utilization of the digestate, and in particular the losses of Ammonia, are assessed and evaluated [44, 45]. However, an important method remains unmentioned by Weiland. To assess the environmental impact of biogas production, life cycle assessment (LCA) methods are a common tool used to evaluate the overall environmental efficiency [46-49]. For policymakers, this tool, which combines the results from various research disciplines, is of major importance.

Although much research has been conducted in recent years, a scientific evaluation of gas production and gas utilization technology on full-scale biogas plants is still missing. Currently, biogas plant development is still carried out based on experience and only in rare cases based on fundamental scientific research. Little is known about the interaction of process technology and process stability, e.g. microbiology beyond laboratory scale, although comprehensive studies on process stability could have been carried out in laboratory scale over the last years [28]. Studies show considerably varied results concerning the process stability of biogas digesters, auxiliary energy consumption, as well as emissions from biogas combustion [50-52], because most of the results are based on laboratory scale research and measurement programs [15, 17, 53, 54].

Why full-scale research?

In practice, biological process stability is not only influenced by process parameters such as organic loading rate, hydraulic retention time and composition of the feed but also by the interaction of process engineering and process biology. However, many important aspects remain unanswered, as laboratory-based research is unsuitable in this regard. To give an example: on the laboratory scale, co-fermentation of renewable energy crops and liquid manure showed stable fermenting processes up to 5 kg oDM/m³ digester volume and day. In full-scale biogas plants, process stability is often endangered at organic loading rates of 3.5 kg oDM/m³ digester volume and day under the same conditions. These problems may be caused by low mixing quality, resulting in unequal distribution of liquid manure or biological inactive zones in the digester [50]. The existence of dead zones in laboratory scale digesters and simulations has been reported by several authors [55, 56]. The total efficiency of the anaerobe conversion of biomass is influenced to a large extent by its auxiliary electric energy demand measured by several authors between 6% and 20% at agricultural biogas plants [15, 54]. Measurements of electric energy consumption of consumer units, in detail and in a the long-term, are missing. Until now there has been a lack of understanding of the importance of electric energy consumption and only a little data is found to compare the efficiency of different biogas plants. A data survey on emissions and electric efficiency at Combined Heat and Power units at different agricultural biogas plants showed a considerable variation depending on engine type and maintenance strategy [57]. Despite a long observation period, the problems of these studies are that only spot measurements for a short time span were conducted and that gas quality and emissions could not be varied. Until now, only a few measurement campaigns on full-scale agricultural biogas plants have been carried out under "ceteris paribus" conditions.

To enhance efficiency at agricultural biogas plants, reliable data is required. Data is gained first of all from laboratory-scale research in which, under standard conditions (temperature, feed supply), a large variety of substrates at a high repeatability can be examined and afterwards transferred to practical application. Due to lower investment costs compared to full-scale biogas plants, technical setups can be tested more efficiently. At present, only a few agricultural biogas plants are fitted with measurement techniques for process control, as this equipment is expensive, unreliable and requires high maintenance (e.g. for calibration). A lack of practical data was determined. To address this shortcoming, several research projects have been carried out focusing on data acquisition from practice [15, 54, 58]. In all these projects, the data acquisition was carried out in accompanying manner without interference or interruption of the operational process. A major advantage of these studies is that a large number of different biogas plants could be measured and evaluated. Very valuable real-life data was hereby collected but without having the chance of changing the operational conditions to make them suitable for research. Despite the enormous growth in knowledge over the last years, the recent data is shown to be very inconsistent often with an undefined quality and many questions still remain unanswered.

The practical scale research biogas plant “Unterer Lindenhof” of the University of Hohenheim offers the opportunity to scale up the research approaches previously conducted on the laboratory scale. A large variety of measurement equipment at the biogas plant enables the recording of measurement data in high resolution and range by ensuring high-quality standards of measurements [59]. The research biogas plant operated under full-scale conditions provides, for the first time, the opportunity to undertake research under ceteris paribus condition, with the ability to adapt and design the process on the research question, not vice versa.

In this thesis, the question will be raised whether full-scale research on a biogas plant uniquely designed for research is suitable to give answers beyond current knowledge and to show its limitations. Measurements under defined conditions at full-scale agricultural biogas plants are necessary, as results from laboratory research need to be verified in practice. Higher efficiency helps to increase overall efficiency, increasing costs of operating resources need to be cut as they lead to lower incomes and finally public pressure is set on biogas plants to comply with environmental and social standards. This study was conducted within a project funded by the Ministry of Rural Areas and Consumer Protection (Ministerium für Ländlichen Raum und Verbraucherschutz Baden-Württemberg), with financial resources from the foundation “Baden-Württemberg Stiftung”, as part of the bioenergy research platform. The joint research project included a study of potentials of solid, liquid and gaseous biomasses from agriculture and forestry, process engineering for conversion of biomass, upgrading and cleaning of biogenic gases, efficient and low-emissions technologies of biogenic gas utilization, integrated plant concepts, system analyses and implementation concepts, as well as the transfer of technology and know-how.

Objectives of this study

The goal of this research project is to identify key parameters for the technical improvement of biogas plant technique and provision of data for the ecological evaluation of the biogas production process, in order to increase the overall efficiency of the fermentative conversion of biomass to biogas. The term efficiency is generally described as ratio of output to input (e.g. energy, material, labor). An increase in efficiency means a minimization of the use of resources per production unit, achieved through technical innovations. In this thesis, the term efficiency is not only understood as a force to gain economic advantages but also to describe the social and especially environmental benefits. To increase the efficiency of the biogas production process, this study focuses on the technical aspects of process energy consumption and reduction of emissions during the conversion of biogas.

To reach the overall target, this thesis addresses two equally important objectives. The first goal was to conduct intensive and long-term measurements on a full-scale research biogas plant to determine the parameters influencing the efficiency and emissions of biogas production. Those results have been published in scientific journals and are presented in this thesis. In particular, the objectives were:

(1) long-term measurements of the electric energy consumption of the biogas plant and its individual components and examination of energy-saving potentials;
(2) development of a method to measure mixing efficiency in the digester and examination of the mixing quality by measuring nutrient distribution in the digester with different agitator setups;
(3) measurements to determine the influence of maintenance strategies on efficiency and emissions of the CHP unit at long-term operation in practical application;
(4) examine the efficiency of an external biological desulfurization plant under practical conditions to enhance fuel quality of biogas;

The second goal was to answer the question of how suitable the instrument of a research biogas plant is to evaluate the efficiency of biogas production beyond the established methods. For this evaluation, a differentiation in the categories mass balancing, process monitoring and process energy consumption has been chosen.

2. Publication 1: Electric Energy Consumption of the Full Scale Research Biogas Plant "Unterer Lindenhof": Results of Longterm and Full Detail Measurements

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Abstract

This work thoroughly evaluates the electric power consumption of a full-scale, 3 × 923 m^3 complete stirred tank reactor (CSTR) research biogas plant with a production capacity of 186 kW of electric power. The plant was fed with a mixture of livestock manure and renewable energy crops and was operated under mesophilic conditions. This paper will provide an insight into precise electric energy consumption measurements of a full-scale biogas plant over a period of two years. The results showed that a percentage of 8.5% (in 2010) and 8.7% (in 2011) of the produced electric energy was consumed by the combined heat and power unit (CHP), which was required to operate the biogas plant. The consumer unit agitators with 4.3% (in 2010) and 4.0% (in 2011) and CHP unit with 2.5% (in 2010 and 2011) accounted for the highest electrical power demand, in relation to the electric energy produced by the CHP unit. Calculations show that 51% (in 2010) and 46% (in 2011) of the total electric energy demand was due to the agitators. The results finally showed the need for permanent measurements to identify and quantify the electric energy saving potentials of full-scale biogas plants.

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Article

Electric Energy Consumption of the Full Scale Research Biogas Plant "Unterer Lindenhof": Results of Longterm and Full Detail Measurements

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Abstract: This work thoroughly evaluates the electric power consumption of a full scale, 3 × 923 m^3 complete stirred tank reactor (CSTR) research biogas plant with a production capacity of 186 kW of electric power. The plant was fed with a mixture of livestock manure and renewable energy crops and was operated under mesophilic conditions. This paper will provide an insight into precise electric energy consumption measurements of a full scale biogas plant over a period of two years. The results showed that a percentage of 8.5% (in 2010) and 8.7% (in 2011) of the produced electric energy was consumed by the combined heat and power unit (CHP), which was required to operate the biogas plant. The consumer unit agitators with 4.3% (in 2010) and 4.0% (in 2011) and CHP unit with 2.5% (in 2010 and 2011) accounted for the highest electrical power demand, in relation to the electric energy produced by the CHP unit. Calculations show that 51% (in 2010) and 46% (in 2011) of the total electric energy demand was due to the agitators. The results finally showed the need for permanent measurements to identify and quantify the electric energy saving potentials of full scale biogas plants.

Keywords: electric power consumption; biogas; electric power measurement; consumer units; full scale research biogas plant

1. Introduction

Energy production from biogas is one part of the strategy of the Federal Government of Germany to achieve a modern, climate-friendly, sustainable and secure energy supply [1]. By the year 2020, a share of at least 30% of the total gross electricity consumption is meant to come from renewable energies [1]. Due to guaranteed feed-in tariffs for "green" electricity under the Renewable Energy Sources Act (EEG) from 2001 and its amended versions of 2004, 2009 and 2012, the number of biogas plants has grown rapidly [2] and reached 5.905 in 2010, with an installed electrical capacity of 2,291 MW [3]. According to certain predictions, the numbers of biogas plants in Germany will increase approximately to 7,521, with an installed electrical capacity of 3,185 MW, by the end of 2012 [3,4]. Electricity production from biogas accounted for 2.8% of the total electricity demand in 2011, supplying the grid with 17.5 TWh of electricity *per annum* [1]. The share of biogas in electricity supplied from renewable energy sources reached 14.4% in 2011 [1]. With an increasing percentage of bioenergy produced from biogas, the question arises of whether this technology has a positive life-cycle assessment compared to others [5,6]. By using renewable energy crops as basic material for the anaerobic conversion to biogas, these substrates represent the main costs of biogas production. This means a great difference to other bioenergy sources such as wind and solar power which work on naturally supplied energy. The prices for biogas substrates on the market are volatile and may rise over time [7]. However, the feed-in tariff is fixed and new tariffs are laid out by the Renewable Energy Sources Act in Germany and many other European countries [8,9], with a possible decrease [7] in the future.

For these reasons, the energy efficiency of a biogas plant is of major importance both for the acceptance of the technology itself and for the profitability of such ventures. For the production of biogas it is at first necessary to produce raw materials with a high energy expenditure. These materials must then be transformed in a technical installation for fermentative conversion using electric power and different equipment [10]. The use of this auxiliary energy input by the biogas plant reduces its net energy production and therefore reduces the positive climate balance of biogas production [11].

The efficiency of energy conversion from biomass varies widely, depending on different technologies [12]. The demand for auxiliary electric energy was measured by a program covering 61 BGP in various regions in Germany. It showed that 5%–10% of the produced electrical energy was used for conversion [13]. Taking this as a reference, 2,291 MW/h electricity from biogas were fed into to the grid in 2010. Furthermore, calculations show that for a given electric energy consumption of 5%–10%, a CHP availability of 95% and an assumed energy price of 0.145 € [14], the total expenditures for electricity vary between 138 and 276 Million € per year.

In practice, only a small number of biogas plants are equipped with sufficient measurement instrumentation. Most operators calculate their percentage of electric energy consumption from the invoices of the energy suppliers. In order to identify the main consumers of electric power on a biogas plants, several measuring activities and programs have been carried out. They showed that the results partly vary over a wide range [11,13,15–17]. In 2005, a survey of the FNR revealed a variation from 1% to 6% of electric energy consumption in relation to the produced electric energy among the majority of the surveyed biogas plants. A study of Lehner and Effenberger [18] on 10 agricultural biogas plants over a period of one to two years, with an electric capacity ranging from 250 to 526 kW, showed that the total energy consumption varied from 3.7% to 17.4% with an average of 8.8% of the produced electricity. Taking the total electric energy consumption into account, the consumer units CHP accounted for 30%–88%, the agitation units for 5.4%–57.8% and the solid feeding system for 0.9%–7.6%, giving an unequal distribution among the biogas plants. The authors pointed out that such substantial differences in electric energy consumption are mainly influenced by the technology applied and the individual plant operating conditions [18]. A survey on 61 biogas plants in Germany showed a range from 5% to 20.7% of electricity, consumed with an average of 7.9%, also in relation to the total electric energy produced by the CHP unit [13]. Electric energy consumption within a range from 3.5% to 17.5% an average of 8.2% was measured on six biogas plants by Dachs and Rehm, without taking into account the biological conditions at these plants [16]. In order to increase the energy efficiency of biogas plants, the interaction of technical equipment and biological parameters have to be taken into consideration. Still, there is a lack of long-term as well as detailed measurement of all relevant electric consumers and their impact on microbial parameters. The "Intensive Measuring Program" project, financed with funds of the Landesstiftung Baden-Württemberg GmbH, aims to examine the influence of the process technology on the auxiliary electrical power consumption of the plant and its influence on the microbial conversion of the biomass. The survey is set on the research biogas plant "Unterer Lindenhof" of the University of Hohenheim.

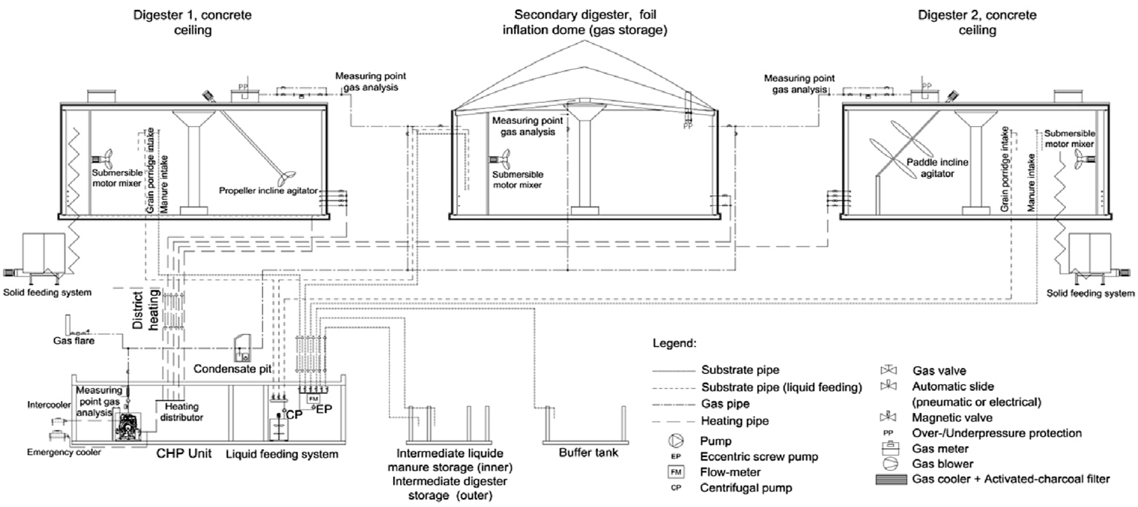
The first project phase focused on measuring and analyzing the auxiliary energy input of this biogas plant. The aim was to examine in detail not only the entire auxiliary electric energy of the biogas plant, but also individual components as set out in this paper. Particularly, the combined heat and power plant (CHP) and its auxiliary drives was of special importance. On the basis of these results the energy production process could then be analyzed and optimized along the closed biomass material cycle.

2. Results and Discussion

2.1. Research Biogas Plant "Unterer Lindenhof"

The research biogas plant of the University of Hohenheim is located at the "Lindenhof" agricultural research estate in the village of Eningen unter Achalm, 35 km south of Stuttgart. The substrates for the conversion process are manure in liquid and solid form (from the 220 livestock unit animal production there), as well as energy crops from 180 ha of arable land and grassland. All renewable energy crops, mainly grass silage, whole-plant grain silage, maize silage and special biogas crop-mixtures from the research fields are stored in five horizontal silos for all year operation. The substrate is premixed in two different vertical mixer systems and fed into the two digesters via two feeding screws. Since all crops are harvested with a forage harvester and cut to a size of 10–65 mm, no additional pretreatment is applied. The biogas plant consists of two digesters, covered with insulation concrete, and one secondary-digester, set up with a 300 m^3 foil inflation dome for gas storage. Every digester has a maximum volume of 923 m^3 and is equipped with different heating systems (Figure 1). All heating systems can be run independently from each other. The digesters are all equipped with submersible motor mixers. Furthermore, digester no. 1 is set up with a propeller incline agitator, whereas digester No. 2 is fitted with a paddle incline agitator unit. The system is fed with a mixture of approximately eight tons of renewable energy crops and two tons of solid manure. Additionally, 6–10 m^3 of liquid manure are added per day. This input allows the six cylinder gas engine to run on 186 kW electrical and 202 kW thermal power. After transformation, the electrical power is fed into the local energy grid. The thermal power is primarily used for digester heating and supplies the thermal energy grid of the research station with the surplus energy. The remaining heat surplus is recooled in emergency cooler systems. The thermal output power extracted from the mixture cooling with 29 kW cannot be used, due to the construction setup. It is recooled with an emergency cooler system. The organic loading-rate related to the organic dry matter (BODM) equals 1.93 kg·m^{-3} day^{-1} oDM with a total hydraulic retention time (HRT) of 120 days. The standard procedure for desulfurization is carried out on a biological basis with a calculated amount of ambient air, injected into the gaseous phase of the digesters and the secondary digester. Before entering the engine, the gas passes through a gas processing module: at first, it reduces the content of water by active cooling. In a second step, it finally cleans H_2S residues from the gas with an activated-charcoal filter. In 2010 and 2011, a full scale external biological desulfurization plant was tested and replaced the internal desulfurization during this period for most of the time. The research biogas plant is designed to measure a maximum of different data for research and is therefore equipped with a central plant control unit for data collection, storage and evaluation. All substrates fed into the biogas process are weighed by the feeding systems or measured with a flow-meter. The substrate temperatures in the fermenting substrate, gas quality, gas temperature, as well as gas quantity are measured continuously in every digester. Samples of input substrates and digester substrate were taken at a weekly routine and analyzed for DM, oDM and volatile fatty acids content in a laboratory. Furthermore, the electrical and thermal energy demand was measured for every key consumer unit.

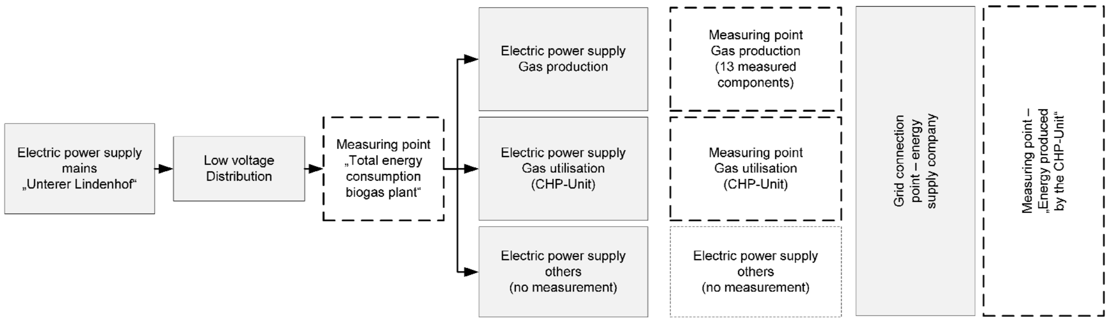
Figure 1. Flow scheme of the investigated research biogas plant.



2.2. Electric Power Measurement

At the research biogas plant electricity is procured from the public power grid via a low voltage distribution (LVD) unit. The individual consumer units of the biogas plant (BGP)—gas production, gas utilization and light & power—are supplied separately from this LVD (Figure 2). The path for gas production runs in a separate switch cabinet and is divided into 13 individual consumer units. The gas utilization path is located in the control cabinet of the CHP, where it is systematically divided into the individual power consumers of the CHP and its peripheral components. At the CHP electricity meter all CHP auxiliary drives and other auxiliary drives supplying the digesters are bundled together. In order to examine the CHP unit in detail, the individual components were monitored over several periods, using external measuring equipment. The results were then analyzed (Table 1). All other small loads, such as outlet sockets and light, were combined in the light & power line, but not explicitly measured, due to their very low energy consumption.

Figure 2. Electric power flow with measuring points at the University of Hohenheim research biogas plant.



The biogas plant was controlled and regulated via a programmable logic controller (PLC), which was joined to the Central Plant Control (CPC) unit via a network. The CPC represents the human machine interface and allows the operator to monitor and control the BGP over a graphic surface. The CPC of the research plant can automatically and simultaneously record, calculate, visualize and archive the data from all measuring points.

Three different methods were applied for the electric energy consumption:

- three-phase electric power consumption measurement,
- single-phase current measurement,
- data acquisition from frequency converters.

2.3. Three Phase Measurement

A calibration-capable, electronic three-phase transformer connected meter (ABB DAB 13000) was used to measure the entire active power input of the biogas plant. This instrument was used for measuring an electric current >80 A via current transformers.

The ABB DBB 23000 meter, used to measure the CHP unit power consumption, measures the current up to 80 A directly at the mains. Each meter was connected with voltage and current coils, using the three watt-meter method, (for three phase 4-wire circuits with a neutral conductor). The meters are able to deal with asymmetrical and symmetrical loads, measuring current (A), voltage (V), frequency (Hz), power factor (cos φ), apparent power (S) and reactive power (Q). The active power (P) is calculated from this source. The electric meter multiplies time (t) with active power, resulting in electric energy consumption. The electric power production of the CHP unit is measured by a manufacturer specific three phase meter. Electronic meters contain analog–digital (AD) converters which generate a digital signal from an analog voltage, current output of the voltage or of a current measuring transformer [7,19]. The microprocessors of the ABB electric meters are able to determine the phase displacement between current and voltage curve from the digitized output values of the AD converters. In a further step, they can calculate the cos φ.

A high precision measurement is achieved with a display error of ±2% related to the N-value of the measuring range, hereby taking all three phases into account. The data from the three meters is transferred to the digital inputs module of the PLC via potential-free contacts. An impulse of 100 ms corresponds to one kilowatt hour electric power demand, which has passed through the meter. The PLC adds up the electric power demand as a cumulative meter value and ensures that the values are achieved and visualized by using the network connection to the CPC.

2.4. Single Phase Measurement

In a 3-phase system it can be assumed that the average power is balanced. Therefore, the current intensity virtually displays the same curve for all phases [19]. Power consumption measurements for three-phase motors can then be carried out with sufficient precision and subsequent conversion on only one phase. In the case of current transformer measuring transducers, the magnetic field of the primary current to be measured induces a secondary current of 4 to 20 mA (on a coil, depending on the consumer load) [19]. This analog signal is transmitted directly to the PLC at the research plant. The active power is calculated by the PLC from the measured current and from the given fixed factor voltage and cos φ. The voltage was assumed to be 400 V, and at the beginning of measurements the value of 0.8 was filed for the power factor cos φ (for all electric motors) and subsequently adapted specifically for each unit. The consumed electric power was added together as a cumulative meter value in kWh and finally transferred to the CPC for visualization and archiving.

2.5. Frequency Converter Measurements

The auxiliary energy demand (in kWh) of units operated via frequency converters (Table 2) can be read off directly from the units and transmitted to the PLC. Again, the consumed electric power was added together as a cumulative meter value in kWh and transferred to the CPC for visualization and archiving.

Table 1. Overview of the auxiliary units at the CHP and measuring methods.

No.	Unit	Measuring method	Active power factor cos φ
1	Gas cooler	Single-phase current measurement	0.757 (measured)
2	Heating-circuit pump	Single-phase current measurement	0.72 (measured)
3	CHP-control unit + aux power units	Single-phase current measurement	0.797 (read at the type plate)
4	Gas compressor	Single-phase current measurement	0.755 (measured)
5	CHP Compartment fan	Single-phase current measurement	0.58 (read at the type plate)
6	Engine lubricating oil pump	Single-phase current measurement	0.9 (manufacturers information)
7	Biogas mixture cooler pump	Single-phase current measurement	0.762 (measured)
8	Biogas mixture cooler fan	Single-phase current measurement	0.797 (read at the type plate)
9	Emergency cooler pump	Single-phase current measurement	0.855 (measured)
10	Emergency cooler fan	Three-phase current measurement	Recorded during the measuring cycle

Table 2. Measured unit, measuring method and electric driving power of the units.

No	Unit	Measuring method	Driving power
1	Propeller incline agitator digester 1	Frequency converter "Danfoss VLC FC 300"	15 kW
2	Submersible motor mixer digester 1	Single phase	13 kW
3	Paddle incline agitator digester 2	Frequency converter "Fuji Electric FA Frenic 5000"	11 kW
4	Submersible motor mixer digester 2	Single phase	13 kW
5	Vertical mixer 1—Solid feeding system digester 1	Single phase	22 kW
6	Vertical mixer 2—Solid feeding system digester 1	Single phase	22 kW
7	Feeding screws—Solid feeding system digester 1	Single phase	5.5 kW
8	Vertical mixer—Solid feeding system digester 2	Single phase	37 kW
9	Feeding screw 1—Solid feeding system digester 2	Frequency converter "Danfoss VLC FC 300"	3 kW
10	Feeding screw 2—Solid feeding system digester 2	Frequency converter "Danfoss VLC FC 300"	7.5 kW
11	Submersible motor mixer—Storage tank	Single phase	7.5 kW
12	Submersible motor mixer—Secondary digester	Single phase	13 kW
13	Manure pump	Frequency converter "Danfoss VLC FC 300"	11 kW
14	Energy counter biogas plant	Three phase	-
15	CHP-electric energy production	Three phase	-
16	CHP-electric energy consumption	Three phase	-

2.6. Additional Measuring Equipment

A HIOKI power quality analyser (3197) with current clamps (9660) was used to measure the auxiliary energy input of all CHP auxiliary units. This measuring device allows the measuring of both single-phase and three-phase current intensities of the individual units for the AC current. Electric current and voltage are determined for the unit over all three phases. The equipment-specific cos φ was measured in advance where possible, or taken from the unit's data sheet. In order to measure a large number of auxiliary units at the same time, the current intensity of one phase was measured at all units and recorded every five minutes. Afterwards, the electric energy consumption in kWh was calculated from current intensity, voltage, cos φ and time unit.

2.7. Data Processing

The data acquisition and monitoring started in October 2008 with a full year of data verification and adjustment of measuring equipment. However, by November 2009 not all data was consistent and representative and therefore not of use for evaluations. As a consequence, the data presented in this paper covers two years, starting from January 2010 to December 2011. At the CPC, the measured data is available in four different compression stages (minutes, hour, day, and month). For further processing, the required data was downloaded, formatted and checked for outliers due to measurement failures. The proportion of electric energy consumption in relation to electric energy, produced by the CHP unit, was calculated as follows:

$$\text{Electric energy consumption}\ \% = \frac{\text{Total electric energy consumption BGP (kWh)} \times 100}{\text{Electric energy production CHP (kWh)}} \tag{1}$$

Table 3 gives a summary of all electrical and additional units used for calculating the results.

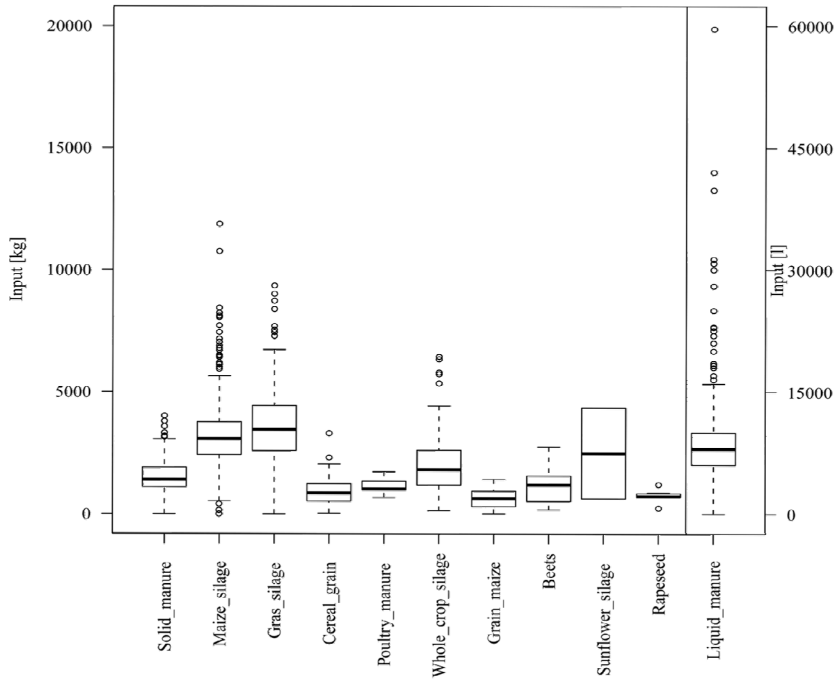
Table 3. Summary of electrical and additional units.

Unit	Unit abbreviation	Symbol
Voltage	U	Volt [V]
Current	I	Ampere [A]
Active power	P	Kilowatt [kW]
Power factor	cos φ	-
Electric energy consumption	P	Kilowatt hours [kWh]
Time	t	[min]
Electric energy consumption	-	[%]

3. Results

As shown in Figure 3 a wide variation within the substrates fed to the digester was observed (for the investigated time). This variation is caused by the changing availability of material at the farm, special research arrangements and technical faults of the solid-feeding systems or the manure pump. A mixture of liquid manure from cattle and pig husbandry with a share of more than 60% was the basis for biogas production. In addition, maize- grass-, and whole plant silage, as well as solid manure and grain were the main energy sources supplied to the digesters. Crops from research fields covered the remaining demand, but did not provide a major share of the feed. Fluctuations in liquid manure supply depend on the livestock units held on the farm and the amount of rainfall on the free-range areas for animals.

Figure 3. Boxplot of input substrates for the years 2010 and 2011.



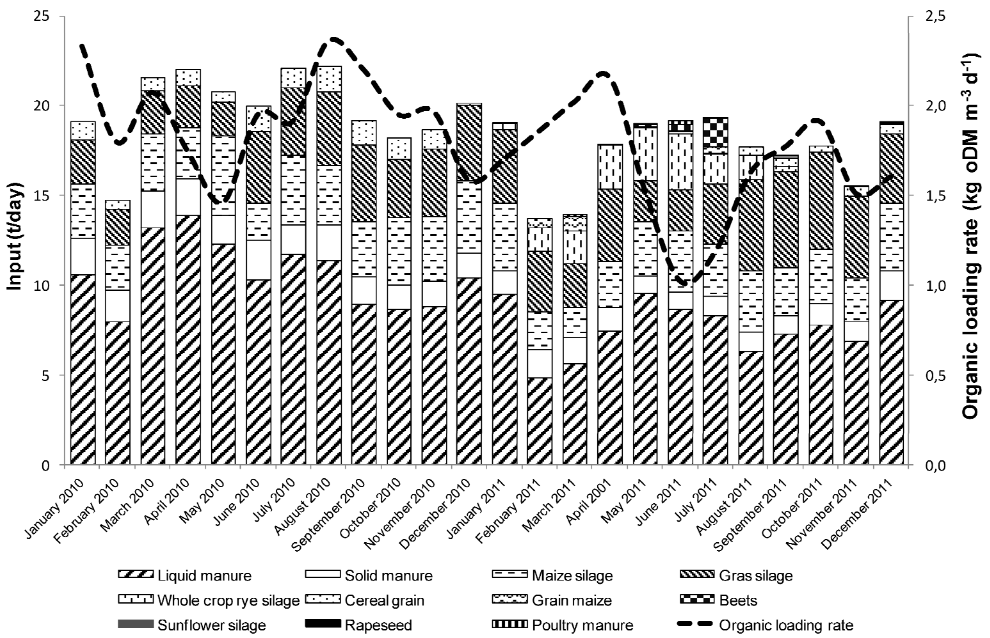
Higher amounts are generally more common during the winter housing season. Livestock units were reduced at the end of 2010, due to structural changes on the farm (Figure 4). This led to a lower supply of liquid manure. The feed of solid manure, maize- and grass-silage was however stable throughout the years. Table 4 shows the mean and STD of DM and oDM of the feeding substrates over the measured period.

Table 4. Characteristics of dry matter (DM) and organic dry matter (oDM) of the main feeding substrates for the years 2010 and 2011.

Input substrates	DM [% FM]		oDM [% DM]	
	$\bar{x}$	SD	$\bar{x}$	SD
Liquid_Manure	3.10	±1.47	67.54	±6.41
Solid_Manure	33.60	±9.98	68.39	±14.2
Poultry_manure	49.90	±25.4	88.14	±1.88
Maize_silage	31.30	±4.29	95.41	±1.10
Gras_silage	32.22	±12.33	89.05	±3.07
Whole_crop_silage	46.27	±4.24	92.93	±2.06
Cereal_grain	86.62	±0.85	97.70	±0.47
Beets	16.80	±NA	69.90	±NA
Sunflower_silage	16.88	±NA	78.68	±NA

The DM for all substrates changed during the period due to different harvesting times, qualities or storage conditions. However, the values were in accordance with the general state of knowledge and therefore fulfilled the expectations. From December 2010 to February 2011 no grain was fed to the biogas plant, due to storage capacity problems. The organic loading rate (OLR) varied at a low level: between 1.5 and 2.3 kg m^{-3} day^{-1}) oDM for both digesters (Figure 4). During the observed period the digestion process showed very stable conditions, while chemical digester conditions were always measured below the detection limit.

Figure 4. Substrate input for 2010 and 2011 and its corresponding organic loading rate.



The recorded results depicted in Figure 5 and 6 show the daily distribution of electrical power produced and procured over the measured period 2010–2011. The procured electrical power is displayed in two lines—the consumer units for gas utilization and gas production. The sum of both lines equals the total electrical energy demand of the biogas plant. Failures in the CPC which lead to falsely recorded data were erased. The characteristic of electrical energy produced by the CHP shows that the engine was running on full capacity for most of the time, only interrupted by maintenance intervals: 10 times for 600 h and five times for 1,800 h each year. As shown in the graphs, fluctuation in gas production leads to lower electric energy production (up to 10% of the possible maximum), due to changes in research questions, variation of raw materials or defects in the feeding systems. From December 2010 on, the gas production was reduced because no grain was added to the process. This naturally leads to a lower amount of biogas and therefore a lower electrical energy production (until February 2011). The demand for auxiliary electric energy for the gas production shows a stable distribution for most of the year. In March and April 2010, the demand for electric energy increased due to higher stirring activity, based on the feeding of large quantities of whole plant silage. Peaks in the demand for electric energy (in the gas production) occur from stirring of the digesters. This is done by submersible motor mixers in order to avoid sinking layers. From March to May 2011 the demand for electric energy of the stirring fluctuated and stayed at a higher level due to experiments on the agitation units. A breakdown of the CPC lead to a failure of the data recording in July 2010 (Figure 5) and February 2011 (Figure 6).

Figure 5. Electric energy produced and procured by the BGP in the measured period 2010.

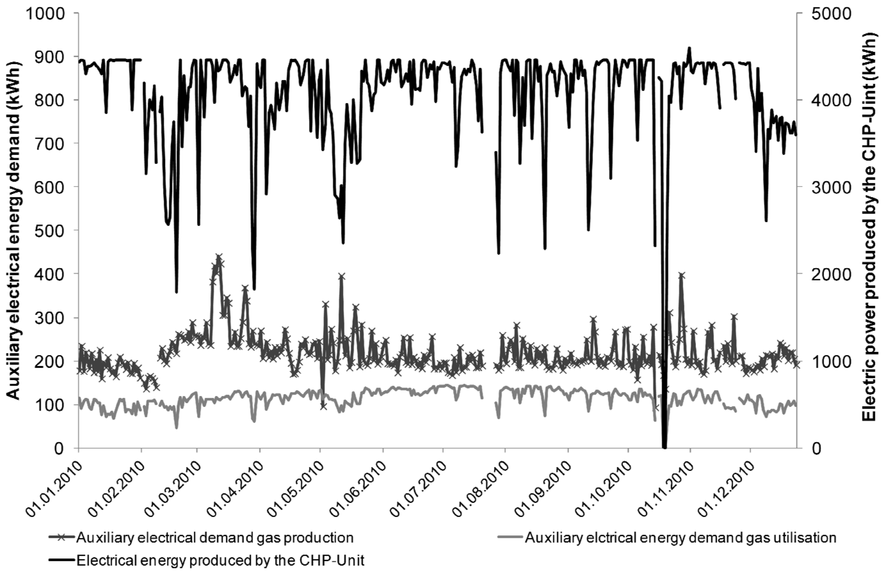
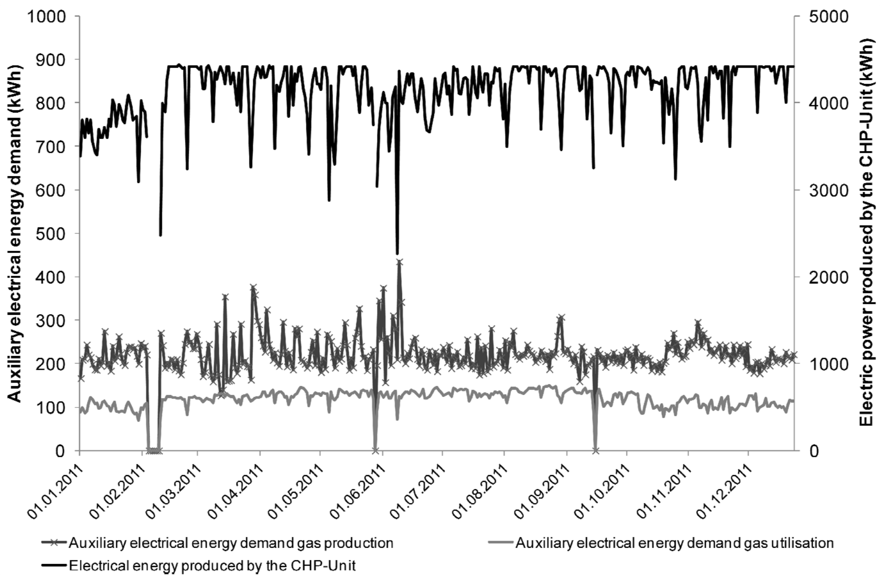


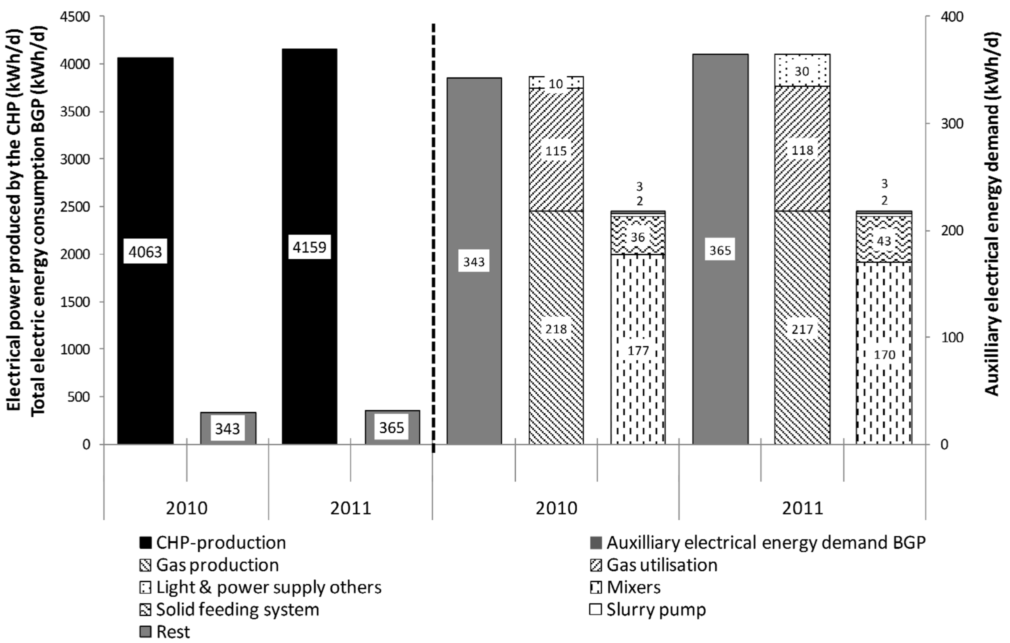
Figure 6. Electrical energy produced and procured by the BGP in the measured period 2011.



The demand for auxiliary energy for gas utilization also shows a balanced distribution between 80 and 140 kWh/day over the measured period. Engine stops lead to decreased energy consumption in the CHP and its auxiliary units (for the time not running). The demand is moreover influenced by the seasons. In winter and spring, when the demand for thermal power is at its maximum, the supply of thermal power increased, whereas the consumption of electric energy for cooling pumps and fans declined.

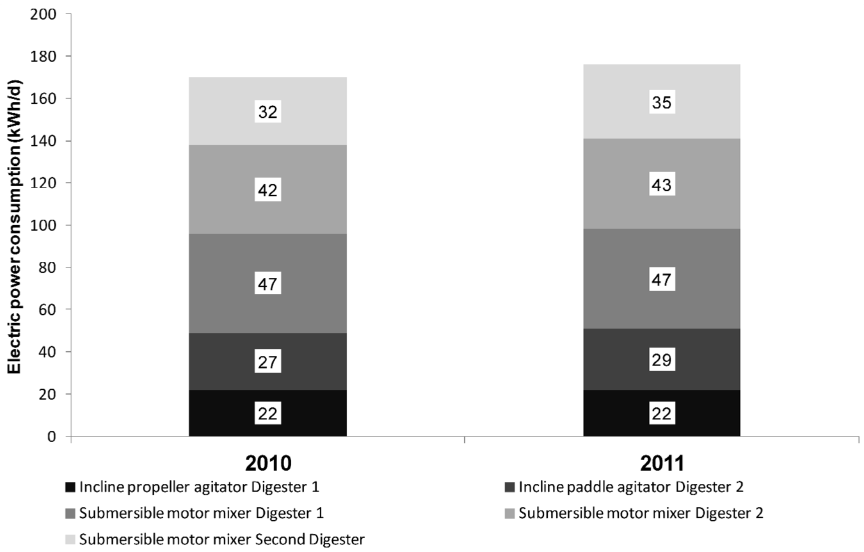
Figure 7 shows the energy produced and procured in 2010 and 2011 (calculated for an average day). The mean value of produced electric energy reached 4063 kWh/day in 2010, while the energy consumed by the auxiliary units added up to 343 kWh/day—leading to a total energy demand of 8.4%. The path for gas production is the biggest consumer and has a requirement of 218 kWh/day, which represents 63% of the total energy demand of the BGP. The path for gas utilization reaches 115 kWh/day (33% of total energy demand of the BGP) whereas the light and power supply reaches 10 kWh/day (3% of the total energy demand of the BGP). A deeper insight in the distribution of the gas utilization path shows that the agitators with 177 kWh/day are the most demanding consumer group, followed by the solid feeding systems with 36 kWh/day. In summary, the agitators consumed 51.6% of the total consumed energy, this being a 4.3% share of the energy produced by the CHP unit. An almost comparable distribution was measured for the year 2011 with a slight rise (2%) in electric energy consumption to 4159 kWh. At the same time, the consumed electric energy increased by 6% to 365 kWh. The only appreciable change measured was an increase in light and power consumption from 10 to 30 kWh a day, due to the supply of electric energy to an external desulfurization plant at the BGP. The amount of electric energy for agitation declined in 2011 by 4% in comparison to the previous year.

Figure 7. Electrical energy production and consumption of the entire BGP for 2010 and 2011.



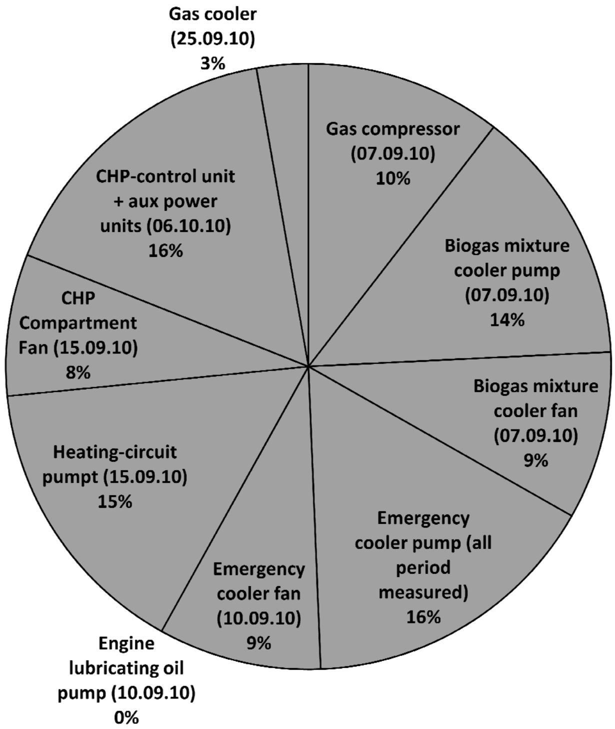
A calculation of the mean values for the agitation units (within the surveyed period) shows an almost steady electric power consumption of the agitation units for both years (Figure 8). The incline agitation units consumed less electric power, compared with the submersible motor mixing systems. In both digesters both agitation units were operated for three minutes every 30 minutes. While the substrate was fed all agitators were operated one minute pre- and post feeding and throughout the feeding process.

Figure 8. Electric power consumption of the agitation units calculated for an average day 2010 and 2011.



The data revealed that approximately 30% of the energy demand of the BGP is consumed by the CHP unit. Therefore, a more exact measurement was conducted for a short period to identify the distribution of consumption in the auxiliary equipment and to identify any possible electric energy saving potential. Detailed measurements could only be conducted by using the HIOKI measurement equipment as the CPC measuring point does not cover each single consumer unit, but rather the whole unit itself. The unit consumption measurements did not record the module management and gas cooler consumption. The module management remains unrecorded, thus leading to a lower output of the CHP production. Furthermore, it was found that the electric energy consumption of the gas cooler is measured by the general electricity consumption meter. The apportioning of the electrical power input into the individual CHP unit aggregates (based on the average daily consumption of 194 kWh) shows that the module management as well as the emergency cooler pump had the highest consumption with 16%. The second biggest consumption groups were the heating-circuit pump with 15% and the gas mixture cooler pump. Within a range of 8%–9% were the room ventilator fan, the gas compressor, the mixer cooling ventilator fan and the emergency cooling ventilator fan. The gas cooler accounted for 3% electric power consumption. The lubricating oil pump could not be instrumentally recorded because of its extremely short operational periods (Figure 9).

Figure 9. Distribution of the auxiliary electrical energy input for all units of the CHP.



4. Discussion and Conclusions

A lot of high quality practical data and experience could be deduced from the detailed and long term monitoring of a full scale research biogas plant. The study proved that long term measurements are needed to understand the electric power production and consumption of a biogas plant. In comparison to recent literature, this study provides deeper insight into the electric power consumption of specific consumer units by also considering the biological parameters, such as input materials and fermenter substrate characteristics. Over the year, the data showed a higher demand of electric energy during the warm summer months, as more recooling of thermal power of the CHP unit is needed compared to winter times. A change in the supply of substrates automatically affects the electric power output of the CHP unit, but does not have an effect on auxiliary electric energy demand. The bacteria react to changes of substrate supply, yet a visible lag in time can be observed. The availability of substrates varies, according to operation management and harvested quantities. The weekly analysis of the fermenting substrate in both digesters showed most VFA results were below the detection limit and only a few within the range of tolerance. Additional calculations of the input substrate degradability for the reporting period proved a degradation rate higher than 70%. Hence, both results confirm a very high digestibility and stable and safe fermenting conditions for both digesters. A comparison of the electric energy production and consumption for the entire BGP in 2010 and 2011 showed only slight differences between the years. The electric power consumption of the CHP is on average 194 kWh/day and represents 4.6% of the electric power generated per day (during the period covered by the study).

It has to be taken into consideration that this higher value results from the intensive measuring of the CHP unit. The data presented in Figure 7 does not include the module control and the gas cooler included in the gas producing path. The distribution of the energy input displays a uniform distribution among the heating pump group and the fans. The module control, which comprises all the auxiliary units of the CHP unit, also accounts for a high proportion of the total consumption. However, in practice this amount of consumed energy can hardly be reduced. One optimization method is to increase the amount of thermal power supplied to the district heating system of the farm and hereby reduce the operation time of emergency cooler pumps and fans. Moreover, the type of the heating pumps could be changed into high energy efficiency pumps.

The increase of energy efficiency, especially of the agitation units, proves to be the biggest challenge for plant operators. In practice, from a wide range of available agitator types different combinations are installed in the digesters. This is to avoid sinking and floating layers, for heat and nutrient distribution and to enable gas lift at high DM contents. The challenge is to ensure a homogenous digestate, although fibrous input substrates on one hand (with a tendency to form floating layers), and fluids on the other hand have to be homogenized while the entire emulsion is subject to thixotropic conditions. The main reasons for high electric energy consumption are long mixing intervals, missing compatibility between engine and propeller, a lack of knowledge of the mixing process and required mixing times. Additionally, lacking measurement devices for the quality of the digestate complicate an appropriate time management of the procedure. At the expense of efficiency in the construction, operators finally tend to select technical units with a stronger focus on construction stability and reliability (with a tendency to oversize). The operation of the research biogas plant showed that these challenges are indeed difficult to solve. In fact, only a very strong focus on research on this specific topic can be one of the appropriate measure for an efficient mixing process. The results can help the plant operators to improve plant controlling, in order to gain a higher level of energy efficiency in the future. Finally, the data will provide a basis for detailed investigations of agitation quality in the digesters in order to improve the electric energy efficiency of the BGP.

To improve the energy efficiency of biogas plants it is necessary to reduce the electric power consumption, thus needing precise information about the energy consumption of BGP. The conduction of intensive, detailed and long-term field tests identified the main electricity consumer units of a full scale biogas plant. Over a period of two years, data has been collected and evaluated. As expected and already shown in other literature, the agitation units consumed most of the procured energy, followed by the CHP unit and the feeding systems. Hence, the saving potential within the agitation technique needs to be investigated more thoroughly in future studies. However, despite the harsh practical conditions, the aim of intensive, detailed and long term measurements proved to be successful.

Acknowledgments

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3. Publication 2: How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters

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Abstract

The goal of this work was to evaluate the efficiency of two different agitation systems by measuring the nutrient distribution in a digester fed with renewable energy crops and animal manure. The study was carried out at the practical research biogas plant of Hohenheim University. A unique probe sampling system has been developed that allows probe sampling from the top of the concrete roof into different parts and heights of the digester. The samples were then analyzed in the laboratory for natural fatty acids concentrations. Three different agitation setups were chosen for evaluation at continuous stirring and feeding procedures. The results showed that the analysis approach for agitator optimization through direct measurement of the nutrients distribution in the digester is promising. The type of the agitators and the agitation regime showed significant differences on local concentrations of organic acids, which are not correlated to the dry matter content. Simultaneous measurements on electric energy consumption of the different agitator types verify that by using the slow-moving incline agitator with large propeller diameters in favor of the fast-moving submersible mixer with smaller propeller diameters, the savings potential rises up to 70% by maintaining the mixing quality.

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Article

How Efficient are Agitators in Biogas Digesters? Determination of the Efficiency of Submersible Motor Mixers and Incline Agitators by Measuring Nutrient Distribution in Full-Scale Agricultural Biogas Digesters

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Abstract: The goal of this work was to evaluate the efficiency of two different agitation systems by measuring the nutrient distribution in a digester fed with renewable energy crops and animal manure. The study was carried out at the practical research biogas plant of Hohenheim University. A unique probe sampling system has been developed that allows probe sampling from the top of the concrete roof into different parts and heights of the digester. The samples were then analyzed in the laboratory for natural fatty acids concentrations. Three different agitation setups were chosen for evaluation at continuous stirring and feeding procedures. The results showed that the analysis approach for agitator optimization through direct measurement of the nutrients distribution in the digester is promising. The type of the agitators and the agitation regime showed significant differences on local concentrations of organic acids, which are not correlated to the dry matter content. Simultaneous measurements on electric energy consumption of the different agitator types verify that by using the slow-moving incline agitator with large propeller diameters in favor of the fast-moving submersible mixer with smaller propeller diameters, the savings potential rises up to 70% by maintaining the mixing quality.

Keywords: biogas; mixing; stirring; agitators; mixers; energy efficiency; nutrient distribution; incline agitator; submersible mixer; renewable energy crops; volatile fatty acids

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1. Introduction

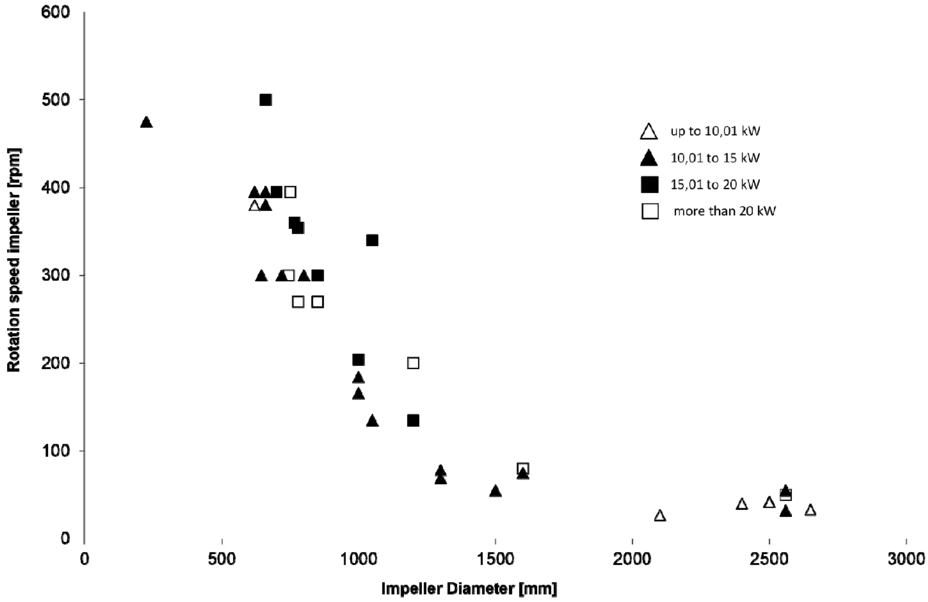
1.1. General Introduction

In most cases, continuous stirred tank reactors (CSTR) are used for producing biogas from energy crops or organic residues [1]. When using this type of biogas digester, the stirring of the substrate in the digesters is vital for the biogas formation process. The purpose of stirring is to distribute the nutrients in the biogas digester uniformly, to form a suspension of liquid and solid parts, to avoid sedimentation of particles, to ensure uniform heat distribution, to prevent foam formation and to enable gas lift from the fermentation substrate at high dry matter (DM) contents [2–8].

Almost all of the agricultural biogas stations based on CSTR use vertical digesters. In these vessels, the circular motion of material in a desired way is induced by agitation. For the agitation of the substrate, different types of agitators, stirrers or mixers are used. Mixing, a physical process carried out by agitators, stirrers or mixers, is physically defined as a random distribution of materials in different phases into another, forming a homogenous dispersion [9]. Mixing is described as one of the most common unit operations in process industries and many different types of mixers and impellers have been designed for varied operations [10].

Companies constructing agitators acknowledge that in agricultural biogas production, specially designed agitators, laid out according to digester volume and substrate properties, are used [11]. At present, there are several state-of-the-art agitation technologies that have been applied commercially. In general, they are known as mechanical, hydraulic or pneumatic mixing systems. In Germany, mechanical agitation is dominating the market for stirring fermenting substrates from agricultural origin [1]. A nationwide study in Germany in 2009 showed that 47% of all completely stirred anaerobic digesters are equipped with fast-rotating submersible mixers. It was found that by moving from substrates such as organic waste or animal manure to energy crops high in fiber, the DM content of the digestate increased significantly. Therefore, the requirements for agitators have changed and this has led to the dissemination of slow-rotating agitators. The authors report that in Germany, a share of 12.9% of the biogas plants (BGP) are equipped with incline shaft agitators, 7.4% with paddle agitators, 6.0% with central agitators and 0.8% with reel agitators. Furthermore, a combination of slow- and fast-rotating agitators is used in 16% of the BGP [1]. Similar results, with a trend towards low-velocity mixers with large agitation wings for continuous operation, were found by Hopfner-Sixt and Amon for BGP in Austria. Their survey showed that 36.6% of the BGP used paddle mixers. Submersible motor mixers were used in 34.7%, long-shaft mixers in 17.8% and paddle mixers in horizontal digesters in 8.9% of the cases [12]. An overview of agitators for biogas digesters is given in Figure 1 and shows that impeller diameters, rotation speed and the electric power requirement vary in a wide range. With increasing impeller diameter, the rotations speeds decline with a tendency towards lower power requirement.

Figure 1. Rotation speed of agitators in relation to the impeller diameter and its respective power requirements of agitation units available on the market (*n* = 46) (source: own survey in 2013).



There is little information on hand about the optimal choice of agitators and their setup in digesters, mixing intervals and the time required for optimal homogenization. Kissel *et al.* [13] presented data showing that operation hours in the first fermenting stage vary due to the agitator design. Reel agitators, central agitators and submersible motor agitators are continuously operated, while all other agitators are operated intermittently between 8 and 28 min per hour. If two stages are applied, the mixing time was reduced in the second step. Hopfner-Sixt found the average mixing time at 3–4 h per day in Austrian BGP [12]. In practice, the BGP operators set their agitator adjustment, its intervals and operating hours based on advice of manufacturers or consultants and after some time, on their own experience.

Weiland *et al.* [14] found that malfunctions in agitation technique accounted for ~15% of the workload on BGP as high wear and tear lead to failures after some years. Hopfner-Sixt [12] reported that 44% of the BGP dysfunctions are caused by agitators.

Up to now, the configuration of agitators in digesters, e.g., numbers, positioning, installation height and alignment in accordance to digester volume and substrate is, in most cases, based on the experience of manufacturers and operators and only in very rare cases based on scientific background. Hence, it is not an easy task for BGP operators to select the equipment, as many aspects have to be considered. The fermentation substrate characteristics, such as fiber content and rheology, as well as the digester design, have to be considered when choosing the agitators [8]. Despite first assumptions for agitator setups, the substrates may vary over the operation time. Furthermore, the capacity of agitators should be dimensioned in a way to react to changes in substrate composition or process failures. Easy access to agitators for maintenance during BGP operation will help to shorten service time [13]. In spite of its important role in performance, mixing quality in digesters has not been adequately quantified or characterized [3].

1.2. Economic Impact

Studies on electric energy consumption at the research BGP of Hohenheim University showed that mixing consumes up to 51% of total electric energy consumption for the biogas production process. The results show in detail that long-shaft agitators consumed up to 5.76 kW h 100 $m^{-3}\cdot d^{-1}$ while the submersible mixers used 11.29 kW h 100 $m^{-3}\cdot d^{-1}$ of electric energy for agitation in the first fermentation stage [15]. A field study showed electric energy consumption for agitation at 30%–50% [16]. Kissel *et al.* [13] reported that at ten pilot plants, the electric energy consumption for agitation accounted for 25% (in the first fermentation stage) of total electric energy consumption from agitation ranging from 6% to 58%.

This high electric energy demand is causing high costs and moreover lowering the CO_2 balance of this bioenergy source. By the end of 2012, approximately 7589 BGP with an installed electrical capacity of 3179 MW have been in operation in Germany [17]. Taking into account that approximately 8% [15] of the produced electricity is used for BGP operation and 50% [15] of this energy is used for agitation, calculations show that 1 billion kW h/a are used for agitation in German biogas stations. At an energy price of around 0.2 €/kW h, approximately 200 million €/a are spent on agitation. This calculation clearly shows the impact on the profitability of BGP operation.

In practice, however, the BGP operators usually evaluate their agitator performance based on visual monitoring of the fermentation substrate. The problem arising with this method is that only the condition and motion surface can be monitored. By doing so, no information can be obtained about the quality of mixing in other parts of the digester underneath the surface. Therefore the BGP operators tend to enhance both frequency and duration of agitation above the recommended intensity to assure the avoidance of technical problems and failures. In practice, it is almost impossible to run agitators at an energetic and qualitative optimum. The optimum of mixing can be defined as achieving homogeneity at the lowest energy input.

1.3. Research on Agitation in Biogas Digesters

Research on mixing quality in anaerobic digestion processes has been described by several authors (we refer to Monteith and Stephenson for older and Wu for latest sources) [6,18]. Early studies focused on the treatment of municipal sludge and later ones on agricultural residues. Research on high viscous fermenting substrate, resulting from the increased use of renewable energy crops, has been carried out in recent years and can be classified as two main research methods, such as intrusive (e.g., experimental research) and non-invasive [computational fluid dynamics (CFD), computed tomography (CT), as well as computer automated radioactive particle tracking (CARPT)]. It was found that researchers combine different methods.

Although "mixing" has been well researched for chemical and industrial applications, it was found challenging when applying those results to the biogas forming fermenting substrate. For engineering calculations, the rheological properties of substrates are required and liquid manure has been researched by many authors. Landry *et al.* [19] reported according to Chen [20] that beef cattle slurries were described as non-Newtonian pseudoplastic fluids, with an increasing deviation from Newtonian behavior by increasing total solid concentration. According to Vesvikar [3], it is more complicated to describe the rheologic properties of biogas substrates due to the fact that digester substrates are opaque and multiphase systems in which the physics are very complex and not fully understood. These multiphase systems contain liquids, solids, diluted minerals, fibrous material of different length, and biogas. Moreover the substrate temperatures vary from 40 °C to 53 °C. With increasing total solids concentration, the fermenting substrate shows non-Newtonian pseudoplastic behavior and viscosity, as well as shear stress, appear to increase exponentially [21]. Kissel [13] and Springer [22] described fermenting substrates as shear thinning. The shear viscosity is not consistently linear depended on the shear rate. As a defined value for viscosity cannot be given, the layout of agitators is hampered.

1.3.1. Effects of Mixing on Biogas Production

Due to the difficult multi-phase fermenting substrates, most of the mixing research in anaerobic fermentation systems is focusing on its effects on biogas yield. The effect of mixing in anaerobic digestion of animal manure was studied on a laboratory scale by Karim *et al.* [23], who showed that mechanical, hydraulic and pneumatic accounted for 29%, 22% and 15% higher biogas yields compared to the unmixed digester. With increasing DM content in the slurry, deposition of solids could be observed. They concluded that mixing is becoming prominent in digesters fed with thicker manure.

Laboratory scale research of anaerobic digestion of sewage water demonstrated that in continuous mixing systems, higher impeller speeds rising from 140 min^{-1} to 1000 min^{-1} did not improve total gas yields and even a slight reduction in gas production occurred [24,25]. By treating animal manure, similar effects on biogas production rates and yields at steady-state conditions of four different mixing intensities (50, 350, 500 and 1500 min^{-1}) could be determined in continuously stirred bioreactors [26]. Higher methane productions by 1.3% and 12.5% could be observed with intermittent and minimal mixing strategies of manure in anaerobic digestion compared to continuous mixing. An increase of 7% in biogas yields was found in pilot-scale studies comparing intermittent to continuous mixing [27]. Gentle and minimal mixing before feeding proved to be advantageous compared to vigorous mixing by high substrate to inoculum ratio in laboratory scale research. In accordance to Kaparaju *et al.* [27], it can be concluded that in biogas digesters fed with manure and solid substrates, mixing is indispensable. The mixing intensity had a small effect on biogas yield and mixing schemes proved to have an effect on anaerobic digestion of manures.

1.3.2. New Approaches in Studying Mixing Efficiency

Monteith and Stephenson [18] analyzed the effects of mixing in full-scale anaerobic digesters (two water pollution and control plants) by tracer methods and found that dead zones accounted for as much as 77% of the volume theoretically available for active mixing, seriously reducing the hydraulic retention time. Deviations from ideal mixing were detected and attributed to short-circuiting.

Karim *et al.* [5] used noninvasive techniques combining computer-automated radioactive particle tracking with CT to identify the flow pattern caused by a mixing unit (gas recirculation) and to calculate various turbulence parameters quantitatively for a 20.32 cm diameter flat-bottom laboratory-scale digester. The results show that 27%–31% of the digester volume was found stagnant at gas flow rates of 28–84 L/h.

Research from Kjellstrand [28] was carried out combining tracer tests, hydraulic modeling and full-scale implementation to study hydraulic behavior in an activated sludge tank. Poor use of reactor volume was identified by using the invasive tracer method. Based on the results of the tracer tests, the hydraulic situation was quantified using a compartment model. The identified short circuiting stream was corrected with measures using CFD for virtual prototyping.

CFD was used by Maier to identify shortcomings of existing BGP and to develop proposals for new facilities by evaluating the flow field in the digester and the resulting mixing characteristics. Six slowly rotating mixing devices positioned in even distribution along the perimeter of a circumferential main digester proved to be the best setup [29].

Brehmer [8,30] combined CFD with experimental methods and showed on a laboratory scale with xanthan fluid that incorrect positioning of submersible mixers can lead to considerable stagnation zones and to a collapse of the bulk flow. In this respect, experimental setup numerical fluid flow simulations showed that a correspondence of agitators could not be achieved through an increase in jet range by raising the propeller speed. He found that the pseudoplastic flow patterns of fermenting substrates tend to build caverns around the mixers, leading to an expansion of the jet stream. For better correspondence between agitators and an increase of agitated volume, he suggested installing the submersible mixers towards the center of the digester to shorten the distance between the agitators. The positioning and geometry of the agitator, as well as the substrate composition and its rheology, influence the mixing characteristics and the mixed volume of the digester, as well as the jet width of the agitators. He concluded that based on the gained knowledge, no rules for mixing intervals and mixing duration can be derived yet, but a better understanding of the process could be achieved [30].

Process tomography was applied by Jobst [31] on a laboratory scale for procedural and energetic optimization of mixing and stirring processes in BGP. With this method, the mixing and flow processes of opaque and fibrous multi-phase systems, with consideration of the physical, chemical, granulometric and rheological characteristics, can be visualized. The results show that the active mixed reactor volume reaches from 60% to 85%. It can be concluded that in practice, the calculation of the dimensioning of the digesters by the loading rate is exceeded and that in digesters, great variations of the local distribution can be found. To obtain sufficient mixing, a minimum shear induced by the agitator is needed but an increase in shear does not necessarily lead to an improvement in mixing quality [32].

Biologically less-active or even dead zones in biogas digesters are also described by other authors. Vesvikar [3] studied visualization of flow pattern and hydrodynamic parameters of a mimic airlift loop anaerobic reactor with the help of CFD and evaluated these results with CARPT. In terms of flow pattern, location of dead zones and trends of velocity profiles, the CFD predations showed very good qualitative comparison with the experimental data, but the experimental velocity data could not be matched accurately with the CFD simulations. He found zones with no-flow or very low velocities in 11%–58.3% of the different digester configurations and classified them as dead or stagnant zones that reduce the effective reactor volume. A degradation of performance in the digester is described due to an increase in pH and temperature in non-mixed regions. Wu [21] explored non-Newtonian fluid flow of manure in anaerobic lab, scale-up and pilot-scale digesters with CFD simulations and described 14%–16% of the digester volume as dead zones.

1.4. Conclusions for This Study

Agitation accounts for approximately 50% of electric energy consumption in agricultural BGP fed with energy crops [15], but in practice, less is known about the selection of adequate mixing solutions. A lack of adequate mixing will lead to incomplete stabilization of raw sludge, inefficient methane yield and a system overdesign to compensate for the loss of digester volume and in the end, to excessive capital costs and increases in operating expenses [32].

Although much research is currently conducted in this field and new methods like CFD are used, it must be stated that all methods are still limited either in extent, e.g., on very short real-time simulation time of approximately 60 s [33], or incorrect assumptions regarding rheological properties, e.g., no varying viscosity, no different fiber length, lack of biogas or different temperature gradients of the fermenting substrate [8]. Furthermore, research is mostly based on laboratory scale work, which does not reflect the characteristics and large-scale effects of full-scale biogas production. Despite the rising numbers of published papers, there is a general lack of knowledge about the quality of stirring in full-scale biogas digesters.

Biogas production is a complex process resulting from incomplete anaerobic mineralization of biomass, carried out in four steps in single-phase BGP [34]. Organic acids formed in the hydrolysis and acidogenesis are intermediates of the biological process and can be described as nutrients for the microbes in the acetogenesis and methanogenesis.

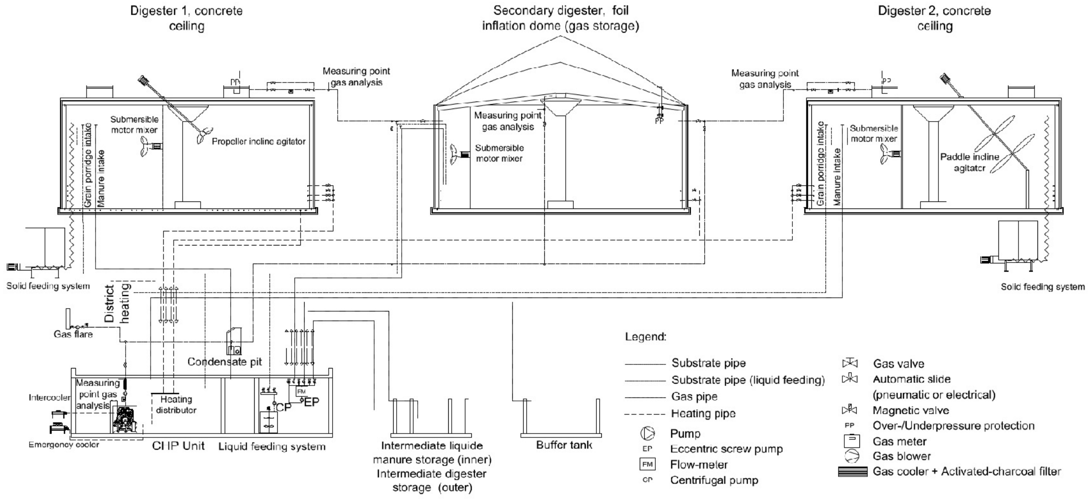
For this study, we conclude that in cases of biological inactive zones, caused by inadequate mixing layout, intermediates will be found unevenly distributed across the digester. An invasive method was chosen to prove the hypothesis that in full-scale research, the agitator type and setup influence the distribution of nutrients and DM in the fermenting substrate. Furthermore, the hypothesis is stated that at equal nutrient distribution, electric energy can be conserved by choosing the optimal equipment. These hypotheses were tested at the full-scale research BGP "Unterer Lindenhof" of Hohenheim University. The specific objectives of this study were:

- Development of an invasive system for spatial resolved sampling in a full-scale biogas digester;
- Studying the effect of stirring with different agitator units on nutrient distribution in the biogas digester.

2. Material and Methods

The research BGP of Hohenheim University is located at the "Lindenhof" agricultural research estate in Eningen unter Achalm (Germany). The substrates for the conversion process are solid and liquid manure from the 220 livestock units, as well as energy crops from 70 ha of arable land and grassland. The solid substrates are premixed in two different vertical mixer systems and fed in 48 equal batches a day into the digesters. Since all crops are harvested with a forage harvester and cut to a size of 10–65 mm, no additional pretreatment was applied. The BGP consists of two digesters, covered with insulated concrete, and a secondary digester, set up with a 227 m^3 foil inflation dome for gas storage. Every digester has a diameter of 14 m and a height of 6 m resulting in a maximum volume of 923 m^3 and is equipped with different heating systems (Figure 2).

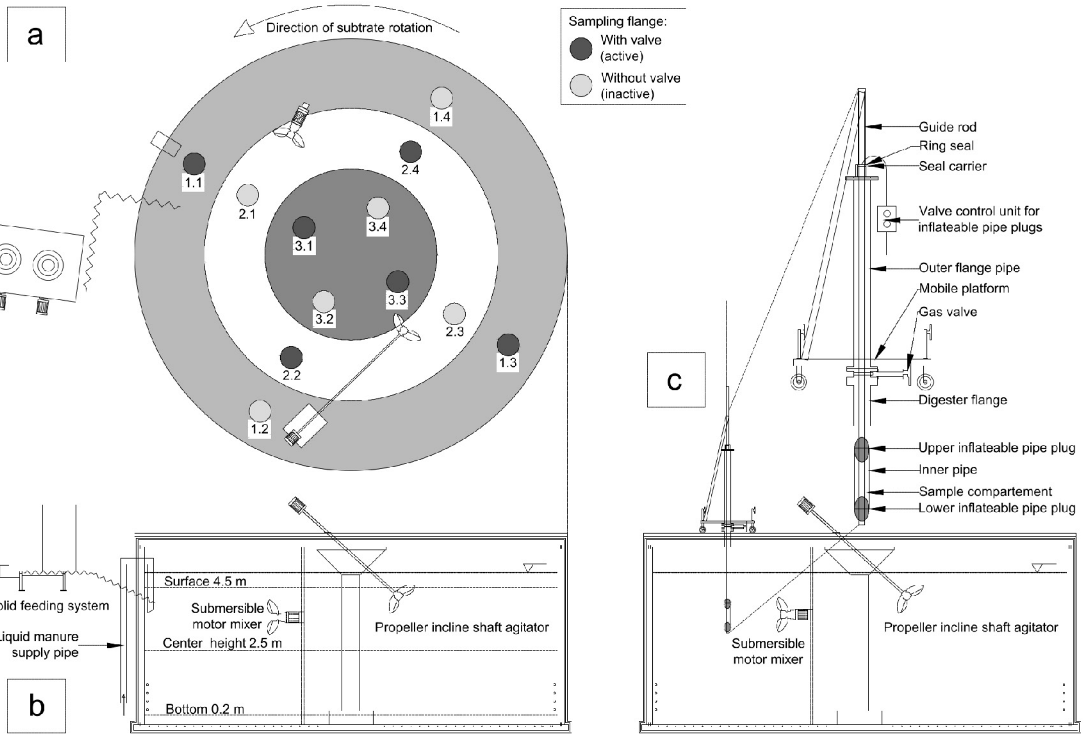
Figure 2. Flow scheme of the investigated research biogas plant (BGP).



All digesters are equipped with submersible motor mixers [35]. Furthermore, digester No. 1 is set up with a propeller incline shaft agitator, whereas digester No. 2 is fitted with a paddle incline agitator unit. Under mesophilic conditions, around 96 m^3/h [standard temperature and pressure (STP)] of biogas are produced, with a composition of approximately 52% CH_4, 48% CO_2 and 500 ppm hydrogen sulfide (H_2S). This allows operation of the combined heat and power (CHP)-unit (six cylinder gas engine MDE MB3066 L4, MTU onsite energy, Augsburg, Germany) at nominal 192 kW electrical and 214 kW thermal power as described by Naegele [36]. After transformation, the electrical power is fed into the local energy grid. The thermal power is primarily used for digester heating (40.5 °C) and the remaining energy is supplied to the thermal energy grid of the research station. The research BGP is equipped with a central plant control (CPC) unit for data collection, storage and evaluation. All substrates fed into the biogas process are weighed by the feeding systems or measured with a flow meter. The substrate temperatures in the fermenting substrate, gas quality and biogas temperature are measured continuously in every digester. Samples of input substrates and fermenting substrate were taken on a weekly basis and analyzed for DM, organic dry matter (oDM), pH, FOS/TAC, Ammonia (NH_4-N) and volatile fatty acids (VFA) content in the biogas laboratory of Hohenheim University. Furthermore, the electrical and thermal energy demand is measured for every key consumer unit [15]. The BGP is controlled and regulated via a programmable logic controller (PLC), which is joined to the CPC unit via a network. The CPC allows the operator to monitor and control the BGP over a graphic surface and automatically record, calculate, visualize and archive the data from all measuring units.

Intensive measurements in the years 2010–2011 at the research BGP of Hohenheim University were conducted to evaluate the effect of agitation technology on nutrient distribution within the framework of the research project "Intensive Measuring Program." Hereto digester 1 was chosen for the experiment and set up with 12 probe sampling holes installed crosswise in the concrete roof with a distance of 1.75 m from the digester wall to the outer ring, 3.3 m to the center ring and 3.75 m to inner ring. Six of the sampling holes are fitted with gas valves. The position and numeration of the sampling holes are given in Figure 3a. Figure 3a,b shows furthermore the sampling holes chosen and fitted with gas valves, as well as the heights chosen for sampling. The samples are taken in three different heights (measured from the digester floor) named bottom (0.2 m), center height (2.5 m) and surface (4.5 m).

Figure 3. Plan view on digester one with probe: (**a**) sampling points and (**b**) sampling heights; (**c**) Represents the probe sampling system on the digester, enlarged and provided with additional technical information.



The samples were taken with a new probe sampling system. This innovative experimental apparatus (Figure 3c) for invasive sampling from the top of the digester is unique on a practical BGP. It is designed to take samples through the gas-phase right into the fermenting substrate. Therefore, special safety precautions were taken into consideration, to ensure overall safety of the personnel and to reduce emissions during sample collection. A mobile platform allows movement of the sampling system to different probe sampling holes. The sampler consists of a pipe-in-pipe system that can be moved with a six meter guide rod. For sample collection, the outer pipe is fitted on the gas valve of a probe hole and secured with a gas seal. The inner pipe contains two pipe plugs. Inflated with compressed air, these valves seal the sample compartment. After the gas valve is fitted, the digester flange is opened and the sealed sample compartment is inserted into the digestate. Reaching the desired height, the lower inflatable pipe plug is deflated via the valve control and the substrate enters the filling chamber. In a second step the upper inflatable pipe plug is opened to guarantee that the filling chamber is completely filled with digestate. To encase the sample, both inflatable pipe plugs are inflated again. Afterwards, the sample compartment is pulled out of the digester and the gas valve is closed. After unscrewing the outer pipe from the gas valve, the sample is released into a box.

The samples are cooled immediately in liquid nitrogen to a temperature below 10 °C. Then the samples are homogenized with an electric cutter (Robot Coupe, Vincennes Cedex, France) for a period of 1 min. The probe sampling system is rinsed with water after every sample collection. The samples are deep frozen until analysis of the VFA content with a gas chromatograph (Varian, Agilent Technologies Inc., South Taft, CO, USA) and DM according to VDI 4630 (The Association of German Engineers, Düsseldorf, Germany).

In the experimental period, two agitation systems, a submersible motor mixer and a propeller incline agitator were tested. The submersible motor mixer is directly driven by an electric motor and the incline propeller agitator is driven via a frequency converted electric motor for energetic speed control at 60% of its maximum power. Both systems can be run separately and simultaneously. During the experiment, a mixing time of one minute prior and two minutes post feeding was set. The substrate was supplied to the digester every 30 min. Permanent mixing during the feeding process was carried out. The agitator positions (Figure 3) stayed unchanged during the experimental period.

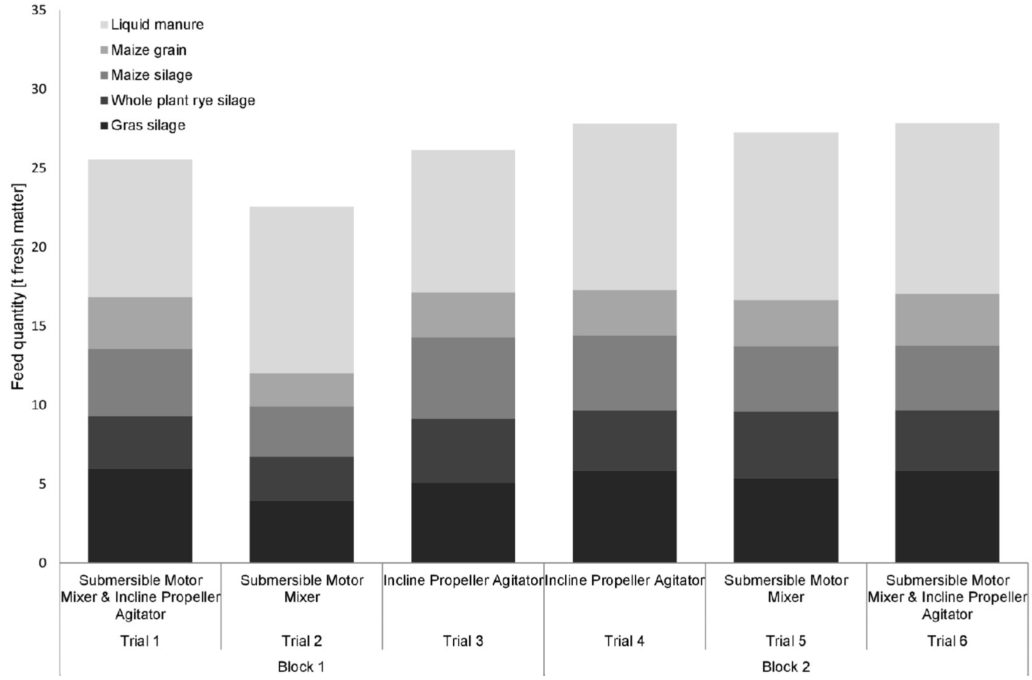
Extensive investigations were carried out prior to the experiments in order to determine the grade of homogenization, cooling, time requirement for probe sampling and handling of the sampling unit, confirming the robustness of the equipment and applicability. The experimental period began on 2 March 2011and lasted until 25 March 2011. It was chosen to test three different agitation setups with two block replications over six measurement periods with a total number of 90 samples. Every period started with an equalizing day on which both agitators were run for 6 h to ensure that the substrate was equally distributed. On the following two days, the agitators were run in the test regime every 30 min, along with the feeding of the digester. The third day was the sampling day on which samples from five sampling holes at three different heights each were taken randomly. The sampling day was followed again by an equalizing day and two days of agitating in the following setup. The samples were taken in between the feeding processes. The data received from the laboratory were processed with the statistical software SAS (SAS Institute Inc., Cary, NC, USA) using a variance analysis and comparison of the means.

3. Results and Discussion

3.1. Feed Intake

As presented in Figure 4, Digester 1 was fed with 22.5–27.8 t of substrate per three days trial time. On average, 26.2 t of substrate were fed into the digester with a share of 38.43% of liquid manure, 20.38% grass silage, 16.22% maize silage, 13.96% whole plant rye silage and 11.09% ground maize grain. The feed supply resulted in a loading rate of 2.2 kg oDM/m^3 × day at an almost even feed supply. Due to a temporary breakdown of the solid feeding system during Trial 2 the feed supply was 3.7 t lower than the mean value for all experimental periods.

Figure 4. Feed supply and proportioning during the three days lasting trial periods.



3.2. Distribution of DM

The results show that the DM was equally distributed in the digester throughout the experimental period and did not show any significant difference. According to Tables 1 and 2, the variance is evenly distributed and no statistical outliers or aggregations could be detected. None of the fixed effects (Agitator type, Position and Height of the sample) had a significant influence on the distribution. The significant influence of the effect block cannot be precisely interpreted. It can be assumed that the blocks differ in loading rate due to a minimal increase in Block 2 affecting the DM content. The block effects are found as errors in the model for DM content and acetic acid. The DM content in the fermenting substrate over the measured period was 13.25% ± 0.5%.

Table 1. Type 3 tests of the fixed effects of dry matter (DM) content on the full model *alpha* = 5%.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr > F*
Block	1	9	28.18	0.0005 ***
Block × Agitator	2	9	1.65	0.2455 ns
Agitator	2	9	0.19	0.8271 ns
Position	5	9	1.29	0.3481 ns
Height	2	44	1.38	0.2611 ns
Position × Height	10	44	1.08	0.3969 ns
Agitator × Position	10	9	0.52	0.8406 ns
Agitator × Height	4	44	0.45	0.7711 ns

***: $p \leq 0.001$, highly significant.

Table 2. Type 3 tests of fixed effects of DM content on the reduced model.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr* > *F*
Block	1	19	44.05	<0.0001 ***
Block × Agitator	2	19	5.21	0.0157 *
Agitator	2	19	0.42	0.6600 ns
Position	5	19	1.70	0.1841 ns
Height	2	58	1.42	0.2489 ns

***: $p \leq 0.001$, highly significant; *: $0.01 < p \leq 0.05$, less significant.

The significance test showed that DM is evenly distributed in the digester. A reason for that may be the high frequency of mixing the substrate every 30 min while substrate was fed to the digester. This short time span in between mixing may prevent DM segregation. It can be concluded that at such high mixing frequencies, the agitator type does not have a statistically verifiable effect. A mixing frequency of every 30 min is a common procedure in agricultural BGP in Germany, therefore, this setup was chosen. However, we would like to recommend investigating the effects of lower mixing frequencies on intermediate distribution as the energy saving potential would be higher in this case. A segregation of DM could only be measured within a few hours after the agitation was stopped during additional tests. Kaparaju [27] reported that stratification of solids occurred within a 2 h mixer-blocking period ("non-stirring interval"). In our study, DM content was found to be lowest on the bottom with increasing values towards the surface. On the contrary, Kaparaju [27] found the highest volatile solid content in the upper and lower part of the digester and lowest solids content in the middle layer. The statistical analysis of the measured parameters showed that the distribution of DM in the digester is not affected by the type of the agitator at high agitation frequencies.

3.3. Distribution of Acetic Acid

Further investigations showed that the fatty acid concentrations did distribute independently from the DM content. In Tables 3 and 4, acetic acid is chosen in representation of all analyzed fatty acids as all others were measured below the limit of detection. A significant influence of the fixed effects agitator, position and height could be proved with the full and reduced model. It was found that the acetic acid concentrations differentiated depending on the measuring points, measuring height and agitation setup. A significant correlation of block and block × agitator was found.

The results of comparisons of means are presented in Table 5 regarding the distribution of acetic acid in position, height and agitator setup. The biological process showed high stability during the experimental period, hence the values for acetic acid did not exceed 1 g/kg. It was found that there was an uneven distribution of acetic acid in the digester. The highest acetic acid value was found at measuring Point 1.1 close to the solid substrate feeding system. Values measured close to the agitators, measuring Points 2.2 and 2.4 showed a significant difference to the measuring Point 1.1. The results show that on the opposite side of the solid substrate feeding system, lower acetic acid values were measured. These differences may be explained by the fact that close to the solid substrate feeding system, the degradation is higher and therefore more intermediates are found. The farther the measurement point is from the feeding system the more diluted the nutrients become. This fact can be interpreted by uneven distribution through the agitators. Regarding the heights, the distribution of fatty acids showed the highest concentration on the bottom (0.68 g/kg) of the digester. The lowest value (0.56 g/kg) was found at the center of the heights and a medium level (0.59 g/kg) underneath the surface. Such different quantitative distributions, with the lowest value in the middle and higher values in the upper and lower part of the digester were presented by Kaparaju [27] for volatile solids.

Table 3. Type 3 tests of the fixed effects of acetic acid content on the full model alpha = 5%.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr* > *F*
Block	1	9	7.36	0.0239 *
Block × Agitator	2	9	4.56	0.0428 *
Agitator	2	11.5	10.90	0.0022 **
Position	5	11.5	4.08	0.0226 *
Height	2	19	5.25	0.0153 *
Position × Height	10	19.5	1.93	0.1030 ns
Agitator × Position	10	11.3	1.98	0.1366 ns
Agitator × Height	4	20.2	0.63	0.6434 ns

*: $0.01 < p \leq 0.05$, less significant; **: $0.001 < p \leq 0.01$, significant.

Table 4. Type 3 tests of fixed effects of acetic acid content on the reduced model.

Effect	Degrees of freedom numerator	Degrees of freedom denominator	*F*-Statistic	*Pr* > *F*
Block	1	12.7	5.73	0.0329*
Block × Agitator	2	12.7	5.92	0.0153*
Agitator	2	23.9	7.18	0.0036**
Position	5	24.1	3.30	0.0208*
Height	2	28.2	4.29	0.0236*

*: $0.01 < p \leq 0.05$, less significant; **: $0.001 < p \leq 0.01$, significant.

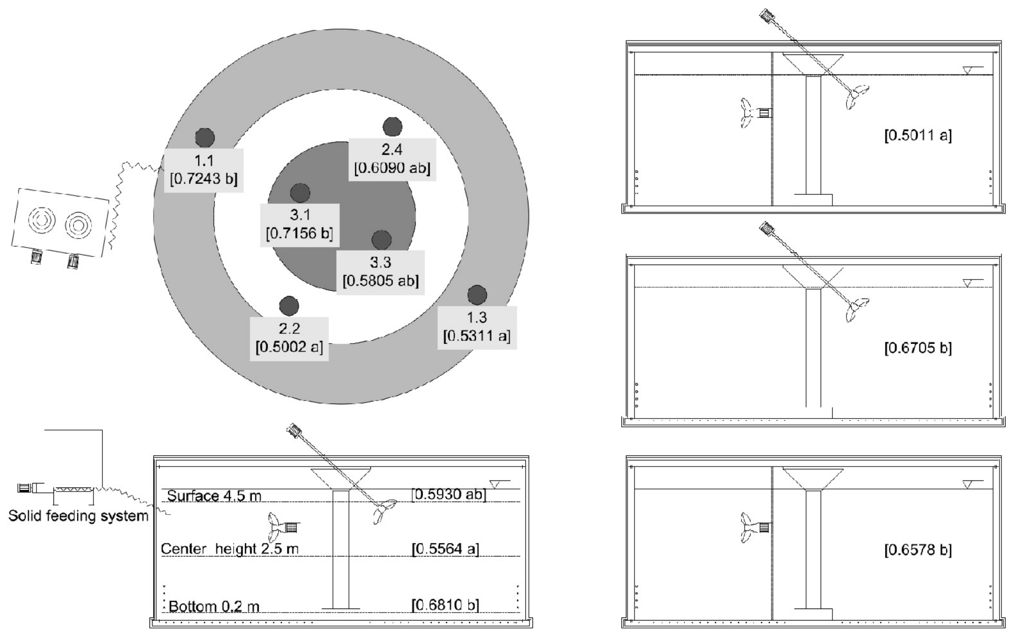
Regarding the influence of the agitator type and regime, the lowest acetic acid value (0.50 g/kg) was found by stirring with both agitators (Table 5). This value was significantly different from the higher values found by stirring with only the incline propeller shaft agitator (0.67 g/kg) or the submersible motor mixer (0.66 g/kg). No measurable correlation was found for gas production and the lower concentration of acetic acid, as this may indicate better degradation and therefore higher biogas production. It is not yet possible to measure the gas production of the digester with sufficient precision. Currently, there is a lack of adequate gas quantity measurement equipment for full-scale digesters, as the gas is wet, corrosive, has extremely low pressure and a flow rate ranging from almost 0 to 60 m^3 biogas per hour. Figure 5 highlights the results from Table 5. It shows a comparison of means of acetic acid concentration with different letters indicating the significant difference between the estimated values. The lower acetic acid value found by agitating with both devices may be a cause of a better nutrient distribution in the digester resulting in better degradation of VFA.

Table 5. Comparison of means of acetic acid with different letters showing the significant difference between the means of estimated values.

Effect	Agitator	Position	Height	Estimated means transformed	Mean raw data (g/kg)	Standard error	df	*t*-value
Height	-	-	Center	−0.2761 a	0.5564	0.02412	43.3	−11.45
Height	-	-	Surface	−0.2477 ab	0.5930	0.02412	43.3	−10.27
Height	-	-	Bottom	−0.1890 b	0.6810	0.02412	43.3	−7.84
Position	-	1.1	-	−0.1500 b	0.7243	0.04126	24.1	−3.63
Position	-	1.3	-	−0.3233 a	0.5311	0.04126	24.1	−7.84
Position	-	2.2	-	−0.3034 a	0.5002	0.04126	24.1	−7.35
Position	-	2.4	-	−0.2501 ab	0.6090	0.04126	24.1	−6.06
Position	-	3.1	-	−0.1446 b	0.7156	0.04126	24.1	−3.51
Position	-	3.3	-	−0.2544 ab	0.5805	0.04126	24.1	−6.17
Agitator	Incline propeller agitator	-	-	−0.1891 b	0.6705	0.02899	24	−6.52
Agitator	Submersible motor mixer	-	-	−0.1962 b	0.6578	0.02899	24	−6.77
Agitator	Submersible motor mixer & Incline propeller shaft agitator	-	-	−0.3276 a	0.5011	0.02899	24	−11.30

Different letters (a & b) indicate the effects with statistical difference (*alpha* = 5%).

Figure 5. Schematic drawing of the results of comparison of the significance test of acetic acid (values in g/kg).

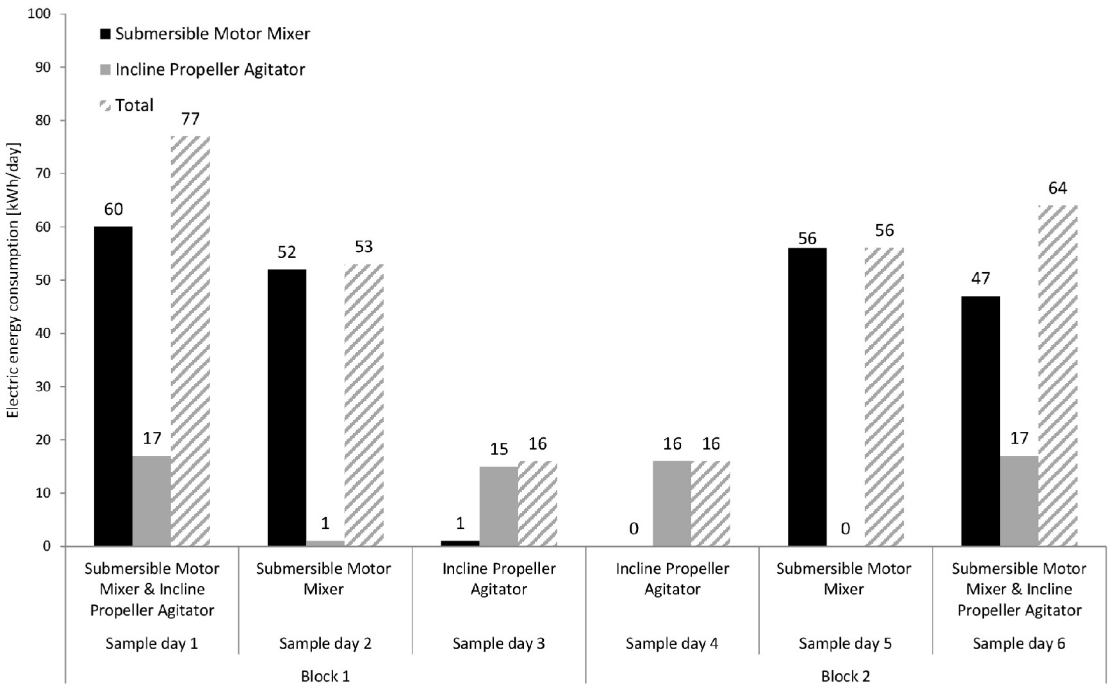


Laboratory scale research or simulation results from and Jobst, show that 15%–25% of the digester volume is not actively used [3,31]. Montheight and Stephenson found as much as 77% of the digester volume is dead zones [18]. In our study on a full-scale digester, no evidence was found that prove those results. Dead zones, as defined, are zones with no organic matter degradation leading to an accumulation of organic matter or zones with no supply of organic matter indicated by extremely low dry-matter contents. Furthermore, dead zones are areas with a limited degradation of organic matter by microorganisms so that no intermediary products can be detected. The results of our study show that DM and VFA were almost evenly distributed in height and position of the digester. Therefore, we conclude that there is no indication of a dead zone in the examined digester under our experimental layout. It seems that in practice, more digester volume is actively used than described by previous authors [3,31].

3.4. Electric Energy Consumption of Agitators and Mixing Quality

In addition to the biological parameters of the fermenting substrate, the electric energy consumption of the agitators was measured during the study. In Figure 6, the results for the days of sample taking are presented. Most of the energy was consumed when both agitators were used in combination as on sample day one and six ranging from 77 kW h/d to 64 kW h/d. The setup with the submersible motor mixer consumed 52 kW h/d at trial day two and 56 kW h/d at trial day five—an almost constant amount of electric energy. The incline propeller agitator setup used a constant amount of 15 kW h/d and 16 kW h/d at trial day three and five.

Figure 6. Electric energy consumption of the agitators according to the agitator setup for all sample days.



The results show that by using the submersible motor mixer alone, the electric energy demand could be reduced by 32.5% and 12.5% compared to the standard setup using both agitators. A reduction of 79% and 75% could be achieved by using the incline propeller mixer alone. By comparing the submersible motor mixer with the incline propeller agitator, the results show a consumption of 69% and 71% lower. The highest electric energy demand was measured using the combination of both agitators, but as a result, the lowest nutrients content in the fermenting substrate was observed. The submersible motor mixer and the incline agitator differed widely in their electric energy consumption but did not show a significant difference in mixing quality described by the nutrient distribution.

Taking into consideration that the mixing quality of the three setups is almost equal, but the energy demands differ widely, a savings of up to 70% of electric energy could be achieved by using the incline agitator in favor of the submersible motor mixer. For the experimental setup and the specific digestate characteristics, we conclude that the slow-moving incline shaft agitator fitted with large propellers is the most suitable and efficient technique. Applying those results to earlier measurements from Naegele [15] showing that up to 51% of the total electric energy consumption of a BGP accounts for agitation, the vast savings potential of those units becomes obvious. It can be highly recommended to adapt the mixing technique to the specific digestate characteristics to increase the mixing quality and to reduce the electric energy consumption of BGP.

4. Summary and Conclusions

An invasive sampling method was applied at a full-scale biogas research BGP to study the efficiency of different agitation systems by measuring the nutrient distribution and DM content in the fermenting substrate, consisting of renewable energy crops and animal manure. For the first time in biogas studies, samples were taken from a full-scale biogas digester and combined with technical process parameters e.g., electric energy consumption for evaluation. Unique and vital results were obtained showing significant differences to laboratory-scale studies and simulations.

The stirring intervals in this study were chosen as they are often found at full-scale BGP. No difference in distribution was found by measuring the DM. However there are differences found in nutrient distribution depending on the investigated agitation system, as well as position and height of the sample. Through all experiments, the highest acetic acid concentration was found on the bottom of the digester and the lowest was measured when both agitation systems were used. Samples taken closer to the solid substrate feeding system showed higher acetic acid values than samples taken on the opposite side. The quality of stirring with the provided agitators can be assumed as sufficient for this specific process. The data show that all three agitator setups differ significantly in their electric energy consumption. The optimum substrate metabolism is achieved with both agitators, due to the fact that the fatty acid concentrations were measured at the lowest level but a considerably higher electric energy input has to be accepted. In this study, an energy saving potential of up to 70% was measured by adapting the mixing system to the specific characteristics of the fermenting substrate.

Despite the first promising results gained with the developed innovative sampling method, it is necessary to conduct further measurements. In particular, a comparison of laboratory results from CFD or CT for the specific substrate and technical setup of the research BGP with the full-scale results from this study will provide a better understanding of the process. Hereto the research BGP offers a wide range of new approaches.

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Conflicts of Interest

The authors declare no conflict of interest.

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4. Publication 3: Influence of Maintenance Intervals on Performance and Emissions of a 192 kWel Biogas Gas-Otto CHP Unit and Results of Lubricating Oil Quality Tests – Outcome from a Continuous 2-Year Measuring Campaign

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Abstract

In the present work, we focus on long-term and permanent measurements of approximately two years on a 192 $kW_{el.}$ Gas-Otto CHP unit at a full-scale research biogas plant. In detail the influence of 600 h and 1,800 h maintenance intervals on fuel consumption and exhaust gas emissions such as NO_x, CO have been studied under real life conditions. Lubricating oil quality analyses throughout the CHP operation time are presented to show the destructive changes in property and its influence on condition based maintenance. The results confirm the well-known fact that after readjustment of the air-fuel ratio after 1,800 h maintenance the emission values for NO_x decline while CO increases. The emission-optimized operation mode leads to lower engine efficiency. The maintenance tasks carried out at 600 h intervals lead to lower NO_x emissions in nine cases while in 14 cases the emissions remained unchanged. The permanent measurements proved their legitimacy showing various emission deviations from the limiting values prior and post maintenance. The results show that by monitoring the lubricating oil quality, the oil change intervals can be maximized while ensuring that engine performance is not endangered. The oil analyses allow the operator to reduce maintenance expenditures while minimizing wear.

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Article

Influence of Maintenance Intervals on Performance and Emissions of a 192 kW$_{el}$ Biogas Gas Otto CHP Unit and Results of Lubricating Oil Quality Tests—Outcome from a Continuous Two-Year Measuring Campaign

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Abstract: In the present work, we focus on long-term and permanent measurements of approximately two years on a 192 kW$_{el}$ Gas Otto CHP (combined heat and power) unit at a full-scale research biogas plant. In detail the influence of 600 h and 1800 h maintenance intervals on electrical efficiency consumption and exhaust gas emissions such as NO_x and CO have been studied under real life conditions. Lubricating oil quality analyses throughout the CHP operation time are presented to show the destructive changes in property and its influence on condition based maintenance. The results confirm the well-known fact that after readjustment of the air-fuel ratio after 1800 h maintenance the emission values for NO_x decline while CO increases. The emission-optimized operation mode leads to lower engine efficiency. The maintenance tasks carried out at 600 h intervals lead to lower NO_x emissions in nine cases while in 14 cases the emissions remained unchanged. The permanent measurements proved their legitimacy showing various emission deviations from the limiting values prior and post maintenance. The results show that by monitoring the lubricating oil quality, the oil change intervals can be maximized while ensuring that engine performance is not endangered, and a longer engine lifespan can be expected. The oil analyses allow the operator to reduce maintenance expenditures while minimizing wear.

Keywords: CHP (combined heat and power) unit; emissions; maintenance intervals; part load; lubricating oil quality; oil change intervals

1. Introduction

1.1. General Introduction

The increased use of renewable energy sources for meeting the European [1] and German [2] political agenda has caused a massive growth in biogas production, especially in Germany. In 2011, approximately 7320 biogas plants were in operation, supplying the grid with 2997 MW of electrical power and providing heat as a secondary energy source. These figures include 80 units for biogas-upgrading and grid-injection, representing 1.09% of all biogas plants in Germany with an equivalent of 7.5% of the total electricity production from biogas [3]. Current forecasts for 2013 predict the number of biogas plants to increase up to 7874, with an increase in electrical power production of up to 3286 MW in Germany [3].

More than 98% of the biogas plants are using combined heat and power units (CHP units) to convert the produced gas into electricity and useful heat. There is no information on hand about the actual number of CHP units in operation, as listed biogas plants may contain more than one CHP unit. CHP units are well established and have been used for more than 100 years for onsite energy production based on natural gas [4]. In general, a great variety of technologies are available [5], but Gas Otto engines and dual-fuel engines are predominantly used for the conversion of biogas. As both systems offer advantages and disadvantages, biogas plant operators have to choose a type of engine depending on the size of the biogas plant, engine efficiency, engine availability, operating costs and potential revenues [6]. However, degradation in performance and maintenance expenditures during the lifetime of the engine is the big unknown in this calculation.

In order to provide more insight in this respect, experimental data collected over a period of more than two years at a 192 kW_{el} Gas Otto CHP unit running at the research biogas plant "Unterer Lindenhof" located near Stuttgart/Germany [7] was analyzed with regard to the schedule of maintenance. The goal of this study was to find a correlation between the efforts in maintenance and service performed at the unit, as well as the degradation in performance and emissions. Since prior studies dealing with this subject were mainly based on spot measurements [6,8–10], the contribution of the analysis presented in the following is its data basis taken from permanent and long-term measurements at a full scale biogas plant running under real-life conditions. The measurements of lubricating oil quality were also analyzed over this period, and results from that study are presented in this paper, as well.

1.2. Fundamentals

For economic and environmental reasons the performance of CHP units in terms of efficiency and emissions over its lifespan is of major importance for biogas plant (BGP) operators. High electrical efficiency is the key issue when choosing a CHP unit. However, operators are also forced to meet the limiting values for exhaust gas emissions given by the technical directives [11]. According to the German regulation TA Luft [12], the limiting values for emissions from biogas CHP units of more than 1 MW total rated thermal input are 1000 mg/Nm^3 CO and 500 mg/Nm^3 NO_x for gas engines, and 2000 mg/Nm^3 CO and 1000 mg/Nm^3 NO_x for dual-fuel engines. In accordance to TA Luft, the limiting values for CHP units with less than 1 MW thermal input power are defined by the Bavarian State Office for Environment (Bayrisches Landesamt für Umwelt). This office also defines a higher limiting value of 1500 mg/m^3 NO_x for dual-fuel engines [8]. Note that all numbers for emissions referring to the operation of CHP units are based on a content of 5% oxygen remaining in the dry exhaust.

Gas Otto engines are able to run solely on biogas, providing high thermal efficiency and low emissions. In contrast, the dual-fuel engine is based on the principle of the diesel cycle, where the ignition is carried out by injection of a secondary fuel into the gas mixture. This type of engine is less sensitive to gas quality, and can run solely on the secondary fuel in part load operation, if necessary. Higher electrical efficiencies are typical for the dual-fuel engine as well as higher emissions, both due to the diesel cycle. Kampmann [13] reports that Gas Otto engines can comply with the limiting values of German regulations regarding exhaust gas emissions TA Luft [14], if homogenous gas qualities are applied and the timing of ignition is optimized. With respect to dual-fuel engines, Kampmann shows that higher concentrations of CO occur, especially during part-load operations.

The use of oxidation catalysts is not recommended for both types of engines, since the hydrogen sulfide concentrations in the biogas cause catalyst poisoning. To avoid this problem, biogas engines are operated at a lean burning mode, referring to a mass ratio of air to fuel, known as air-fuel ratio (AFR), higher than necessary for stoichiometric combustion. Hence, there is a high content of excess air in the gas-air mixture, which tends to cool the combustion, resulting in a significant reduction of NO_x emissions. Unfortunately, engine efficiency is also reduced due to the lower temperatures of the heat supply to the thermodynamic cycle. Moreover, the excess air contributes to lower flame speed, causing incomplete combustion and the production of CO and unburned hydrocarbons (CnHm), e.g., formaldehyde (HCHO).

Emissions of formaldehyde from the exhaust gases of CHP units running on biogas are of special importance, since formaldehyde has been classified as a carcinogenic substance [15].

For that reason, a reduction of the limiting value of 60 mg/Nm^3 according to TA Luft was discussed. As a result, the issue 2009 of German Renewable Energy Sources Act (EEG) has been granting an anti-air pollution bonus if emissions of formaldehyde are kept below 40 mg/Nm^3. Emissions of formaldehyde have been measured and discussed by several authors. Neumann and Hofmann measured 97 CHP units at full and part load by the year 2008. Some of the CHP units exceeded the limiting value of 60 mg/Nm^3. The authors emphasize the importance of regular maintenance and exhaust treatment for a successful operation [16]. HCHO emissions exceeding the TA Luft limiting value of 60 mg/Nm^3 (that applies to biogas plants >1 MW total rated thermal input) were measured at 25% of all units analyzed by Moczigemba [17]. Ebertsch and Fiedler [10] measured the performance of various CHP units, partly equipped with oxidation catalysts. The results before and (after) 2009 showed that 30% (2%) of the Gas Otto engines comprised HCHO emissions >60 mg/Nm^3, 50% (96%) of <40 mg/Nm^3 and 20% (2%) between 40 and 60 mg/Nm^3. 44% of the dual-fuel engines revealed HCHO emissions >60 mg/Nm^3, 26% of <40 mg/Nm^3 and 30% between 40 and 60 mg/Nm^3 before the year 2009. After 2009, 100% of the dual-fuel engines showed formaldehyde emissions of

<40 mg/Nm^3, with 90% below 10 mg/Nm^3. However, these low emissions were achieved at the expense of engine efficiency. A study by Bauer and Wachtmeister [9], of two full-scale biogas plants, indicated that HCHO emissions in the exhaust gas could be reduced to a level far below the limiting value by using exhaust gas treatment systems such as an oxidation catalyst and a thermo reactor. The thermo reactor showed high conversion rates, higher operation complexity and required more intensive maintenance. The oxidation catalyst appeared to have a lower conversion rate, and is highly vulnerable to H_2S and dust. The authors recommended further research to reduce the HCHO emissions by studying both the catalysts and the engine.

Evidently, there exists a direct connection between engine efficiency and environmental impact of CHP units, which is strongly affected by any efforts spent on maintenance and service of the unit. Gronauer *et al.* [18] conducted one of the early measurement campaigns in this respect. The analysis of four dual-fuel engines (22 kW_{el}, 50 kW_{el}, 80 kW_{el}, 132 kW_{el}) and one Gas Otto engine (13 kW_{el}), based on 4 spot-measurements over a period of 7 months, showed that four out of the five engines exceeded the limiting values of NO_x and CO in every campaign. The authors found that emissions differed significantly due to a sensitivity caused by fluctuating gas quality, engine load and service conditions. Furthermore, it was found that engines at part load caused higher emissions. The authors conclude that the engines require optimal maintenance and engine adjustment to the gas quality, with respect to the content of methane, in order to reduce emissions to a minimum [19]. Aschmann *et al.* [6,11] analyzed the influence of different maintenance strategies by focusing on electrical efficiency and exhaust gas emissions for three dual-fuel and three Gas Otto engines. This study includes discontinuous measurements at full-load operation only. The results showed that in most cases the limiting value for NO_x was exceeded. In one extreme case an engine showed emissions six times higher than the limiting value (500 mg/Nm^3 NO_x) stated in the TA Luft.

NO_x-emissions below the limiting value could be measured for five engines only right after the manufacturer had serviced them. In some cases it was found that a compliance of emissions with the limiting values resulted in a lower engine efficiency. In general, the results revealed a strong impact of maintenance strategy, especially on engine efficiency depending on engine type and size. A study by Moczigemba [17] showed that 60% out of 25 CHP units exceeded the limiting value of 500 mg/Nm^3 for NO_x-emissions.

The electrical efficiency of nine CHP units with a capacity ranging from 30 to 526 kW_{el} was investigated by Aschmann and Effenberger [19] over a period of 6 years. In this study, discontinuous measurements of four hours each were interpolated for the observation periods. The study showed that the electrical efficiency declined over the time of operation. The level of decline was hereby strongly affected by the maintenance strategy and engine overhauling. Maintenance and overhauling of the engine carried out by the engine manufacturer showed best results. The electrical efficiency of the investigated CHP units was on average found to be 3 percentage points lower (36.1%) than the manufacturer specifications (39.2%). Furthermore, exhaust gas emissions were measured for a 526 kW_{el} engine, showing that NO_x and CO values were above the limiting values before the maintenance intervals. A general engine overhaul showed a positive impact on exhaust gas emissions [19]. Effenberger [20] indicated a decrease in efficiency of 0.5–0.6 percentage points every 10,000 h of operation for biogas engines under regular maintenance. Calculations showed that a decline in efficiency of one percentage point for a 526 kW engine (with a utilization rate of 97%) corresponds to an equivalent 6 ha Maize [20].

From this outline, one may conclude that engine adjustments mainly focus on efficiency and profitability, and by this means to the expense of the environment due to increased exhaust gas emissions. In theory most CHP manufacturers comply with the standards regarding to emissions set by the directives. Regular service intervals and engine adjustments may ensure the completion of environmental directives and emission limits throughout the CHP lifetime. In practice, the efficiency of the CHP units is expected to decline over time, leading to lower profits [11]. This can be overcome, to a certain extent, by a consistent maintenance strategy [6,11,20].

The extension of the lifetime of the lubricating oil is another key issue in CHP technology. Assessing the quality of the oil in the CHP unit ensures engine safety, and also keeps performance and operational costs at an economical level. The limiting values of lubricating oil for stationary gas engines (including special fuels such as biogas) are based on a guideline developed by lubricant and gas engine manufacturers as well as research laboratories and machinery insurers (Table 1).

The durability of the lubricating oil in a Gas Otto engine is heavily dependent on thermal and oxidative load, fuel quality (biogas composition) and reactions of combustion products with the oil, impact of acidic reaction products as well as the mode of engine operation. Those influences yield a change in oil properties, which can be determined by measuring characteristic parameters. General specifications are wear, soiling, oil condition, additives and additional tests as a sign of oil and engine aging and contamination with process media. The guideline mentioned above suggests additional measures to standardize sample collection, sample containers, sample labeling, sample quantity, sample-collection methods as well as sampling intervals. After laboratory tests the results are interpreted according to the limiting values by lubricant and gas engine manufacturers [21]. The intervals between oil checks depend on engine type, fuel and mode of operation and must be set individually for each engine, according to the manufacturer's instructions [22]. Although there is no clear statement of when the oil should be changed, since many interactions of factors have to be taken into consideration, the experts rely primarily on oil condition and additional tests, then on soiling and finally on wear. The monitoring of the trend of all parameters within approximately 1000 operational hours is of major importance for ensuring an adequate quality of the lubricating oil.

Finally, it must be stated that most of the available data regarding the influence of maintenance on emissions, as well as the effects of lubricating oil quality on engine performance, was found in German literature, as there is still only a little international data available on the use of CHP units in the biogas sector, especially regarding the aforesaid topics. However, the economic, environmental and technical performance of CHP systems, and their use in industry and buildings, has been described by various authors [4,23–27]. Pourmovahed *et al.* [27] tested the performance of 7 kW_{th} and 1 kW_{el} biogas CHP units in terms of thermal and electrical power output, individual and overall efficiencies, as well as exhaust gas emissions.

Table 1. Limiting values for oil in stationary Gas Otto engines [21,22].

Parameter	Unit	Limiting Value
Wear		
Iron	mg/kg	21
Chrome	mg/kg	5
Tin	mg/kg	5
Aluminum	mg/kg	10
Nickel	mg/kg	3
Copper	mg/kg	15
Lead	mg/kg	20
Molybdenum	mg/kg	5
Soiling		
Silicon/Dust	mg/kg	4–7
Potassium	mg/kg	25
Sodium	mg/kg	Fresh oil + 25
Water	m%	0.2
Glycol	ppm	500 (pos)
Oil-condition		
Viscosity at 40°C	mm^2/s	SAE 40: min. 12 max.
Viscosity at 100°C	mm^2/s	18SAE 30: min. 9 max. 15
Viscosity index	–	increase max 3
Oxidation	A/cm	20
Nitration	A/cm	20
Sulfurization	A/cm	25
Additives		
Calcium	mg/kg	±20% compared to fresh oil
Magnesium	mg/kg	
Boron	mg/kg	
Zinc	mg/kg	
Phosphorus	mg/kg	
Barium	mg/kg	
Additional tests		
TBN	mg KOH/g	>50% of fresh oil but >2
TAN	mg KOH/g	Fresh oil value + 2.5
i-pH	–	>4
SAN	mgKOH/g	unverifiable
Soot	%	1.5

2. Materials and Methods

As outlined in the introduction, this study is based on experimental data from the operation of a 192 kW_{el} Gas Otto CHP unit running at the "Unterer Lindenhof" biogas plant. The CHP unit started operation in August 2008; the measuring campaign started in March 2009 and it ran continuously over a period of more than two years until June 2011.

The "Unterer Lindenhof" research biogas plant consists of two digesters with concrete coating, which are connected to one post digester, fitted with a double membrane roof for gas storage during maintenance or CHP shut down. Digesters and post digester are of the same size, with a diameter of 14 m and a height of 6 m and a gross volume of 923 m^3 each [28]. To run the CHP unit at full load, approximately eight tons of liquid and solid manure from cow, pig, sheep and poultry husbandry and another eight tons of renewable energy crops such as maize silage, grass silage, whole crop rye or wheat silage and ground grain are required for the daily biogas production in both digesters. The organic loading rate related to the organic dry matter (B_rODM) equals 1.93 kg/(m^3 d^{-1}) with a hydraulic retention time (HRT) of 120 days in total. Under mesophilic conditions, approximately 96 Nm^3/h of biogas are produced, at a quality of approximately 52% CH_4, 48% CO_2 and 500 ppm hydrogen sulfide (H_2S) based on molar fractions. Hydrogen sulfide is reduced from the initial state by a biological desulfurization performed by ambient air injection into all three digesters. In addition, the biogas leaving the post digester is treated in a separate gas-conditioning module (Schnell Motoren AG, Amtzell, Germany). Here, the biogas is cooled by a double-pipe heat exchanger in order to reduce the contents of water vapour and other soluble impurities, such as ammonia or sulfur, and finally cleaned by an activated carbon filter for absorption of the remaining H_2S to almost zero. In practice, not all CHP units are equipped with an effective purification technology. The results presented in this publication are only applicable to CHP units using such technology. After this treatment the biogas is converted in a CHP unit (MTU Onsite Energy GmbH, Augsburg, Germany). The CHP unit has an electrical power of 192 kW and a thermal power of 214 kW (nominal data). The main components are a 6-cylinder Gas Otto engine coupled with a synchronous-generator, the heat utilization unit and the switchboard. The electricity is completely fed into the local grid. Part of the useful heat is supplied to the digesters and the post digester in order to ensure an optimal process temperature of 40.5 °C. The remaining thermal energy is supplied to the district heating system of the research station. Any excess heat is rejected to the ambient by a cooler (Güntner AG & Co. KG, Fürstenfeldbruck, Germany). For engine lubrication Tectrol MethaFlexx HC PLUS (BayWa AG, München, Germany) is used in 1,000 liter batches. An oil laboratory regularly checks the lubricating oil (OILCHECK GmbH, Brannenburg, Germany). The analyzed result is then interpreted by experts from the lubricant supplier (BayWa AG) and from the engine manufacturer (MTU Onsite Energy GmbH, Augsburg, Germany). The biogas plant operator is provided with a diagnostic report of oil condition, contamination and equipment wear condition with recommendations for date of the next oil inspection and maintenance actions. The nominal data of the CHP unit based on the manufacturer's specifications is summarized in Table 2.

The CHP unit is maintained every 600 h by in-house personnel according to a service schedule prescribing maintenance tasks from MTU Onsite Energy GmbH for this specific engine. The tasks include, e.g., replacement of sparkplugs and ignition cables check and adjustment of ignition timing, measurement and adjustment of valve clearance as well as replacement of the air filter cartridge. In addition, the engine manufacturer carries out further maintenance under a maintenance contract with the biogas plant operator. Additional maintenance is supplied to the engine in each level every 1800 h, which are graded in 3600, 5400, 7200 and 10,800 h. Some of the tasks include lambda probe replacement, turbo charger check or cooling water check. The exhaust gas values are checked every 1800 h and the air-fuel ratio is readjusted if the manufacturer maintenance personnel detects any emissions exceeding the limiting values. This indicates that every third service is a major service and the time between two services roughly equals the length of a month at continuous operation of the CHP unit.

Table 2. Nominal data of the CHP unit at the "Unterer Lindenhof" research station.

Technical specification	System specification	System parameter
Engine	CHP unit	MDE MB 3066 L4
	Engine type	6 cylinder Gas Otto engine
	Electrical output power	192 kW
	Thermal output power (engine + exhaust gas cooling)	214 kW
	Thermal output power (gas mixture cooling)	29 kW
	Biogas input power (at 55% CH_4)	499 kW
	Engine lubricating oil	Tectrol MethaFlexx HC Plus
Emission limits	NO_x-emissions (at 5% O_2 in the dry exhaust)	<500 mg/Nm^3
	CO_2-emissions (at 5% O_2 in the dry exhaust)	<1000 mg/Nm^3

In order to gain as much knowledge as possible from the operation of the CHP unit, an extensive system for control and data acquisition was installed. In total 41 values, recorded every 5 min, are stored and saved each day in a selected file for further analysis. In detail, the data consists of

- electrical and thermal output of the CHP unit;
- utilization of thermal energy by the biogas plant and the district heating system;
- composition, flow, temperature and pressure of the biogas;
- composition and temperature of the exhaust gas;
- supplementary temperatures, pressures and further data from the CHP unit;
- additional data taken on demand for any extra information needed.

Since emissions are discussed in detail in the following, more information should be provided regarding the exhaust gas analysis. In the exhaust line of the CHP unit an exhaust gas analyzer testo 350 (Testo AG, Lenzkirch, Germany) is installed capable of measuring the contents of O_2, CO, NO, NO_2 and SO_2. Additionally, the temperature of the exhaust gas after the exhaust gas heat exchanger is detected on its way to the chimney. The analyzer's principle of operation is based on electrochemical cells for each component, and the analyzer can be equipped with 6 different cells. The measurements are performed continuously in a way that the analyzer takes continuous data during the first 10 min of every hour. The remaining 50 min are used for purging the analyzer with ambient air. This method for taking the data was specifically developed in order to ensure the durability of the device during the 2-year measurements. Moreover, the low content of H_2S in the exhaust gas, due to the efforts for purification of the biogas entering the engine, helped to apply the analyzer at this site. In order to ensure a constant accuracy over the period of the measuring campaign, the exhaust gas analyzer was calibrated in intervals of approximately six months. Compared to the basic uncertainties, no major deviations of the device were observed; hence, there was no noticeable drift of the electrochemical cells. However, long-term measurements of hydrocarbons in the exhaust could not be performed by using the analyzer Testo 350, since the electrochemical cell for detecting HC revealed a significant drift over time.

3. Results and Discussion

First, the effects of maintenance on electrical efficiency and emissions are discussed. From the experimental data collected over the two-year campaign, the data of the days the unit was serviced was analyzed.

Table 3. Effects of maintenance on electrical efficiency and emissions.

Maintenance	**Effects due to maintenance**		
Major/Minor	**Concentration of NO_x**	**Concentration of CO**	**Electrical efficiency**
8-Apr-09	decrease (t)	increase (t)	ns
7-May-09	decrease	increase	decrease (PL)
29-May-09	decrease (t)	increase (t)	decrease (t)
29-Jun-09	nd	nd	constant
27-Jul-09	decrease	increase	decrease (little)
20-Aug-09	decrease (t)	increase (t)	ns
23-Sep-09	decrease	increase	nd
14-Oct-09	nd	nd	nd
9-Nov-09	constant	constant	nd
3-Dec-09	decrease (t)	increase (t)	nd
22-Dec-09	constant	constant	nd
14-Jan-10	increase	constant	nd
3-Feb-10	constant	constant	nd
03-&04-Mar-10	increase	constant	nd
29-Mar-10	constant	constant	nd
29-Apr-10	constant	constant	nd
20-May-10	constant	constant	increase (PL)
15-Jun-10	constant	constant	constant
8-Jul-10	decrease	increase	ns
5-Aug-10	constant	constant	increase
1-Sep-10	decrease (t)	constant	decrease (t)
22-Sep-10	constant	constant	constant (PL)
20-Oct-10	constant	constant	constant
15-Nov-10	constant	constant	constant
3-Dec-10	constant	constant	ns
23-Dec-10	constant	constant	ns
24-Jan-11	constant	constant	ns
23-Feb-11	decrease	increase	decrease
22-Mar-11	decrease	increase	decrease
09-April-11(sp)	decrease	increase	decrease (little)
15-Apr-11	constant	constant	constant
25-April-11(sp)	decrease	increase	ns
9-May-11	constant	constant	constant
14-June-11	nd	nd	constant (PL)

nd: no data; ns: no statement possible due to part load; PL: part load may affect the results as well; t: small time lag between maintenance and effect; sp: additional change of spark plugs (no regular change of spark plugs during the next service).

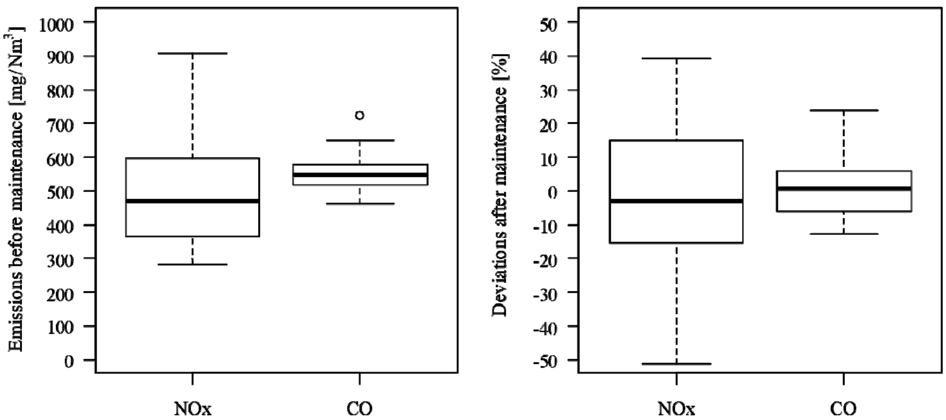
Table 3 shows the effects of maintenance on the concentrations of NO_x and CO in the exhaust gas as well as on electrical efficiency. In the left column of Table 3 the dates of the services are shown, and it is denoted, if a minor or a major service was scheduled. For a better understanding of the various effects, different colors are used in order to depict an increasing or a decreasing result. In detail, a full red box indicates a decrease, while a light red box is attributed to a decrease of little magnitude, a decrease partly affected by part-load operation or a decrease occurring with a time lag of one to three days before or after the date of the service. The same scheme is applied to indicate increasing values using full green and light green colors.

From Table 3, it can be seen that, that besides the service dates with no changes detectible in most cases a decrease of NO_x-emissions is connected to an increase of CO-emissions and often connected to a decrease in electrical efficiency after service [8]. This result compares to the expectations and results published in the literature for Gas Otto engines running on a lean mixture, as stated previously. To be precise, the results are caused by an adjustment of air-fuel ratio (AFR) during service, which will be proved by the change of oxygen content in the exhaust gas in the following. An increase of AFR yields a reduction in temperature in the combustion zone due to the higher content of the inert gas nitrogen in the cylinder. By this means the formation of thermal NO_x, which is the major path of NO_x-production, is repressed. As a result, electrical power and efficiency of the CHP unit are also reduced; the first due to the smaller amount of fuel in the cylinder and the latter due to the lower temperature of heat supply to the thermodynamic cycle. However, the reduction in electrical power could be overcome by opening the throttle for fuel inlet a little more. In addition to Table 3 data of NO_x and CO emissions for 5 days before and after every maintenance interval are presented in Figure 1. The evaluation shows that the majority of NO_x values range between 350 and 600 mg/Nm^3 with the total span ranging from 300 to 900 mg/Nm^3. Maintenance has an effect of ±15% (50% of the data) on emissions with a slight trend to lower NO_x values (−2.5%). However, the deviations after maintenance for all NO_x data fluctuated in a very wide range from −50% to 40%. The majority of the values for CO ranged between 550 and 600 mg/Nm^3 within a span of 460 to 650 mg/Nm^3. After maintenance, a trend of a slight increase of 0.6% in CO was found. The results show that 50% of the data for CO range from −5% to +5% and from −14% to 24% for the total CO data set, after maintenance.

As previously mentioned these effects are well known from practical engines and published in the literature [6–8]. However, the data presented in Table 3 proves this theory from practical experience over a 2-year period of continuous measurements, and it shows the evolution of the impact of maintenance for a longer period of operation of the CHP unit. A finding is that wide ranging fluctuations of emissions are found and that maintenance does not have the desired effect of lower emissions in every case.

Based on the assumption of a stochiometric air fuel mixture, an increase in AFR will lower CO-emissions, since there is more oxygen available helping to completely convert the hydrocarbons to CO_2. On the other hand, an increase in AFR tends to lower the temperature in the combustion zone and therefore slows the speed of the chemical reaction for converting the hydrocarbons to CO_2 and water. Evidently, this effect works against the higher concentration of oxygen in the combustion zone, and at a certain value any further increase in AFR yields an increase of CO-emissions, since the speed of the chemical reaction has become too small, resulting in incomplete combustion, as shown *i.e.*, in [29]. Due to the fact that almost 50% of biogas is made up by CO_2, which can be seen as an inert gas, the combustion of biogas is in principle slower compared to the combustion of pure methane. For that reason, the AFR applied for lean combustion of biogas in Gas Otto engines is already in the range where any further increase does not tend to lower CO-emissions, but on the contrary, yields an increase of CO-emissions. This is proven by the data collected from the CHP unit, as shown in Table 3 and Figure 1.

Figure 1. Boxplot of NO_x and CO emissions five days before maintenance and its change in percentage points five days after the maintenance over all maintenance intervals.



In order to provide more insight into the data collected during the measuring campaign and the evaluation around the dates of maintenance, Figures 2–4 present electrical power, electrical efficiency and emissions plotted versus time. Due to the fact that it is not worthwhile to display the complete data of 2 years and 3 months in one diagram, a time span of 3 months, namely from mid March 2009 until mid June 2009, has been selected for presentation. For further discussion of the effects of maintenance, the relevant dates are marked in the diagrams. It can be seen that a major maintenance was performed on 8-Apr-09 and two minor maintenances were performed on 7-May-09 and 29-May-09. Evidently, the presentation in Figures 2–4 is a compromise between the large amount of data available and a comprehensive description of the various effects. It should be noted that a more detailed discussion is given in Thomas and Wyndorps [7]. Here, the data is displayed around the major maintenance of 23-Feb-11, in high resolution.

From the diagram for electrical power (Figure 2) it can be seen that the nominal power of 192 kW_{el} was not reached. Instead, a maximum electrical power of 186 kW could be achieved, which is attributed to the location of the biogas engine at the research station at a geodetic height of 440 m above sea level. This fact is not often taken into account for economic calculations even though the decline in electrical output might be quite significant, as shown here by a reduced power of at least 3 percentage points. Moreover Figure 2 displays that it was not possible to run the CHP unit on full load continuously. In particular, around 25-Mar-09, 24-Apr-09 and 9-May-09, significant phases of electrical power fell below 192 kW. This indicates part-load operation. Comparing this to the diagram of electrical efficiency (Figure 4) reveals that electrical efficiency drops during part-load operation from 38% to 39%, while a peak efficiency of 40% is reached during continuous periods of operation at full power, only. Unfortunately, this effect sometimes interferes with the influence of maintenance on electrical efficiency, preventing a clear evaluation for the decrease in electrical efficiency. All dates relevant to this situation are marked in Table 3 by "(PL)" or "ns" for part load.

Figure 2. Recorded data for electrical power from 10-Mar-09 to 17-Jun-09.

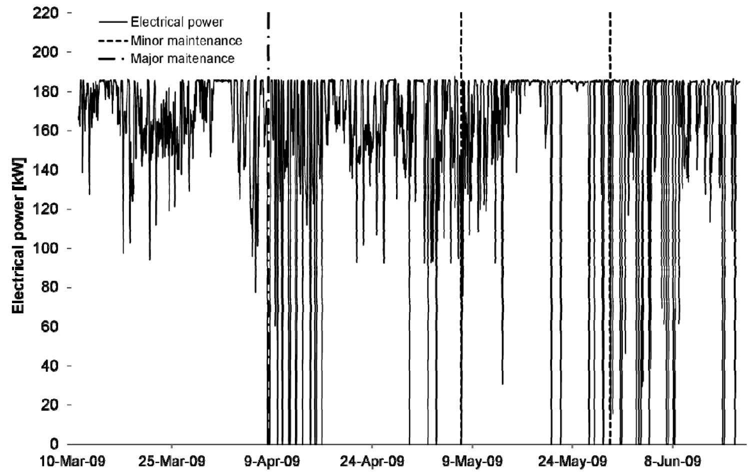
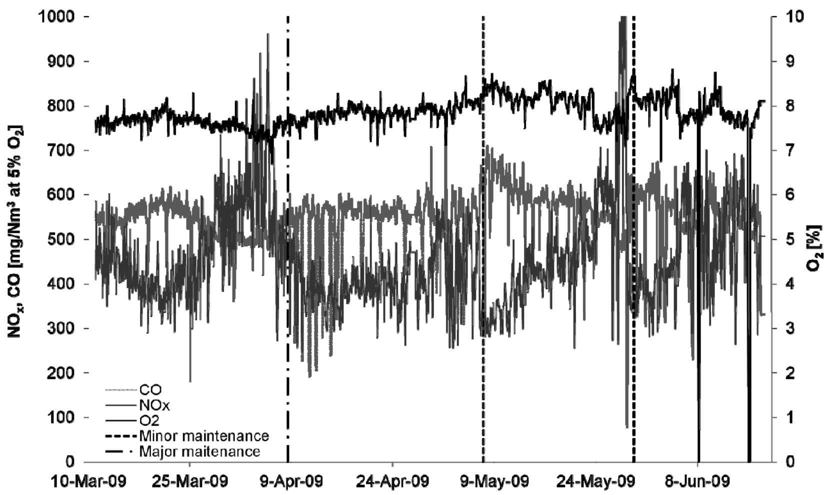
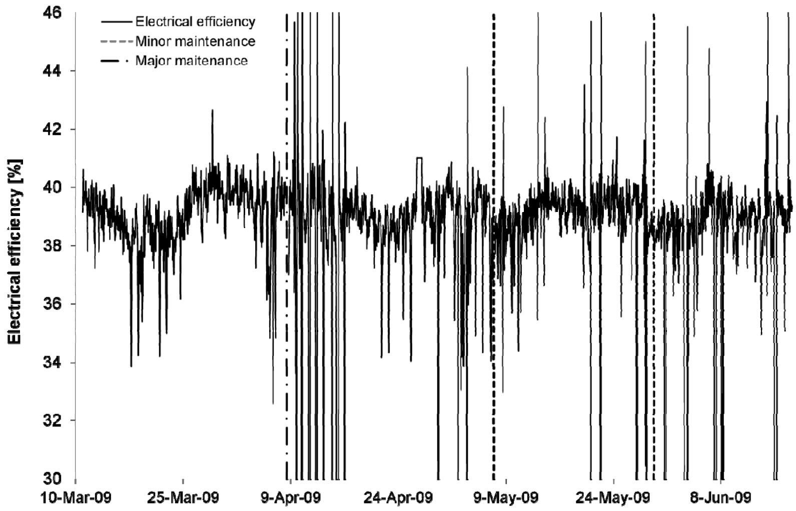


Figure 3. Recorded data for emissions from 10-Mar-09 to 17-Jun-09.



Looking at the diagram for emissions (Figure 3), it is obvious that NO_x-emissions always decrease around the three dates marked for maintenance. However, especially for the major maintenance on 07-Apr-09, there is a time lag visible between the drop of NO_x-emissions and the date for maintenance. An exact reason for this time lag cannot be determined. However, the drop of NO_x-emissions always coincides with an increase in oxygen concentration in the exhaust, as displayed in the diagram. This clearly indicates an increase in AFR proving the previously stated theory that an increase in AFR tends to lower NO_x-emissions. For the two minor maintenances depicted in Figure 3, the associated drop in electrical efficiency can be observed and it also coincides with the increase in oxygen content in the exhaust, which proves the theory with regard to the effect of AFR on electrical efficiency. Finally, the increase of CO-emissions also corresponds to the increase in oxygen concentration. Hence, the data presented in Figure 3 proves the fact that for Gas Otto engines running on biogas in lean mode, an increase in AFR yields higher CO-emissions, as shown by Zacharias for an AFR above 1.6 [29].

Figure 4. Recorded data for electrical efficiency from 10-Mar-09 to 17-Jun-09.



For evaluation of the global trend of electrical efficiency over time all data points need to be fitted by a linear function in order to level out any effect by part load or adjustment of AFR as described before. However, due to various changes in the measurements of the biogas volume flow rate between August 2009 and April 2010 consistent data in this respect is available for the time between May 2010 and June 2011, only. For this period of 13 months net electrical efficiency shows a decline of 0.76% absolute, which is a bit higher compared to 0.5%–0.6% per 10,000 h of operation as published by Effenberger [20].

Regarding oil quality the complete results are presented in Table 4 complemented by fresh oil values, as well as limiting values. The data is taken from the inspection records and it covers the entire period of operation of the CHP unit. Figures 5 and 6 and Table 4 show that the first batch of oil lasted for more than 13,600 h with the first oil check after 6103 h. Until the first oil change after 19 months the oil was checked regularly in six intervals between 900 and 1800 h according to expert recommendations. The second oil change was completed 17 months later, after an operation time of more than 11,500 h. In the second period the first oil check was carried out after 6549 h with three additional checks before the oil was changed. The intervals for the check were set between 1285 and 1827 operation hours. In the third period the first check was carried out after 7616 h with an additional check after 2273 h of operation. The last check conducted for this study was carried out on 10-Aug-12 at a total CHP unit operation time of 34,186 h.

Table 4. Summary of oil inspection records.

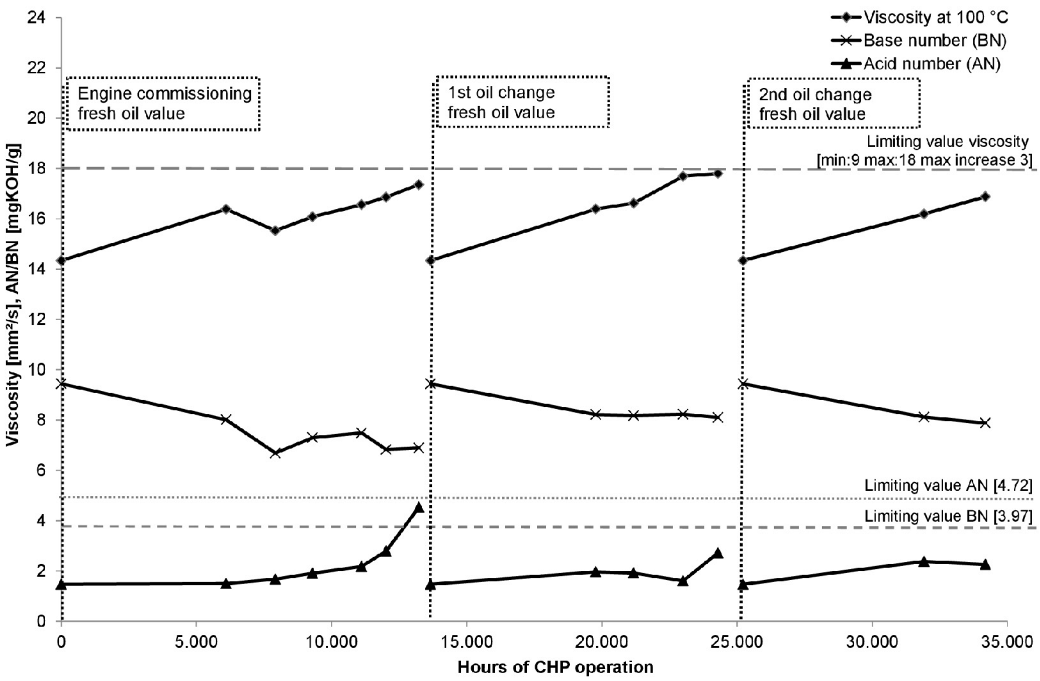
Number of analyses	**Unit**	**Fresh oil values**	**Limiting values**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Date of laboratory analyses	–	–	–	17-Apr-09	30-Jun-09	31-Aug-09	16-Nov-09	23-Dec-09	15-Feb-10	07-Dec-10	27-Jan-11	15-Apr-11	10-Jun-11	04-May-12	10-Aug-12
Date of sample taking	–	–	–	08-Apr-09	29-Jun-09	28-Aug-09	13-Nov-09	22-Dec-09	11-Feb-10	26-Nov-10	25-Jan-11	13-Apr-11	09-Jun-11	02-May-12	08-Aug-12
Date of last oil change	–	–	–	–	–	–	–	–	–	03-Mar-10	03-Mar-10	03-Mar-10	03-Mar-11	18-Jul-11	18-Jul-11
Operation time since last oil change	h	–	–	6,103	7,921	9,299	11,113	12,014	13,226	6,112	7,512	9,339	10,634	6,695	8,968
Total CHP operation time	h	–	–	6,103	7,921	9,299	11,113	12,014	13,226	19,775	21,175	23,002	24,297	31,913	34,186
Oil change	–	–	–	No	No	No	No	No	No	Yes	No	No	No	Yes	No
Fresh oil supply	–	–	–	No	No	No	No	No	No	Yes	No	No	No	Yes	No
Wear															
Iron	mg/kg	0	21	3	2	2	3	3	3	2	2	2	3	2	3
Chrome	mg/kg	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Tin	mg/kg	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Aluminium	mg/kg	0	10	4	4	4	5	5	5	2	2	2	3	3	4
Nickel	mg/kg	0	3	0	0	0	0	0	0	0	0	0	0	0	0
Copper	mg/kg	0	15	3	4	5	7	7	8	2	2	2	4	2	3
Leald	mg/kg	0	20	1	0	1	0	1	1	0	0	0	1	0	0
Molybdenum	mg/kg	0	5	0	0	0	0	0	0	0	0	0	0	0	0
PQ-Index	–	OK	–	OK	OK	OK	OK	OK	OK	OK	–	–	–	–	–
Soiling															
Silicon/Dust	mg/kg	7	4-7	2	2	2	2	2	1	2	3	3	4	2	3
Potassium	mg/kg	22	25	29	26	25	26	22	26	24	25	24	27	21	20
Sodium	mg/kg	3	28	1	2	2	3	1	4	5	6	5	4	9	6
Water	%	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Diesel fuel	%	0		0	0	0	0	0	0,3	0	0	0	0	0	0
Biodiesel	%	0		0	0	0	0	0	0,3	0	0	0	0	0	0
Vegetable oil	%	0		0	0	0	0	0	1	0	0	0	0	0	0
Soot	%	0.1	1.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 4. *Cont.*

Number of analyses	Unit	Fresh oil values	Limiting values	1	2	3	4	5	6	7	8	9	10	11	12
Date of laboratory analyses	–	–	–	17-Apr-09	30-Jun-09	31-Aug-09	16-Nov-09	23-Dec-09	15-Feb-10	07-Dec-10	27-Jan-11	15-Apr-11	10-Jun-11	04-May-12	10-Aug-12
Date of sample taking	–	–	–	08-Apr-09	29-Jun-09	28-Aug-09	13-Nov-09	22-Dec-09	11-Feb-10	26-Nov-10	25-Jan-11	13-Apr-11	09-Jun-11	02-May-12	08-Aug-12
Date of last oil change	–	–	–	–	–	–	–	–	–	03-Mar-10	03-Mar-10	03-Mar-10	03-Mar-11	18-Jul-11	18-Jul-11
Operation time since last oil change	h	–	–	6,103	7,921	9,299	11,113	12,014	13,226	6,112	7,512	9,339	10,634	6,695	8,968
Total CHP operation time	h	–	–	6,103	7,921	9,299	11,113	12,014	13,226	19,775	21,175	23,002	24,297	31,913	34,186
Oil change	–	–	–	No	No	No	No	No	No	Yes	No	No	No	Yes	No
Fresh oil supply	–	–	–	No	No	No	No	No	No	Yes	No	No	No	Yes	No
Oil-condition															
Viscosity at 40 °C	mm²/s	134.33	min 9;	147.1	152.1	155.4	165.67	171.26	175.8	164.06	169.02	178.02	185.66	164.09	172.05
Viscosity at 100 °C	mm²/s	14.34	max 18	16.38	15.53	16.08	16.56	16.68	17.36	16.39	16.62	17.69	17.8	16.19	16.88
Viscosity index		105	max increase 3	118	104	108	105	104	106	105	103	108	104	102	104
Oxidation	A/cm	0	20	12	15	14	15	21	18	9	14	18	18	16	10
Nitration	A/cm	0	20	1	1	1	2	1	1	1	1	1	1	1	1
Sulfurization	A/cm	0	25	0	0	0	3	0	0	0	0	0	0	0	0
Phenolic anti-oxidant	%	127.37	–	0	60.67	43.09	30.03	28.09	19.36	49.39	42.62	30.19	23.59	59.58	38.36
Addivtives															
Calcium	mg/kg	2,594	2,075–3,112	2,515	2,416	2,397	2,549	2,498	2,517	2,530	2,767	2,841	3,147	2,813	2,995
Magnesium	mg/kg	1	0.8–1.2	3	3	2	3	3	2	0	3	3	5	6	7
Boron	mg/kg	1	0.8–1.2	1	1	0	1	1	1	1	1	1	1	2	2
Zinc	mg/kg	5	4–6	4	4	5	5	2	7	4	4	6	7	10	11
Phosporus	mg/kg	564	451–676	517	496	478	487	482	488	531	550	569	617	558	581
Barium	mg/kg	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sulfat	mg/kg	5,001		4,480	4,048	4,429	4,378	4,063	4,273	6,145	6,522	6,580	7,217	6,776	6,507
Additional tests															
Base number (BN)	mgKOH/g	9.44	4.72	8.01	6.69	7.3	7.49	6.83	6.89	8.22	8.18	8.23	8.1	8.12	7.88
Acid number (AN)	mgKOH/g	1.47	3.97	1.5	1.68	1.91	2.18	2.79	4.53	1.97	1.92	1.61	2.72	2.38	2.26
i-pH-value	–	6.67	>4	5.96	4.76	5.08	5.27	4.74	4.99	5.66	5.77	5.53	5.28	5.67	5.88

In Figure 5 selected results for oil condition and additional tests are shown, which explain some important factors for oil quality and oil-change schedule decision making. In addition, three fresh oil values are added to show the changes after the new oil was supplied. As already discussed, the decision for an oil change depends on various factors. Viscosity at 100 °C as an indicator for oil condition and acid number (AN) as well as base number (BN) from additional tests were chosen to highlight the decision making for an oil change in Figure 5. The viscosity describes the fluidity of the oil, and it increases due to oil aging, nitration, soot and evaporation of light volatile components. The AN increases due to a reaction of the oil with oxygen. The oxidation products may build organic acids that can lead to corrosion or deposits even if a base buffer is found. Acids are reaction products of the combustion process that are formed by aging and nitration. The buffer of bases is described by BN and characterizes the capacity for neutralization in the oil. Through reaction with acids, this capacity declines over time, especially if the engine runs contaminated gases such as biogas. Figure 5 shows that the viscosity slightly increases during operation. The oil was changed for the first time after the limiting values for viscosity and AN were almost reached after six analyses. Due to a lower AN found in analysis five, the oil was kept for another 1200 operating hours. After the first oil change the viscosity increased again until it reached its limiting value. However, the oil was kept another 2295 h due to an AN well below the limiting value. The BN decreased over the operating time, but it was measured always well above its limiting value. This implies that viscosity and AN are the most important parameters for oil change decisions.

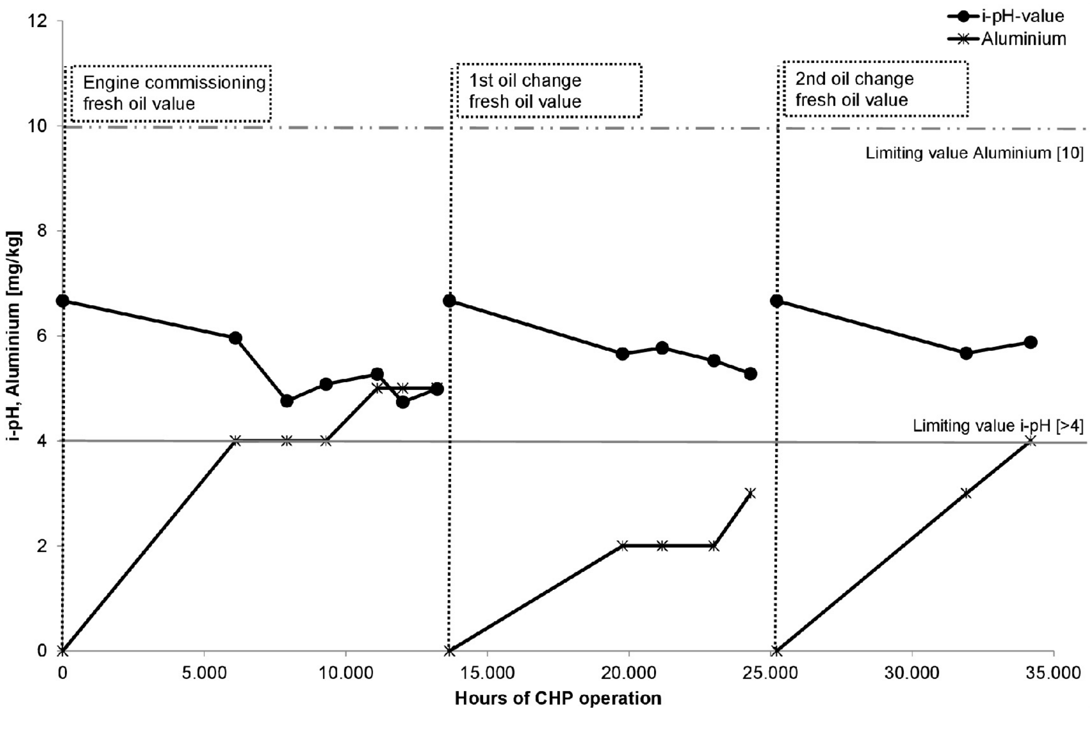
Figure 5. Results for viscosity, base (BN) and acid number (AN) complemented by fresh oil values at times of oil changes.



The value i-pH for additional tests and the content of aluminum for indication of wear are presented in Figure 6. Because the BN does not give complete information about the neutralization capacity of the oil, the i-pH value supplies essential information in this respect, especially for lubricating oils in biogas engines about the load with corrosive acids [22]. Any aluminum found in the oil indicates engine wear, since aluminum is a typical element in pistons and plain bearings or it is found in contaminated inlet air.

The results presented in Figure 6 show a declining i-pH value with operating time, as expected. In addition, it can be seen that the i-pH value always stays well above the limiting value of 4. The results show that the content of aluminum in the oil increased over operating time to a level between two and five mg/kg and did not reach the limiting value of 10. Both i-pH value and content of aluminum were not responsible for any oil-change decisions. The content of aluminum in the oil is still low due to the comparably short lifetime of the engine. It can be presumed that the fast increase of aluminum from zero to four in the first period was due to the startup phase, when oil in the engine was soiled with production residues from engine commissioning. However, the fast increase of aluminum concentration in the third period may be a sign of engine aging.

Figure 6. Results for i-pH and content of aluminum complemented by fresh oil values at times of oil changes.



4. Conclusions

The results from the 2-year measuring campaign regarding effects of maintenance on emissions and electrical efficiency coincide with common knowledge from the literature. It must be stated that due to the effective gas purification installed at the research biogas plant, the results of this study are only applicable to installations using such technology. In 2008, such units were not standard, but over the past years many biogas plants retrofitted such systems. Nevertheless, the results gained in this study prove that the use of effective gas purification technology can be highly recommended and currently the use of a gas purification unit is compulsory for some CHP units.

It was found that any increase in AFR during a service, which could be detected by an increased content of oxygen in the exhaust gas, yields a reduction in NO_x-emissions, but an increase in CO-emissions and a reduced electrical efficiency. In addition, the results proved the decline in electrical efficiency at part-load operation. This drawback should be kept in mind when discussing the operation of biogas CHP units for balancing production and demand of electricity in smart grids.

Moreover, the continuously collected data revealed that even after adjusting AFR during a service, a decline in oxygen content right after the service is not unlikely. Evidently, this indicates a decrease of AFR and, consequently, an increase in NO_x-emissions again, which was also detected from the experimental data. This emphasizes the need for a service of CHP units on a regular and professional basis, in order to prevent unacceptable exhaust gas emissions. This request can be found in the literature, as well. However, it will be most consequential to call for an online monitoring, in order to prevent any emissions beyond the limiting values between the services. Based on the results from the measuring campaign, this request can easily be fulfilled by monitoring the AFR of the CHP unit, which must be detected for lambda control anyway, since there is a direct connection between NO_x-emissions and oxygen content in the exhaust gas. Nevertheless, the results from this paper demand an improvement of lambda control. Even though the quality of the control may be sufficient for the operation of the Gas Otto engine in lean mode, the risk for excessive NO_x-emissions due to the remaining variations in AFR are is still too high. The results of the oil inspections prove that on-demand oil change intervals based on regular oil checks are in favor of fixed, time-based intervals. As the oil quality declines in dependence on gas purity, and full or part load of the engine over its lifetime, the appropriate time for the oil change cannot be precisely predicted. The assessment of the oil parameters revealed whether the oil was ready to be changed, or if it was suitable for further operation. The analysis provided the confidence that maximizing the oil change intervals did not endanger system performance. This saves maintenance costs and simultaneously minimizes wear. The frequency of oil analyses as carried out for this Gas Otto CHP unit proves to be the right strategy as unscheduled downtime due to unexpected changes in the oil was avoided and the engine equipment reliability improved. The oil analyses allowed a monitoring of the engine components with respect to wear of metal. As metal components in CHP units differ depending on the manufacturer and are difficult to distinguish, as they occur several times in an engine, a close consultation with the specific CHP manufacturer is required to evaluate the data and to precisely detect component failure. Taking into consideration that the engine will be operated for a long time, component failure may be detected in advance. This will allow maintenance to be scheduled in advance and thus reduce engine downtime in case of a component failure. Currently, no online measurement equipment for oil quality is available for biogas CHP units that allows the parameters to be measured permanently.

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Conflict of Interest

The authors declare no conflict of interest.

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5. Publication 4: Effects of Temperature, pH and O_2 on the Removal of Hydrogen Sulfide from Biogas by External Biological Desulfurization in a Full Scale Fixed-Bed Trickling Bioreactor (FBTB)

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Abstract

Hydrogen sulfide (H_2S) is a critical component of biogas formed under anaerobic conditions by sulfur and sulfate reducing bacteria from animal manure and renewable energy crops. H_2S causes high corrosion in equipment, has a negative environmental impact, inhibits the biogas formation process and is furthermore odorous and toxic. Although several methods for internal and external desulfurization found their way into practice and have been researched at laboratory scale, no data is available on the performance of such methods in full-scale practice, especially for an external fixed-bed trickling bioreactor (FBTB). The effect of temperature, pH and air ratio on H_2S removal efficiency (RE) was studied. The study was conducted at a research biogas plant with a given output of 96 m^3biogas per hour, and an H_2S concentration ranging between 500-600 ppm. The FBTB column has been designed to hold a packing volume of 2.21 m^3 at a gas retention time of 84 seconds being loaded at an average of 3,098 g $H_2S/m^3/h$. The highest H_2S removal efficiency of 98% was found at temperatures between 30-40°C. A major decline in RE to 21-45% was observed at temperatures from 5-25°C. The results clearly show a temperature optimum range for sulfate reducing bacteria. The results revealed that RE is little affected by different pH values and air ratios. During the experimental period, the practical suitability of the FBTB system could be proved while avoiding the disadvantages of internal biological desulfurization methods.

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Effects of temperature, pH and O_2 on the removal of hydrogen sulfide from biogas by external biological desulfurization in a full scale fixed-bed trickling bioreactor (FBTB)

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Abstract: Hydrogen sulfide (H_2S) is a critical component of biogas formed under anaerobic conditions by sulfur and sulfate reducing bacteria from animal manure and renewable energy crops. H_2S causes high corrosion in equipment, has a negative environmental impact, inhibits the biogas formation process and is furthermore odorous and toxic. Although several methods for internal and external desulfurization found their way into practice and had been explored at laboratory scale, no data were available on the performance of such methods in full scale practice, especially for an external fixed-bed trickling bioreactor (FBTB). The effects of temperature, pH and air ratio on H_2S removal efficiency (RE) were studied. The study was conducted at a research biogas plant with a given output of 96 m^3 biogas per hour, and an H_2S concentration ranging between 500 ppm and 600 ppm (1 ppm=1 cm^3/m^3) on average. The FBTB column has been designed to hold a packing volume of 2.21 m^3 at a gas retention time of 84 seconds being loaded at an average of 32.88 g $H_2S/(m^3 \cdot h)$. The highest H_2S RE of 98% was found at temperatures between 30℃ and 40℃. A major decline in RE to 21%-45% was observed at temperatures from 5℃ to 25℃. The results clearly showed a temperature optimum range for sulfate reducing bacteria. The results reveal that RE is little affected by different pH values and air ratios. During the experimental period, the practical suitability of the FBTB system could be proved while avoiding the disadvantages of internal biological desulfurization methods.

Keywords: external biological desulfurization, fixed-bed trickling bioreactor (FBTB), H_2S removal efficiency (RE), hydrogen sulfide, biogas, full scale biogas research plant
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1 Introduction

In the course of the objective target of the European Parliament and the Council of the European Union to cover 20% of the total energy production in Europe with renewable sources by 2020[1], the use of renewable energy has increased during recent years. In this context the use of biomass has been increased significantly throughout Europe till now, supplying more than 69% of all renewable energy, followed by hydropower (19%),

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wind power (7%) and others (5%)[2]. In Germany, renewable energy sources contribute to 12.2% of the final energy consumption, with a share of 38% generated by wind power plants, 30% by biomass, 16% by hydropower and approximately 16% by photovoltaic power plants[3]. Especially in Germany, the production of biogas, which is produced by microbial anaerobic conversion, has an increasing importance for the supply of electric power. In 2012, the number of biogas plants in Germany with on-site electricity production was estimated to be 7 521 with a total capacity of 3 185 MW of electric power[4]. Based on the assumption that 83 new biogas upgrading plants are in use since 2012, supplying the grid with 460 million Nm^3 biomethane (~220 MWel. or 0.6% of the German natural gas consumption), almost 98.9% of all biogas plants use Combined Heat and Power (CHP) Units for energy production[5]. The renewable energy source "biogas" is defined as mixture of gases, consisting of methane (CH_4), carbon dioxide (CO_2), hydrogen sulfide (H_2S) and traces of other gases like nitrogen (N_2), oxygen (O_2), hydrogen (H_2) and ammonia (NH_3). The composition of biogas depends on the organic material as well as on the conversion technology used, varying between 50%-75% CH_4, 25%-45% CO_2 and 0-20 000 ppm (1 ppm=1 cm^3/m^3) H_2S[6,7]. The concentration of the especially significant trace gas H_2S in biogas is influenced by the composition of the organic material fermented[8]. Table 1 illustrates the sulfur (S) content of typical biogas substrates in percent of fresh matter[9]. The range of H_2S varies from 10 ppm to about 10 000 ppm[8]. H_2S is created through anaerobic fermentation of sulfate-containing feedstock, such as rapeseed or animal excrements[10]. It is created through microbial reduction of inorganic sulfate by sulfate reducing bacteria in the digester[11]. Academic literature, however, still lacks in reliable data on detailed conversion rates of inorganic sulfate to H_2S for typical biogas substrates. Sulfur deficiency in crop production is described to be a major problem in most parts of the world, due to higher crop yields, decreasing aerial deposition of sulfur and decreasing mineralization of S from soil organic matter[12]. The recovery of sulfur from the biogas process can help to compensate this shortage. Grant[12] reported that sulfate forms of S in fertilizers are immediately plant-available and good sources for use in the year of application, whereas elemental sulfur must oxidize to sulfate. However, this may require a certain process depending on environmental conditions, before it is plant-available in the year of application.

Table 1 Sulfur content in % of fresh matter and in g/kg for typical biogas substrates

Substrate	Sulfur content in % fresh matter
Maize silage	0.05-0.07
Grassland	0.05-0.08
Winter oilseed rape	0.061-1.14
Substrate	**Sulfur content in g/kg**
Cattle manure	0.7-0.8
Poultry manure	2.8-3.2
Cattle slurry	4.0-6.0
Pig slurry	6.0-7.0

H_2S, a kind of highly toxic[13,14] and corrosive gas[15], inhibits the biogas process directly, as well as indirectly in the case of higher H_2S concentrations in the fermenter[10]. The reduction of substrate-bound elementary sulfur and sulfates to H_2S is a competing reaction to hydrogenotrophic methane formation[10]. More importantly, the corrosive aspect is one of the main challenges, resulting in an acidification of the CHP-engine oil, deposits, adhesive contacts and harmful gas emissions during combustion[15]. The destruction of oxidation catalysts leads to increased operating costs (e.g., shorter oil change intervals) and reduced sales through engine failures. It finally results in a shorter lifetime of the CHPs and its components.

To avoid those negative impacts, a reduction of the H_2S-concentration in biogas is required before combustion. Internal and external desulfurization methods are well known and employed in most biogas plant using CHP units[16]. Chemical oxidation, carbon adsorption and external biological desulfurization are among the most commonly used methods for external desulfurization[17].

Biological desulfurization via injection of ambient air into the gas headspace in the digester is the most widely used process for internal desulfurization applied in 90% of all biogas plants and followed by the addition of iron salts to the fermenting substrate[18]. Depending on the proportion of oxygen injected into the gas phase, H_2S is oxidized into elementary sulfur, sulfate-S or sulfite-S[19]. A reformation of S into H_2S by an unintended return of accumulated degradation products from the colonization surfaces into the fermentation substrate is one of the crucial drawbacks of this method[20].

Recently, external biological desulfurization methods have become much more popular in order to remediate the problems resulting from internal desulfurization. Biogas plants with external desulfurization units are finding their way into the market. Several methods for external biological desulfurization such as two-stage bioscrubbers, one stage-biotrickling filter have been described in the literature[21,22]. In two-stage bioscrubbers, the H_2S in the raw gas is absorbed first by contacting with water in a scrubber and afterwards biologically degraded in a bioreactor[23]. A further option is a one-stage bio-trickling filter, where the raw biogas passes through a fixed bed reactor, filled with plastic packing materials. Washing water is trickled periodically over the fixed bed to promote a biofilm generation on the packing material, enabling the immobilization of microorganisms. Dissolved H_2S is oxidized by certain microbial group to elementary sulfur and sulfate[24]. The H_2S degradation rate of the bacteria depends on several parameters which could be better controlled with a recirculated water phase (pH, temperature, addition of nutrients, removal of accumulated salts, etc.)[25]. The effects of different operational settings for pH, oxygen and temperature have been described in recent literature. Especially, a wide range of pH was reported for H_2S removal in biofilters. Gabriel and Deshuesses[26] have discovered that pH levels decreased during the adaptation phase and stabilized at pH 2. The decrease in pH resulted in an increased hydrogen sulfide degradation rate up to 99%[26]. Another study showed pH values ranging from 2 to 7 and observed removal efficiencies from about 95% at pH 2, to 97% at pH values from 3 to 7[27]. Other experiments in the mentioned study revealed an optimal pH value of 6 for autotrophic bacteria. These differences in degradation performance for different pH values are explained by the fact that within the genus of the sulfur compound bacteria Thiobacillus, some species are found favoring pH-neutral environments and others favoring low pH values[25]. An insufficient availability of oxygen in the bioreactor leads to an incomplete removal of H_2S[28]. Schneider et al.[29] reported a stochiometric demand of 4%-6% (v/v) air in biogas as optimal for a complete oxidation. For the degradation of organic compounds they recommended a higher air flow rate to provide the microorganisms with sufficient oxygen. For an optimal desulfurization performance, an amount of about 8%-12% air fed into the biogas flow was suggested by Mollekopf et al[19]. It was reported that higher air application rates resulted in lower CH_4 content in the biogas and a lower calorific value[19]. The influence of temperature on H_2S degradation was studied by Schneider et al.[29] and revealed an impairment of microorganism activity, which led to a reduction of the degradation capacity at temperatures below 20℃ in a bio-scrubber. For maximum H_2S degradation, the study of Mollekopf et al.[19] revealed an optimal washing water temperature at 35℃, due to an increased bacterial activity at higher temperatures. Furthermore, the study showed that temperatures above 35℃ inhibit the microbial activity and reduce the degradation of H_2S[19].

The present scientific work intends to test the efficiency of a full scale external biological desulfurization plant. The fixed-bed trickling bioreactor (FBTB) was integrated on the research biogas plant, at the experimental station Unterer Lindenhof (University of Hohenheim). For this purpose, a FBTB was investigated in order to determine the effect of each operational parameter such as pH, O_2 content and temperature degradation products on FBTB performance under full-scale conditions. To the best of our knowledge, this is the first literature to report on the performance of a full-scale FBTB for H_2S biogas treatment.

2 Materials and methods

2.1 Experimental setup

The FBTB "BioSulfidEx" was investigated on the research biogas plant "Unterer Lindenhof", an

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experimental station of the University of Hohenheim. The biogas plant consists of two digesters (each with a volume of 923 m^3) with concrete coating and one secondary digester (volume 923 m^3), fitted with a double membrane roof for gas storage. The gas is combusted inside a gas-otto-engine with a capacity of 186 kW_{el} and 202 kW_{th} power. Depending on the respective availability, approximately eight tonnes of liquid and solid manure from cow, pig, sheep or poultry husbandry are required for the daily biogas production in both digesters, with addition of approximately eight tonnes of renewable energy crops such as maize silage, grass silage, whole crop silage and ground grain. The organic loading rate related to the organic dry matter (Br_{ODM}) equals 1.93 $kg/m^3 \cdot d$ with a hydraulic retention time (HRT) of 120 days in total[30]. Under mesophilic conditions, around 96 m^3/h of biogas is produced, at a quality of approximately 52% CH_4, 48% CO_2 and 500 ppm to 600 ppm H_2S. The raw biogas formed in both digesters is stored in the secondary digester, later on supplying the Combined Heat and Power Unit. With the installment of the FBTB, the regular desulfurization method was replaced, originally consisting of biological desulfurization by 0.5% air injection into all three digesters and including a final biogas cleaning, before entering the CHP unit by an activated carbon filter (used as a polishing filter). The desulfurization unit (DSU) was integrated into the gas pipeline, between the secondary digester and the CHP-unit. The FBTB column has been designed to hold a packing volume of 2.21 m^3 at a gas retention time of 84 seconds being loaded at an average of 32.88 g $H_2S/m^3 \cdot h$.

The DSU consists of one FBTB and a subsequent carbon filter thereby a complete desulfurization is ensured in case of a FBTB breakdown. At regular conditions, the gas flows from the secondary digester into the FBTB and then through the activated carbon filter (both in upstream mode), before entering the CHP-unit. Various operation modes can be chosen by adjusting different gate valves to run either the FBTB or the carbon filter independently. Alternatively, the DSU can be shut down (Figure 1). Ambient air is injected by three air compressors into the biogas supply pipeline in front of the FBTB, while volume flow is adjusted by ball valves. A flow monitor, controlling the biogas flow, turns the air-compressors on and off, in case of a CHP stop, hereby preventing a surplus of air entering the system and causing technical or safety problems (Figure 1).

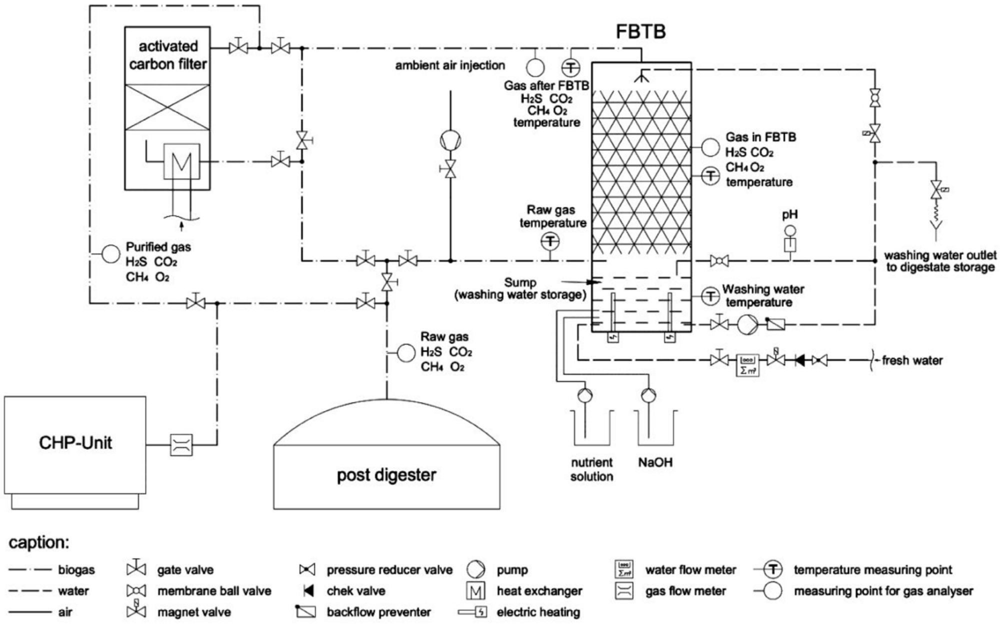

Figure 1 Piping diagram and instrumental drawing of the DSU

The non-insulated FBTB column is made up of polyethylene (PE) and filled with fixed-bed packing material for surface and bioreaction volume enlargement, with a volume of 2.21 m^3 above the gas supply pipe. The lower part of the FBTB (sump) is used for washing water storage, with a maximum capacity of 0.4 m^3. Four electric heating systems in the sump allow an adjustment of the washing water temperature, which is independent from the ambient temperature. The washing water in the sump was continuously circulated by a pump to allow permanent pH measurement. The fixed-bed was percolated with washing water from the sump for two minutes with ten-minute intervals and exchanged with fresh water every 1.5 hours for four minutes. The washing water containing decomposition products is flushed out before the fresh water is supplied. A membrane pump injects a small dosage of screened manure (as nutrient solution: 4 410 mg/L N, 250 mg/ L P, 4 860 mg/ L K) into the sump, while fresh water is added. To maintain the pH-value in the washing water, NaOH is injected into the sump by a membrane pump (controlled by a pH-measuring transducer). The insulated carbon filter was heated by a water heat exchanger, in order to reduce condensate formation (Figure 1).

2.2 Measurement equipment

As shown in Table 2, numerous measuring devices were installed at the biogas plant. This was to ensure the accurate measurement of all operating and consumption data. Gas quality was analyzed in a cycle of approximate 3.3 h by a multisensor analyzing system Union INCA 4000 (Union Instruments GmbH, Germany) for CH_4, CO_2, H_2S and O_2 at four different measuring points: raw gas; gas in FBTB; gas after FBTB and purified gas. CH_4 (measurement range and accuracy 0-100% Vol. ±1%) and CO_2 (0-100% Vol. ±1%) were measured by a nondispersive infrared (NDIR) sensor, H_2S (0-5 000 ppm ±5% & 5 000-10 000 ppm ±10%) and O_2 (0-25% Vol. ±1%) with electrochemical sensors. The gas quantity was continuously measured before the CHP unit by Esters (Esters Elektronic GmbH, Germany) GD 100/50/3 Ex gas flow meter based on the Fluidistor measurement principle. Temperatures were detected every 15 minutes by NiCr-Ni temperature gauges GTF 103 G ½ (Greisinger Elektronik GmbH, Germany) at four measurement points: raw gas, gas in FBTB, gas after FBTB and washing water temperature. The measurements were stored in Testo (Testo AG, Germany) 175-T3 data loggers. The ambient temperature was logged with two Testo Type 175-H2 data loggers. The pH-value was measured by a universal glass electrode line 201020 (JUMO GmbH & Co. KG, Germany) in the washing water pipeline after the circulation pump. The pH-electrode was thereby calibrated trough a two-point calibration, every second week. The data of gas quality and quantity were stored automatically at the central control system of the biogas plant and the pH-value data was saved by the central control system of the DSU. Electrical energy and water consumption were also captured by an active current counter Finder 7E (FINDER S.p.A., Italy) and a water flow Meter (N/A) (Table 2).

Table 2 Measuring instruments, measuring point and measuring interval

Measurement	Unit	Measuring point	Measuring interval
Gas analyzer Union INCA 4000			
CH_4	%	Raw gas; gas in FBTB; gas after FBTB; purified gas	20 min, every 3.3 h
CO_2	%	Raw gas; gas in FBTB; gas after FBTB; purified gas	20 min, every 3.3 h
O_2	%	Raw gas; gas in FBTB; gas after FBTB; purified gas	20 min, every 3.3 h
H_2S	ppm	Raw gas; gas in FBTB; gas after FBTB; purified gas	20 min, every 3.3 h
Esters GD 100/50/3 Ex			
Gas quantity	m^3/h	Gas supply pipe CHP-Unit	Continuously
Jumo 202535			
pH-value		Washing water after circulation pump	Every 10 min
Temperature sensor GTF 103, data logger 175-T3			
Temperature	℃	Raw gas; gas in FBTB; gas after FBTB; washing water	Every 15 min
Water flow meter			
Water consumption	m^3	Water inlet	Continuously
Finder 7E.36.8.400.0000			
Active current counter	kWh	Power inlet	Continuously

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2.3 Laboratory analysis

The washing water was analyzed for the degradation products such as total sulfur, sulfate and sulfite every week at an external laboratory (Synlab Stuttgart). The sulfate and sulfite content was determined by ion chromatography (IC) and total sulfur by inductively coupled plasma mass spectrometry (ICP-MS) (Table 3).

Table 3 Laboratory analysis plan and method

Measurement	Unit	Measuring method	Measuring interval
Total sulfur	mg/L	DIN EN ISO 11885 (E22)	Once per week
Sulfate	mg/L	DIN EN ISO 10304-2	Once per week
Sulfite	mg/L	DIN EN ISO 10304-3 (D22)	Once per week

2.4 Experimental phases

The experiments were split into six different experimental periods (EP), as shown in Table 4. Following a trial run, the desulfurization bacteria in the first EP were expected to grow and adapt themselves to the fixed-bed material and to the conditions of the DSU. The oxygen content was kept at 1%. No external pH-regulation was used, thus the pH level adjusted itself, depending on the rising acidification capacity through H_2S degradation. The washing water temperature was not regulated initially, but influenced by the raw gas and ambient temperature. As it is reported in literature, temperature is a key factor for high H_2S elimination capacities, therefore the effect of FBTB heating was investigated during EP 2. In the following four experimental periods, the influence of washing water pH (pH 2 and pH 7, respectively) and oxygen content of 0.5% and 2% in the biogas on the H_2S-elimination capacity was analyzed. The heating system was not used during summer time, hereby addressing EP 3 and 4. An electrical heating system was used for EP 5 and 6 during autumn and winter, to keep the washing water temperature at a level of approximately 35℃. Hereby, the negative effect of fluctuating ambient temperatures could be minimized.

Table 4 Experimental plan

Phase	Experimental days	pH-value	O_2-content	Washing water temperature
Experimental period 1 (adaptation phase)	52	No control	1%	Variable
Experimental period 2 (temperature influence)	60	2	0.5%	10 - ~35℃
Experimental period 3	26	7	0.5%	Variable
Experimental period 4	30	7	2%	Variable
Experimental period 5	22	2	2%	~35℃
Experimental period 6	28	2	0.5%	~35℃

2.5 Analyses

H_2S-loading is calculated as a function of inlet gas flow and H_2S concentration over the filter volume in relation to molecular mass of H_2S and the molecular standard volume of gases as shown in Equation (1).

$$\text{Loading}=\frac{\text{gas flow}\left[\frac{1}{\text{h}}\right]\ H_2S_{\text{input}}\ [\text{ppm}]\ 34.08\left[\frac{\text{g}}{\text{mol}}\right]}{\text{filter volume}\ [\text{m}^3]\ 22.41\left[\frac{1}{\text{mol}}\right]\ 10^6} \tag{1}$$

The removal efficiency (RE) of H_2S in the FBTB is calculated as given in Equation (2).

$$\text{Removal efficiency} = \frac{(H_2\ S_{\text{Input}}\ [\text{ppm}] - H_2\ S_{\text{Output}}\ [\text{ppm}]}{H_2\ S_{\text{Input}}\ [\text{ppm}]} \times 100\% \tag{2}$$

The elimination capacity (EC) of the FBTB is given by the H_2S-input concentration minus H_2S-output concentration multiplied with the gas-flow and divided by the filter volume, as shown in Equation (3).

$$\text{EC}=\frac{\text{gas flow}\left[\frac{1}{\text{h}}\right]\left(H_2S_{\text{input}}\ [\text{ppm}] - H_2S_{\text{output}}\ [\text{ppm}]\right)\ 34.08\ [\frac{\text{g}}{\text{mol}}]}{\text{filter volume}\ [\text{m}^3]\ 22.41\ [\frac{1}{\text{mol}}]\ 10^6} \tag{3}$$

To compare the sulfate, sulfite and total sulfur content in the washing water, the data had been converted from sulfate into sulfate-S, from sulfite into sulfite-S and from total sulfur into elementary sulphur, by multiplying with a conversion factor that reduces the influence of oxygen weight (Equations (4), (5), and (6)).

$$\text{Sulfate-S [mg/L]} = \text{Sulfate [mg/L]} \cdot \frac{1}{2} \tag{4}$$

$$\text{Sulfite-S [mg/L]} = \text{Sulfite [mg/L]} \cdot \frac{2}{3} \tag{5}$$

$$S_{\text{elementary}}\ \text{[mg/L]} = \text{Total sulfur [mg/L]} - \text{Sulfate-S [mg/L]} - \text{Sulfite-S [mg/L]} \tag{6}$$

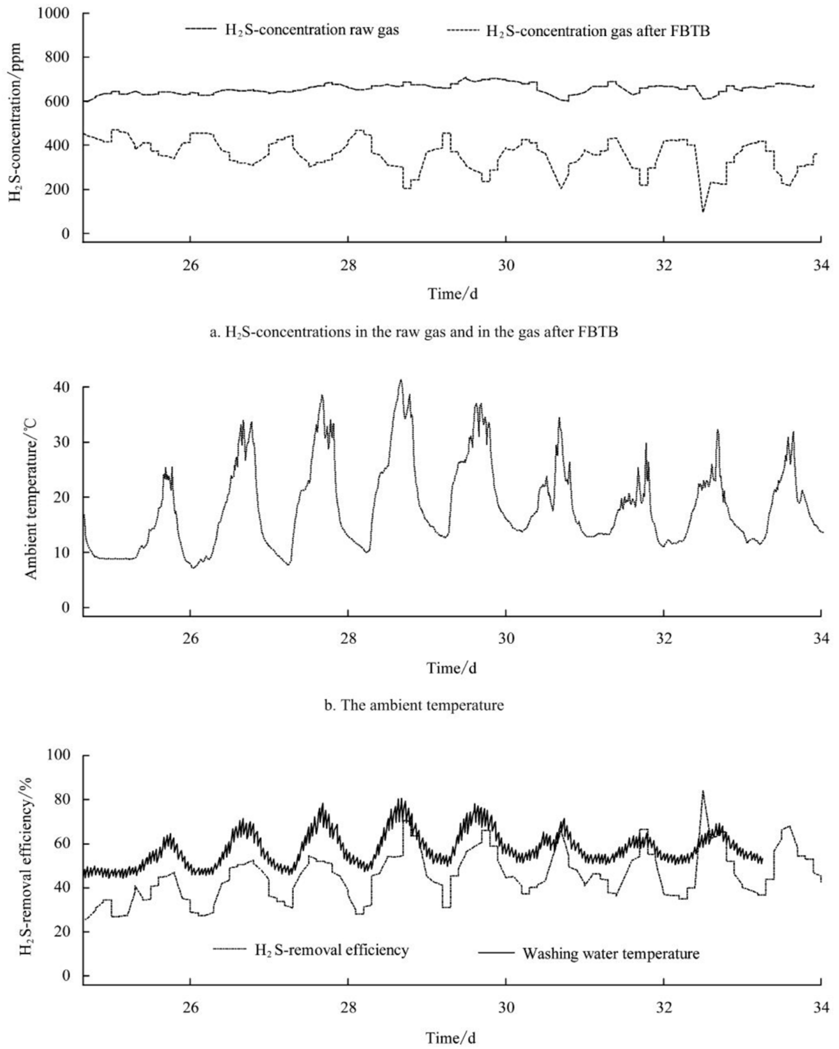
The data of the experimental periods 2-6 were divided into groups and statistically evaluated.

3 Results

3.1 Adaption phase-EP 1

Figure 2 shows the ambient air temperatures, H_2S concentrations and RE during the adaption phase.

In Figure 2a, the time is plotted over the H_2S-concentration in the raw gas and after the FBTB during the adaption period. The y-axis represents the H_2S-concentration in ppm, while the x-axis stands for the time in days. Figure 2b shows the ambient temperature over the time line of the adaption phase and finally Figure 2c shows the H_2S-removal efficiency and the washing water temperature.



a. H_2S-concentrations in the raw gas and in the gas after FBTB

b. The ambient temperature

c. The removal efficiency and the washing water temperature during EP 1 "adaption phase"

Figure 2 Air temperatures, H_2S concentrations and removal efficiency during the adaption phase

Over the adaption period, the H_2S-concentration of the raw biogas ranged between 600 and 800 ppm, while the H_2S-concentration after the FBTB fluctuated within a wide range. It could only be lowered down to a minimum of 200 ppm, but could not be kept at a constant level. After day 24, the margin between the raw gas and gas after the FBTB expanded. High variations in H_2S-concentrations after the FBTB could be observed.

Fluctuations closely linked to temperature were obviously caused by the alternation of day and night. At the same time, the ambient temperature values ranged between 5℃ and 40℃, with higher temperatures towards the end of the adaption phase. Over this monitored period, a variation of the H_2S RE and washing water temperature was detected. At washing water temperatures between 15℃ and 40℃, the H_2S RE fluctuated between 20% and 80%. It is quite obvious that the ambient temperature has a direct influence on the H_2S RE. Higher temperatures resulted in a better H_2S RE. In summary, a significant influence of the ambient temperature on the H_2S concentration in gas after FBTB was found. The higher the ambient temperature, the lower the H_2S-concentration after the FBTB was found. Day and night fluctuations are clearly visible (Figure 2).

3.2 Influence of temperature on the removal efficiency-EP2

The influence of temperature on the RE was investigated in the experimental period 2. The ambient temperature was fluctuating between -10℃ and 30℃, with an average value by approximately 8℃ during this period. The temperature of the washing water was kept at a range between 25℃ and 38℃ via a heating system. It was observed that the washing water temperature could vary between -5℃ and 25℃ when the heating system was turned off. The washing water temperature influenced the temperature in the FBTB significantly, while the RE changed rapidly with temperature fluctuations. Figure 3 shows the effect of temperature fluctuations on the RE. On the y-axis, the RE is plotted over eight temperature ranges from 0℃ to over 40℃.

The average RE was 21% at a temperature range of 0-10℃ and was then increased constantly to a level of ~ 45% at temperatures between 20 and 25℃. The variance of the RE varied within a wide range for each group of temperature range such as 0-10℃, 10-15℃ and 15-20℃. At an increase in temperature from 20-25℃ to 25-30℃, a sharp increase in the average RE (of up to ~ 90%) was monitored, hereby showing a decreasing variance. RE of up to 98% with very small variances were measured for the temperature ranges of 30-35℃ and 35-40℃. Above 40℃, a minor deterioration in RE (down to 95%) was observed with an increase in variance (Figure 3).

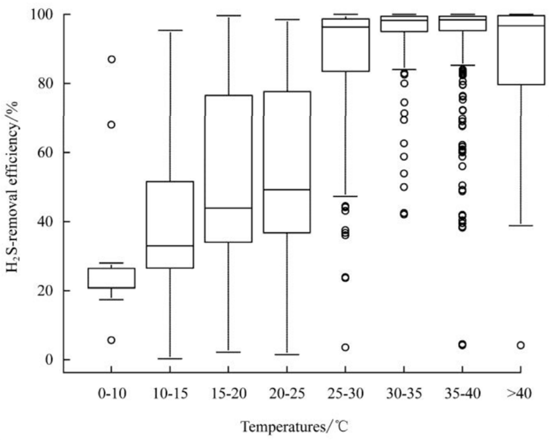


Figure 3 Influence of different washing water temperatures on the removal efficiency for experimental period 2

3.3 Influence of pH and O_2-content

In Figure 4, all results for the experimental periods (EP 3-6) are presented in one graph. The y-axis is given as elimination capacity (EC) in g H_2S m^{-3} h^{-1} over the H_2S loading in g H_2S m^{-3} h^{-1} on the x-axis (for the filter volume). The fitted line represents the 100% elimination capacity. For the sake of better understanding, this data has been divided into two classes: washing water temperatures between 20-30℃ and above 30℃. The closer the data comes to the line, the higher is the EC. At EP 3 and 4, at pH 7 and with O_2 at 0.5 and 2%, the FBTB remained unheated, but temperatures were kept above 20℃, influenced by warm summer climate conditions. During the transition period from autumn to winter, electric heating systems in the FBTB have been retrofitted to maintain a target temperature of approximately 35℃. The temperatures could be kept above 20℃ throughout the EP 3-6. A pH value of 7 was targeted in EP 3 and EP 4 and pH 2 was achieved in EP 5 and EP 6 by adding lye. In summary, no obvious influence of temperature levels on EC could be observed at temperatures above 20℃. The data depicted in EP 5 and 6, at constant heat supply, show a lower variance at high EC; with less data between 20-30℃, compared to

EP 3 and 4. At pH 7, a change from 0.5% (EP 3) to 2% (EP 4) of O_2 resulted in lower variance, whereas a change from 2% (EP 5) to 0.5% (EP 6) of O_2 at pH 2 showed no major deviation. At pH 2, a slightly increased EC was found. No definite correlation of pH and O_2 concentration on the EC was observed (Figure 4).

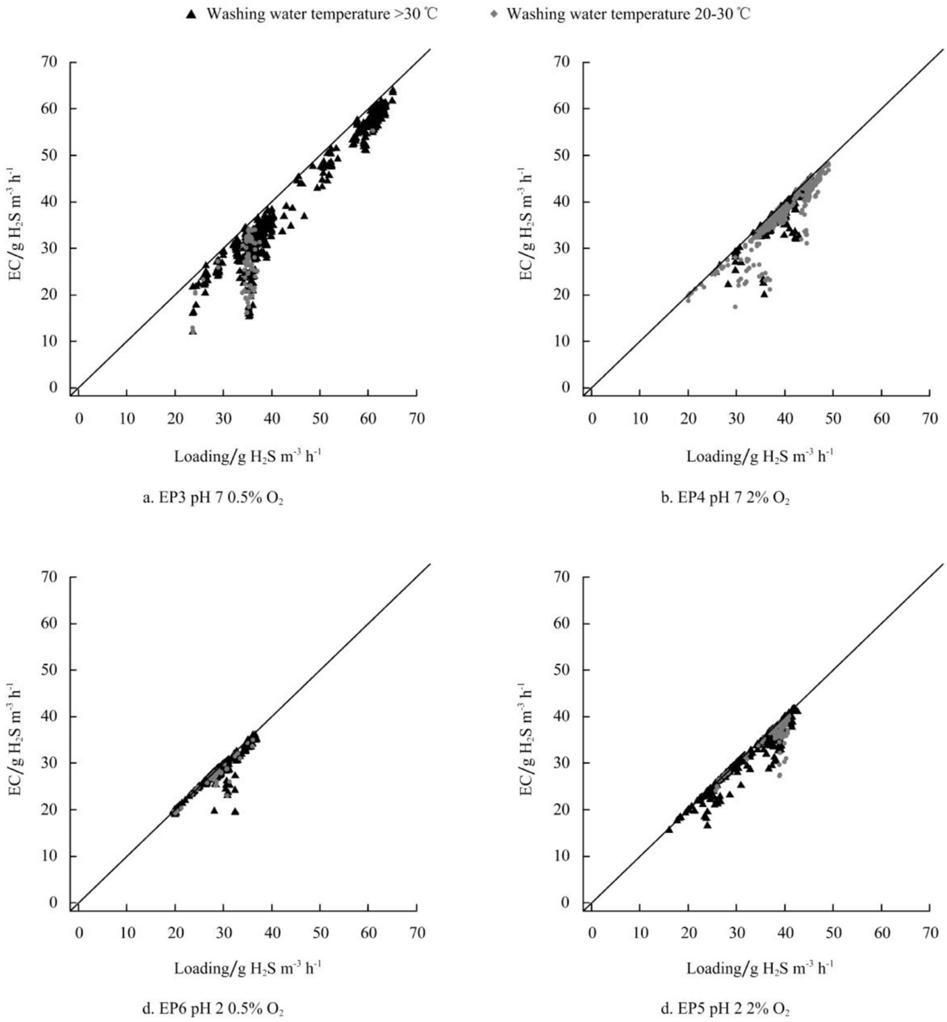


Figure 4 Link of loading in relation to the elimination capacity and the influence of temperature groups from 20-30℃ and over 30℃ described for the EP 3 (pH 7, 0.5% O_2), EP4 (pH 7, 2% O_2), EP5 (pH 2, 2% O_2) and EP6 (pH 2, 0.5% O_2)

Figure 5 shows the allocation of data for RE of the experimental periods 3-6. Again, this data comprises results for pH 7 and pH 2, at 0.5% and 2% oxygen supplies, with temperatures below and above 30℃.

On average, the RE was above 85% in all experimental periods. A higher RE was found for EP 5 and 6 at pH 2. An increase in RE can be observed at pH 7, when the oxygen supply increased from 0.5% to 2%. At pH 2 an inverse correlation could be observed. The highest RE was found in EP 6, with minor deviations in variance. At constant temperatures above 20℃, as it was measured for all experimental periods, a high RE could be achieved again, with less variance in summertime or at heat supply. No significant differences were found for temperature classes below and above 30℃. The results showed no clear causal link for pH and oxygen adaption on RE.

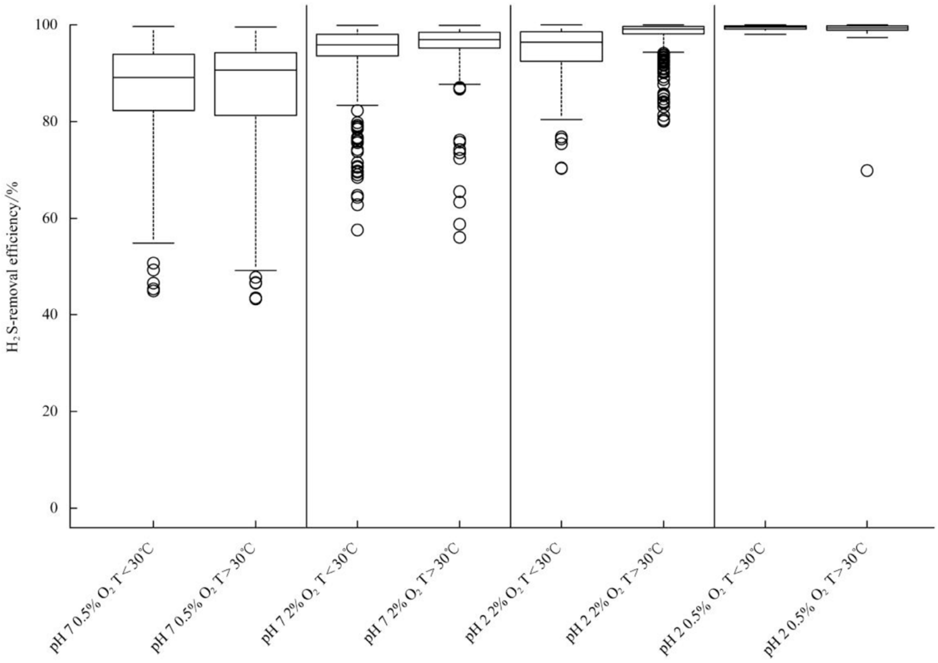


Figure 5 Boxplot depicts the influence of different temperature groups from 20-30℃ and over 30℃ at pH-values of 7 and 2 for O_2 content of 0.5%, and 2% on the removal efficiency for the experimental periods 3-6

3.4 Degradation products

In addition to the efficiency and the performance of the FBTB, the appearance and quantity of degradation products were of major interest in this study. The results of the samples analyzed at the laboratory are presented in Figure 6. They show the allocation of sulfate-S, sulfite-S and elementary sulfur in mg/L during the experimental periods 3-6. After H_2S was eliminated in the gas, the transformation products appeared in different concentrations in the washing water. As they are dissolved in the washing water, the degradation products are flushed out of the FBTB in defined periods. In EP 3, at pH 7 and 0.5% O_2, an amount of 334.89 mg/L of sulfate-S was found as the largest proportion, followed by elementary sulfur at 171.86 mg/L. An increase in sulfate-S to 580.83 mg/L and elementary sulfur to 431.54 mg/L was observed in EP 4 at pH 7 and 2% O_2. No elementary sulfur was found in EP 5 at pH 2 and 2% O_2 but 526.67 mg/L sulfate-S was determined. By lowering the oxygen supply to 0.5% at pH 2, the content of sulfate-S was found at 189 mg/L, with a minor amount of 20.6 mg/L elementary sulfur. Sulfite-S could only be determined in a significant quantity in EP 3. It was found, that at 2% oxygen supply the amount of sulfate-S was at its maximum. Elementary sulfur was found in measurable quantity and in a significant proportion at pH 7. To summarize the findings, it can be shown that the degradation products are found in the washing water and can therefore be flushed out of the FBTB system via a washing water outlet and reintroduced into the digestate

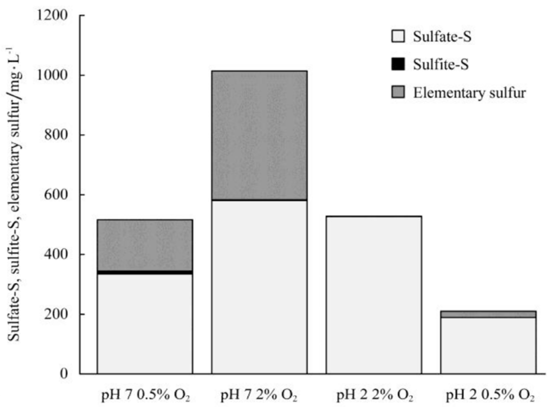


Figure 6 Composition of the degradation products sulfate-S, sulfite-S and elementary sulfur for the experimental periods 3-6

Storage, thus closing the nutrient cycle of the biogas plants. However, different sulfur components and quantities appeared, depending on the pH value and oxygen conditions (Figure 6).

3.5 Consumption of operating resources

Table 5 shows the consumption of operating resources in EP 1 and EP 3-6. The consumption of resources amounted to approximately 1 100 L/d water, ~25 kWh/d electric power and ~15 kWh/d of electric power for the washing water heating system. In EP 3 and 4, 4 L of lye and in EP 5 and 6, 0.6 L of lye were used per day to keep the pH-value at a constant level. To ensure the supply of nutrients in the washing water, ~2 L/d liquid and screened manure were dosed into the digester (Table 5).

Table 5 Consumption of operating resources for all experimental periods (EP)

	EP 1	EP 3	EP 4	EP 5	EP 6
	Adaption phase	pH 7 0.5% O_2	pH 7 2% O_2	pH 2 2% O_2	pH 2 0.5% O_2
Fresh water supply (L/d)	1103	1170	1188	966	10830
El. power consumption (kWh/d)	25.90	19.35	23.25	27.20	52.34
El. power heating (kWh/d)				10.2	21.45
Lye (L/d)		4	4	0.6	0.60
Liquid manure (L/d)	2.18	2.18	2.18	1.50	2.18

4 Discussion

The study of a FBTB under full-scale operational conditions appeared to have specific requirements and proved to be challenging. External influences and failures of measurement technique or technical breakdowns of the plant strongly affected the measurements. Keeping the settings for the different operating parameters at a constant level was one of the major challenges. A fluctuating ambient temperature had a decisive impact on temperatures in the FBTB, and on the washing water. Despite these challenges, reliable data of high quality could be gained and an excellent desulfurization performance could be achieved.

Throughout the experimental periods, the FBTB was able to provide a constant quality of purified biogas. The long duration of the adaption phase can be explained by starting of the plant in winter when temperatures were found below 0℃, thereby inhibiting bacterial growth. It was concluded that by adequate heat supply and insulation of the FBTB, the adaption phase can be shortened.

The results of EP 2 clearly confirm the significant influence of temperature in the FBTB and the washing water temperature on the RE, testifying best performance at a temperature range between 30℃ and 40℃. A direct influence of ambient temperature on temperature in the FBTB and on washing water could be observed. The living environment of the desulfurization bacteria responds immediately to low and high temperature in negative and positive way. The results proved that adequate heat supply, which can be achieved by heating the washing water or the biogas, is crucial for an efficient H_2S removal in the FBTB. In addition, an insulation of the FBTB can be strongly recommended. A replacement of the electrical heating system by a surplus heating system (supplied by CHP-unit) would be more energy efficient, due to the fact that heat oversupply is found at most biogas plants. The data for lower elimination capacities or removal efficiencies in Figures 2 and 3 could be explained by technical failures, e.g. pump or valve failure, thus leading to an absence of washing water trickled over the fixed bed. The improved elimination capacities in EP 5 and 6 could be the result of a stronger adaptation of the bacteria over time. The results of the temperature experiment are comparable to the results by Mollekopf et al.[19], who reported an optimum temperature of 35℃. Furthermore, the results of Schneider et al.[29] could be confirmed showing low efficiency of the FBTB at temperatures below 20℃ caused by the impairment of desulfurization bacteria.

No significant influence of different pH values could be noted. The results showed a slight increase in RE from pH 7 to pH 2. However, this could have superimposed by the effects of temperature fluctuations or technical failures. According to existing literature, various species of desulfurization bacteria are found, which have optimal living conditions at pH-values between pH 2 and pH 7[25]. These findings could be proved by the overall high desulfurization efficiencies found in this study. An important aspect of different pH values is the impact on consumption of operating resources and on corrosion behaviour. To keep the pH value at around 7, a large quantity of lye was needed to compensate the acidification, this causing an increased workload and rising variable costs. An enhanced corrosion exposure of the pump and all other metal parts was observed at a pH value of 2.

In the experimental periods with different oxygen concentrations, no clear effect on the H_2S RE was ascertained. At pH 7, an oxygen content of 2% was superior to 0.5% and was found at pH 2 being exactly the opposite[19]. In addition, the differences (as already discussed for the temperature influence), are too small to draw precise conclusions, as side effects could superimpose the results. Furthermore, no explicit influence of temperature could be observed at temperatures above 20℃. In contrast to the study by Schneider et al.[29], who recommended 4% to 6% vol. of air, a significantly lower amount of air (0.5% O_2 ~ 2.4% vol. air) was fed in this study. At 2% O_2 supply, the value of air reached 8% and 12% vol., as mentioned by Mollekopf et al.[19]. The effect of lower gas quality and an increasing gas quantity at high air application rates could be observed, leading to a dilution of methane as described by Mollekopf et al.[19]. The results of both studies could be confirmed, as high desulfurization efficiencies were found for both supply rates at 0.5% and 2% O_2. The experimental research has shown that at lower O_2 contents, the operation safety of the CHP-unit and the biogas plant safety improved. Based on the results of this study, the authors of this article can recommend 0.5% O_2 supply as adequate for desulfurization and optimal for general biogas plant safety.

The results of the laboratory analysis for degradation products vary heavily, although the samples were taken directly before the washing water was exchanged. A breakdown of elementary sulfur crusts, resulting in a formation of deposits on the column tray and, the influence of the sample taking, could be a possible explanation for the measured differences. These interferences could be reduced by an active mixing system in the column sump or by taking samples directly out of the column. As shown by Mollekopf et al.[19] a higher sulfate formation was observed at 2% oxygen supply. The results generally showed that the degradation products formed can be removed from the system by purging. The formation of strong sulfuric acid at pH 2 leads to a high corrosion on pumps and on all other metallic components. Therefore, a stringent material selection for all components is absolutely necessary. A clogging of pipes or the expansion material trough sulfur could not be determined during this study. Nevertheless, the sulfur deposits in the column sump should be removed after a preset time. To ensure an economic operation, the consumption of operating resources as well as the effort for technical maintenance should be kept at a constant low level. To obtain exact measurement data and operational safety, a high quality of measurement equipment and regular maintenance is required.

5 Conclusions

High removal efficiencies could be achieved under full-scale conditions with the FBTB investigated in this study. By using this method, external biological desulfurization confirmed the expected results and proved suitability for the given H_2S loadings. At the same time problems of internal biological desulfurization were avoided. A temperature of about 35℃ was shown to be absolutely inevitable for the efficiency of the process. Different oxygen contents did not have a significant effect on desulfurization efficiency, but 0.5% oxygen can be recommended for general plant safety. No direct conclusion can be drawn for the influence of the pH value as the desulfurization efficiency has been on a similar level. However, operation at pH 7 caused high consumption of operation resources, whereas pH 2 imposed particularly high requirements for anti-corrosion.

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6. General discussion

To increase the efficiency of biogas plants in terms of energetic efficiency and reduction of emissions, a reliable data source and therefore reliable measuring instruments are needed. In contrast to other studies in the biogas sector, the measurements of this study have been conducted under full-scale conditions at a research biogas plant. Research projects at full-scale level, due to the practical conditions, are more complex and difficult to control than laboratory research. Compared to monitoring programs they require more time, more effort and considerable investments in measurement technologies and data processing units for data acquisition on agricultural biogas plants.

The full-scale biogas plant "Unterer Lindenhof" is equipped with diverse measurement equipment for electricity and heat quantity, biogas quality, biogas quantity, ambient and gas pressure, substrate and gas temperature and feed quantities. Furthermore, additional process data from the CHP unit is transferred to the plant control unit.

The overall aim of this research project was to identify key parameters for the technical improvement of biogas plants in order to increase the overall efficiency of the fermentative conversion of biomass to biogas. To reach the overall target, two objectives were addressed. The first goal was to conduct long-term measurements at the full-scale research biogas plant to determine the parameters influencing the efficiency and emissions of biogas production. In the framework of this study, essential parameters could be identified and the outcomes are presented in scientific papers.

The second goal was to answer the question of how well the research biogas plant, as an instrument itself, can evaluate the efficiency of biogas production beyond the established methods. This will be discussed for the categories:

- mass balancing,
- process monitoring,
- process energy consumption.

Mass balancing

Measuring the input and output materials provides an important data basis to evaluate the efficiency of biogas plants. A so-called mass balance provides a basis to describe the production processes and can help the operator to identify weak points. Therefore, all substrates used in the biogas process need to be measured and recorded.

For solid substrate dosing, weight measurement technology is available for almost every feeding system on the market and used at many biogas plants. At the research biogas plant, substrate is filled into the dosing system according to a program in the Central Plant Control (CPC) that determines the amount of maximum five solid substrates, calculated in advance by the researchers. The calculation is based on weekly measurements of DM and oDM contents of all input substrates and from the results for specific methane yields for those substrates from laboratory research. The dosing quantity is set in a recipe and scheduled for feeding frequency. The feeding of the digesters starts automatically, according to the time set in the scheduler, until the dosage quantity is reached. The accuracy of the weighing device is checked every six months with a defined weight, and corrected if needed.

The system showed high reliability throughout the operation time but some obstructions were found. The weight of the solid substrates is measured via load cells mounted on the feeding systems, but the solid substrate feeding systems dead weight (40% of permissible total weight) is leading to deviations. In addition, the motion of the mixing screws in the feeding system causes high dynamic loads while feeding, especially when the system is fully loaded, hereby causing a fluctuation of weights that leads to an inaccuracy of measurements. Furthermore, the solid substrate feeding systems are uncovered and exposed to weather, thus rain or sunshine will greatly affect the DM and oDM content of the substrate. The feeding system will only feed according to weight, not according to DM or oDM content. As a result, changing weather conditions lead to an insufficient supply of organic matter (too much or too less) into the digester, thus influencing the organic loading rate. Substrate feeding can be better controlled under laboratory conditions, as weather, measurement fluctuations or dosage accuracies can be better controlled. Unlike in the case of measurement programs, the accuracy of the research biogas plant is higher due to the high effort spent for data reliability.

To improve data quality, covering the feeding systems is indispensable and is highly recommended. Additionally, an integration of an online measurement of DM and oDM content of the substrate using near-infrared spectroscopy (NIRS) is suggested. This will achieve an increase in accuracy. The error of dynamic loads can be minimized by feeding larger amounts. Nevertheless, for some experiments it was indispensable to feed small amounts of substrates. To limit this problem, long periods of observation are needed in full-scale research.

Liquid substrate supply, substrate transfer processes in the BGP and substrate discharge is carried out by a cavity pump, and the quantity is measured by a magnetic flow meter. The measuring accuracy is tested every six months by pumping a defined amount of substrate that is then compared with the results displayed in the CPC. To quantify the substrate flow within a biogas plant, the installation of a central pump in combination with a flow meter is essential. Overall, the pump performs reliably, but problems occurred when the substrate content of the digesters exceeded 10% DM. Stones and particles were found in the substrate, blocking the pump at such high DM contents. In the event of pump failure, no supply of liquid substrate and substrate transfer within the digesters could be carried out. In this case, the solid substrate supply must be stopped, as a ratio of 30% manure supply must be guaranteed at all times, according to the EEG. An interruption of feed supply leads directly to a reduction in gas production and to lower electric energy production. To solve this problem, a stone extraction unit or a replacement pump for fast exchange should be kept on site to serve as a backup unit. Unfortunately, this results in additional costs. Laboratory scale studies don't face the challenges of research in compliance with feed-in tariffs.

The measurement of gas quantity is one of the most challenging tasks. Wet, soiled, corrosive and humid biogas, as well as the low pressure, quickly led to failures of measurement equipment installed after the digesters. A flow meter installed before the CHP unit had much better results after the gas was dehumidified, cleaned from H_2S and after the pressure was raised by a fan. To increase reliability and data quality, the installation of at least two measurement instruments based on different measurement principles is highly recommended. For this reason, a measurement instrument based on the fluidistor principle was installed parallel to the existing vortex measurement device in this study. The verification and calibration of the flow meters proved to be difficult. It must be ensured that the flow meters are installed in a bypass system that allows removing the devices for calibration without disrupting the production process during this time.

Despite the efforts to gain reliable data, the full-scale application is not suitable for measuring biogas yield of single substrates. The reliability of substrate and gas quantities data acquisition cannot compete with laboratory scale methods. In addition, the number of replications is very limited at full scale as only two digesters are available.

Nevertheless, the study showed the high impact of mixing systems on gas release from the fermenting substrate. By using fast-moving agitators, a rapid gas release from the substrate compared to the slow-moving agitator was observed [60, 61]. Such effects of technical units and their setup on the biological conversion process can only be studied in full-scale applications. More research is needed to clarify the issue of mixing on gas release and gas yield from the digesters. The measuring instruments at the research biogas plant provide an excellent basis. Even the topic of simple gas quantity measurements on biogas plants is a challenge, and a valuable subject for future research. The importance of an accurate recording of gas quantities will increase as biogas production is currently legally bound to maximum gas production limits instead of electrical capacity of the CHP unit.

Gas quality is an essential factor for process monitoring, especially for linking data of biological processes to the technical performance of utilization units [62, 63]. As process failures will lead rapidly to lower gas quality, this is a first signal for operators. At the research biogas plant, permanent measurements of biogas quality at five strategic points (every 1,5h) allowed us to monitor the fluctuating quality. By observing the oxygen content in the biogas, the supply for desulphurization could be properly adjusted and reduced to a minimum, thus ensuring a high H_2S removal efficiency by maintaining a high calorific gas value. Failures of the internal desulphurization unit lead to higher H_2S in the biogas and could be detected and remedied within a short time. A slowly rising H_2S concentration measured after the activated carbon filter indicated a loading of the filter and allowed an operation based exchange. Gas quality data has been used to calculate the efficiency of the CHP unit [62].

To study the performance of the FBTB, it was indispensable to measure the main components and hereby to precisely vary O_2 to study the effect of different O_2 application rates on H_2S removal capacity [63]. At the beginning of the study, data for gas quality showed stable values but a drift was observed after some time. A weekly manual calibration routine with test gas was introduced and helped to improve data quality by readjusting the sensor drift. Due to the very harsh environment and constant operation, corrosion of unsuitable materials, as well as wear and tear, constant maintenance was required. In addition, sub-zero temperatures caused clogging of the condensate in the gas supply pipes to the measuring unit after the digesters, thus preventing the sample points to be measured. To guarantee frost-free conditions, proper insulation of the sampling tube is required. Despite the challenging task of keeping the gas quality at a high level, the results gained from these long-term measurements at several sampling points are unique. Compared to laboratory scale research and monitoring programs, high-quality results could be gained over a long period giving deep insight on full-scale operation. Nevertheless, the full-scale application may not be suitable to measure the gas composition of single substrates for the same reasons as already discussed for gas quantity. Very little needs to be changed on the research biogas plant regarding gas quality, only an automatic calibration routine would be a major advantage. For practice, it can be suggested that operators should implement gas quality measurement instruments in the pipeline entering the CHP unit. Measurements at more points (e.g. after the digester(s)) are also recommended to obtain knowledge about the gas quality within the process. Many different measurement instruments are available on the market, offering a wide choice of application.

Knowledge about the ambient pressure and gas temperature at the site is needed for calculating the standard conditions of gas quantity. Both measurements are standard methods and a large number of measuring devices are available on the market. Low maintenance effort, maximum availability and seamless integration into the automation system could be observed for those instruments on the research biogas plant. By knowing the gas pressure, additional information is gathered about failures such as pipe blockages caused by foam, soiling or growth of Sulfur in the pipe, and can be detected and remedied before serious damages occur.

Process monitoring

For monitoring and controlling the biochemical process in the digester, several parameters are used, such as dry matter (DM), organic dry matter (oDM) and volatile fatty acids (VFA). The samples were taken weekly in a standard procedure and stored in a fridge at 7°C until transportation to the university laboratory where the samples were deep frozen until they were measured. Like at most biogas plants, 500 ml samples are taken at one specific sampling point at the digester of the research biogas plant in representation of the total volume. From a share of 0.0001%, conclusions are drawn about the digester conditions, thus correct sample taking is of major importance.

An increase in DM content may be an indicator for a higher demand of stirring of the fermentation substrate, as temperature distribution and proper pumping must be ensured at any time. The total concentration of VFA and the relation between the propionic and acetic acid are the most important parameters to monitor the biological stability of the anaerobic microbiological conversion process. The knowledge about these parameters is essential for every biogas plant, thus regular analyses are mandatory.

A major obstacle of sample collection at full-scale biogas plants is the time delay between sampling, storage, analyzation and evaluation, as a minimum of 24 h is needed in the best case. If critical biochemical conditions are found, this time span may be too high to react. A direct monitoring feedback of digester conditions could be obtained within seconds by integrating an online sensor (e.g. NIRS). With the support of online data, the feeding procedure and mixing processes could be managed according to the digester conditions, hereby ensuring a high digestion performance. Studies on laboratory scale digesters showed that this technique is not ready for practical use yet, as calibration of the device and data evaluation consumes valuable time and resources, and does not show the necessary reliability [30].

VFA concentration can be best measured at laboratory scale, as the technique ensures optimal conditions for digestion, such as complete stirring, constant temperature and nutrient distribution. Currently, there is no knowledge about the spatial distribution of DM, oDM and VFA in practical digesters. There is a total lack of information concerning the influence of technique on the spatial distribution of those parameters. The research biogas plant offers the unique opportunity to increase physical access to spaces that have never been investigated before. Via a sampling system, access is gained into different heights and sections of the digester, thus a broader view is provided. As VFA are nutrients for methanogenic microorganisms, they can be used to determine the mixing quality by measuring their distribution in the digester [60]. The study showed that VFA are distributed unevenly in height and space of the digester. Different agitation units and setups were found to have an effect on VFA concentration and their spatial distribution. In contrast to other studies carried on laboratory scale, or using simulations, no dead zones could be found. Studying the mixing quality by measuring the nutrient distribution in the digester showed a potential savings of up to 70% of the electric energy consumed by the agitators [60]. More research is needed on both laboratory- and full-scale research to increase the efficiency of the digester volume.

The digestate is a very complex material, as it contains fluids, large particles, and gas. It is also warm and opaque. Currently there is very little known about the rheological behaviors of this substrate although many researchers are working on this topic [56, 64]. The parameter viscosity can be used to describe the physical behavior of digestate, but science is just beginning to understand its properties. Among various measurement instruments, tube-type viscometers (measuring pressure differentials) are known to produce promising results in laboratory scale research. An integration of such a scale-up viscometer on the research biogas plant will allow the collection of online measured data to monitor the full-scale conditions. This will provide a unique basis for studying the rheological parameters in combination with technical processes.

As well as the aforementioned biochemical parameters, additional technical information is provided to monitor the technical process. The CHP unit and its auxiliary drives are controlled and regulated with its own control unit. This also includes the total heat management. Therefore a wide selection of values measured at the CHP unit, such as cooling water temperatures, exhaust gas temperatures, intake air temperature, generator electricity parameters, lambda values, active power, room temperature, lubricating oil pressure and engine speed are transferred to the CPC. All the data given provides valuable information about the condition and performance of the CHP unit with its auxiliary drives.

The monitoring of exhaust gas emissions from the CHP unit is a key issue for assessing the environmental impacts of the gas utilization unit. The measurements of O_2, CO, NO, NO_2, SO_2 and exhaust gas temperature were performed continuously for 10 minutes every hour for the studied period [42]. Contrary to other studies performed over longer periods, but only focusing on spot measurements prior and post maintenance, the data provides more insight on the development of emissions in between these times. The permanent measurements proved their legitimacy showing various emission deviations from the limiting values prior and post maintenance, an effect that has not been reported so far by other authors. Nevertheless much effort has been spent as regular maintenance and calibration is the basic condition for gaining high-quality data. Permanent monitoring of exhaust gas emissions, in practice, is hampered by the fact that the instruments available are expensive and only reliable if checked regularly [62]. In addition, lubricating oil quality analyses throughout the CHP operation time were conducted to show the destructive changes in property and its influence on condition-based maintenance. The oil analyses allow the operator to reduce maintenance expenditures while minimizing wear [62].

The advantages of full-scale research are convincing especially for engine research: engine emissions and performance can be measured more precisely under test-bench conditions, but due to high costs, only for a short period of time. By conducting permanent and long-term measurements, a great amount of valuable data can be collected from practical application. These practical conditions, such as changing gas quality and quantity, and fluctuating loads, ambient temperatures or maintenance conditions will affect engine performance. Measuring programs cannot measure in such a high resolution as it is costly and requires a lot of maintenance. Nevertheless, more engines can be measured in such programs offering the possibility to study a wider range of engines.

At the research biogas plant, great amounts of data are available and can be displayed and combined in various ways at the CPC. Currently, the data is not interlinked automatically and the evaluation of data requires time and knowledge. Automatically generated energy balances of key parameters such as feed, electric, heat and others provided on a daily, weekly or monthly basis will help the operator to identify major deviations. This type of management and controlling tool with alert limits set for significant deviations will help the operator to quickly evaluate and understand the process, and to compare it with other plants.

Process energy consumption

As electric energy consumption is one of the most important drivers of efficiency at a biogas plant, the detailed measurement of every consumer unit is indispensable. In the framework of this study, all measurement equipment for electricity consumption has been verified using external instruments before the data collection began. The verification showed that much effort has is necessary to ensure reliable data acquisition and deviations of up to 30-70% were found. Nevertheless, the measurement instruments for electricity consumption of different units are easy to implement, cost-efficient and vital at biogas plants.

Despite its generous reserve capacities (low engine capacity vs. large digester volume) the electric energy consumption of the research biogas plants (8.4% and 8.7% of electric energy produced) [65] was similar with findings from various other studies [15, 54, 58, 66]. In addition to those studies, complementary data is given showing results after two years of permanent measurement of the individual components.

To improve energy efficiency of the gas utilization path, not many options are found as the energy consumption of the module control can hardly be optimized. Energy saving potential was found for the auxiliary drives such as heating circuit pumps and cooling fans. Most energy was consumed during the summer time when only little heat could be supplied to the district heating system and the remaining heat was discharged via the emergency cooling system. By optimizing the layout of the coolers and pumps electric energy can be saved. Electric energy consumption can also be further reduced via the systematic use of external heat-recovery concepts [65]. Very little has to be changed regarding the electric energy measurements, but an expansion of the measurements to cover the heat-circuit pumps and emergency coolers of the CHP unit is suggested.

By using the latest technologies, such as exhaust gas power generation, substrate pretreatment systems or drying facilities, the share of electric energy consumed is changing and increasing. To evaluate the efficiency of these technologies and to maintain economics, a strong focus on electric energy consumption is needed [67]. Laboratory scale research is not suitable to provide information about electric energy consumption of biogas plants. Measuring programs are much better suited to cover this topic but they are lacking in depth and intensity. This demonstrates the unique advantages offered by the research biogas plant as new techniques can be implemented and tested under full-scale conditions over a long period of time, even if they have a negative effect on the economics of the station.

External heat provision is a key factor of biogas plants as it positively affects the profitability of biogas production. If heat remains unused, valuable renewable resources are wasted, thus having a negative effect on the energy balance of the system, and lowering the social acceptance of the biogas technology. To give an insight on heat production and consumption on the research biogas plant, seven heat meters have been installed for heat production and cooling from the CHP unit, district heating and four for digester heating. The data for heat demand for the secondary digester had the most unexpected result, as it was twice as high compared to a single digester, although it was fed only with pre-heated substrate. The non-insulated inflatable membrane roof and a lower microbiological activity may have caused the heat loss. No significant effect of time or season of the year was found for heat transferred to the district heating system, as the district heating system can be utilized all year long [42]. This heating system, built in the 1960s, is outdated, which is the cause for major inefficiency. This results in a lower heat transfer capacity. In practice, not only the biogas plant should be the focus of efficiency measures. In terms of heat, the total system needs to be taken into consideration.

As previously mentioned for electric energy consumption, the technical process parameter heat at a biogas plant cannot be measured under laboratory scale research. Heat measurement has garnered very little attention in measurement programs, as it is costly and difficult to implement. Full-scale research on the research biogas plant closes this gap by providing unique and detailed data. In general, heat measurement instruments are reliable, but as malfunctions can occur, all consumer units of heat should be equipped with measuring instrumentation. In the event that one single unit fails, the heat quantities can be determined by way of calculation. The use of heat meters is highly recommended.

How suitable is the concept of research on a specially designed full-scale research biogas plant?

The advantages of laboratory-scale research, measuring programs and full-scale research have already been discussed. One of the central questions of the study was whether full-scale research is required and what knowledge gap it may address.

The full-scale biogas research digester is >28,000,000 times the size of the smallest laboratory scale digester in Hohenheim (HBT), thus differences due to scale effects can be expected and have to be taken into account when looking at different research questions. In contrast to laboratory experiments, full-scale research offers the opportunity to study the interactions of technique and biology from gas production to gas utilization. This is a characteristic that distinguishes it from laboratory research. Although it was not possible to create ceteris paribus conditions in full-scale application, very precise data was gained. In contrast to laboratory-scale research, studying under full-scale conditions is challenging and calls for special requirements. The process stability of the system must be ensured at all times and stirring and feeding operations may be shut off for only a certain amount of time. Changes in operation mode, such as increasing the organic loading rate, are very time consuming, require planning efforts and is cost intensive. Furthermore, not every desired organic loading rate may be achieved, as the gas produced should be utilized in the CHP for environmental and economic reasons. Substrates on the biogas plant are limited in quality and quantity, thus limiting the numbers of replications. Biogas production in full-scale is subject to various fluctuations caused by many factors such as input material, impacts of technology and climate, as well as human factors such as the operators. In laboratory scale, most of these fluctuations can be avoided, but in practice, a lack of consistency, fluctuations and very long observation periods lead to a higher variance of data. One of the major restraints is the lag of time between changes on the plant and the following reaction of the process due to the long retention times. In contrast to laboratory scale research, the retention time cannot be reduced by simply adding water. Due to the smaller volumes reactions are faster and a start-up after digester failure is much easier to carry out.

In order to assess the impact of agricultural biogas production on the economic, technical, ecological and social scales, measurement programs have been implemented. It can be noted that such research programs have been carried out as a result of political interest, to examine the effects of a changed regulatory framework as set in the EEG. To gain qualitative and quantitative data a selection of agricultural biogas plants are chosen and accompanied measurements are conducted for a certain period of time [15, 54]. The advantage of these applied studies is that the entire biogas plant as a system, as well as the geographical distribution, is considered. Hereby, the technical, economic, environmental and social constraints can be assessed, and amendments written that lead to changes in new legislations and government subsidies. However, this method has a number of disadvantages. Due to high effort and costs, such comprehensive surveys are not regularly performed. The latest study was conducted in 2009 [15] and no detailed information about the present state or the latest developments of the sector is given. The monitoring programs are lacking in detailed measurements and periods of observation are often short due to the poor availability of expensive measurement equipment or frequency of sample collection. Measurement programs are not suitable for process technique development because the data quality does not allow quantifying the practicality and efficiency of technical components. Another major drawback of this method is that the biogas plants have to be operated under economic conditions, thus the options for interventions in processes and substrate selection are strictly limited. In contrast to agricultural biogas plants, the research biogas plant is designed to study a wide range of potential applications and offers many possibilities for mounting and dismounting additional equipment and implementation of measurement technique. Especially in the biogas sector, many technical innovations are tested at the expense of the customer. These innovations promise massive increases in efficiency e.g. agitators, solid substrate feeding systems, substrate pretreatment units or process additives, just to mention a few. Only in rare cases is the applicability scientifically proven at full-scale. With the research biogas plant, an instrument has been established that meets the requirements to test the capacity, efficiency and practicality of these upcoming technical innovations.

The concept of a research biogas plant is a useful instrument to provide answers to economic, environmental and social questions raised by the public. The full-scale research biogas plant links all kinds of topics from crop production to the use of digestate. Therefore, holistic answers to critical questions can be given. The research biogas serves as a role model where good agricultural practice is applied. From this, suggestions for improved biogas production can be derived.

The studies at the research biogas plant are limited by the fact that the station is operated according to the regulations of the EEG 2004 and 2009. This implies that not every desired input substrate or process additives can be used without violating the law, thus risking the payment and endangering the profitability of the biogas plant. Without these compliances the scope of the research could be enlarged.

Conclusion and outlook

The production of biogas affects economic, environmental and social issues, and is subject to heavy criticism. The research biogas plant, as an instrument itself, was found to be a helpful tool to address criticism. But it would be presumptuous to state that this study will answer all of the questions. The interrelationship of biogas production is complex and many different research disciplines are affected. A joint research project in all fields of agriculture, such as plant breeding, plant production, sociology, environmental protection or economics may provide a holistic approach for sustainable biogas production. The answers to the multifaceted questions are of crucial importance for the future of biogas production and only science can provide independent statements. The findings and conclusions will provide information for social and political opinion making and will serve a basis for strategic policy development. As we are now at the crossroads where important decisions have to be made, it's appropriate to call for further research to answer critical questions and to find new and more efficient ways for economically, environmentally and socially sound biogas production. The exchange of information and the transfer of knowledge between the project partners from various disciplines of research within the joint research project "Bioenergieforschungsplattform Baden-Württemberg" has been an important element of the research project. Hereby, the latest data could be used to improve the quality of the results.

For the research biogas plant, the following conclusions can be drawn and some short-term proposals can be made to improve future research in the fields of gas production, gas upgrading and gas utilization.

The study showed that among the electric energy consumers, the agitation units used 50% of the total electric energy consumed. Although the slow-moving incline agitators are suitable for high viscos substrates while demanding very little electric energy, more research has to be conducted. Only by combining electric energy consumption, nutrient distribution, gas release and viscosity, can the mixing quality of agitators be measured and consistently developed. To improve the degradability of organic material, substrate pretreatment technology should be the focus of further studies to maximize the potential of unexploited substrates and the impact of pretreated material on technical parameters such as mixing requirements.

To upgrade biogas, the external biological desulfurization unit was tested, as it is one of the only ways to clean the gas from H_2S outside the digester and to keep the sulfur, a valuable plant nutrient. The full-scale biogas plant was well suited to study the performance of the FBTB as gas quantity, gas quality, heat and electric energy consumption can be measured. With regard to ongoing studies of the CHP unit, the provision of a cleaned gas is still of major importance. More studies must be conducted to increase the durability and reliability of the data, and to lower maintenance costs of such systems.

The great advantage of full-scale research is to intensively study gas utilization. Full-scale research was well suited to conduct long-term measurements by measuring all relevant parameters. An increase in engine efficiency can be achieved through a change in the air-fuel ratio. As a lower lambda value may lead to an increase in emissions, future studies should focus on exhaust gas scrubbing systems. The total efficiency of the research biogas plant can be increased by implementing and studying techniques such as exhaust gas power generation, demand oriented energy supply, biogas upgrade to SNG, repowering (replacement of technical components), heating concepts, storage technologies and micro gas grids. To improve the heat utilization, the system farm as heat consumer and biogas plant as heat producer should be considered to be one unit and the optimization potential should be studied.

The biogas sector is still growing, but the demand for efficient biogas production becomes more important every year. New and improved systems are entering the market, therefore future research is still of major importance. Biogas production is becoming more complex, as farmers apply new techniques to ensure sufficient income and compliance with regulations. Research can hardly keep up with the speed of new equipment implementation and questions arising from operators.

In the overall context, biogas production is strengthening the agricultural sector and rural areas. This implies that the efficiency of biogas production und utilization will still have to grow in economic and ecological aspects. To increase the efficiency of biogas production, process engineering and technology has to be further developed. The research biogas plant is the perfect instrument to develop and test those new techniques under standardized full-scale conditions.

7. Summary

The number of biogas plants and their electric output has grown rapidly over the past decade in Germany. In the medium to long term, the economic success of the biogas plants is endangered as prices for operation resources and agricultural raw materials are rising with legally bound feed-in tariffs that are fixed for 20 years. Furthermore, the biogas sector is facing public criticism. The growth in the biogas sector has caused an increase in land cultivated for maize silage production, thus changes in crop rotations and landscape may lead to negative environmental impacts. In addition, social aspects such as the competition between food and fuel, and the promotion of biogas production are discussed critically. In order to remedy these problems and to mitigate the negative effects, the efficiency and environmental impacts of agricultural biogas plants must be addressed, so reliable data is necessary. Measured high-quality data are required to identify optimization potentials. Because data for the entire process chain was still missing, studies within a joint research project "Bioenergieforschungsplattform Baden-Württemberg" were carried out. The sub-project "Intensive Measuring Program" conducted its experiments at the research biogas plant "Unterer Lindenhof" of the University of Hohenheim. The study focused on process engineering for the conversion of biomass, and utilization of the gas obtained by fermentation. In this study, several topics regarding efficiency and emissions have been addressed by conducting intensive and long-term measurements.

In detail, our objectives were (1) to conduct long-term measurements of the electric energy consumption of the biogas plant and its individual components and examination of energy-saving potentials; (2) to develop a method to measure mixing quality in the digester and to examine the mixing quality by measuring nutrient distribution in the digester with different agitator setups; (3) measure the influence of maintenance strategies on efficiency and emissions at long-term operation in practical application; (4) examine the efficiency of an external biological desulfurization plant under practical conditions to enhance biogas fuel quality.

The results of electric energy measurement over a period of two years showed that a percentage of 8.5% (in 2010) and 8.7% (in 2011) of the produced electric energy was required to operate the biogas plant. The consumer unit agitators with 4.3% (in 2010) and 4.0% (in 2011) and the CHP unit with 2.5% (in 2010 and 2011) accounted for the highest electrical power demand, in relation to the electric energy produced by the CHP unit. Calculations show that the agitators consumed 51% (in 2010) and 46% (in 2011) of the total electric energy demand. The results stress the need for further research in the fields of substrate

homogenization in biogas plants in order to reduce the demand for electric energy. Based on the results of electric energy consumption, follow-up studies have been conducted on nutrient distribution, which depends on agitator type and agitator regime. The investigation showed that significant differences in local concentrations of organic acids, which are not correlated to DM content, are found in dependence on agitator type and agitation regime. Measurements on electric energy consumption of the different agitator types verified that, depending on the agitator type, the saving potential rises up to 70%. The results for emissions and efficiency of the CHP unit confirm the fact that after readjustment of the air-fuel ratio (Lambda value), the emission values for NO_x decline while CO increases. However, the emission-optimized operation mode leads to lower engine efficiency. The permanent measurements proved their legitimacy showing various emission deviations from the limiting values prior and post maintenance. In addition, the results show that by monitoring the lubricating oil quality, the oil change intervals can be maximized, while ensuring that engine performance is not endangered. This allows the operator to reduce maintenance expenditures while minimizing wear. To increase engine efficiency, the reduction of the lambda value combined with exhaust gas scrubbing and exhaust gas power generation is a promising approach. However, that would presuppose a permanent and almost total removal of H_2S from the biogas.

The fourth part of the study examined the technical and economic feasibility of a Fixed Bed Trickling Bioreactor (FBTB) for external biological desulfurization of biogas. In contrast to well-established biological methods to oxidize H_2S, the FBTB allows removal of these from the biogas process, thus ensuring a constant low H_2S concentration in the biogas.

The FBTB showed H_2S removal efficiencies (RE) of 98% at temperatures between 30-40°C. A major decline in RE in a range of 21-45% was observed when temperature in the FBTB dropped to a range of 5-25°C. The results revealed that different pH values of the percolation fluid and air ratios have little effect on RE. The practical use of the investigated FBTB system is an interesting technological alternative as disadvantages of internal biological desulfurization methods are being avoided. Due to high expenditures for operation resources and maintenance for FBTB operation during the research, a technical optimization is necessary to ensure economical operation.

The results presented in this thesis show that the scientific instrument “research biogas plant” is the ideal supplement to methods such as laboratory scale research and measuring programs. Research at full scale offers an entirely new opportunity to determine the interaction of process technique and process biology and to conduct long-term studies of gas utilization. Compared to measuring programs at commercial biogas plants, the research biogas

plant has the advantage of being significantly better equipped with measurement technologies and that economic success is not the overall goal. Despite the criticism, biogas is a key factor in the provision of bioenergy. Biogas production will make a decisive contribution to the production of bioenergy from renewable resources in the future, as it can use variable input substrates, has the lowest fossil fuel consumption and the highest agricultural land use efficiency. It can be utilized for on-site combustion in CHP units, upgraded to biomethane, used as vehicle fuel and is suitable for storage.

8. Zusammenfassung

Bei der Anzahl und Leistung der Biogasanlagen in Deutschland konnte in den letzten Jahren ein sehr starker Anstieg verzeichnet werden. Durch steigende Preise für Betriebsmittel und landwirtschaftliche Rohstoffe bei gleichzeitig gesetzlich fixierten Einspeisevergütungen für einen Zeitraum von 20 Jahren wird jedoch mittel- bis langfristig die Wirtschaftlichkeit der Biogaserzeugung gefährdet. Überdies steht die Erzeugung von Biogas auch in der Öffentlichkeit unter Kritik. Durch die Ausweitung des Silomaisanbaus und damit einhergehenden Änderungen im Landschaftsbild und den Fruchtfolgen, werden ökologische Beeinträchtigungen erwartet. Des Weiteren werden die Förderung der Biogasproduktion und die Konkurrenz zwischen Nahrungsmittel- und Bioenergieproduktion heutzutage im Hinblick auf soziale Aspekte kritisch diskutiert.

Um diesen negativen Effekten entgegenzuwirken ist es unabdingbar, die Effizienz der Biogasproduktion unter ökonomischen und ökologischen Aspekten weiter zu steigern, wozu verlässliche Daten notwendig sind. Vor diesem Hintergrund wurden im Rahmen des Forschungsverbundes „Bioenergieforschungsplattform Baden-Württemberg“ umfangreiche Studien entlang der gesamten Prozesskette der Biogaserzeugung durchgeführt, um Optimierungspotenziale identifizieren und quantifizieren zu können. Die Untersuchungen dieser Arbeit wurden im Rahmen des Teilprojektes „Intensivmessprogramm“ an der Forschungsbiogasanlage „Unterer Lindenhof“ der Universität Hohenheim durchgeführt. Der Fokus der Untersuchungen lag dabei auf der verfahrenstechnischen Konversion der Biomasse und der Nutzung der durch Fermentation gebildeten biogenen Gase. Die Teilziele der Untersuchung gliederten sich wie folgt: (1) Durchführung von Langzeitmessungen zur elektrischen Hilfsenergieaufnahme der Biogasanlage und seiner einzelnen Verbrauchskomponenten sowie die Identifizierung von Einsparmöglichkeiten; (2) Entwicklung einer Messmethode zur Bestimmung der Durchmischungsqualität im Fermenter unter Einfluss verschiedener Rührwerke durch die Erfassung der Nährstoffverteilung; (3) Messung des Einflusses der Wartungsintervalle auf Effizienz und Emissionen des Blockheizkraftwerkes im praktischen Langzeitbetrieb; (4) Untersuchungen zum Wirkungsgrad einer externen biologischen Entschwefelungsanlage im Praxisbetrieb zur Steigerung der Brennstoffqualität des Biogases.

Die Ergebnisse einer zweijährigen Untersuchungsreihe zur elektrischen Hilfsenergieaufnahme zeigen, dass 8,5% (2010), bzw. 8,7% (2011) der vom BHKW produzierten elektrischen Energie zum Betrieb der Biogasanlage aufgewendet werden mussten. Den höchsten Verbrauch wiesen dabei die Rührwerke mit 4,3% (2010), bzw. 4,0%

(2011) und das Blockheizkraftwerk mit 2,5% (2010 und 2011) bezogen auf die produzierte elektrische Energie auf. Somit lag der Energiebedarf der Rührwerke bei 51% (2010), bzw. 46% (2011) der gesamten zur Biogaserzeugung und Nutzung benötigten elektrischen Energie. Diese Ergebnisse verdeutlichen die Notwendigkeit der Forschung im Bereich der Substrathomogenisierung in Fermentern an Biogasanlagen zur Reduktion des Eigenstrombedarfs.

Auf der Basis der Untersuchungen zum Eigenenergiebedarf wurden Studien zur Nährstoffverteilung in Abhängigkeit des Rührregimes und der Rührwerksart im Fermenter durchgeführt. Im Rahmen dieser Untersuchungen konnte eine signifikant unterschiedliche und von der Trockenmasse unabhängige Verteilung von organischen Säuren in Abhängigkeit von Rührwerkstyp und –kombination nachgewiesen werden. Durch Messungen des elektrischen Hilfsenergieaufwandes konnte in Abhängigkeit des Rührwerkstyps ein Einsparpotenzial von bis zu 70% ermittelt werden.

Die Ergebnisse zu Emissionen und Effizienz des Blockheizkraftwerkes bestätigten, dass durch eine Korrektur des Luft-Kraftstoff Verhältnisses (Lambda-Wert) die NO_x Emissionen reduziert werden, während die CO Emissionen zunehmen. Der emissionsoptimierte Betrieb führte jedoch zu einem geringeren elektrischen Wirkungsgrad. Die Bedeutung der dauerhaften Emissionsüberwachung wird durch zahlreiche Überschreitungen der Emissionsgrenzwerte auch zwischen den Wartungen bestätigt. Durch die Überwachung der Schmierölqualität können die Abstände zwischen den Ölwechselintervallen verlängert werden, ohne dabei die Leistung des Motors zu beeinträchtigen, was sich in geringeren Wartungskosten und Verschleiß niederschlägt. Um den Wirkungsgrad des Motors zu erhöhen, ist eine Reduzierung des Lambdawertes in Kombination mit einer Abgasaufbereitung und einer Abgasnachverstromung ein vielversprechender Ansatz. Eine nahezu vollständige Entfernung des Schwefelwasserstoffs aus dem Biogas ist hierzu jedoch zwingend notwendig.

Im vierten Teil dieser Arbeit wurde die technische und ökonomische Eignung eines Fixed-Bed-Trickling-Bioreactors (FBTB) zur externen biologischen Entfernung des Schwefelwasserstoffs aus Biogas untersucht. Im Gegensatz zur etablierten biologischen Schwefelwasserstoffoxidation innerhalb des Fermenters bietet der FBTB die Möglichkeit, den Schwefel aus dem Biogasprozess auszuschleusen, so dass dauerhaft niedrige H_2S-Konzentrationen im Biogas erreicht werden können. Im Rahmen der Untersuchungen konnten Entschwefelungsleistungen des FBTB von bis zu 98% bei Temperaturen zwischen 30-40°C erreicht werden. Ein spürbarer Rückgang der Entschwefelungsleistung auf 21-45% wurde bei einem Abfall der Temperatur im Reaktor auf 5-25°C beobachtet. Ein Einfluss des pH-Wertes der Perkolationsflüssigkeit und des Sauerstoffüberschusses konnte nicht nachgewiesen werden. Die Verwendung des untersuchten externen biologischen Entschwefelungsverfahrens ist damit technisch eine interessante Alternative, da die Probleme interner Verfahren umgangen werden. Aufgrund der zum Untersuchungszeitpunkt hohen Betriebs- und Wartungskosten der Anlage ist eine technische Optimierung jedoch notwendig, um einen wirtschaftlichen Betrieb des FBTB zu ermöglichen.

Die Untersuchungen zur vorliegenden Arbeit zeigten, dass das wissenschaftliche Instrument „Forschungsbiogasanlage" eine ideale Ergänzung zu Laboruntersuchungen und Messprogrammen darstellt. Insbesondere zur Determination von Interaktionen zwischen Verfahrenstechnik und Prozessbiologie, sowie zu Langzeituntersuchungen zur Gasnutzung eröffnet der Full-scale-Maßstab der Forschungsbiogasanlage vollkommen neue Möglichkeiten. Im Vergleich zu Messprogrammen an kommerziellen Biogasanlagen wirken sich dabei die wesentlich bessere messtechnische Ausstattung sowie die geringeren wirtschaftlichen Zielsetzungen des Anlagenbetriebes vorteilhaft aus.

Trotz diverser Kritiken nimmt Biogas eine Schlüsselposition bei der Bereitstellung von Bioenergie ein. Durch die Nutzung verschiedenster Substrate, geringen Verbrauch fossiler Brennstoffe, hohe Landnutzungseffizienz sowie vielfältige Verwendbarkeit in Blockheizkraftwerken, als Biomethan und Treibstoff sowie seine Speicherbarkeit, wird Biogas bei der Bereitstellung von Energie aus natürlichen Ressourcen auch in Zukunft einen entscheidenden Beitrag leisten.

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