Comparison of the Mesophilic and Thermophilic Anaerobic Sludge Digestion from an Energy Perspective

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ABSTRACT: Anaerobic digestion promotes simultaneous sludge stabilisation and bioenergy generation. Increasing the net energy production would contribute in reducing the energy demand of sewage treatment plants. Thermophilic digestion may be used to upgrade (conventional) mesophilic digestion, a major drawback being increased energy requirements. The objective of this study is to compare the mesophilic and thermophilic sludge digestion from an energy perspective. Data from laboratory-, pilot- and full-scale digesters are used to compare the energy balance and ratio of full-scale systems. The results highlight the importance of sludge characteristics on the effectiveness of the process, and the need to recover energy from digestates in thermophilic digesters. Net energy production is comparable in thermophilic with half the retention time of mesophilic systems (10–15 vs. 20–30 days).

INTRODUCTION

ANAEROBIC digestion enhances simultaneous sludge stabilisation and energy recovery from the biogas produced, in such a way that anaerobic digesters can potentially be "energy-sufficient". Sludge heating accounts for the major energy demand, although electricity is required for sludge pumping and mixing. Energy production is defined by the methane production rate, hence by the organic solids removal; which depends on the substrate biodegradability and process parameters, including temperature, sludge retention time (SRT) and organic loading rate (OLR), amongst others.

Thermophilic anaerobic sludge digestion, in one or two-stage systems, is a successful approach to upgrade (conventional) mesophilic digestion. It increases the reaction rate and enhances pathogen destruction [1]. A major drawback is increased energy consumption. According to Zupančič and Roš (2003) [2], heat requirements in thermophilic digesters are about twice those of mesophilic digesters; but they may be covered by combined heat and power (CHP) generation from the biogas produced and heat recovery from digested sludge. Zábranská *et al.* (2000) [3] reported that heat requirements for two-stage thermophilic digesters are fully covered by increased biogas production; additionally surplus electricity is generated.

Besides temperature considerations, some authors point out the importance of solids concentration in the feed sludge, since dilute sludges (total solids < 4.7%) result in poor biogas production and increased heat requirements [4]. In such a case, digesters may not be able to self-sustain even mesophilic operation [5]. With solids contents above 4 %, mesophilic and thermophilic single-stage digesters should have a positive heat balance, which would be improved by implementing a two-stage hyperthermophilic-thermophilic process (70ºC + 55ºC) [6].

The objective of this study is to compare the mesophilic and thermophilic anaerobic sludge digestion from an energy perspective. To this end, data from laboratory-, pilot- and full-scale sludge digesters are used to estimate energy production and consumption (i.e. energy balance and ratio) of full-scale systems, under a range of operating conditions.

FUNDAMENTALS OF THE ENERGY BALANCE

In anaerobic digesters, organic matter is converted

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into a primary fuel source (biogas). This fuel source may then be converted into usable energy through different processes, including the combustion in boilers or in combined heat and power units. In the present study, the second alternative is considered, resulting in two forms of output energy (electricity and heat).

The anaerobic digesters considered are completely stirred tank reactors (CSTR), which means that input electricity is needed for sludge mixing and pumping. Since sludge digesters operate in the mesophilic (30–40ºC) or thermophilic (50–60ºC) range of temperature, input heat is needed to raise sludge temperature from ambient (0–20 ºC) to process temperature; and to compensate for the heat loss through the walls of the digester and piping. Heat losses depend on the insulation of the tank, the heat transfer coefficient being 1 and 5 W m^{-2} $ºC^{-1}$ with and without insulation, respectively [7].

A schematic diagram of the energy balance in the anaerobic digester considered is shown in Figure 1. The system and energy balance proposed are described in detail by Ferrer et al. (2009) [8].

The energy ratio between output and input energy, electricity or heat, is calculated according to Equations 1 through 3. This value enables to compare the efficiency of different reactors and processes [9, 10].

$$\text{Energy ratio} = \frac{E(\text{output})}{E(\text{input, electricity}) + E(\text{input, heat})} \quad (1)$$

$$\text{Energy ratio} = \frac{E(\text{output, electricity})}{E(\text{input, electricity})} \quad (2)$$

$$\text{Heat ratio} = \frac{E(\text{output, heat})}{E(\text{input, heat})} \quad (3)$$

RESULTS

Process Performance

Tables 1 and 2 summarise results from the literature on the performance of laboratory-, pilot- and full-scale reactors treating sewage sludge. Generally, the comparison of data from different studies is not straightforward due to the variability between operating parameters. Some authors have compared the efficiency of mesophilic and thermophilic reactors operating under the same conditions. Similar results are observed with SRT above 20 days, regardless of process temperature: biogas production rates around 0.3–0.4 m^3_{biogas} m^{-3} d^{-1} and volatile solids (VS) removals around 53% [11, 12]. On the other hand, in thermophilic reactors with low SRT of 15 days biogas production rate is increased by 60% (from 0.36 to 0.6 m^3_{biogas} m^{-3} d^{-1}) and VS removal by 12% (from 41.6 to 46.3%) compared to mesophilic ones with 20 days SRT [13, 14]. At even lower SRT of 10 and 8 days, biogas production rate is 100% and 200% higher in thermophilic compared to mesophilic systems [15]. Therefore, by operating within the thermophilic range of temperature, it is feasible to reduce the SRT, while increasing methane production. Methane content in biogas is 60–70% (Tables 1–2).

Volatile solids removal ranges between 30–60 %. Values below 30% correspond to digesters treating waste activated sludge (WAS), in which gas production rate is also the lowest, below 0.2 m^3_{biogas} m^{-3} d^{-1} [5, 15]. The methane yield is defined by the substrate composition, thus for sludge it should be constant. However, literature results clearly show some variability between 0.1 and to 0.8 m^3_{CH4} kg $VS_{removed}^{-1}$ (Tables 1–2). This is a consequence of sludge heterogeneity, resulting from several factors like the proportion of

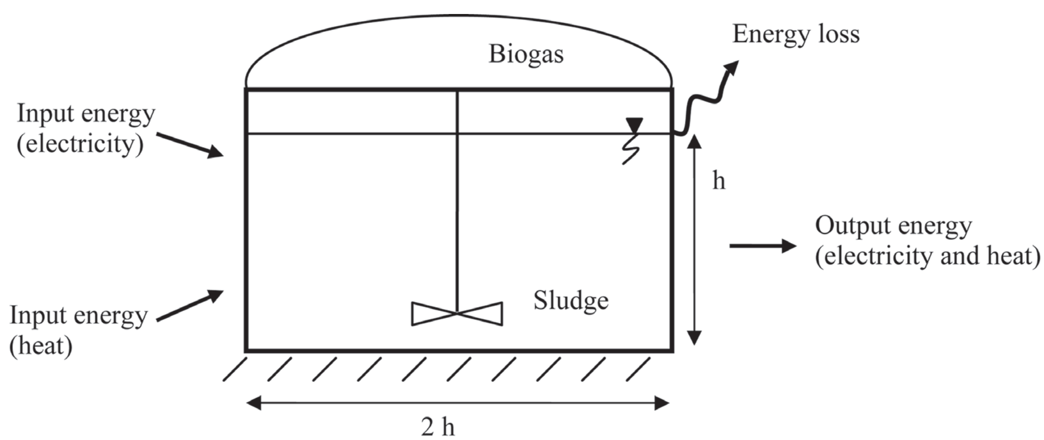

Figure 1. *Schematic diagram of the energy balance of the anaerobic digesters considered.*

primary sludge (PS) and WAS in the mixture, and the SRT of activated sludge units in the case of WAS [5], amongst others. Methane yields are consistently higher with PS (0.4–0.8 m^3_{CH4} kg $VS_{removed}^{-1}$) compared to WAS (0.17–0.43 m^3_{CH4} kg $VS_{removed}^{-1}$) or to the mixture of PS and WAS, both in mesophilic (0.8 vs. 0.3–0.5 m^3CH_4 kg $VS_{removed}^{-1}$) [11, 14, 16] and thermophilic systems (0.4–0.6 m^3_{CH4} kg $VS_{removed}^{-1}$) [13, 14, 17].

Energy Ratios

Theoretical energy ratios of mesophilic and thermophilic single-stage digesters with energy recovery from biogas, and from biogas and digested sludge are shown in Tables 1 and 2, respectively. Values above 1 indicate excess (or net) energy production, while values below 1 indicate insufficient energy generation to fulfil the system's consumption.

According to the results, sludge digestion always yields surplus electricity (electricity ratios > 1). Indeed, output electricity from cogeneration with the biogas produced is much higher than input electricity for sludge pumping and mixing. Electricity ratios basically depend on the methane production rate, and the best ratios are obtained with the lowest SRT and highest OLR (Nº 19–22 in Tables 1 and 2).

On the other hand, heat ratios depend on ambient temperature, and thus on tank insulation. Heat requirements are defined by the difference between influent sludge and process temperature; and heat losses through the walls of the tank by the difference between process and ambient temperature. As shown in Table 1, only mesophilic digesters treating PS and WAS are capable of self-sustaining process temperature with energy recovery from biogas (Nº 13–17 in Table 1). Thermophilic reactors and mesophilic treating WAS do not fulfil the heat demand with residual heat from cogeneration engines (heat ratios < 1).

However, if heat is also recovered from digested sludge by means of a sludge-to-sludge heat exchanger [16], heat ratios increase to values above 1 in digesters treating PS and WAS, both under mesophilic and thermophilic conditions (Nº 13–28 in Table 2). In general, reactors treating WAS are not capable of self-sustaining process temperature in this case either. This suggests that cogeneration is not appropriate when WAS is digested as a sole substrate.

Overall energy ratios are consistently higher for digesters treating PS and WAS, compared to digesters treating only WAS, both under mesophilic and thermophilic conditions (Tables 1 and 2). The proportion between PS and WAS in the mixture may account for the differences between energy ratios of reactors operating at the same temperature, SRT and OLR; but with different sludge composition. Also, long SRT during the activated sludge process decrease WAS biodegradability and specific biogas production. With reduced OLR and specific methane production, even mesophilic temperature cannot be self-sustained, especially during cold seasons [5].

It is important to highlight that most systems operate at low OLR (< 3 kg VS m^{-3} d^{-1}), because the total solids concentration of thickened sludge is generally below 5% (data not shown). However, concentrated sludges result in higher solids destruction and increased methane production rate, while consuming the same input energy for an equal SRT. Indeed, in the survey carried out by Speece (1988) [4], diluted sludges were identified as a major root cause of several negative impacts on digester operation, including reduced SRT, reduced VS destruction, reduced methane generation, reduced alkalinity, increased volumes of digested sludge, increased costs for digested sludge post-treatment and disposal, and increased heating requirements.

Energy Balances

Comparing the energy ratios of mesophilic and thermophilic digesters, similar net energy production is expected from thermophilic digesters with SRT of 10–20 days and mesophilic with SRT of 20 days. Therefore, thermophilic systems can either be smaller (i.e. reactor volume) or have a higher treatment capacity (i.e. sludge flow rate) being as energy efficient as mesophilic ones.

To exemplify this, Figure 2 shows a comparison between mesophilic and thermophilic digesters with the same working volume. In Figure 2(a) the energy balance of a mesophilic reactor treating a sludge flow rate Q (100 m^3 d^{-1}) at 20 days SRT, is plot beside the energy balance of a thermophilic reactor treating a sludge flow rate 2Q (200 m^3 d^{-1}) at 10 SRT. In Figure 2(b), the energy balance of a mesophilic reactor treating a sludge flow rate Q (100 m^3 d^{-1}) at 30 days SRT, is plot beside the energy balance of a thermophilic reactor treating a sludge flow rate 2Q (200 m^3 d^{-1}) at 15 SRT. This enables the comparison between digesters with the same working volume: thermophilic at 10 days SRT vs. mesophilic at 20 days SRT; and thermophilic at 15 days SRT vs. mesophilic at 30 days SRT.

From an energy perspective, thermophilic reactors treating twice the sludge flow rate (2Q) are as efficient as mesophilic reactors (Q), with the same working vol-

Table 1. Energy Ratios for Anaerobic Digesters with Energy Recovery from Biogas.

	Experimental Conditions and Results					100 m^3 sludge d^{-1}		Energy Ratio				Heat Ratio				Electricity Ratio	
Nº	Sludge	T (ºC)	SRT (d)	OLR (kg VS m^{-3} d^{-1})	CH_4 Rate (m^3 CH_4 m^{-3} d^{-1})	V (m^3)	Surface Area (m^2)	Insulated 20ºC	Insulated 0ºC	Non-Insul. 20ºC	Non-Insul. 0ºC	Insulated 20ºC	Insulated 0ºC	Non-Insul. 20ºC	Non-Insul. 0ºC	All	Reference
1	WAS	35	8	–	0.055	800	252	0.22	0.13	0.19	0.11	0.13	0.08	0.11	0.06	**1.30**	[15]
2	WAS	35	10	–	0.057	1,000	293	0.29	0.17	0.24	0.13	0.17	0.10	0.14	0.08	**1.49**	[15]
3	WAS	37.6	21	1.000	0.117	2,100	480	**1.00**	0.63	0.74	0.44	0.60	0.37	0.44	0.25	**3.80**	[5]
4	WAS	38.5	20	0.800	0.046	2,000	465	0.35	0.23	0.27	0.16	0.21	0.13	0.16	0.09	**1.46**	[5]
5	WAS	36	22	0.800	0.098	2,200	495	0.93	0.58	0.70	0.40	0.57	0.34	0.42	0.23	**3.20**	[5]
6	WAS	35	33	0.700	0.052	3,300	649	0.74	0.45	0.53	0.29	0.48	0.27	0.32	0.17	**1.84**	[5]
7	WAS	34.5	37.2	0.530	0.068	3,720	703	**1.10**	0.66	0.77	0.41	0.72	0.40	0.48	0.24	**2.45**	[18]
8	WAS	34	40	1.000	0.026	4,000	738	0.46	0.27	0.32	0.17	0.30	0.17	0.20	0.10	0.94	[5]
9	WAS	55	8	–	0.160	800	252	0.29	0.22	0.24	0.18	0.16	0.13	0.14	0.10	**3.82**	[15]
10	WAS	55	10	–	0.112	1,000	293	0.25	0.19	0.20	0.15	0.14	0.11	0.12	0.09	**2.92**	[15]
11	WAS	55	18	–	0.080	1,800	433	0.31	0.24	0.24	0.17	0.18	0.14	0.13	0.10	**2.51**	[19]
12	PS	55	15	0.693	0.146	1,500	384	0.48	0.37	0.37	0.27	0.27	0.21	0.21	0.15	**4.36**	[17]
13	PS+WAS	35	20	1.140	0.229	2,000	465	**2.14**	**1.30**	**1.63**	0.09	**1.31**	0.76	**1.00**	0.52	**7.36**	[14]
14	PS+WAS	37	20	1.433	0.250	2,000	465	**2.09**	**1.32**	**1.58**	0.92	**1.26**	0.77	0.94	0.53	**8.04**	[11]
15	PS+WAS	37	20	1.380	0.355	2,000	465	**2.96**	**1.87**	**2.25**	**1.30**	**1.79**	**1.09**	**1.33**	0.75	**11.39**	[20]
16	PS+WAS	37	20	1.380	0.385	2,000	465	**3.21**	**2.03**	**2.44**	**1.41**	**1.94**	**1.19**	**1.44**	0.81	**12.36**	[20]
17	PS+WAS	35	27	1.300	0.250	2,700	568	**3.02**	**1.84**	**2.21**	**1.21**	**1.90**	**1.09**	**1.34**	0.70	**8.45**	[12]
18	PS+WAS	43	36	0.442	0.121	3,600	688	**1.27**	0.89	0.88	0.56	0.78	0.52	0.52	0.32	**4.33**	[21]
19	PS+WAS	55	10	3.034	0.400	997	292	0.89	0.69	0.73	0.54	0.51	0.39	0.41	0.30	**10.43**	[22]
20	PS+WAS	55	15	2.063	0.404	1,504	384	**1.32**	**1.02**	**1.03**	0.76	0.76	0.58	0.59	0.43	**12.06**	[21]
21	PS+WAS	55	15	1.519	0.391	1,500	384	**1.28**	**1.00**	**1.00**	0.73	0.73	0.56	0.56	0.41	**11.66**	[14]
22	PS+WAS	55	15	2.190	0.400	1,500	384	**1.31**	**1.01**	**1.02**	0.75	0.75	0.57	0.58	0.42	**11.93**	[13]
23	PS+WAS	55	20	1.870	0.220	2,000	465	0.94	0.72	0.70	0.51	0.54	0.41	0.40	0.29	**7.07**	[12]
24	PS+WAS	55	20	1.433	0.257	2,000	465	**1.09**	0.84	0.82	0.60	0.63	0.48	0.47	0.34	**8.24**	[11]
25	PS+WAS	55	20	1.870	0.260	2,000	465	**1.11**	0.85	0.83	0.61	0.64	0.49	0.47	0.34	**8.35**	[13]
26	PS+WAS	55	27	1.480	0.190	2,700	568	**1.06**	0.82	0.76	0.55	0.62	0.47	0.44	0.31	**6.49**	[13]
27	PS+WAS	55	31	0.643	0.161	3,087	621	**1.01**	0.78	0.71	0.51	0.59	0.45	0.41	0.29	**5.61**	[21]
28	PS+WAS	55	40	0.800	0.170	4,000	738	**1.33**	**1.03**	0.90	0.65	0.79	0.60	0.52	0.37	**6.17**	[13]
29	PS+WAS	55	75	0.420	0.020	7,500	1,122	0.26	0.20	0.16	0.11	0.16	0.12	0.09	0.06	0.77	[13]

Numbers in bold highlight energy ratios ≥ 1.

Table 2. Energy Ratios for Anaerobic Digesters with Energy Recovery from Biogas and Digested Sludge

	Experimental Conditions and Results					100 m^3 sludge d^{-1}		Energy Ratio				Heat Ratio				Electricity Ratio	
[5] Nº	Sludge	T (ºC)	SRT (d)	OLR (kg VS m^{-3} d^{-1})	CH_4 Rate (m^3 CH_4 m^{-3} d^{-1})	V (m^3)	Surface Area (m^2)	Insulated 20ºC	Insulated 0ºC	Non-Insul. 20ºC	Non-Insul. 0ºC	Insulated 20ºC	Insulated 0ºC	Non-Insul. 20ºC	Non-Insul. 0ºC	All	Reference
1	WAS	35	8	–	0.055	800	252	0.84	0.53	0.49	0.26	0.68	0.37	0.33	0.16	0.91	[15]
2	WAS	35	10	–	0.057	1,000	293	**1.03**	0.66	0.59	0.31	0.85	0.46	0.40	0.19	**1.09**	[15]
3	WAS	37.6	21	1.000	0.117	2,100	480	**3.11**	2.05	**1.53**	0.84	**2.64**	**1.47**	1.02	0.51	**3.11**	[5]
4	WAS	38.5	20	0.800	0.046	2,000	465	**1.14**	0.76	0.56	0.31	0.94	0.54	0.37	0.19	**1.19**	[5]
5	WAS	36	22	0.800	0.098	2,200	495	**2.84**	**1.83**	**1.41**	0.74	**2.50**	**1.33**	0.95	0.45	**2.63**	[5]
6	WAS	35	33	0.700	0.052	3,300	649	**1.96**	**1.26**	0.95	0.48	**1.90**	0.96	0.66	0.30	**1.59**	[5]
7	WAS	34.5	37.2	0.530	0.068	3,720	703	**2.77**	**1.77**	**1.33**	0.67	**2.78**	**1.37**	0.94	0.41	**2.15**	[18]
8	WAS	34	40	1.000	0.026	4,000	738	**1.12**	0.71	0.54	0.27	**1.16**	0.56	0.38	0.17	0.84	[5]
9	WAS	55	8	–	0.160	800	252	**1.29**	**1.00**	0.69	0.49	0.85	0.63	0.42	0.29	**2.67**	[15]
10	WAS	55	10	–	0.112	1,000	293	**1.07**	0.82	0.55	0.38	0.71	0.52	0.33	0.23	**2.12**	[15]
11	WAS	55	18	–	0.080	1,800	433	**1.17**	0.89	0.53	0.37	0.81	0.58	0.32	0.22	**2.00**	[19]
12	PS	55	15	0.693	0.146	1,500	384	**1.88**	**1.44**	0.89	0.62	**1.29**	0.93	0.54	0.36	**3.39**	[17]
13	PS+WAS	35	20	1.140	0.229	2,000	465	**6.55**	**4.17**	**3.34**	**1.72**	**5.84**	**3.03**	**2.28**	**1.05**	**5.98**	[14]
14	PS+WAS	37	20	1.433	0.250	2,000	465	**6.61**	**4.33**	**3.29**	**1.78**	**5.63**	**3.10**	**2.20**	**1.08**	**6.53**	[11]
15	PS+WAS	37	20	1.380	0.355	2,000	465	**9.37**	**6.13**	**4.67**	**2.52**	**7.99**	**4.39**	**3.12**	**1.53**	**9.26**	[20]
16	PS+WAS	37	20	1.380	0.385	2,000	465	**10.17**	**6.65**	**5.06**	**2.73**	**8.66**	**4.76**	**3.38**	**1.66**	**10.04**	[20]
17	PS+WAS	35	27	1.300	0.250	2,700	568	**8.49**	**5.42**	**4.17**	**2.13**	**7.93**	**4.05**	**2.88**	**1.31**	**7.23**	[12]
18	PS+WAS	43	36	0.442	0.121	3,600	688	**3.67**	**2.57**	**1.60**	0.96	**3.05**	**1.85**	**1.04**	0.58	**3.79**	[21]
19	PS+WAS	55	10	3.034	0.400	997	292	**3.82**	**2.93**	**1.96**	**1.37**	**2.55**	**1.86**	**1.19**	0.80	**7.58**	[22]
20	PS+WAS	55	15	2.063	0.404	1,504	384	**5.22**	**3.98**	**2.47**	**1.70**	**3.56**	**2.57**	**1.49**	**1.00**	**9.39**	[21]
21	PS+WAS	55	15	1.519	0.391	1,500	384	**5.04**	**3.85**	**2.38**	**1.65**	**3.44**	**2.48**	**1.44**	0.97	**9.07**	[14]
22	PS+WAS	55	15	2.190	0.400	1,500	384	**5.16**	**3.94**	**2.44**	**1.68**	**3.52**	**2.54**	**1.48**	**1.00**	**9.28**	[13]
23	PS+WAS	55	20	1.870	0.220	2,000	465	**3.45**	**2.63**	**1.55**	**1.06**	**2.41**	**1.72**	0.94	0.62	**5.74**	[12]
24	PS+WAS	55	20	1.433	0.257	2,000	465	**4.03**	**3.07**	**1.80**	**1.24**	**2.81**	**2.01**	**1.09**	0.73	**6.70**	[11]
25	PS+WAS	55	20	1.870	0.260	2,000	465	**4.08**	**3.11**	**1.83**	**1.26**	**2.84**	**2.04**	**1.11**	0.74	**6.79**	[13]
26	PS+WAS	55	27	1.480	0.190	2,700	568	**3.61**	**2.75**	**1.54**	**1.05**	**2.58**	**1.83**	0.94	0.62	**5.49**	[13]
27	PS+WAS	55	31	0.643	0.161	3,087	621	**3.31**	**2.51**	**1.38**	0.94	**2.40**	**1.69**	0.84	0.56	**4.83**	[21]
28	PS+WAS	55	40	0.800	0.170	4,000	738	**4.07**	**3.09**	**1.63**	**1.11**	**3.02**	**2.12**	**1.00**	0.66	**5.46**	[13]
29	PS+WAS	55	75	0.420	0.020	7,500	1,122	0.66	0.50	0.25	0.17	0.53	0.36	0.15	0.10	0.72	[13]

Numbers in bold highlight energy ratios ≥ 1.

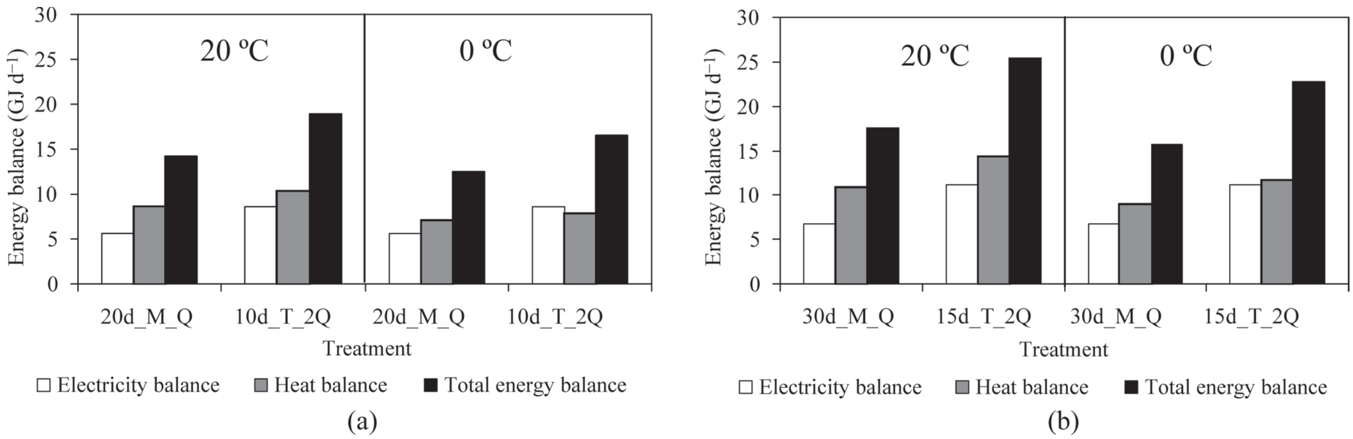

***Figure 2.** Electricity, heat and total energy balance of anaerobic digesters treating 100 m^3_{sludge} d^{-1} (Q) at SRT of 20 or 30 days under mesophilic conditions; and treating 200 m^3_{sludge} d^{-1} (2Q) at SRT of 10 or 15 days under thermophilic conditions. Energy is recovered from the biogas and digested sludge. The digesters are insulated and ambient temperature is 0ºC or 20ºC.*

ume. Notice that in this example insulated digesters with energy recovery from biogas and digested sludge are considered.

CONCLUSIONS

The energy assessment of the anaerobic sludge digestion highlights the following conclusions:

1. Anaerobic digesters are net electricity producers, since output electricity from cogeneration with biogas is higher than input electricity for sludge pumping and mixing. The best results are obtained with low SRT (10–15 days) and high OLR (2–3 kg VS m^{-3} d^{-1}).
2. Residual heat from cogeneration fulfils the heat requirements of mesophilic digesters treating mixed PS and WAS. Thermophilic digesters self-sustain process temperature with additional heat recovery from digested sludge.
3. Digesters treating WAS as a sole substrate are not capable of self-sustaining process temperature with residual heat from cogeneration. In this case, cogeneration with biogas does not seem a good option.
4. The energy efficiency increases with the ORL, resulting from decreased SRT and concentrated feed sludge. Thus, increasing the solids concentration of thickened sludge entering digestion is a way of increasing the net energy production.
5. From an energy perspective, the performance of thermophilic digesters working with half the SRT (10–15 days) of mesophilic digesters (20–30 days) is comparable. In this way, it is possible to reduce the size or increase the treatment capacity of the system, with subsequent savings in terms of sludge and wastewater treatment costs.

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