

# Vacuum evaporation treatment of digestate: full exploitation of cogeneration heat to process the whole digestate production

S. Guercini, G. Castelli and C. Rumor

## ABSTRACT

Vacuum evaporation represents an interesting and innovative solution for managing animal waste surpluses in areas with high livestock density. To reduce operational costs, a key factor is the availability of an inexpensive source of heat, such as that coming from an anaerobic digestion (AD) plant. The aim of this study was to test vacuum evaporation for the treatment of cattle slurry digestate focusing on heat exploitation. Tests were performed with a pilot plant fed with the digestate from a full-scale AD plant. The results were used to evaluate if and how cogeneration heat can support both the AD plant and the subsequent evaporation of the whole daily digestate production in a full-scale plant. The concentrate obtained (12% total solids) represents 40–50% of the influent. The heat requirement is 0.44 kWh/kg condensate. Heat power availability exceeding the needs of the digester ranges from 325 (in winter) to 585 kW (in summer) versus the 382 kW required for processing the whole digestate production. To by-pass fluctuations, we propose to use the heat coming from the cogenerator directly in the evaporator, tempering the digester with the latent heat of distillation vapor.

**Key words** | anaerobic digestion, digestate treatment, heat recovery, vacuum evaporation

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## INTRODUCTION

In regions with high livestock density, such as the Po Valley (northern Italy), Brittany (France) or the southern Netherlands, to cite some of the major livestock producers in Europe, local use of manure on agricultural soils has led in the recent past to an over-application of nutrients that resulted in pollution of the surface and ground water. As an example, the average  $\text{NO}_3$  concentration of surface water in Brittany increased from 5 mg  $\text{NO}_3/\text{L}$  before the intensification of livestock production in this region (1970) to 35 mg  $\text{NO}_3/\text{L}$  more recently (Bernet & Béline 2009).

To solve this environmental problem, the European Commission established a directive (91/676/CEE, also known as the Nitrate Directive), which is intended to control nitrate leaching by limiting the land application of animal manure to 170 kg or 340 kg of nitrogen per hectare per year in vulnerable or not vulnerable zones, respectively.

In this context, the local application of livestock manure as a fertilizer must be limited, and alternative solutions should be developed.

The simplest solution involves the transport of excessive manure from areas with surpluses to areas with shortages;

however, especially for liquid manure (i.e., slurry), this solution is often limited by transportation and spreading costs given the high water content and low nutrient concentrations (Bonmati & Flotats 2003).

Therefore, the concentration of nutrients in a smaller volume is required. One option involves vacuum evaporation treatment, a process consisting of the removal of water from liquid waste through its evaporation and subsequent recovery as a condensate. As the process occurs in a closed system, it complies with air emission regulations, which are represented within EU countries by the 2010/75/UE IPPC Directive.

Vacuum evaporation is currently applied in various industrial and agro-industrial domains but it is still on trial for livestock effluents. Key factors for its successful application in agriculture are the availability of an inexpensive source of heat to run the process and reduce operational costs and the possibility of discharging condensate into a watercourse to limit the storage volume to the concentrated fraction.

The heat necessary for the process can be provided by anaerobic digestion (AD), which is thus intended to be a prior treatment for the effluent. Currently, only part of the

heat produced by the cogeneration unit (i.e., the combined heat and power – CHP – unit) of a biogas plant is used; the amount exceeding the needs of the biological reactor is generally wasted in the atmosphere, leading to a great inefficiency from an environmental viewpoint. In Italy, since 2013, the use of heat from the CHP unit to process digestate and produce a fertilizer has been promoted through extra bonuses in the feed-in tariff (Decree 06-07-2012). Furthermore, in France, with Decree 2011/190 and in Spain (Bonmati *et al.* 2003), incentives exist for the recovery and use of heat.

Accordingly, the question is: how much of the effluent can be processed with the heat produced by the CHP unit? Indeed, from the perspective of a full-scale evaporation plant coupled with an AD plant, the entire daily digestate production should be treated.

In respect of the quality of condensate, in view of its discharge into a watercourse, the critical parameters are ammonia and chemical oxygen demand (COD), the latter of which is affected by volatile fatty acids and volatile organic compounds.

AD removes volatile organic matter and, consequently, allows for a condensate with very low residual COD content to be obtained (Teri 2012).

To prevent ammonia volatilization, the acidification of the influent to evaporation is common practice. However, if applied to digestate, acidification requires significant quantities of acid. Teri (2012) highlights a requirement of 32 L/m<sup>3</sup> for a 35% sulphuric acid solution to reduce the influent pH from 7.6 to 5.0, resulting in more than 99% of ammonia nitrogen in the ionized, non-volatile form (Masse *et al.* 2008). Moreover, previous acidification does not assure the possibility of discharging the condensate, and further agronomical use is compromised by the low pH (Teri 2012). Finally, operational costs are increased, and there are also safety problems for the on-farm storage of this chemical.

A solution to match the discharge limits for the condensate may be its subsequent filtration on reverse osmosis (RO) membranes. Many studies confirm the efficiency of this treatment in the recovery of ammonia from a solution (ten Have *et al.* 1990; Masse *et al.* 2007, 2008).

The aim of this study was to test vacuum evaporation on cattle slurry digestate, focusing on heat exploitation. Tests were performed using a one-stage pilot plant fed with the liquid fraction of beef cattle slurry and corn silage digestate from a full-scale AD plant. No previous acidification was used. The evaporation efficiency, characteristics of the concentrate and condensate, and heat requirements were evaluated.

The results were then used to evaluate if and how the heat produced by the CHP unit could support both the

biological reactor and the subsequent evaporation of the whole daily digestate production in a full-scale concentration plant.

## MATERIAL AND METHODS

### Experimental design

Eight tests of 6 to 8 hours each were performed, using a single-effect semi-continuous evaporation pilot plant. The influent flow rate was approximately 140 kg/h.

During each test, the inflow of digestate and outflow of condensate were continuous, while the concentrate accumulated at the bottom of the boiling chamber and was discharged only at the end of the work session. The evaporator (Table 1, Figure 1) was installed close to a full-scale AD plant treating beef cattle slurry and corn silage (Table 2). The heat necessary for the evaporation process was provided by hot water coming from the CHP unit of the biogas plant.

The pilot plant was fed with the liquid fraction of the digestate obtained by a screw-press solid-liquid separator with a 0.5 mm sieve. No previous acidification of the influent was used. To prevent foam formation in the boiling chamber, a specific antifoam product was added at the dosage of 2.0–2.5 kg/t of influent.

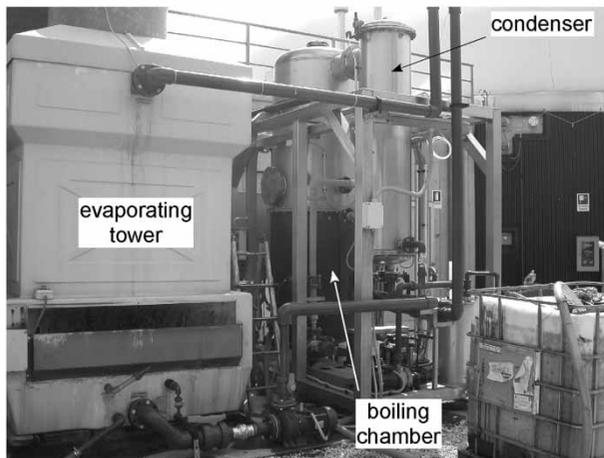
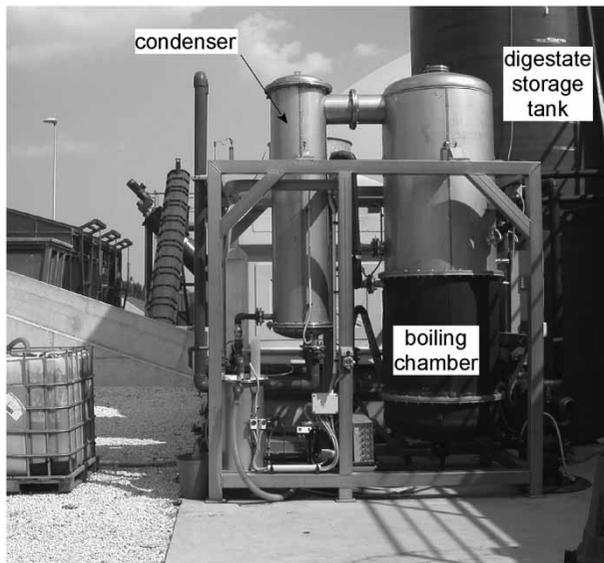
For each test, samples of influent and concentrate were taken at the beginning and at the end of the working session, while samples of condensate were taken every 2 hours.

### Analytical methods

The total solids (TS), ash, total suspended solids (TSS), COD, total Kjeldahl nitrogen (TKN), ammonia nitrogen

**Table 1** | Main characteristics of the evaporation pilot plant

|                                |  |
|--------------------------------|--|
| Type                           | One-stage, forced recirculation evaporator |
| Delivery capacity (max)        | 200 kg/h of condensate                     |
| Boiling chamber volume         | 800 L                                      |
| Vacuum degree                  | 705 mmHg                                   |
| Actual electric power          | 14 kW                                      |
| Cooling fluid in the condenser | Water from evaporating tower               |



**Figure 1** | The vacuum evaporation pilot plant.

**Table 2** | Main characteristics of the AD plant

|   |  |
|---|--|
| CHP electric capacity                         | 560 kW   |
| CHP thermal capacity (complete heat recovery) | 650 kW   |
| Power for AD purposes                         | 10% in summer (April to October) (=65 kWth); 50% in winter (November to March) (=325 kWth) |
| Operational temperature level                 | Mesophilic (38–40 °C)  |
| Raw digestate production                      | 40 t/d   |

(N-NH<sub>4</sub><sup>+</sup>) and total phosphorus (P) were analyzed following APAT-CNR-IRSA (2003) Standard Methods (Table 3).

COD and TSS were not analyzed in the concentrated fraction because it is considered a solid.

**Table 3** | Chemical parameters analyzed in the samples of influent, condensate and concentrate

| Parameter  | Unit                | Influent, condensate | Concentrate |
|--|---------------------|----------------------|-------------|
| TS   | % p/p               | X                    | X           |
| Ash  | % p/p               | X                    | X           |
| TSS  | mg/kg               | X                    | –           |
| COD  | mgO <sub>2</sub> /L | X                    | –           |
| TKN  | mg/kg               | X                    | X           |
| Ammonia nitrogen (N-NH <sub>4</sub> <sup>+</sup> ) | mg/kg               | X                    | X           |
| Total phosphorus (P)                               | mg/kg               | X                    | X           |

The volumetric reduction ( $V_{\text{red}}$ , %) of the influent was determined as follows (1):

$$V_{\text{red}} = (q_{\text{cond}}/q_{\text{in}}) \cdot 100, \quad (1)$$

where  $q_{\text{cond}}$  and  $q_{\text{in}}$  are the mass flow of condensate and influent (kg/h), respectively.

The nitrogen distribution ( $N_{\text{dis}}$ , %) between the condensate and concentrate was also determined (2):

$$N_{\text{dis}} = (N_{\text{c}}/N_{\text{i}}) \cdot 100, \quad (2)$$

where  $N_{\text{c}}$  and  $N_{\text{i}}$  (kg/h) are the nitrogen mass flow in the condensate and in the influent, respectively.

The thermal consumption ( $p$ ) for the evaporation process was determined based on the average flow rate of the pump bringing hot water to the evaporator plant and on the temperature difference of the water before and after heat exchange (3):

$$p = Q \cdot c_s \cdot \Delta T \quad (3)$$

where  $p$  is heat flow rate (kWh);  $Q$  is hot water flow rate (kg/h);  $c_s$  is water specific heat (kWh/(kg · °C));  $\Delta T$  is the difference in the temperature of water before and after the evaporation process (°C).

## RESULTS AND DISCUSSION

### Evaporation efficiency, concentrate and condensate characteristics

The influent, condensate and concentrate characteristics are summarized in Table 4.

**Table 4** | Composition of influent (A), concentrate (B) and condensate (C) as average, standard deviation, minimum and maximum values

|   |        | TS (% p/p) | TSS (mg/kg) | VS (% p/p) | COD (mgO <sub>2</sub> /l) | TKN (mg/kg) | N-NH <sub>4</sub> <sup>+</sup> (mg/kg) | N-NH <sub>4</sub> <sup>+</sup> /TKN (%) | Ptot (mg/kg) | pH   |
|---|--------|------------|-------------|------------|---------------------------|-------------|--|---|--------------|------|
| A | avg    | 4.24       | 30,886      | 3.00       | 41,150                    | 3,058       | 1,766                                  | 57.8                                    | 676          | 7.9  |
|   | dev.st | 0.75       | 8,685       | 0.88       | 11,050                    | 501         | 408                                    | 13.3                                    | 398          | 0.08 |
|   | min    | 3.10       | 27,280      | 1.90       | 27,700                    | 2,230       | 1,105                                  | 35.3                                    | 124          | 7.8  |
|   | max    | 5.10       | 42,550      | 4.40       | 57,000                    | 3,760       | 2,097                                  | 78.5                                    | 1,400        | 8.0  |
| B | avg    | 11.88      | na          | 7.79       | na                        | 4,687       | 1,138                                  | 24.3                                    | 1,902        | 8.9  |
|   | dev.st | 1.38       |             | 0.76       |                           | 707         | 176                                    | 3.8                                     | 630          | 0.2  |
|   | min    | 10.00      |             | 7.00       |                           | 3,555       | 790                                    | 17.6                                    | 799          | 8.6  |
|   | max    | 14.20      |             | 9.10       |                           | 5,900       | 1,317                                  | 28.0                                    | 2,640        | 9.1  |
| C | avg    | nd         | nd          | nd         | 96.2                      | 3,379       | 2,776                                  | 82.2                                    | nd           | 8.5  |
|   | dev.st |            |             |            | 99.8                      | 1,029       | 928                                    | 11.5                                    |              | 0.16 |
|   | min    |            |             |            | 22.8                      | 2,141       | 1,351                                  | 63.1                                    |              | 8.3  |
|   | max    |            |             |            | 317.5                     | 5,148       | 4,440                                  | 95.8                                    |              | 8.8  |

nd = not detected; na: not analyzed.

Starting from a 4.2% TS influent, a 12% TS concentrate was obtained, which represents 46% of the influent (Table 5A).

These results are similar to those obtained by Teri (2012) with the liquid fraction of a pig slurry digestate: starting from a 3.4% TS influent, a 15.1% TS concentrate was produced, with a mass reduction of 80%. The lower evaporation efficiency gained in the present study is most likely due to the type of concentration plant used. Teri (2012) worked with a scraped-surface heat exchanger evaporator, which consists of a boiling chamber in which the heat exchanger surface is equipped with scraping blades cleaning the surface of the heat exchanger from deposits that could inhibit the heat transfer. The evaporator used in the present study was a falling film, which was not shown to be suitable for viscous materials such as digestate due to the absence of a cleaning device; slurry tended to deposit on the exchange surfaces of the boiling chamber, rapidly inhibiting heat transfer and limiting the concentration efficiency.

The amounts of total nitrogen and ammonia transferred to the condensate were 46% and 74%, respectively (Table 5B). The average concentrations were 3.3 g/L of

TKN and 2.7 g/L of N-NH<sub>4</sub><sup>+</sup>, resulting in a N-NH<sub>4</sub><sup>+</sup>/TKN ratio of approximately 82%.

In the condensate, because of their low concentrations, TS, TSS, VS and phosphorus could not be detected (the minimum values required are 0.1%, 5 mg/L, 0.1% and 10 mg/L, respectively). The average COD was 96 mg/L.

These results are consistent with those reported by Teri (2012), as summarized in Table 6: without previous acidification, 78% of the initial nitrogen was removed from the influent, resulting in a condensate almost free of TS and VS, with 3.7 g/L TKN and 2.55 g/L TAN (total ammonia nitrogen).

With reference to the possible discharge of condensate into a watercourse, and comparing the condensate analysis to the threshold concentration allowed by current Italian regulation (Legislative Decree 03-04-2006 n. 152) summarized in Table 7, the condensate does not meet the requirement for ammonia. A further treatment is therefore needed. One solution may be subsequent filtration on RO membranes. Several studies confirm the efficiency of this treatment in the recovery of ammonia from a solution (ten Have et al. 1990; Masse et al. 2007, 2008).

**Table 5** | A: average flow rate of influent, concentrate and condensate from evaporation tests. B: % distribution of TKN and N-NH<sub>4</sub><sup>+</sup> between concentrate and condensate

|             | A             |            | B              |                                |
|-------------|---------------|------------|----------------|--------------------------------|
|             | Flow rate     |            | % distribution |                                |
|             | (kg/h)        | (%)        | TKN            | N-NH <sub>4</sub> <sup>+</sup> |
| Influent    | 140 (123–156) | 100        | 100            | 100                            |
| Concentrate | 64 (52–72)    | 46 (40–50) | 54 (41–68)     | 26 (19–44)                     |
| Condensate  | 76 (64–84)    | 54 (50–60) | 46 (32–59)     | 74 (56–81)                     |

Minimum and maximum values in parentheses

**Table 6** | Composition of influent, concentrate and condensate resulting from the evaporation of the liquid fraction of a pig slurry digestate processed in a single-stage evaporator plant without previous acidification (Teri 2012)

|             | pH  | TS (%) | VS (%) | TKN (g/L) | TAN (g/L) |
|-------------|-----|--------|--------|-----------|-----------|
| Influent    | 7.6 | 3.4    | 1.8    | 4.55      | 2.33      |
| Concentrate | 8.6 | 15.1   | 11.4   | 5.35      | 1.47      |
| Condensate  | 7.7 | nd     | nd     | 3.72      | 2.55      |

TAN = total ammonia nitrogen; nd = not detected.

**Table 7** | Comparison between the average experimental concentration in the condensate and the threshold values allowed by current Italian regulation (Legislative Decree 03-04-2006 n. 152) for the discharge of wastewaters into a watercourse

| Parameter        | Unit                                 | Threshold concentration | Average experimental concentration |
|------------------|--------------------------------------|-------------------------|------------------------------------|
| pH               |                                      | 5.5–9.5                 | 8.5                                |
| TSS              | mg/L                                 | 80                      | nd                                 |
| COD              | mg O <sub>2</sub> /L                 | 160                     | 96                                 |
| Ammonia          | mg N-NH <sub>4</sub> <sup>+</sup> /L | 11.66                   | 2,776                              |
| Total phosphorus | mg P/L                               | 10                      | nd                                 |

nd = not detected.

### Heat requirement and hypothesis for improved heat exploitation

The heat requirement for the evaporation process was calculated to be 0.87 kWh per kg condensate produced and was reduced to 0.44 kWh/kg if adopting a double-effect evaporator (as usually occurs in a full-scale plant). These data are consistent with previous studies reporting a heat consumption of 0.43 kWh/kg condensate produced (Regione Lombardia 2009; Teri 2012).

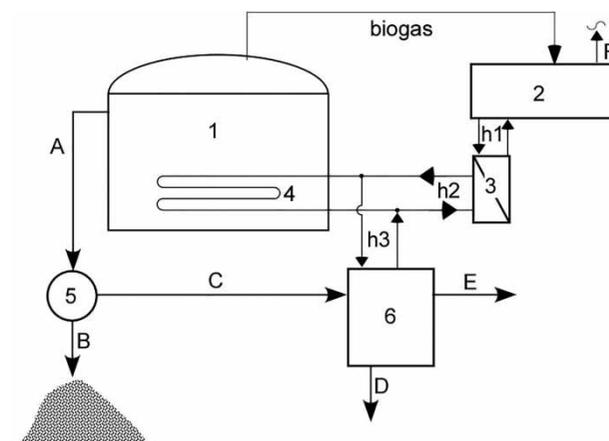
With reference to the AD plant, to process the entire daily production of digestate (35 t/d, corresponding to 21 t/d of condensate) in a two-stage evaporator, a thermal power of 382 kW is needed (Table 8).

In a conventional scheme, the heat available for the evaporation process comes from the amount exceeding the needs of the AD plant (Figure 2); in our case study, the availability ranges from 585 kWth in the summer – April to October – to 325 kWth in the winter – November to March – (Table 2), thus allowing treatment of the daily digestate production during almost the entire year, with a 15% deficit in winter.

To increase the heat availability, the solution proposed is to integrate the evaporation plant in the CHP unit-AD plant line (Figure 3).

**Table 8** | Data used for the calculation of the heat necessary to process the daily digestate production of the guest AD plant with a full-scale two-stage evaporator

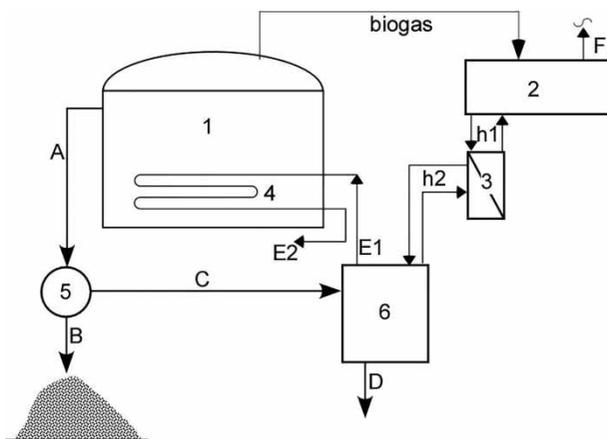
| Parameter   | Unit       | Value |
|---|------------|-------|
| Liquid fraction of digestate to the evaporation plant | t/d        | 35    |
|   | t/h        | 1.46  |
| Condensate production                                 | % influent | 60    |
|   | t/d        | 21    |
| Concentrate production                                | t/h        | 0.875 |
|   | % influent | 40    |
| Heat requirement per kg condensate produced           | t/d        | 14    |
|   | t/h        | 0.58  |
| Heat requirement to process 35 t/d of digestate       | kWh        | 0.44  |
| Heat requirement to process 35 t/d of digestate       | kWh        | 382   |



**Figure 2** | Conventional layout. Heat from the CHP unit (h1) is directly used for tempering the reactor (h2). The excess amount (h3) is used for the evaporation process; compared with h1 (650 kW), this value ranges from a maximum of 585 kW in the summer (90%) to a minimum of 325 kW in the winter (50%). 1. AD reactor, 2. CHP unit, 3. CHP heat exchanger, 4. AD reactor heat exchanger, 5. solid-liquid separator, 6. evaporation unit (including two-stage evaporators, distiller and evaporating tower). Flows: A. raw digestate, B. solid fraction after solid-liquid separation, C. liquid fraction to the evaporator, D. concentrated fraction, E. condensed fraction, F. electric energy. Heat: h1. warm water from CHP unit, h2. warm water to the heat exchanger of the reactor, h3. warm water to the evaporator.

Hot water exiting the CHP unit at approximately 90 °C is directly and entirely used for the evaporation process, while distillation vapor, exiting at 50–55 °C, is condensed in the heat exchanger of the AD plant, releasing its latent heat to the reactor, which must be maintained at 38–40 °C.

Compared with the conventional layout, in which the heat source for the biological process is hot water exiting the CHP unit (Figure 2), the reduced temperature difference in the heat exchanger between the warmer and cooler fluid (distillation vapor and digestate in the reactor) requires a



**Figure 3** | Working hypothesis. Heat from the CHP unit ( $h_1$ ) is used directly for the evaporation process ( $h_2$ ); distilled vapors exiting from the evaporator (E1) pass through a heat exchanger (4), allowing both the tempering of the reactor and its condensation (E2). 1. AD reactor, 2. CHP unit, 3. CHP heat exchanger, 4. AD reactor heat exchanger, 5. solid-liquid separator, 6. evaporation unit (including two-stage evaporators, distillers and evaporating tower). Flows: A. raw digestate, B. solid fraction after solid-liquid separation, C. liquid fraction to the evaporator, D. concentrated fraction, E1. distilled vapors for the heating of the anaerobic reactor, E2. condensed fraction, F. electric energy. Heat:  $h_1$ . warm water from CHP unit,  $h_2$ . warm water to the evaporator.

higher heat exchange surface. Consequently, an external heat exchanger may be considered a good solution both for a new AD plant and in the case of revamping an existing one, thus increasing its heat-exchange surface.

## CONCLUSIONS

The results obtained confirm that vacuum evaporation may be considered of interest for the treatment of digestate originating from agricultural and livestock biomasses.

Starting from a 4.2% TS influent, a 12% TS concentrate was obtained, with a volumetric reduction of 54%.

As expected, without previous acidification of the influent to the evaporator, the condensate produced cannot be discharged into a watercourse because of its ammonia content. However, matching discharge limits is a key factor for the successful application of vacuum evaporation in agriculture, given the possibility of reducing storage volumes only to the concentrated fraction.

The heat necessary for the evaporation process is provided by the CHP unit of the AD plant; however, when the aim is to treat the entire daily digestate production, the amount exceeding the needs of the digester (generally wasted in the atmosphere) is not sufficient. With a heat requirement from the concentration plant of 382 kW and a heat availability ranging from 325 kW in the winter to

585 kW in the summer, there is a 15–17% heat deficit in the winter for the evaporation process. To ensure the treatment of 100% of the daily digestate production during the entire year, the solution proposed is to use hot water exiting the CHP unit directly for the evaporation process, leaving the residual heat of the distillation vapors to temper the digester.

This solution has the advantage of fully exploiting the limited heat available considering that the evaporation process has the highest heat requirement that can be satisfied by the hot water exiting the CHP unit, while the residual heat of the distilled vapors is sufficient for tempering the AD reactor.

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