Electronic Supplementary Material (ESI) for Environmental Science: Water Research & Technology.

Supplementary information

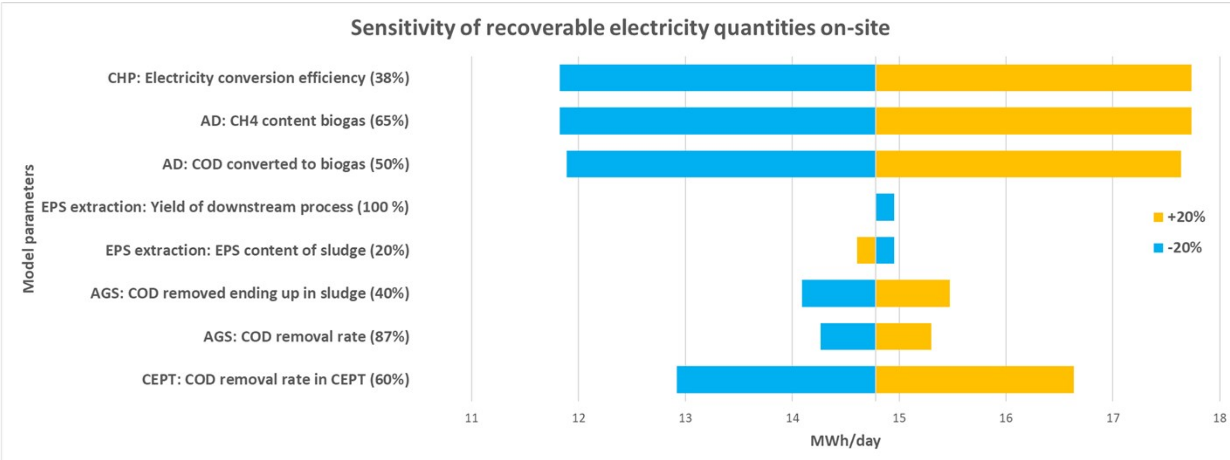
Article: Exploring resource recovery potentials for the aerobic granular sludge process by mass and energy balances - Energy, biopolymer and phosphorous recovery from municipal wastewater

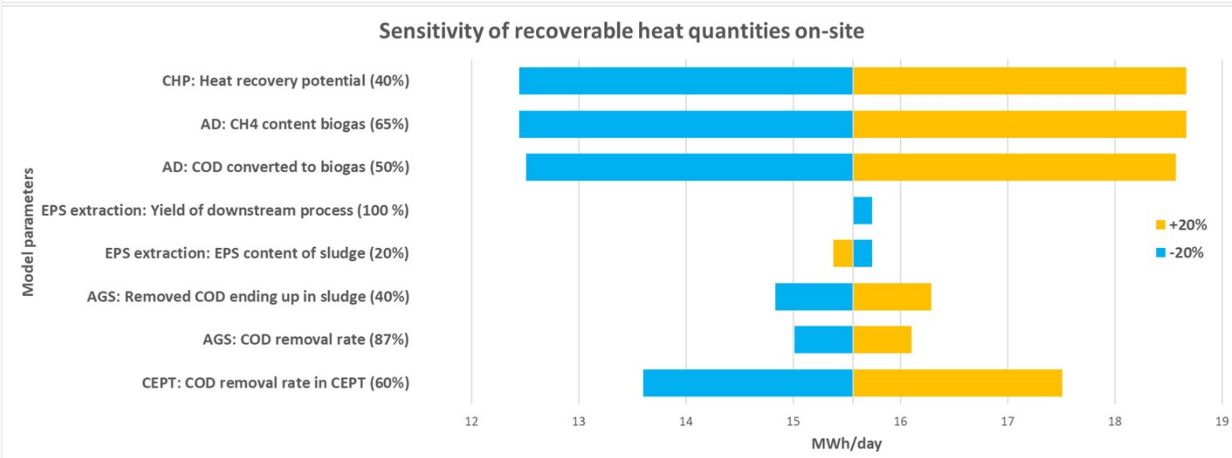
Model parameters

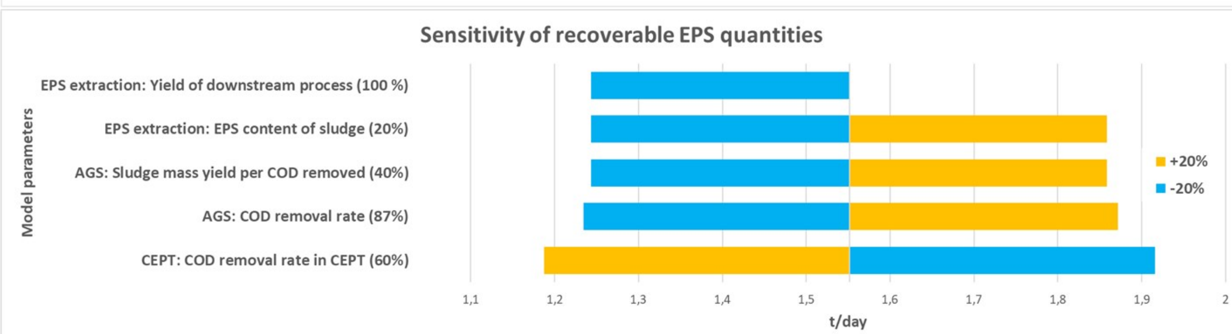
Influent			
Average flow rate	64400	m^3/d	Personal communication
COD	729,8	mg/l	Personal communication
BOD	287,3	mg/l	Personal communication
TSS	314,4	mg/l	Personal communication
TKN	60,6	mg/l	Personal communication
NH_4-N	70	%/TKN	(Hartley, 2013)
Organic-N	30	%/TKN	(Hartley, 2013)
P-total	8,4	mg/l	Personal communication
Ortho-P	67	%/P-total	(Henze and Comeau, 2008)
Organic-P	33	%/P-total	(Henze and Comeau, 2008)
Fe total	1,0	mg/l	(Wilfert et al., 2015)
Fe^{3+} share	100	%	(Wilfert et al., 2016)
Fe^{3+} forming vivianite	100	%	(Wilfert et al., 2016)
Energy content COD	17,8	kJ/g COD	(Heidrich et al., 2011)
Coarse screen			
No impacts on any relevant flows are assumed			
CEPT			
Coagulant	Polymer		(Klute and Hahn, 1994)
COD removal	60	%	(Wan et al., 2016)
TKN removal in conventional primary settler (with 40% COD removal, no coagulant)	16,4	%	based on (Hartley, 2013)
P-total removal in conventional primary settler (with 40% COD removal, no coagulant)	11	%	(Cornel and Schaum, 2009)
Effect of coagulation compared to conventional primary settler with 40% COD removal:			
TKN effluent concentration	-9,4	%	based on (Klute and Hahn, 1994)
P-total effluent concentration	-33,3	%	based on (Klute and Hahn, 1994)
AGS			
COD oxidized	60	%	(Winkler, 2012)
COD into sludge	40	%	(Winkler, 2012)
COD removal rate	87	%	based on (Pronk et al., 2015)
Sludge mass yield per COD removed	40	%	Wan et al. 2016
TKN removal rate	94	%	(de Kreuk et al., 2005)
TKN into sludge	20	%	(Matassa et al., 2015)
Organic-N converted to NH_4	90	%	(Makinia et al., 2011)
Organic-P removal	87	%	based on (Pronk et al., 2015)

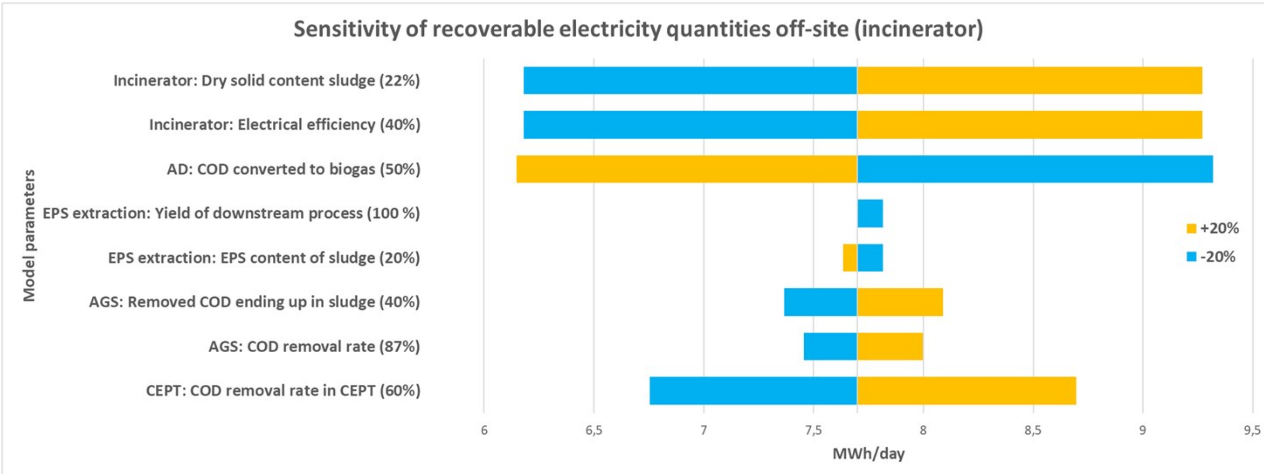
Ortho-P removal	91	%	based on (Pronk et al., 2015)
Organic-P converted to PO_4	90	%	(Krishnaswamy et al., 2011)
Fe-P removed with sludge	100	%	own assumption
EPS extraction			
EPS content of sludge	20	%	(van der Roest et al., 2015)
Yield of downstream process	100	%	own assumption
C content EPS	47,05	wt%	(Felz et al., 2019)
N content EPS	7,61	wt%	(Felz et al., 2019)
P content EPS	2,92	wt%	(Felz et al., 2019)
Anaerobic digester			
COD converted to biogas	50	%	(Khiewwijit et al., 2016)
CH_4 content biogas	65	%	(Frijns et al., 2013)
Producible amount of CH_4	0,35	Nm^3 CH_4/kg COD	(Frijns et al., 2013)
Calorific value CH_4	35,9	MJ/Nm3	(Frijns et al., 2013)
Organic-N converted to NH_4	100	%	(Mehta et al., 2015)
Organic-P converted to PO_4	100	%	(Mehta et al., 2015)
Combined heat and power			
Electricity conversion efficiency	38	%	(Verstraete and Vlaeminck, 2011)
Heat recovery potential	40	%	(Verstraete and Vlaeminck, 2011)
Decanter centrifuge			
COD ending in liquid fraction	10	%	(Andreoli et al., 2007)
NH_4-N ending in liquid fraction	13	%	(Khiewwijit et al., 2016)
PO_4-P ending in liquid fraction	13	%	(Khiewwijit et al., 2016)
Incinerator			
Energy content COD	0,0178	kJ/mgCOD	(Heidrich et al., 2011)
Electrical efficiency	40	%	(Faaij, 2006)
Dry solid content sludge	22	%	(Frijns et al., 2013)
P recovery rate from ash	80	%	(Lundin et al., 2004)
Struvite crystallization			
PO_4 crystallization rate	80	%	(Martí et al., 2010)
Required molecular ratio of (Mg^{2+}:NH4$^+$:PO_4^{3-})	1:1:1		(Verstraete et al., 2009)
O_2 consumption AGS reactor			
COD removal rate	87	%	(Pronk et al., 2015)
COD into CO_2	60	%	(Winkler, 2012)
NH_4 per TKN in	70	%	(Hartley, 2013)
Organic-N per TKN in	30	%	(Hartley, 2013)
Organic-N hydrolyzed to NH_4	90	%	(Makinia et al., 2011)
NH_4 removal rate	94	%	(de Kreuk et al., 2005)
NH_4 uptake in AGS	20	%	(Matassa et al., 2015)

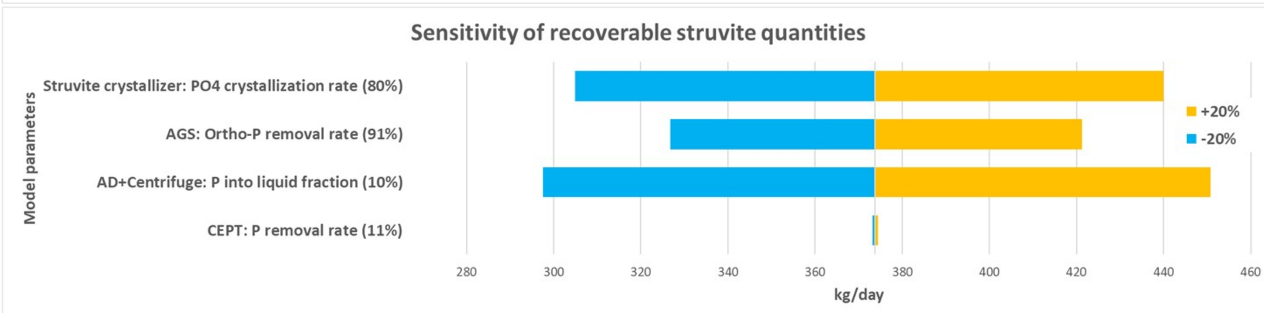
Sensitivity analysis

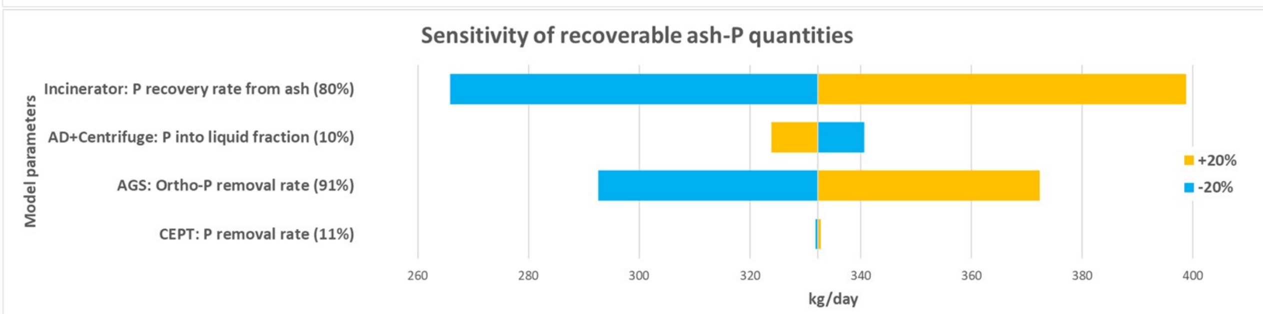












Effluent qualities

All designs would meet the Dutch legal effluent requirements.

Pollutant	Legal	Design					
mg/l	(Pronk et al., 2015)	Status quo	AD	AD/CEPT	EPS	AD+EPS	AD/CEPT+EPS
COD	125	92,3	95,7	44,0	92,3	94,8	43,6
P-Total	1	0,7	0,8	0,5	0,7	0,8	0,5
TKN	7	5,3	5,9	4,6	5,9	5,9	4,6

Biodegradable-COD:N ratio AGS reactor

To ensure a sufficient denitrification in the AGS reactor it is important to maintain a high enough bCOD:N ratio. During CEPT ca. 60% bCOD (Wan et al., 2016) but only ca. 25% TKN (Hartley, 2013; Klute and Hahn, 1994) can be assumed to be removed before AGS treatment. Therefore, it needs to be checked if sufficient bCOD is still present in the AGS reactor. Assuming that the total influent-COD consists to 75% of biodegradable COD (bCOD) (Hartley, 2013; Pasztor et al., 2009), a bCOD:N ratio of 4,9 can be expected in those designs with CEPT integration.

References

Andreoli, C.V., Sperling, M. von, and Fernandes, F. (2007). Sludge treatment and disposal (London: IWA Publ).

Cornel, P., and Schaum, C. (2009). Phosphorus recovery from wastewater: needs, technologies and costs. Water Sci. Technol. *59*, 1069–1076.

Faaij, A.P.C. (2006). Bio-energy in Europe: changing technology choices. Energy Policy *34*, 322–342.

Felz, S., Loosdrecht, M.C.M. van, and Lin, Y. (2019). Structural extracellular polymeric substances from aerobic granular sludge.

Frijns, J., Hofman, J., and Nederlof, M. (2013). The potential of (waste)water as energy carrier. Energy Convers. Manag. *65*, 357–363.

Hartley, K. (2013). Tuning biological nutrient removal plants (London: IWA Publ).

Heidrich, E.S., Curtis, T.P., and Dolfing, J. (2011). Determination of the Internal Chemical Energy of Wastewater. Environ. Sci. Technol. *45*, 827–832.

Henze, M., and Comeau, Y. (2008). Wastewater Characterization. In Biological Wastewater Treatment: Principles, Modelling and Design, (London: IWA Pub), p.

Khiewwijit, R., Rijnaarts, H.H.M., Keesman, K.J., and Temmink, B.G. (2016). New wastewater treatment concepts towards energy saving and resource recovery.

Klute, R., and Hahn, H.H. (1994). Chemical Water and Wastewater Treatment III (Berlin, Heidelberg: Springer Berlin Heidelberg).

de Kreuk, M.K., Heijnen, J.J., and van Loosdrecht, M.C.M. (2005). Simultaneous COD, nitrogen, and phosphate removal by aerobic granular sludge. Biotechnol. Bioeng. *90*, 761–769.

Krishnaswamy, U., Muthuchamy, M., and Perumalsamy, L. (2011). Biological removal of phosphate from synthetic wastewater using bacterial consortium. Iran. J. Biotechnol. *9*, 37–49.

Lundin, M., Olofsson, M., Pettersson, G.., and Zetterlund, H. (2004). Environmental and economic assessment of sewage sludge handling options. Resour. Conserv. Recycl. *41*, 255–278.

Makinia, J., Pagilla, K., Czerwionka, K., and Stensel, H.D. (2011). Modeling organic nitrogen conversions in activated sludge bioreactors. Water Sci. Technol. *63*, 1418–1426.

Martí, N., Pastor, L., Bouzas, A., Ferrer, J., and Seco, A. (2010). Phosphorus recovery by struvite crystallization in WWTPs: Influence of the sludge treatment line operation. Water Res. *44*, 2371–2379.

Matassa, S., Batstone, D.J., Hülsen, T., Schnoor, J., and Verstraete, W. (2015). Can Direct Conversion of Used Nitrogen to New Feed and Protein Help Feed the World? Environ. Sci. Technol. *49*, 5247–5254.

Mehta, C.M., Khunjar, W.O., Nguyen, V., Tait, S., and Batstone, D.J. (2015). Technologies to Recover Nutrients from Waste Streams: A Critical Review. Crit. Rev. Environ. Sci. Technol. *45*, 385–427.

Pasztor, I., Thury, P., and Pulai, J. (2009). Chemical oxygen demand fractions of municipal wastewater for modeling of wastewater treatment. Int. J. Environ. Sci. Technol. *6*, 51–56.

Pronk, M., de Kreuk, M.K., de Bruin, B., Kamminga, P., Kleerebezem, R., and van Loosdrecht, M.C.M. (2015). Full scale performance of the aerobic granular sludge process for sewage treatment. Water Res. *84*, 207–217.

van der Roest, H., van Loosdrecht, M., and Langkamp, E.J. (2015). Recovery and reuse of alginate from granular Nereda sludge. Water21 Mag. *April 2015*.

Verstraete, W., and Vlaeminck, S.E. (2011). ZeroWasteWater: short-cycling of wastewater resources for sustainable cities of the future. Int. J. Sustain. Dev. World Ecol. *18*, 253–264.

Verstraete, W., Van de Caveye, P., and Diamantis, V. (2009). Maximum use of resources present in domestic “used water.” Bioresour. Technol. *100*, 5537–5545.

Wan, J., Gu, J., Zhao, Q., and Liu, Y. (2016). COD capture: a feasible option towards energy self-sufficient domestic wastewater treatment. Sci. Rep. *6*.

Wilfert, P., Kumar, P.S., Korving, L., Witkamp, G.-J., and van Loosdrecht, M.C.M. (2015). The Relevance of Phosphorus and Iron Chemistry to the Recovery of Phosphorus from Wastewater: A Review. Environ. Sci. Technol. *49*, 9400–9414.

Wilfert, P., Mandalidis, A., Dugulan, A.I., Goubitz, K., Korving, L., Temmink, H., Witkamp, G.J., and Van Loosdrecht, M.C.M. (2016). Vivianite as an important iron phosphate precipitate in sewage treatment plants. Water Res. *104*, 449–460.

Winkler, M.-K.H. (2012). Magic granules (S.l.: s.n.).