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Drying Characteristics of Biogas Digestate in a Hybrid Waste-Heat/Solar Dryer

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Abstract: The use of biogas plants has increased sharply in recent years. A typical biogas plant of 500 kW_{el} produces approx. 10,000 t of digestate per year, with a moisture content of more than 90%. For the purpose of reducing the transport mass and increasing the nutrient concentration, the digestate has to be dried. Using renewable energy is a way to treat biogas digestate without any additional fossil energy requirement for drying. In this study a solar greenhouse dryer was modified to use additional waste-heat from the combined heat and power unit (variant S-CHP), as well as the exhaust gas from a micro turbine (variant S-CHP-MT). The hybrid waste-heat/solar dryer achieved a moisture content for the digestate of 10.9%, and 10.5%, after 13 d of drying for variant S-CHP-MT and S-CHP-MT, respectively. Due to the higher energy input by additional use of the micro turbine, the specific energy consumption is higher for the variant S-CHP-MT. In general, the results showed that the combination of solar energy and waste-heat from electricity generation of a biogas plant is a suitable way to reduce the moisture content of the digestate to a safe level for further handling and storage.

Keywords: drying process; waste-heat usage; biogas digestate; energy consumption

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1. Introduction

Primary biogas energy production worldwide amounted to 16.9 GW in the year 2017, compared to 6.7 GW energy produced in the year 2008. In Europe, 11.9 GW were produced in the year 2017, whereas Germany holds the biggest share, with 4.5 GW produced biogas energy, having 9331 biogas plants operating by the end of the year 2017. An additional installation of approximately 160 new biogas plants was prognosticated for 2018 [1,2]. A byproduct of the fermentation process of biogas plants are fermentation residues (further called digestate). A typical wet fermentation biogas plant with an installed electrical power of 500 kW produces approx. 10,000 t of digestate per year with a moisture content of 90–95% [3]. Möller and Müller calculated the total amount of digestate in Germany for the year 2011, at approx. 65.5 million cubic metres [4].

Biogas plants are predominantly installed in rural areas with intensive livestock farming, as well as high amounts of slurry. Compared to liquid and solid manure, the share of ammonium is generally higher in biogas digestate, which leads among other things to a positive effect regarding plant growth [5,6]. These regions with intensive livestock farming and biogas plants are often also regions with a surplus of plant nutrients. The application of nitrogen is limited at EU level by the European Nitrate Directive. Fertilizers like digestate, liquid manure and artificial fertilizers are limited regarding their amounts and times of application to the fields so that, e.g., nitrogen and phosphorus inputs into water bodies and groundwater are avoided, and the environment is not polluted.

The anaerobic digestion of renewable raw materials in biogas plants additionally leads to an increase regarding the amount of farm fertilizers. This made it necessary to transport the digestate from those regions with high livestock density to regions with a deficit of nutrients. From an economic point of view, it is not feasible to transport the digestate over long distances due to the high water and comparatively low nutrient content [7–12]. Therefore, a digestate processing technology is needed with the aim of mass reduction, to handle digestate as well as to ensure the utilization of the plant nutrients. Delzeit et al. [13] investigated the influence of the location of biogas plants, transport distance for digestate, as well as the most cost efficient digestate processing technology for the profitability of a biogas plant. The results show that in regions with small amounts of agricultural land, as well as a large heterogeneity within agricultural areas, the profitability of a biogas plant can be enhanced by digestate processing technology. Several possibilities for digestate processing are known, like separation into a liquid and solid phase with a screw press separator, a decanter centrifuge, belt filters or a discontinuous centrifuge. By using this technology, both fractions can be used (as liquid and solid fertiliser), or further processed with technologies like drying and/or composting (solid fraction) or for the liquid fraction, nitrogen recovery (stripping, struvite precipitation, ion exchange), as well as nutrient concentration with membrane technologies, or by evaporation [10]. Most of these technologies are associated with high costs for biogas digestate management, but it can be necessary to process digestate in a biogas plant due the described lack of agricultural land for digestate application or storage capacities in a biogas plant.

In a waste water treatment plant, where sludge treatment is an essential processing step in waste water management systems, recent studies stated that the disposal and treatment of the sludge takes up a share of more than 50% of the construction and operation costs [14–16]. Sludge treatment with solar dryers is a comparatively simple technology, and has achieved quite good results with regard to the specific energy consumption [17–19]. Furthermore, solar drying of digestate seems to be a suitable option to reduce the use of resources, and to decrease the environmental impact compared to other digestate management systems [11]. By using solar energy with the support of the waste-heat from a cogeneration unit and micro turbine, stemming from the combustion of biogas, it is possible to harness the existing energy available, and to avoid high additional energy costs. Thus, solar drying, combined with waste-heat utilization, can be a promising step for digestate processing.

The objective of this study was to investigate the drying parametres of digestate in a hybrid waste-heat/solar dryer without previous separation steps to decrease the volume and weight of the digestate. The aim of this research is (i) to describe the water evaporation and the drying behaviour of the digestate in a hybrid waste-heat/solar dryer, and (ii) to calculate the energy consumption and the efficiency of the drying process under different operating parametres.

2. Materials and Methods

2.1. Description of the Drying System

The investigations were carried out in a pilot hybrid waste-heat/solar dryer, developed by the University of Hohenheim in cooperation with the company Thermo-System. The dryer was located at a farm in Baden-Württemberg, Germany (49°14′30″ N, 9°38′23″ E, 340 m a.s.l.). The dryer is a solar greenhouse dryer with a drying area 480 m^2, and was modified to use, beside solar energy, waste-heat from the combined heat and power unit (CHP) as well, and the exhaust gas from the micro turbine.

The waste-heat from the CHP is launched via water-air heat exchangers, which are installed in the headspace of the dryer. The exhaust gas from the micro turbine was mixed with ambient air and injected into the drying hall at the front side. The drying hall was built in a greenhouse style with a transparent polyethylene air bubble foil with a transmission coefficient (τ) of 0.82. During the drying process, the digestate was mixed automatically with a rotary cultivator up to twelve times per day to avoid casehardening of the digestate surface. A programmable logic controller controlled the dryer (Figure 1).

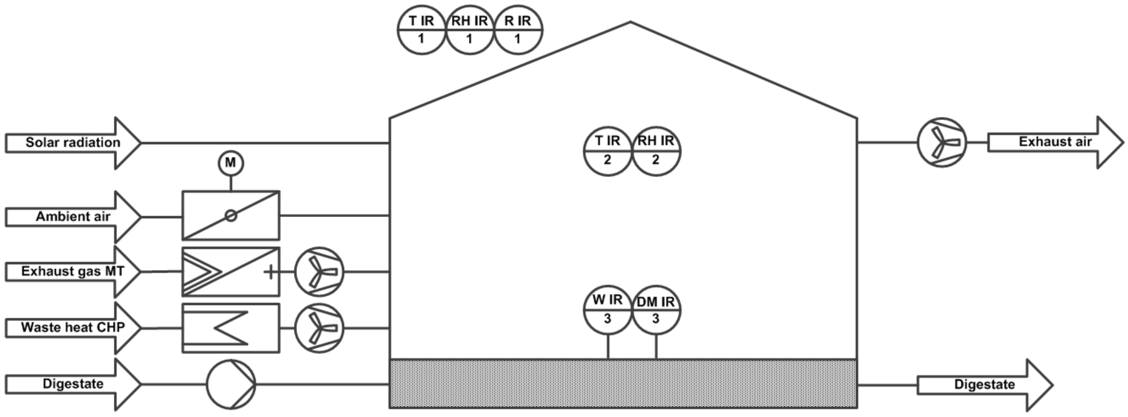

Figure 1. Scheme of the hybrid waste-heat/solar dryer with measuring-points for temperature (T), rel. humidity (RH) with continuous recording (IR).

The digestate for the drying experiments originated from the biogas plant of the farm. The feedstock composition for the biogas plant is a mixture of several biomasses: Residues from food and feed production (40%), cattle slurry (20%), energy plants and pig slurry (15%, each), as well as husk and dried poultry dung (5%, each). The biogas plant is a co-fermentation plant with a thermophilic wet process management. It consists of two fermentation digesters with a total volume of 2200 m^3 and a post fermentation digester with a volume of 1600 m^3. The produced biogas is used in a CHP and a micro turbine to generate electricity that is fed into the electric grid, and the waste-heat as well as the hot exhaust gas of the micro turbine is used for drying the digestate. In total, the biogas plant produces 10,000 t of digestate per year. The major part of the digestate (6500 t) is applied as liquid fertilizer on the fields of the farm. The minor part (3500 t) is dried in the hybrid waste-heat/solar dryer. Table 1 shows the technical data of CHP and micro turbine.

Table 1. Technical data of onside combined heat and power unit (CHP) and micro turbine (MT).

Performance Indicator	CHP	MT
Electric power, kW	335	200
Electrical efficiency (η_{el}), %	35	33
Thermal power, kW	528	280
Thermal efficiency (η_{th}), %	55	46
Total power, kW	863	480
Cogeneration efficiency, %	90	79

2.2. Description of the Drying Process

Trials have been performed with solar energy and the waste-heat from the CHP (S-CHP), and with the additional use of the exhaust gas of the micro turbine (S-CHP-MT). Variant S-CHP has been performed in June and variant S-CHP-MT in September for 13 days each. For each of the variants a typical day was chosen to present ambient weather conditions in terms of temperature, relative humidity and solar radiation (Figure 2).

The total heat input E_{total} for the drying process was calculated by summing up the components:

$$E_{total} = E_{solar} + E_{CHP} + E_{MT} \quad (1)$$

where E_{solar} is heat input by solar energy, E_{CHP} is waste-heat from the CHP, and E_{MT} is the heat of the exhaust air from the micro turbine.

The energy input E_{solar} was calculated as:

$$E_{solar} = R \cdot \tau \quad (2)$$

with solar radiation R and the transmission coefficient τ = 0.82.

The heat input from CHP was measured by a heat meter in the water flow and the heat input from the micro turbine E_{MT} was calculated as:

$$E_{MT} = E_{el} \cdot \frac{\eta_{th}}{\eta_{el}} \tag{3}$$

where E_{el} is the electrical energy generated by the micro turbine, and η_{th} and η_{el} are the thermal and the electrical efficiency of the micro turbine, respectively.

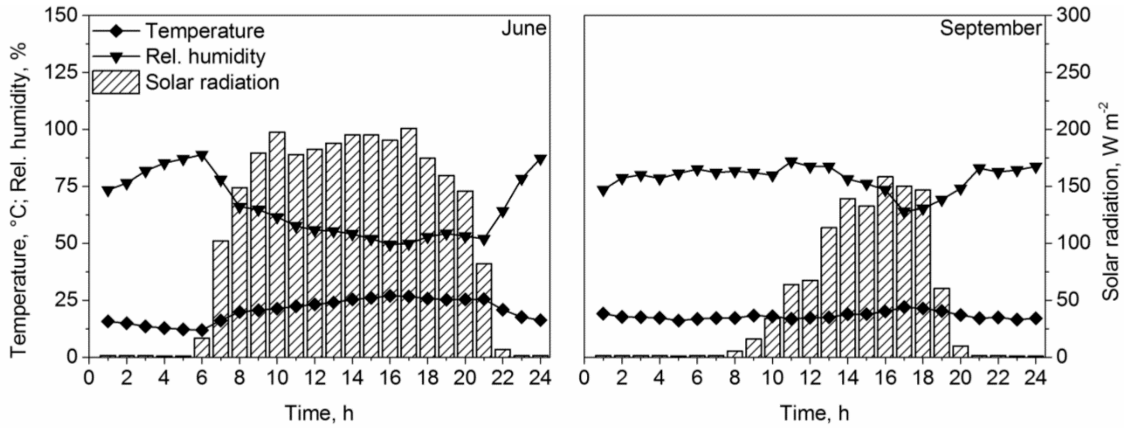

Figure 2. Ambient temperature, rel. humidity and solar radiation on an exemplary day; (left) in June for variants using the waste-heat of the combined heat and power unit (S-CHP); (right) in September for variants using additionally exhaust air of a micro turbine (S-CHP-MT).

To describe the drying behaviour of the digestate, as well as to determine the drying progress and the efficiency of the dryer, the moisture content of the digestate was measured daily at 4 × 5 grid points across the drying area during the experiments. Three samples were taken per grid point and analyzed for moisture content (MC, wet base) by oven drying at 105 ± 2 °C according to the standard method [20]. The average moisture content for the drying period was calculated as a daily mean value. The *t*-test was conducted to test the differences among means (p = 0.05).

The mass of evaporated water m_{evap} in the dryer was calculated as:

$$m_{evap} = \frac{m_{ini} \cdot \left(MC_{ini} - MC_{fin}\right)}{\left(100 - MC_{fin}\right)} \tag{4}$$

where m_{ini} is the initial mass of digestate at the beginning of drying and MC_{ini} and MC_{fin} are initial and final moisture contents of the digestate, respectively.

The evaporation performance EP was defined as mass of evaporated water per m^2 and day:

$$EP = \frac{m_{evap}}{A_D \cdot t} \tag{5}$$

where A_D is the drying area of the greenhouse dryer and t is drying time in days.

Specific energy consumption for evaporation $E_{spec.}$ was calculated as:

$$E_{spec.} = \frac{E_{total}}{m_{evap}} \tag{6}$$

3. Results and Discussion

3.1. Dying Characteristics and Energy Input

Energy input shares from different energy sources are shown in Figure 3. The input solar energy with 15 MWh for S-CHP in June, and 14 MWh for S-CHP-MT in September, was similar, and amounted to a share of 15.9% and 9.5%, respectively. The difference was caused by the additional heat from the micro turbine, which increased the total energy input for the drying process from 95.1 MWh for S-CHP to 150.4 MWh for S-CHP-MT. As there was no significant increase in the mass of evaporated water within 13 d of drying, the specific energy input increased from 6.1 to 9.7 MJ per kg evaporated water (Table 2). A specific energy consumption of 3.5 to 7.0 MJ per kg of evaporated water was measured by Bux and Starcevic [19] for the drying of sewage sludge in a similar dryer. Awiszus et al. [21] measured the specific energy consumption of a two-belt conveyor dryer by drying separated digestate with an MC of 75.6%, and the results showed that a specific energy consumption of 3.2 to 3.7 MJ per kg of evaporated water can be achieved at drying temperatures of 45 °C to 80 °C. Consequently, the variant S-CHP-MT seems inefficient regarding the exploitation of the water absorption capacity of the drying air, compared to the results mentioned before. Furthermore, a two-belt conveyor dryer appears to be more efficient in terms of heat and energy input utilization. For the variant S-CHP-MT, in total 58% more thermal energy was used compared to variant S-CHP for achieving the same drying results regarding drying time and final moisture content. Hence, using additional exhaust heat from the micro turbine for the drying of biogas digestate in the waste-heat/solar dryer is not a favorable option in terms of energy efficiency.

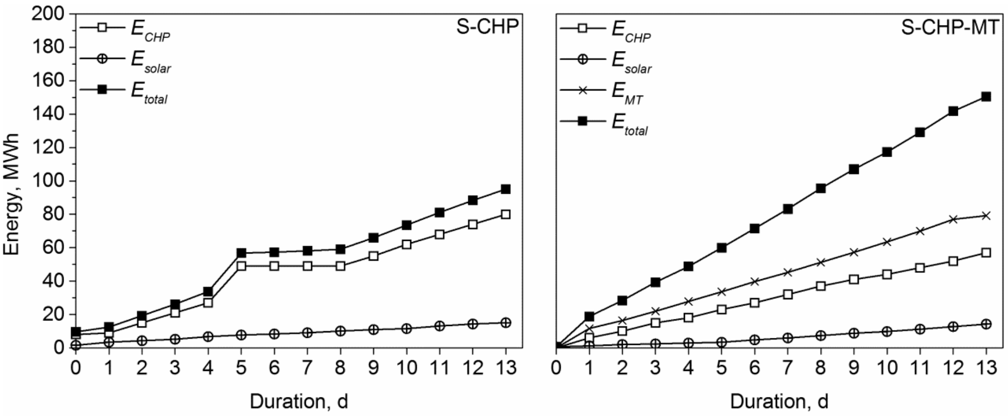

Figure 3. Cumulative energy input E_{total} from solar energy E_{solar}, waste-heat from a combined heat and power unit E_{CHP} and exhaust gas from a micro turbine E_{MT} for drying of biogas digestate; (left) variant S-CHP with solar energy E_{solar} and waste-heat of a combined heat and power unit E_{CHP}; (right) variant S-CHP-MT with solar energy E_{solar}, waste-heat of a combined heat and power unit E_{CHP} and exhaust gas from a micro turbine E_{MT}.

Table 2. Initial and final moisture content MC_{ini} and MC_{fin}, mass of evaporated water for the drying of digestate in a solar greenhouse dryer with waste-heat from CHP (variant S-CHP) and additional heat from a micro turbine (variant S-CHP-MT). Mean values ± standard deviation.

Variant	m_{ini}	t	MC_{ini}	MC_{fin}	m_{evap}	EP	E_{total}	$E_{spec.}$
	t	d	%	%	t	kg m^{-2} d^{-1}	MWh	MJ kg^{-1}
S-CHP	60	13	94.6 ± 0.1^a	10.9 ± 2.1^a	56.4 ± 1.3^a	9.0 ± 0.2^a	95.1	6.1 ± 0.0^a
S-CHP-MT	60	13	93.8 ± 0.6^b	10.5 ± 4.3^a	55.9 ± 2.8^a	8.9 ± 0.4^a	150.4	9.7 ± 0.0^b

Values in columns with same letters are not significantly different at $p < 0.05$.

3.2. Drying Performance of Biogas Digestate

The drying rate of the digestate and the uniformity of the drying process across the drying area indicate the quality of the air distribution in the dryer. The uniformity of drying ensures a safe product during further processing and storage of the dried digestate in term of its microbial activity. Figure 4 visualizes the spatial pattern of the moisture content across the drying area based on the interpolation of 20 grid measurements for variants S-CHP and S-CHP-MT after drying for 1, 7 and 13 d.

The pattern of MC shows a more homogeneous drying process across the drying surface in the variants S-CHP, which indicates a more even air distribution. After 7d of drying the MC varied between 67.3% and 83.3%, and at the end of drying after 13 d, this MC was more homogeneous, and varied between 8.3% and 16.5%. The conditions have been different in the variant S-CHP-MT, where after 7d of drying MC varied between 40% and 84.8%, and after 13 d of drying it still varied between 7.3% and 23.3%. The variation of the moisture content in S-CHP-MT is the result of inefficient air distribution in the dryer, and increased air flow through the inlet air volume flow. The exhaust fans in the dryer are controlled by the inlet air flow. If more drying air is supplied via the micro turbine, the total air flow rate is higher and more air is expelled by short-circuit without passing the drying surface. Therefore, the water absorption capacity of the drying air cannot be fully utilised. For a more efficient use of waste-heat from a micro turbine, the control system of the hybrid waste-heat/solar dryer should be adapted to the changed operating mode. The variation in the moisture content of the digestate could consequently be minimised and the drying efficiency increased.

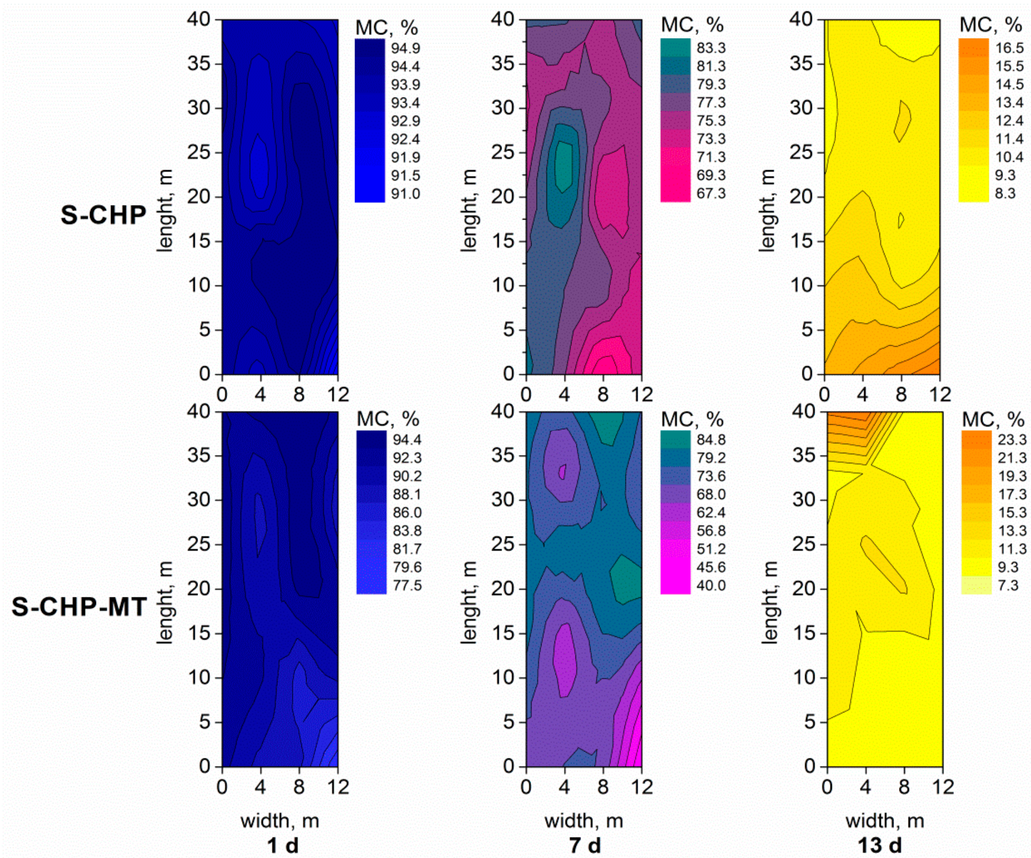

Figure 4. Spatial pattern of the moisture content (MC) of the digestate across the drying area based on the interpolation of 20 grid measurements after 1, 7 and 13 d of the drying with solar energy and waste-heat of a combined heat and power unit (S-CHP) and with additional use of the exhaust air of a micro turbine (S-CHP-MT).

Figure 5 shows the course of the average moisture content from 20 grid measurements during drying. The comparison of the drying processes under different operating modes shows that the moisture content has a higher standard deviation for each day in variant S-CHP-MT, as compared to the variant S-CHP. Thus, the operational mode without the exhaust gas from the micro turbine shows a more homogenous drying behaviour. This indicates an uneven air distribution across the drying surface, as described before.

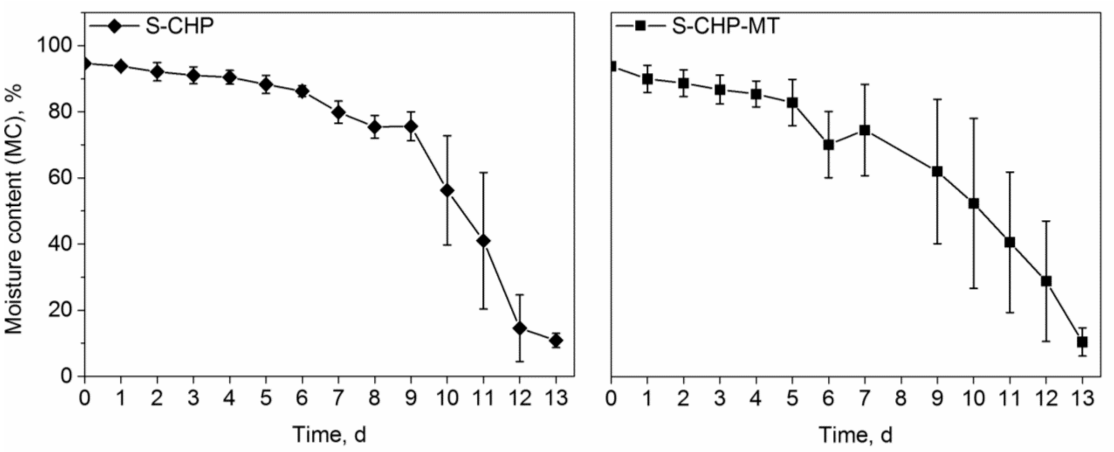

Figure 5. Course of moisture content MC during drying of biogas digestate; (left) variant S-CHP with solar energy and waste-heat of a combined heat and power unit; (right) variant S-CHP-MT with solar energy, waste-heat of a combined heat and power unit and exhaust air of a micro turbine. Mean values of 20 spatial grid measurement, error bars represent the standard deviation.

After 13 d of drying variants S-CHP and S-CHP-MT reached average moisture content of 10.9% and 10.5%, respectively. This indicates that the impact of using additional waste-heat from the micro turbine is negligible in terms of drying behaviour, and does not result in a shorter drying time. By reaching this moisture content, the dried digestate can be stored, as an MC of less than 15% is a common target value for safe storage, whereby further degradation and microbiological processes in the digestate can be avoided [22].

Concerning the drying costs, the investment costs for the solar drying hall are calculated by the company at approx. 320,000 Euro [23,24]. Investment and operation costs for the combined heat and power unit and for the micro turbine have not been allocated to the drying process because the main purpose is the generation of electricity, whereas the waste-heat is a byproduct. Specific electricity costs for solar drying systems with waste-heat support are 60 to 80 kWh per ton of evaporated water [25]. The use of waste-heat might be subsidized by governmental programs. For example, biogas plants in Germany that were approved in accordance to the Renewable Energy Source Act of 2009 (EEG 2009), receive a bonus of 0.03 EUR/kWh on the feed-in tariff for the drying of digestate [26]. However, those subsidies are not guaranteed in the long term: In the EEG 2014 this bonus was removed again.

Our study has shown that waste-heat from electricity generation can considerably contribute to solar digestate drying, which is corroborated by an economic analysis of Jacobs [25], who found that this practice of waste-heat assisted solar drying can reduce the drying costs by 20 to 26%, compared to pure solar drying.

4. Conclusions

The objective of this research was to investigate the parameters of digestate drying in a waste-heat/solar dryer regarding water evaporation and energy consumption for the drying process under different operating parameters.

The results showed that the combination of solar energy and waste-heat from a combined heat and power unit is a suitable way to reduce the moisture content of digestate after 13 d of drying to less than 15%, this then being a safe condition for further handling and storage. Regarding the energy input from the waste-heat of the micro turbine, the results revealed that there is no significant improvement in terms of evaporation performance, the evaporation performance was 8.9 $kg \cdot m^{-2} \cdot d^{-1}$ and 9.0 $kg \cdot m^{-2} \cdot d^{-1}$ for the operation with and without the waste-heat of the micro turbine, respectively. In contrary, the specific energy consumption in S-CHP-MT with 9.7 MJ kg^{-1} was 59% higher compared to S-CHP (6.1 $MJ \cdot kg^{-1}$).

Further research is necessary to investigate the environmental effects of waste-heat utilisation for digestate drying as well as to compare different drying systems regarding their respective economic feasibility.

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Conflicts of Interest: The authors declare that they have no conflict of interest.

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