Improvement of the anaerobic digestion of activated sludge: thermal and economical perspectives

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Abstract

The treatment of municipal or industrial wastewaters generates primary and secondary sludge that in medium and large wastewater treatment plants (WWTPs) are stabilized by means of anaerobic digestion (AD) processes. Due to several causes like the increasingly cogent European and national laws concerning the quality of sludge after stabilization, the high costs of landfilling and the profit of energy generated by renewable sources, different technologies are under consideration in order to enhance the performances of the AD of sludge, in particular secondary sludge.

With reference to a WWTP with a capacity of more than 2 million equivalent inhabitants that generates an average daily flow of 6,000 m3 primary and secondary sludge (at a total solid, TS, content of about 1%), two solutions aimed at improving the performances of the AD process were evaluated considering technical and economical aspects.

The possible first solution planned the thickening of secondary sludge, with the aim of searching for the optimal TS content able to guarantee the thermal sustainability of the AD process. TS content ranging from 3.5% to 8% was considered in the calculations. It was verified that the achievement of a TS content of 4% is enough to make the AD of both primary (at a TS content of 3.5%) and secondary sludge independent of the employment of an auxiliary fuel. Higher TS values for secondary sludge, although enhancing the production of thermal energy, are not recommended because of the worsening of their rheological behaviour.

On the other hand, the possible second solution planned the pre-treatment of secondary sludge using low-temperature (< 100°C) processes that could be performed by making use of heat exchangers or overheated vapour. It was

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demonstrated that if all the heat generated by burning biogas is transferred to the secondary sludge through heat exchangers, a TS content of 3.70% is enough to make the thermal pre-treatment at 70°C independent of the employment of an auxiliary fuel.
Keywords: anaerobic digestion, wastewater treatment plant (WWTP), primary and secondary sludge, energy balance.

1 Introduction

Conventional processes carried out in municipal WWTPs generate primary and secondary sludge that have to be stabilized before disposal. AD is a useful technique for the treatment of sludge because, in addition to reducing the overall amount of biosolids to be disposed of (by about 40%) and stabilizing organic substance, it produces biogas, made of methane and carbon dioxide, that can be exploited for energy recovery. Nevertheless, the AD process is not completely effective towards some typologies of organic matter: one of these is the activated sludge from WWTPs.

In fact, AD of secondary sludge, and in particular the hydrolysis step, is limited by the presence of the walls of sludge cells. Sludge cells may be disintegrated by lysis processes, thus permitting the release of intracellular matter that becomes more accessible to anaerobic microorganisms. This fact improves the overall digestion process velocity and the degree of sludge degradation thus reducing anaerobic digester retention time and increasing methane production rates [1, 2]. Lysis processes may be grouped into biological, thermal, chemical and mechanical processes as well as different combinations of these.

In a previous work [3] the efficiency of low temperature (< 100°C) thermal pre-treatments in rising the biogas/methane production from secondary sludge AD was tested on lab-scale. The efficiency of the thermal pre-treatments was quantified using the disintegration rate (DR) parameter, that is the ratio between the COD transferred in the liquid phase and the COD of the whole sludge sample. For the considered treatment times (1–15 hours), an increase in the DR parameter from 15 to 25% for the temperature value of 70°C, from 15 to 28% for the temperature value of 80°C and from 19 to 30% for the temperature value of 90°C was observed. The increase in the specific biogas production (biogas volume/TVS content) was verified using 6L-mesophilic digesters in batch modality. Comparing the results obtained in the digestibility test, the treated samples showed increases from 15 to 26% in the biogas production compared to the untreated samples. Moreover, it was demonstrated that increases in operating parameter values (time, temperature) seemed not to considerably improve the performances of the systems involved in AD tests in terms of biogas and methane production. In particular, low-temperature (70°C) and short-lasting pretreatments (3 hours) seemed to promote the starting phase of the digestibility process, thus causing a greater daily biogas production in the first days of the test. On the other hand, high-temperature or longer-lasting pretreatments (then energy disadvantaged) seemed to partially inhibit the performances of the AD process.

The implementation of traditional or innovative processes for the possible improvement in the management of sludge in existing WWTPs has to be subjected to careful technical and economical evaluations as shown in [4]. By means of a technical and economical assessment, this work provides a comparison between the present way of management of primary and secondary sludge carried out in a large WWTP (more than 2 million of equivalent inhabitants) and two possible new scenarios that plan the thickening of sludge or the combination of thickening of both types of sludge and low temperature thermal pretreatment of secondary sludge.

2 Materials and methods

The plant involved in the technical and economical assessment is a WWTP that treats municipal and industrial wastewater with a capacity of more than 2,000,000 of equivalent inhabitants (about 1.5 million of civil inhabitants and 800 industrial plants). It consists of one line devoted to wastewater treatment and one line for sludge treatment. The line devoted to the wastewater treatment, with an average flow rate of about 25,000 m^3/h, is made up of the following processes: grid screens, grit and grease removal, primary sedimentation, pre-denitrification, biological treatment, secondary sedimentation, phosphorous removal and final filtration. The wastewater treatment process generates an average amount of primary and secondary sludge equal to about 300–350 m^3/h (with an average TS content of 1%) that is sent to the sludge treatment. The sludge treatment line is made up of the following unit operations: pre-thickening, mesophilic anaerobic digestion, post-thickening and final dewatering. The pre-thickening process, carried out by means of gravity devices with the addition of polyelectrolyte for the thickening of secondary sludge, reduces the amount of sludge to be treated by AD to about 110 m^3/h, with an average TS content of 2.75% for both primary and secondary sludge. The total sludge flow rate is split among five anaerobic digesters, in fact the plant has six reactors, one of which cyclically in maintenance. In the present working conditions two digesters are filled with primary sludge, two with secondary sludge and the last with mixed sludge.

Each digester has a volume of 12,000 m^3 (for a total volume useful to the digestion process of 72,000 m^3), a D/H (diameter, height) ratio of 26/30, a filling coefficient of 0.8, an hydraulic retention time (HRT) of about 17 days, a fed sludge amount of 23.5 m^3/h with a TS content of 2.75%, for a mass flow rate of dry substance of 650 kg/h. The digestion process is carried out in mesophilic conditions, at the temperature value of 38°C.

In order to heat the sludge from the average temperature of 15°C (ambient temperature) to 38°C and keep the process temperature constant, each digester is coupled with a double-tube heat exchanger fed by the hot water (90°C) circuit. The heat necessary to the hot water circuit is supplied by the cogeneration engines (GE-Jenbacher JMS 420 GS-B.L.) that produce heat and electricity by burning the biogas generated in the AD process. The cogeneration engines have thermal efficiency of 42.4% and electrical efficiency of 41.9%.

A boiler fed by methane taken from the external gas supply copes with the possible energetic deficiency. The mixing of the material subjected to AD into the digesters is performed by means of injection of biogas through nozzles.

The energy balance presented in this paper is aimed at evaluating the performances of the AD process when carried out in the present condition and under the hypothesis of improving its efficiency by implementing the processes planned by the two scenarios as described in the following:

- Future scenario 1: thickening of primary and secondary sludge until a TS value capable to guarantee the complete self sustainability of the AD process.
- Future scenario 2: combing thickening of primary and secondary sludge to thermal pre-treatment at low temperature values (< 100°C) of secondary sludge in order to improve the performances of the sludge treatment process.
- Present scenario – in order to keep the process temperature (38°C) constant into the digester, the heat exchanger must provide an amount of heat sufficient to warm the sludge and to offset the heat losses through the digester walls due to the exchange with the exterior environment (Qa). The heat losses with the outside were evaluated by taking into account the geometry of the digester and the materials employed for its construction; the temperature of pre-thickened sludge (15°C), soil (15°C) and outside (exterior environment, as monthly averages as reported in the UNI 10349 rule, [5]).

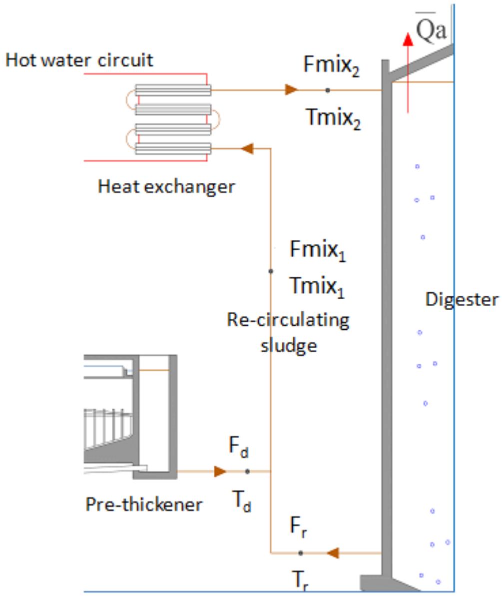

Figure 1: Scheme of the digested sludge re-circulation for the new sludge heating.

In order to obtain a good homogenization between the incoming sludge and the waste already present into the digester, the sludge coming from the thickener devices (flow rate 23.5 m^3/h, 15°C) is mixed with an amount of sludge already digested and re-circulated to the digester (flow rate 250 m^3/h, 38°C). As in Figure 1, the mixing between the pre-thickened sludge and the already digested sludge re-circulated to the digester allows the temperature of the sludge that enters the heat exchanger to be risen to $Tmix_1$ value, obtained from the mass and heat balance as in (1):

$$Tmix_1 = (T_d F_d + T_r F_r)/Fmix_1 \quad (1)$$

where:
- F_d, T_d, flow rate (F) and temperature value (T) of the sludge from the pre-thickeners;
- F_r, T_r, flow rate (F) and temperature value (T) of the sludge already digested and re-circulated;
- $Fmix_1$, $Tmix_1$, flow rate (F) and temperature value (T) of the sludge that enters the heat exchanger.

For the development of the energy balance to the AD system, the average methane production of the primary sludge was fixed to 0.385 Nm^3/kgVS (VS, volatile solid) and the average methane production of the secondary sludge to 0.167 Nm^3/kgVS (data supplied from the plant).

Future scenario 1 – this scenario plans to improve the management of the AD process by the improvement of the efficiency of the thickening processes of both primary and secondary sludge. The main hypothesis that undergoes this scenario is to acquire dynamic thickeners to devote to the thickening of secondary sludge. In this way all the gravity devices available in the WWTP presently employed for the treatment of both primary and secondary sludge may be destined to primary sludge only. It is expected that the TS content of primary sludge may rise from the present 2.75% to about 3.50%. Dynamic thickeners may guarantee TS values of 8–9% in secondary sludge. The evaluation of the performances of the afore mentioned devices on both primary and secondary sludge is presently under consideration.

For the development of the energy balance, thickening of the primary sludge to a TS content of 3.50% and thickening of the secondary sludge to a final TS content ranging from 3.50% to 8%, by considering subsequent increases of 0.5%, were taken into account.

The economical assessment performed for this scenario does not consider the costs for purchase and installation of the new dynamic thickeners, the increased amount of electricity necessary for working of the new pieces of equipment and, in the end, the avoided costs due to the stop in the polyelectrolyte employment.

Future scenario 2 – this scenario plans to improve the management of the AD process by combining the improvement in the thickening of both primary and secondary sludge with low temperature (< 100°C) thermal pre-treatment of secondary sludge.

The operating conditions included in this scenario are as in the following list:

- Thickening of primary sludge to a TS content of 3.50% using all the available gravity devices (see Future scenario 1).
- Thickening of secondary sludge to a range of TS from 3.5% to 8% using dynamic thickeners on-purpose acquired (see Future scenario 1).
- Low-temperature thermal pre-treatment of secondary sludge at temperature values of 70, 80 or 90°C. For the development of the energy balance to the AD system, the average methane production of the untreated primary sludge was fixed to 0.385 Nm^3/kgVS (see present scenario) and the average methane production of the secondary sludge respectively to 0.202, 0.216 and 0.219 Nm^3/kgVS, depending on the temperature of the pre-treatment process, 70, 80 or 90°C (data from [3]).
- Final mixing of the thermal pre-treated secondary sludge with thickened primary sludge, with the aim of homogenizing the sludge sent to digesters and using the heat of the treated secondary sludge to increase the temperature of the mix.

The thermal pre-treatment includes two phases: a first phase in which the sludge is heated from the ambient temperature (15°C) to the temperature value at which the pre-treatment is carried out (70, 80 or 90°C) and a second phase in which the process temperature value is maintained for the whole duration of the thermal treatment (3 hours).

For the assessment of the technical feasibility of this scenario, we calculated the flow rate of thermal pre-treated secondary sludge that, after mixing with primary sludge (TS 3.5%, at ambient temperature), was able to maintain the resulting mix (primary sludge plus secondary sludge) at the process temperature value (38°C) by offsetting the thermal losses with the outside.

3 Results and discussion

With reference to the present scenario for the management of primary and secondary sludge, the main outcomes from the energy balance are listed in Table 1. The reported figures refer to one digester for both primary and secondary sludge.

Table 1: Energy balance for primary and secondary sludge digestion in the present scenario.

	Primary sludge	Secondary sludge
Specific CH_4 production (Nm^3/kgVS)	0.385	0.167
Produced CH_4 (Nm^3/h)	174.4	75.6
Produced energy (MJ/h)	6,257	2,714
Produced heat (MJ/h)	2,653	1,151
Produced electricity (MJ/h)	2,609	1,132

The amount of heat necessary to warm the sludge until the process temperature and offset the heat losses through the digester walls was equal to about 2,425 MJ/h as yearly average. The balance between the heat produced from the AD process and the heat necessary to sustain the process is detailed for both primary and secondary sludge, month by month, in Figure 2. The positive values found for secondary sludge indicated that energy from another source (combustion of methane taken from the external gas supply) was necessary to keep the system in the desired conditions. On the other hand, the negatives values found for primary sludge indicated that some extra thermal energy was available for the plant need.

From the outcomes of the energy balance, an economic assessment of the whole AD process, involving both primary and secondary sludge, may be performed. This assessment must take into account the price of the methane employed as an auxiliary fuel, taken from the external gas supply, equal to 0.40 €/Sm^3 and the revenue from the electricity selling, equal to the sum of the electricity price, 0.14 €/kWh and green certificates, 0.077 €/kWh (data from Electrical Service Company), for a total of 0.217 €/kWh.

The economic value of the electricity produced from the AD of primary sludge (hourly basis, one digester) was 157.2 €/h. For the secondary sludge the economic value from the selling of electricity would be of 68.2 €/h (hourly basis, one digester), but from this value the charge for the auxiliary fuel purchase has to be deducted. The net economic value, as a yearly average, from the selling of electricity generated from the AD of secondary sludge was then equal to about 55 €/h.

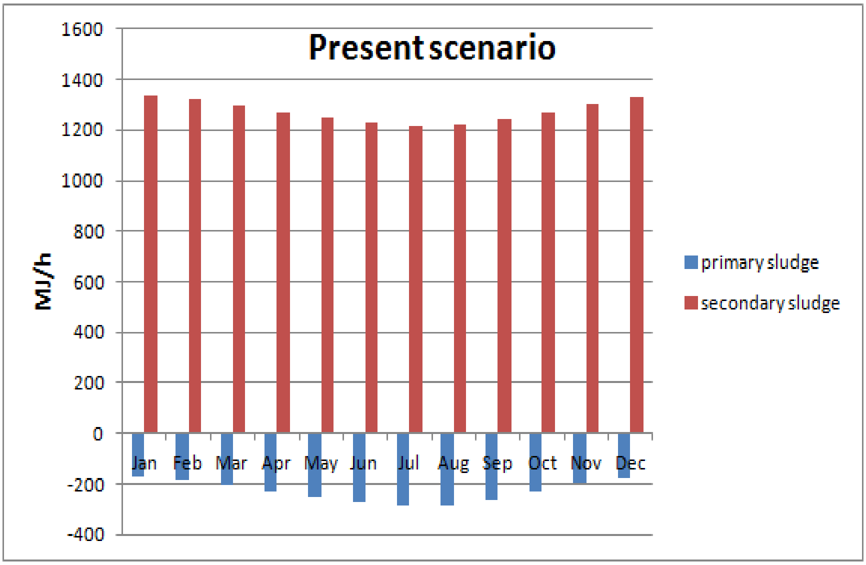

Figure 2: Comparison between the heat produced from the AD process and the heat necessary to sustain the process, month by month.

To conclude, for the present scenario of sludge management, in which 2.5 digesters are employed for the AD of primary sludge and the remaining 2.5 digesters for the AD of secondary sludge, the outcome of the economical assessment was positive, by returning a total revenue of 530 €/h. However, it has to be taken into account that the whole system was not able to completely sustain by itself, because the heating of secondary sludge to the process temperature required an average consumption of auxiliary fuel of about 35 Sm^3/h (with peaks of 40 Sm^3/h in the winter season).

With reference to the Future scenario 1, the increase in the TS content of primary sludge from 2.75% to 3.50% would determine the reduction in the number of employed digesters from 2.5 to 2. Because the amount of dry matter per hour sent to the AD process did not vary in comparison with the previous scenario, the amount of produced energy (15642 MJ/h – this value may be obtained by multiplying the corresponding value of Table 1 "Produced energy for primary sludge" by 2.5) and produced heat (6632 MJ/h) will be the same. However, the reduction in the number of employed digesters will determine an extra amount of heat (1865 MJ/h as yearly average, in this scenario, vs. 575 MJ/h in the present scenario) not employed for the heating of primary sludge and maintenance of the process temperature in the digesters, that can be destined to the heating of secondary sludge.

The results of the energy balance carried out on the AD of secondary sludge only (TS from 3.50% to 8%, with increases of 0.5%) are shown in Table 2.

For the AD process of the secondary sludge, from 1 to 2 digesters were required depending on the achieved TS content. The balance between the produced heat and the heat necessary to warm the sludge and maintain the required temperature (38°C) into the digesters was negative (that is some extra thermal energy was available for plant requirements) when the TS content was of more than 6%.

The results of the combination of primary (TS 3.50%) and secondary sludge (TS from 3.50% to 8%, with increases of 0.5%) are detailed in Table 3. The total number of digesters necessary for the stabilization of primary and secondary sludge ranged from 3 to 4, depending on the TS content achieved for the secondary sludge (the main hypothesis that underwent this scenario was the TS content of primary sludge equal to 3.5% in all cases). The balance between the produced heat and the heat necessary to warm the sludge and keep the temperature into the digesters to the required value for mesophilic conditions was zero when the TS content was approaching 4%.

The implementation of this scenario that plans the employment of all gravity devices available in the WWTP for thickening of primary sludge until 3.50% TS content and the acquisition of dynamic thickeners to devote to secondary sludge only, may guarantee a total revenue of about 564 €/h from the selling of the produced electricity, provided the achievement for secondary sludge of TS content of 4%. The comparison between the Future scenario 1 and the present scenario returned a higher revenue (564 €/h vs. 530 €/h) from the selling of electricity. Moreover the conditions that underwent this scenario were able to guarantee the complete energetic sustainability of the process.

Table 2: Results of the energy balance and economical assessment carried out on the AD of secondary sludge only (TS 3.5–8%).

TS amount (%), secondary sludge	3.5	4	5	5.5	6	6.5	7	8
Sludge flow rate (m^3/h)	46.2	40.4	32.4	29.4	27.0	24.9	23.1	20.2
Number of employed digesters	2	2	2	2	2	1	1	1
Sludge flow rate fed to one digester (m^3/h)	23.1	20.2	16.2	14.7	13.5	24.9	23.1	20.2
HRT (days)	17.3	19.8	24.7	27.2	29.7	16.1	17.3	19.8
Produced CH_4 (Nm^3/h)	189.1	189.1	189.1	189.1	189.1	189.1	189.1	189.1
Produced heat (MJ/h)	2877	2877	2877	2877	2877	2877	2877	2877
Required heat (MJ/h)	4767	4211	3432	3149	2913	2555	2383	2105
Balance (MJ/h)*	1890	1334	555	272	36	-322	-494	-772
Produced electricity (MJ/h)	2827	2827	2827	2827	2827	2827	2827	2827
Revenue (€/h)**	143.5	151.5	162.6	166.7	169.7	170.5	170.5	170.5

*Positive values indicate that energy from an auxiliary source is necessary to keep the system in the desired conditions. Negative values indicate that extra thermal energy is available. **As a yearly average.

With reference to the Future scenario 2, the main outcomes of the energy balance are detailed in Table 4.

The outcomes given back from the energy assessment showed that for the considered conditions (i.e. flow rate of thermal pre-treated secondary sludge that, after mixing with primary sludge, was able to maintain the resulting mix at the process temperature value into the digesters, 38°C, by offsetting the thermal losses with the outside) the balance between the heat necessary to maintain the system at the process temperature and the heat generated from the burning of the produced biogas was negative, that is extra thermal energy was available for plant requirements.

From this starting condition, other calculations may be done in order to search for the condition in which the balance was equal to zero, that is all the generated heat was employed for the maintenance of the AD process. For each pre-treatment temperature value, the main features of the researched condition are detailed in Table 5.

Table 3: Results of the energy balance and economical assessment carried out on the whole system (AD of primary, TS 3.5%, and secondary sludge, TS 3.5–8%).

TS amount (%), secondary sludge	3.5	4	4.5	5	6	7	8
Number of employed digesters	4	4	4	4	4	3	3
Produced CH_4 (Nm^3/h)	625.1	625.1	625.1	625.1	625.1	625.1	625.1
Produced heat (MJ/h)	9509	9509	9509	9509	9509	9509	9509
Required heat (MJ/h)	9534	8977	8545	8199	7679	7150	6872
Balance (MJ/h)*	25	-532	-964	-1310	-1830	-2359	-2637
Produced electricity (MJ/h)	9345	9345	9345	9345	9345	9345	9345
Revenue (€/h)**	562.8	563.7	563.7	563.7	563.7	563.7	563.7

*Positive values indicate that energy from an auxiliary source is necessary to keep the system in the desired conditions. Negative values indicate that extra thermal energy is available. **As a yearly average.

Table 4: Main outcomes of the energy balance carried out on the mix made of primary sludge (TS 3.50%) and thermal pre-treated secondary sludge.

Pre-treatment temperature (°C)	70	80	90
Minimum flow rate (m^3/h, secondary sludge)	39.7	30.3	23.4
Heat from the digester to the outside, maximum value on yearly basis (MJ/h)	220.5	220.5	220.5
Number of employed digesters	4	4	3
HRT (days)	18.6	21.0	17.3
Maximum TS content (%)	4.07	5.34	6.90
Required heat (MJ/h)	9146	7894	7357
Produced heat (MJ/h)	10105	10352	10412
Balance (MJ/h)*	-959	-2458	-3055
Increased revenues from electricity (€/h)	35.3	49.9	53.5

*Negative values indicate that extra thermal energy is available.

Table 5: Main outcomes of the energy balance carried out on the mix made of primary sludge (TS 3.50%) and thermal pre-treated secondary sludge – balance between the produced heat and the required heat equal to zero.

Pre-treatment temperature (°C)	70	80	90
Minimum flow rate (m^3/h, secondary sludge)	43.9	38.1	33.2
Heat from the digester to the outside, maximum value on yearly basis (MJ/h)	220.5	220.5	220.5
Number of employed digesters	4	4	4
HRT (days)	17.8	19.0	20.2
Maximum TS content (%)	3.69	4.25	4.88
Required heat (MJ/h)	10105	10352	10412
Increased revenues from electricity (€/h)°	35.3	49.9	53.5

°With respect to the present scenario.

The results of Table 5 demonstrate that if all the heat generated by burning biogas was transferred to the secondary sludge through heat exchangers, a TS content of 3.70% was enough to make the thermal pre-treatment at 70°C independent of the employment of an auxiliary fuel. The required TS content for secondary sludge rose to 4.25% and 4.9% for pre-treatment temperatures respectively of 80 and 90°C.

Limitations in the implementation of the Future scenario 2 could derive from the difficulty for the thickened sludge, due to its rheology, to flow into the heat exchangers.

4 Conclusions

The implementation of traditional or innovative processes for the possible improvement in the management of sludge in existing WWTPs has to be subjected to careful technical and economical evaluations. This paper provides a comparison between the present management of primary and secondary sludge in a large WWTP (more than 2 million of equivalent inhabitants) and two possible new solutions that plan the thickening of sludge or the combination of thickening of both types of sludge and low temperature thermal pretreatment of secondary sludge.

For the present scenario of sludge management, in which 2.5 digesters are employed for the AD of primary sludge (TS 2.75%) and the remaining 2.5 digesters for the AD of secondary sludge (TS 2.75%), the outcome of the economical assessment returns a total revenue of 530 €/h. However, it has to be noted that the whole system is not able to completely sustain by itself, because the heating of secondary sludge to the process temperature requires an average consumption of auxiliary fuel of about 35 Sm^3/h (with peaks of 40 Sm^3/h in the winter season).

With reference to the Future scenario 1, the increase in the TS content of primary sludge from 2.75% to 3.50%, obtained by destining all the gravity devices available in the WWTP to primary sludge only, would determine the reduction in the number of employed digesters from 2.5 to 2. The total number of digesters necessary for the stabilization of primary and secondary sludge ranges from 3 to 4, depending on the TS content achieved for secondary sludge. The balance between the produced heat and the heat necessary to warm the sludge and keep the temperature into the digesters to the required value for mesophilic conditions is zero when the TS content is approaching to 4%. The implementation of this scenario may guarantee a total revenue of about 564 €/h from the selling of the produced electricity and a complete energetic sustainability of the process. However, the evaluation of the performances of the thickening devices for both primary and secondary sludge is still under consideration.

The calculations done for the technical and economical assessment of the Future scenario 2 demonstrate that the total number of digesters necessary for the stabilization of primary and secondary sludge is 4 and a TS content of 3.70% in secondary sludge is enough to make the thermal pre-treatment at 70°C independent of the employment of an auxiliary fuel, provided that all the heat generated by burning biogas is transferred to the secondary sludge through heat exchangers. A TS content of about 5% in secondary sludge is necessary for the complete sustainability of the system if 90°C is chosen as temperature for the pre-treatment.

The implementation of this last scenario may guarantee, other than the complete energetic sustainability of the process, total revenues from the selling of the electricity that are increased of amount ranging from 35 to 53 €/h, depending on the pre-treatment condition chosen for the management of the process, with respect to the present scenario.

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