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Vacuum Evaporation of a Liquid Digestate from Anaerobic Digestion: A Techno-economic Assessment

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The current boom of biogas plants (BGP) in Europe is associated with major digestate production. Digestate contains large amounts of nutrients but in low concentrations compared to artificial fertilizers. Storage and transportation of the digestate represents significant financial burden for BGP owners, especially in areas with intensive agricultural production. Vacuum evaporation (VE) is a technology which allows to efficiently reduce volume of the digestate. Benefits of VE include a simple design, operational reliability, and ability to utilize available waste heat. Integration of evaporation technology in BGP must respect concrete operating conditions and should be properly justified in terms of technical and economic aspects. This paper discusses central part of a mathematical model which may be used for technical-economic assessment of VE. Typical BGP is used in a case study to show how the integration of VE is facilitated with the increase in transportation distances and a decrease of electricity feed-in tariffs. It is shown that integration of VE is not necessarily beneficial for every BGP.

1. Introduction

Digestate is a by-product of anaerobic digestion, which typically takes place in biogas plants (BGP) – a widespread technology for biomass conversion and electricity production. Digestate could be considered as a valuable natural fertilizer, rich in nitrogen, potassium, and phosphorus (Heviánková et al., 2014). For certain types of crops and production conditions, the digestate may be comparable with mineral fertilizers (Nkoa, 2014). However, several disadvantages are connected with the digestate production, such as high water content and low nutrients concentration, a high cost of transportation and storage and legislative restrictions aiming at groundwater protection (Vondra et al., 2016). Technologies and processes for efficient treatment and utilization of the digestate have been subjected to comprehensive research in recent years (Vaneeckhaute et al., 2017). Production, processing and use of digestate are considered to be crucial areas for further research of BGP (Fan et al., 2017).
Mechanical separation of the digestate into solid and liquid fractions is the primary digestate processing method. The liquid fraction, the so called liquid digestate (LD), contains considerable amount of nutrients (Drosg et al., 2015). Dry matter content in LD commonly ranges from 2 to 6 % and takes up most of the original volume. Difficulties related to large volumes of digestate also apply to its liquid fraction.
Vacuum evaporation (VE) is one of technologies for LD treatment, with the advantage of simple construction and robust operation. Evaporators are capable of significant dewatering of the LD up to the 15 % of its original volume (Heviánková et al., 2014). Volume reduction is much appreciated by BGP, since transport costs may account for up to 40 % of all costs of BGP (Bojesen et al., 2015). However, VE may not be a suitable method for LD treatment in every BGP. Drosg et al. (2015) argue that VE is beneficial only for those BGP which produce excess of heat energy or for those which have waste heat available from other processes. According to Guercini et al. (2014), there may be a shortage of the heat available for VE especially during winter season. Tampio et al. (2016) compared several technologies and VE turned out to be the most efficient technology energy-wise but only in combination with reverse osmosis which further increases operating and investment costs of the whole technology. Melse and Verdoes (2005) compared technologies for processing of liquid manure and conclude that a selection of a specific treatment technology must reflect local conditions and

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particularities, especially economic aspects. As decisive economic factors, other authors mention transport distances and incentives for customers purchasing the digestate (Auburger et al., 2015), costs related to purchase of necessary chemical components (Chiumenti et al., 2013) or electric power demands (Vondra et al., 2018). A complex techno-economic assessment of VE has not been so far a subject-matter of more thorough research.

To fully understand the conditions under which the evaporator integration into BGP is economically and technically feasible, a mathematical model was developed and its central part is described in this study. Using a wide range of operational parameters and commodity prices, the model is able to determinate the maximum allowable cost of the project or the required payback period for a particular BGP. This crucial information for the investment planning is useful for the plant owner as well as for the technology manufacturer. This paper aims to describe the proposed method for techno-economic assessment of VE and present results for typical operational parameters. The presented central part of the model consists only of the top-level set of equations and do not consider more detailed calculation of mass and heat balance of individual unit operations.

2. Materials and Methods

2.1 Definition of BGP Involved in the Study

Evaluation of practical application potential of evaporation technology in BGP cannot be based solely on technical parameters and features of the technology itself; the whole issue must be assessed in a larger context of BGP's operating conditions. The operating conditions may differ in dozens of parameters: technical parameters (BGP capacity, type of processed biomass, amount of available heat, pretreatment of the digestate, final use of the digestate), economic parameters (electricity feed-in tariffs, purchase prices of materials and services, human labor costs), legal parameters (contracts with suppliers and customers, terms of operations permissions, restrictions imposed on agricultural land by the Nitrates Directive (1991)), social parameters (for example, relationships with businessmen and citizens in the local community).

Since no general evaluation of integrating the evaporation technology into BGP is possible, this study evaluates BGP under the following conditions:

a) All digestate is processed in a mechanical separator and separated into liquid and solid fraction.
b) All the produced LD is sold as a fertilizer and transported to distant regions.
c) BGP uses heat only for heating of the fermenter, rest of the heat is wasted in air-cooled chillers.
d) LD is commonly stored in containers with agitators. The agitators prevent solid particles from depositing, which would otherwise impede the pumping of the LD.
e) Produced electricity is used for the purposes of the BGP only, excess is supplied into the power grid.
f) There are no legal or social restrictions imposed on BGP in relation to the LD treatment.

These requirements may be met by BGPs which were established due to high electricity feed-in tariffs and whose production is not associated with agricultural production. Owners of these BGPs are interested in suitable technologies for LD processing.

2.2 Evaporator Selection

Various types of evaporators may be used for thickening of LD. Particular evaporators differ in many aspects, such as design complexity, energy demands, heat source, maximum dry matter content in the concentrate and, of course, purchase price of the evaporator. For the purposes of this study, type of the evaporator is not important. What is important are the specific operating parameters of the evaporator and ability to process LD. With respect to low power demands, evaporators which allow to recover waste heat and have no additional electrical appliances such as vapor compression or heat pump are recommended. Vondra et al. (2018) specifically name evaporators with forced circulation, falling film or multi-stage flash evaporators, they further give necessary computational relations for concrete configurations.

2.3 Impact of Evaporator Integration on BGP's Economic Situation

Integration of evaporators in BGP must be an economically viable project. Leaving the investment costs aside, introduction of a new technology will have impact on current operational income and expenses of BGP. Integration of a concrete evaporator will affect only few process apparatuses and only few operational processes. The affected processes are displayed in Figure 1.

First, there are costs related to operations of the evaporator itself. The costs entail technology maintenance (CTS_{evap}^{mnt}, EUR) and necessary chemicals (CTS_{evap}^{chem}, EUR) for reduction of pH and foam formation of the LD. Annual maintenance and service costs can usually be estimated by a ratio ($k_{evap}^{mnt}, -$) of the technology's purchase price (INV, EUR) according to the Eq(1). Annual costs for chemicals depend on amount of processed LD (V_{ldig}, m^3) and specific price of chemicals ($sPR_{chem}, EUR/m^3$) according to Eq(2).

$$CTS_{evap}^{mnt} = k_{evap}^{mnt} \cdot INV \tag{1}$$

$$CTS_{evap}^{chem} = sPR_{chem} \cdot V_{ldig} \tag{2}$$

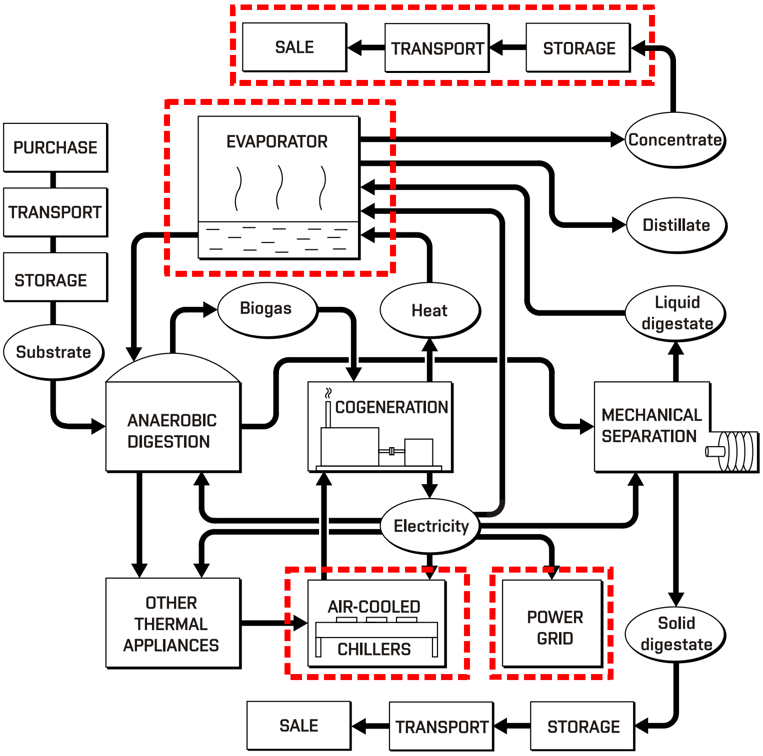

Figure 1: Units and processes of BGP affecting operating costs and income

If it is assumed that the distillate is of quality sufficient enough to be discharged (via adjustments to pH), the total volume of digestate, that must be stored, transported or sold, will change thanks to evaporation. Ratio between concentrate volume (V_{conc}, m^3) and volume of the original LD (V_{ldig}, m^3), is crucial for the transportation as it directly affects costs of transportation performed in specially equipped containers. Total change in annual transportation costs ($\Delta CST_{conc}^{tran}, EUR$) will be directly proportionate to original annual variable transportation costs ($CST_{conc}^{tran,var}, EUR$) according to Eq(3). These depend on average transportation distance and amount of annually transported material.

$$\Delta CST_{conc}^{tran} = CTS_{conc}^{tran,var} \cdot \left(V_{conc}/V_{ldig} - 1\right) \tag{3}$$

Decrease in LD concentration will have positive impact also on customers who use the concentrate as a fertilizer. Customers will thus experience decrease in variable costs on storage and application ($CTS_{apl}^{ldig,var}, EUR$). It may be assumed that reduction in volume is associated with increase in price of the concentrate – used as a fertilizer. This fact will affect income from sale (REV_{conc}^{sale}, EUR) for BGP owners according to Eq(4). However, this doesn't apply to every BGP.

$$\Delta REV_{conc}^{sale} = CTS_{apl}^{ldig,var} \cdot \left(1 - V_{conc}/V_{ldig}\right) \tag{4}$$

Major impact on economy of the plant is sale of electricity. Electricity is BGP's most valuable production commodity and is usually purchased at reasonable prices designed for supported energy sources. Changes to total income from electricity sale ($\Delta REV_{el}^{sale}, EUR$) are negatively affected by demands of evaporation technology (PC_{evap}, kWh), they are, however, positively affected by savings from air-cooled chillers' power consumption ($\Delta PC_{ac}, kWh$) and savings from mixers in storage tanks ($\Delta PC_{agit}, kWh$). Changes are directly proportionate to electricity feed-in tariffs ($PR_{el}, EUR/kWh$) according to Eq(5).

$$\Delta REV_{el}^{sale} = PR_{el} \cdot (\Delta PC_{ac} + \Delta PC_{mich} - PC_{evap}) \tag{5}$$

Total impact of the changes on operational cash flow may be defined using Eq(6) as a difference between revenues and costs:

$$REV - CTS = \Delta REV_{el}^{sale} + \Delta REV_{conc}^{sale} - \Delta CTS_{conc}^{tran} - CTS_{evap}^{chem} - CTS_{evap}^{mnt} \quad (6)$$

Plus or minus value of Eq(6) is the first indicator of viability of the investments in given operating conditions. But overall economic evaluation requires to consider investment costs (INV, EUR) and their payback period ($PP, years$). Their relationship together with annual cash flow (Eq(6)) is described by Eq(7).

$$PP = INV/(REV - CTS) \quad (7)$$

With respect to a broad variability in the selection and design of evaporators, defining investment costs is a difficult task that cannot be solved in one single study. For purposes of a techno-economic assessment, total investment costs were identified as a function of payback period which investors define based on their business strategy. This method brings the result of techno-economic assessment in the form of the maximum price of the project which is identical to INV. This is an amount of investments the investor is willing to tolerate in relation to the required payback period. This information is necessary not only for the investor, but also for supplier or manufacturer of the evaporation technology. Once the INV is calculated, it is possible to start planning the development phase and formulate the arrangement and design of the unit which has the potential to comply with financial requirements imposed on particular BGP. Final equation Eq(8) for identification of INV is obtained by modification of Eq(7) and including Eq(1) through Eq(6).

$$INV = PP \cdot (\Delta REV_{el}^{sale} + \Delta REV_{conc}^{sale} - \Delta CTS_{conc}^{tran} - CTS_{evap}^{chem}) / (PP \cdot k_{evap}^{mnt} + 1) \quad (8)$$

2.4 Input Data for Case Study

The proposed techno-economic assessment may be applied to various types of BGP with different operating parameters. For purposes of this study, operating parameters were chosen (Table 1) which are considered as typical and representative of agricultural BGP. Data on performance of the VE (Multi-stage flash evaporator) were taken from a paper by Vondra et al. (2018) and is also part of Table 1. In the case study, impact of anticipated payback period, feed-in tariffs and average transportation distance were observed.

Table 1: Case study input parameters (own estimates and Vondra et al., 2018)

Parameter	Value	Unit	Parameter	Value	Unit
Payback period	2–8	y	Digestate production	15,000	$m^3/MW_{el}/y$
El. feed-in tariff	0.08–0.28	EUR/kWh	BGP	1	MW_{el}
Hours of operation	8,760	h/y	Dry matter in digestate	8	%
LD application costs	2.70	EUR/m^3	Dry matter in LD	4	%
Costs coefficient k_{evap}^{mnt}	0.1	-	Dry matter in concentrate	12	%
Chemicals price	1.95	EUR/m^3	Dry matter in separate	25	%
Transportation costs	0.07	$EUR/m^3/km$	Specific heat input of the VE	240	kWh/m^3
Average transport distance	2–50	km	Specific el. input of the VE	14	kWh/m^3
El. efficiency of cogeneration	40	%	Share of fermentor in heat consumption of the BGP	30	%
Th.efficiency of cogeneration	45	%			
Input heating water temp.	90	°C	Specific el. input of agitators	10	W/kW_{el}
Output heating water temp.	75	°C	Specific el. input of chillers	8	W/kW_{th}

El. = electricity, Th. = thermal

The model calculation included the following assumptions:

a) Purchase and sales prices of a unit of energy, materials and services are constant and do not change in time.
b) The BGP's heat and electricity demands are identical for every year.
c) Amount and composition of produced digestate are identical for every year.
d) Increase in concentration of nutrients in the LD leads to proportionate increase in its price (customers experience decreases in costs for application of the LD).
e) Costs of LD transportation by pumps once the LD is stored are negligible.
f) Operating conditions do not change over the course of the year.

3. Results and discussion

Figure 2 and Figure 3 represent results for the case study input parameters. When considering transport distance of 30 km and feed-in tariffs between 0.08 and 0.28 EUR/kWh, the maximal cost of the project ranges from 40 to 140 k EUR (Figure 2). The results suggest that only projects with long payback period will be viable. From the Figure 2 it is also clear that integration of evaporator into BGP has bigger potential in facilities where the electricity is forced to be sold at lower feed-in tariffs. The reason is that financial losses caused by integration of the new electrical appliance are lower in those types of BGP. Electricity demands of the evaporation technology is partially compensated by savings in demand of air-cooled chillers and agitators in the storage tanks. It is interesting to note that high feed-in tariffs of electricity basically function as an impediment for investments into evaporation technologies. This conclusion holds true for other LD processing technologies. The state subsidies can be viewed as a negative factor, which prevents BGP from searching for novel, efficient and environmentally-friendly technologies.

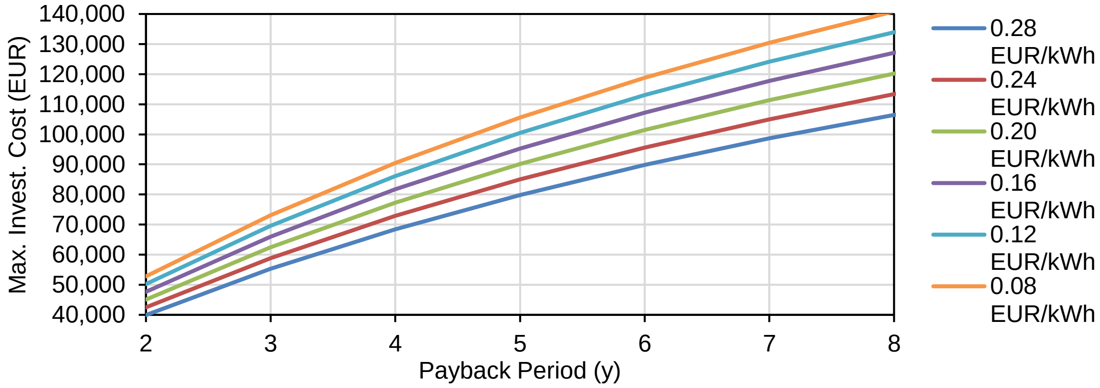

Figure 2: Maximum investment cost of the project as a function of required payback period and feed-in electricity tariffs, transport distance 30 km.

Transportation distance has even bigger impact on profitability of the investments. Figure 3 proves that increase in maximum investment costs is caused by increase in transportation distances. For the given feed-in tariff of 0.12 EUR/kWh and transportation distances between 2 and 50 km, the maximal cost of the project ranges from -19 to 240 k EUR (Figure 3). In certain cases (transport distance <= 5 km) the evaporator integration may even yield a negative cash flow of the project. It is obvious that only projects where average transportation distance exceeds 20 km are worth analyzing in terms of economic viability. This conclusion applies only to a concrete facility with electricity feed-in tariff of 0.12 EUR/kWh but it gives us a general knowledge that integration of evaporation technology is not a solution suitable for every BGP and that sometimes it may yield no positive economic benefits. As an example, we may mention BGP that apply digestate on a nearby land in areas with low intensity of agricultural production.

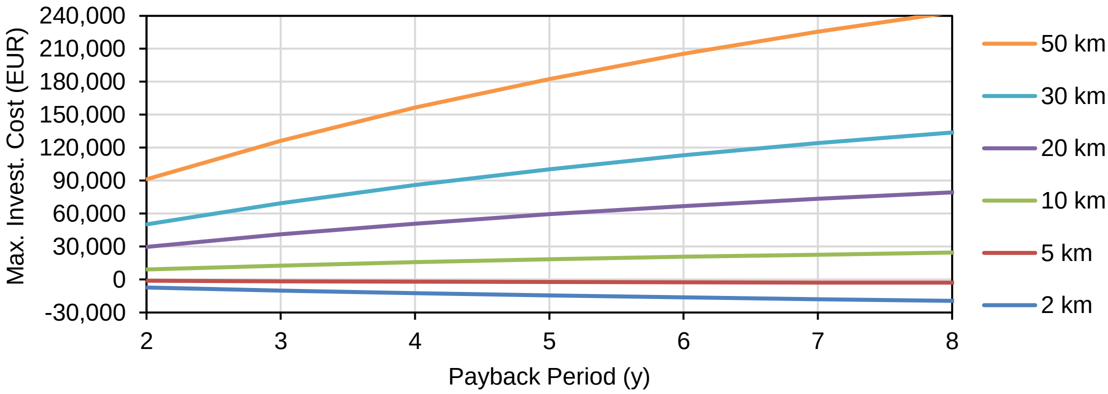

Figure 3: Maximum investment cost of the project as a function of required payback period and transport distance, feed-in electricity tariff 0.12 EUR/kWh.

4. Conclusions

This study describes central part of a mathematical model which allows to assess evaporation technology for LD processing in BGP. Based on the case study using typical input parameters, it can be concluded that the evaporator's integration is not a viable solution for every BGP. The evaporator's integration seems reasonable with the increase of transport distances. On the contrary, electricity feed-in tariffs could be considered as factors pushing against the evaporator usage. For the given feed-in tariff of 0.12 EUR/kWh, a minimum of 20 km in the transport distance would be required. Under the examined operational conditions, the maximum reasonable project price may vary between 30,000 and 240,000 EUR. Final decision on integration of the evaporator must always be preceded by a thorough techno-economic assessment. Results also show how incentives for electricity production discourages plant owners from adopting energy efficient and environmentally friendly solutions.

Future work should be focused on the analysis of other factors with a possible influence on the project feasibility such as BGP capacity, thermal power consumption, final dry matter concentration, chemicals consumption and electricity demand of the evaporator. Further research will also focus on the expansion of the current mathematical model and incorporation of detailed calculation of individual process operations and apparatuses.

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