Heat recovery during treatment of highly concentrated wastewater: economic evaluation and influencing factors

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ABSTRACT

This paper assesses the economics of heat recovery from biological wastewater treatment plants (WWTPs) treating concentrated wastewater, as higher concentrations result in higher heat generation in the treatment basin. A heat balance model has been applied to calculate the amount of recoverable heat from the system and the effect of the heat extraction capacity on the economics of a heat pump installation, evaluated using the internal rate of return. A sensitivity analysis has been performed to evaluate the effect of several parameters on the economics of heat recovery in this type of WWTP: the electricity price, the price of the fuel substituted by heating savings, the investment costs, the coefficient of performance (COP) and the amount of heat extracted from the system. It was calculated that the heat pump capacity has to be high enough to recover a significant amount of heat, but low enough to improve the economics of the system. The economic performance of the system is very dependent on the energy prices of both electrical power to run the heat pump and the fuel (heat) cost substituted by the heat pump.

Key words | energy efficiency, heat pump, resource recovery, wastewater treatment

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INTRODUCTION

Heat is an important resource that is generated in wastewater treatment plants (WWTPs) during biological conversions and can be extracted from these systems. Heat generation increases with increasing biological conversions, so wastewater with high concentrations of organic matter and/or nitrogen show a higher potential for recovery. Nevertheless, WWTPs seldom operate at temperatures above 35 °C, which is rather low for practical heat recovery applications. In order to increase the temperature of the available heat and therefore its usefulness, heat recovery from biological treatment processes can be performed with heat pumps (Hughes 1984; Svoboda & Evans 1987). The extracted heat could fulfill diverse requirements, such as those from hospitals, retirement homes, or greenhouses, which require auxiliary heating during the whole year.

This study addresses the economic evaluation of heat recovery by means of a heat pump from a nitrification/denitrification basin of a WWTP treating the liquid fraction of raw manure after centrifugation. This type of treatment is one of the most widely applied management options for excess manure in nitrate-vulnerable zones, as it helps to prevent marine eutrophication (Corbala-Robles *et al.* 2018). In Flanders, Belgium, 80 out of 120 installations in 2015 applied this technique for manure treatment (VLM 2015). Furthermore, this treatment system can reach high temperatures during the summer, requiring cooling. This makes this a strong example to evaluate the possibility of direct heat recovery from the basin. The theoretical heat recovery potential from the system was calculated from a heat balance model set up in a previous study (Corbala-Robles *et al.* 2016). In this study, the economic feasibility of heat recovery was evaluated. A sensitivity analysis was performed in order to evaluate the effect of electricity and fuel prices and the investment costs and coefficient of performance (COP) of the heat pump on the economics.

MATERIALS AND METHODS

Heat recovery potential

A prerequisite to determine the theoretical heat recovery potential is a heat balance model for temperature prediction. The heat balance model described by Corbala-Robles *et al.*

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(2016) has been implemented to calculate the theoretical heat recovery over a one-year period ($Q_{extracted}$; $MWh_{th}.year^{-1}$) from a basin performing denitrification/nitrification to treat the liquid fraction of manure after centrifugation (Table 1). This heat balance model allows for dynamic basin temperature prediction. Changes in weather conditions (e.g. cloud cover, solar radiation and air temperature) were taken from the typical reference year dataset from Belgium (Dogniaux *et al.* 1978). Influent temperature, ground temperature and other input parameters have been accounted for on a half-hour basis. The time step considered in the integration was half an hour.

The recoverable heat was defined as the surplus heat that can be extracted from the system while maintaining a critical temperature, here assumed as $T_{crit} = 20\ °C$, provided enough heat was produced. The critical temperature must be chosen to be as low as possible to increase the amount of extractable heat but high enough to maintain biological activity and a good removal of nutrients (Evans *et al.* 1982). The direct effect of temperature on biological activity goes beyond the scope of this paper. Instead, the system was assumed to maintain its performance (90% organic carbon removal efficiency and 88% nitrogen removal efficiency, see Table 1). This assumption is reasonable given the system's long solids retention time (i.e. SRT > 25 days), allowing the bacteria sufficient time to degrade the influent nutrients and sustain growth. The minimum SRT to achieve nitrification at, for example, 14 °C is approximately 6 days (Ekama & Wentzel 2008).

Table 1 | Basin and average influent characteristics for the plant under study

Characteristic	Value	Unit
Basin volume	2,846	m^3
Basin surface area	547	m^2
Basin depth	5.2	m
Wall thickness	0.3	m
Amount of aerators	68	–
Aerator power	809	W
Aerator efficiency	75	%
Influent	57.9	$m^3.d^{-1}$
Aeration flow	1,360	$m^3.h^{-1}$
Organic carbon influent concentration	30	kg $COD.m^{-3}$
Organic carbon removal efficiency	90	%
Nitrogen influent concentration	4.5	kg NH_4-$N.m^{-3}$
Nitrogen removal efficiency	88	%

Heat pump characteristics

For the economic analysis of the heat pump installation, three heat pump characteristics must be specified: (1) the heat delivery capacity (HDC; kW); that is, the amount of useful heat that can be provided per unit of time; (2) the heat extraction capacity (HEC; kW); that is, the heat that can be taken from the aerobic treatment basin per unit of time; and (3) the COP (Equation (1)); that is, the ratio between the heat delivered by the heat pump and the electrical power it uses to deliver this heat – the electrical power requirement was considered as the difference between the heat delivered and extracted.

$$COP = \frac{HDC}{HDC - HEC} \quad [-] \tag{1}$$

The COP depends on the temperature at both the extraction and delivery points, and is therefore usually specified for a given temperature situation. The COP values used in this study were calculated for a possible heat pump arrangement at steady state (Figure S1, available with the online version of this paper). The calculations were performed in CoolPack v1.50 (IPU n.d.), considering a global minimum temperature difference in the heat exchangers ($\Delta T_{minimum}$) of 10 °C, the use of refrigerant R-134a as a heat transfer medium, and a 90% efficiency in the compressor (Figure S1). For the reference case, it was assumed that warm water at 60 °C was the objective. The corresponding COP values ranged between 3.68–4.33 (Table 2), depending on the average basin temperature at which heat is extracted (20–28 °C; Figure S1), and interpolating from the COP values obtained with CoolPack. The COP value used in the calculations referred to the average temperature of the basin during the extraction period. For the sensitivity analysis, COP values were recalculated considering different possible temperature levels at which water is provided by the heat pump (50 and 40 °C; Table 2).

In order to obtain the actual amount of heat extracted from the system throughout the year ($Q_{extracted}$; $kWh.year^{-1}$), it was assumed that the rate for heat extraction (kW) could be any value between 50 and 100% of the heat extraction capacity of the heat pump system – as lower efficiency is expected when operating below this 50%. These rates of extraction at each point of time depended on the available surplus heat in each time-step.

The heat extracted from the basin ($Q_{extracted}$) must be transferred by the heat pump to fulfill heating requirements (e.g. building's heating/warm-water requirements). This useful heat supplied by the heat pump is called the delivered heat

Table 2 | Parameter values for the reference scenario. The range used in the sensitivity analysis is shown within brackets

Parameter	Value	Unit
Heat extraction capacity (HEC)	150 [1–500]	kW
Electricity price (EP; operational cost)	121[a] [84–121]	€.MWh^{-1}
Heat price (FP; savings)	34.4[b] [34.4–45.6]	€.MWh^{-1}
COP – average basin temperature dependent, providing warm water at 60 °C (sensitivity analysis providing warm water at 50 and 40 °C)	3.68–4.33 (60 °C) 4.62–5.60 (50 °C) 5.96–7.59 (40 °C)	–
Investment per kW heat delivery capacity (IPK_{HDC100})[c]	500 [250–750]	€.kW^{-1}

[a]Average electricity price for the first semester of 2017 – Non- household in *Euro-area*, annual consumption between 500–2,000 MWh (Eurostat 2017a).
[b]Heat price considering a boiler efficiency of 90% – gas price for non-household in *Euro-area,* annual consumption between 2,778–27,778 MWh (Eurostat 2017b).
[c]Calculations done assuming the given IPK_{HDC100} for an HDC = 100 kW; values at different HDC were calculated according to the cost-curve method $PRICE_a = PRICE_{100HDC} * (HDC_a/HDC_{100kW})^n$; with $n = 0.652$ (Croteau & Gosselin 2015). Values encountered varied from around 220 €.kW^{-1} to 1,800 €.kW^{-1} (EMERSON 2011; Nishihata 2013; INNERS 2015).

($Q_{delivered}$; $MWh_{th}.year^{-1}$). $Q_{delivered}$ depends on $Q_{extracted}$ and the heat pump's coefficient of performance, in exactly the same way as HDC depends on HEC and the COP (Equation (1)).

Economic evaluation

For the economic evaluation of the heat pump, five distinct factors were considered: (1) the selected heat extraction capacity (HEC); (2) the electricity price (cost to operate the heat pump); (3) the fuel price (savings due to heat delivered by the heat pump); (4) the COP; (5) the investment cost per kW of heat delivery capacity (HDC). The parameter values used for the reference scenario are summarized in Table 2. A sensitivity analysis has been performed to see the effect of these parameters on the economics of the heat pump installation.

The economic evaluation was done in terms of internal rate of return; therefore, through calculation of an interest rate, which would result in a net present value of 0 euro for the operational period considered (Figure S2, available with the online version of this paper). The net-cash-flow (Equation (2); €.year^{-1}) was considered as constant through an operational period of 15 years (considered the useful life span of the equipment); no depreciation or taxes were considered. The relationship between heat demand and availability throughout the year was not considered in this study. For the results, it was assumed that the delivered heat ($Q_{delivered}$) would be useful in its entirety and it is thus reflected in savings (from the fuel that would be saved by this heat supply). This can be considered as 'the most optimal scenario'; if heat extraction from this system can be economically feasible, a more detailed analysis can be done in a later stage.

$$Net-cash-flow = C_{savings} - C_{operation} - C_{maintenance} \quad [€.year^{-1}] \tag{2}$$

In this equation, $C_{savings}$ (€.year^{-1}) reflects the costs for fuel that would be required to provide $Q_{delivered}$ if no heat pump was used, $C_{operation}$ (€.year^{-1}) is the electricity costs to operate the heat pump, and $C_{maintenance}$ (€.year^{-1}) is the maintenance costs. The annual cost of maintenance usually varies from 2 to 10 percent of the capital investment of an installation, depending on the severity of operation (Green & Perry 2007). For the present study, it was considered that maintenance costs were 3% of the capital investment ($C_{investment}$). The capital investment was obtained by multiplying the heat delivery capacity (HDC) and the investment per kW of heat delivery capacity (IPK). Economics of scale were accounted for using the cost curve method with $n = 0.652$ (Croteau & Gosselin 2015; Table 2).

$$C_{savings} = Q_{delivered} \cdot FP \quad [€.year^{-1}] \tag{3}$$

$$C_{operation} = W_{electricity} \cdot EP \quad [€.year^{-1}] \tag{4}$$

$$C_{maintenance} = 0.03 \cdot C_{investment} \quad [€.year^{-1}] \tag{5}$$

$$C_{investment} = HDC \cdot IPK \quad [€] \tag{6}$$

RESULTS AND DISCUSSION

Extracted heat as a function of heat recovery capacity

The basin temperature depended on the heat that was extracted from it (Figure 1(a)), at least for temperatures above or close to the critical temperature. The maximum extractable heat, Q_{max}, thus corresponds to the theoretical maximum surplus heat that can be removed from the basin while maintaining the critical temperature; that is, when Q_{max} is extracted from the basin, its temperature never surpasses the critical temperature. A higher heat pump extraction capacity (HEC) resulted in lower basin

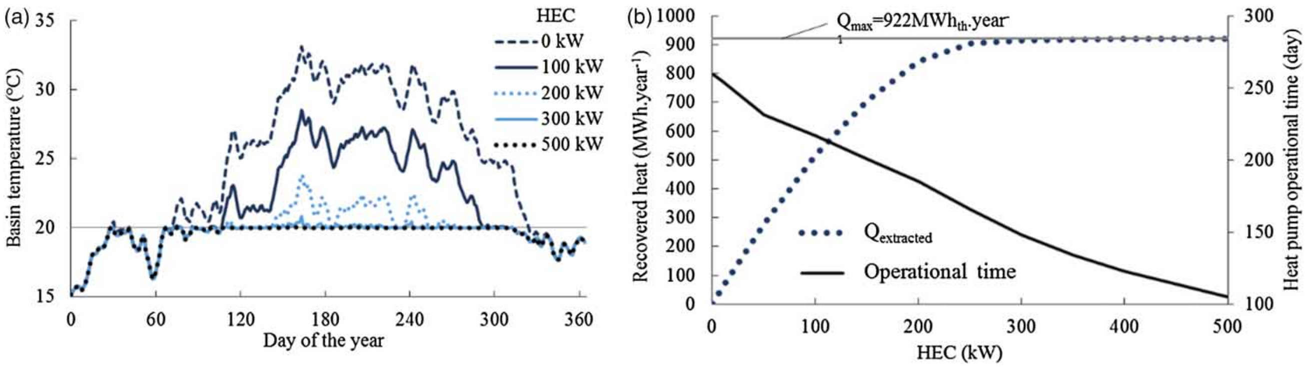

Figure 1 | As functions of the heat extraction capacity (HEC). (a) Basin temperature; (b) $Q_{extracted}$: heat extracted and heat pump's operational time.

temperatures since more heat could be extracted from it. This higher HEC translated into a higher amount of recoverable heat from the system ($Q_{extracted}$), but as the basin temperature approached the critical temperature for heat extraction ($T_{crit} = 20\,°C$; Figure 1(a)), the potentially extractable heat diminished. When an HEC of 250 kW was assumed, 98% of Q_{max} was extracted from the system; that is, $Q_{extracted} = 904\ MWh_{th}.year^{-1}$ out of $Q_{max} = 92\ MWh_{th}.year^{-1}$ (Figure 1(b)). Doubling the heat pump's extraction capacity to HEC = 500 kW resulted in a 1.7% increase ($16\ MWh_{th}.year^{-1}$) of the extracted heat, while decreasing it to HEC = 150 kW resulted in a 22% decrease ($199\ MWh_{th}.year^{-1}$) of the extracted heat.

Even though the effect of increasing the HEC on increasing the extracted heat ($Q_{extracted}$) diminishes as the HEC increases, the effect of increasing the HEC on the heat pump's time in operation was considerable throughout the evaluated range (0–500 kW_{HEC}; Figure 1(b)). Every 30 minutes (corresponding with the time step in the simulation) the heat pump can be turned 'ON' for the following time-step, provided there is enough heat available to be extracted while maintaining T_{crit}. Higher HECs resulted in a more 'intermittent' heat pump operation and a shorter overall operational time. Furthermore, the heat pump was assumed to operate from 50 to 100% of its capacity (HEC). Consequently, when higher capacity heat pumps were used, they operated further from their maximum capacity for longer periods of time. As a result, the extracted heat ($Q_{extracted}$) increases less than linearly with increasing HEC. Heat pump dimensioning should therefore consider that higher heat extraction corresponds to an underuse (in terms of operational time) of the heat pump.

In the simulated scenario (Figure 1(a)), heat was recovered mainly from May–October (days 120–270) and peaking in June (days 150–180). In a practical implementation study, more attention should be paid to match demand and heat availability.

Economic evaluation of the reference scenario

The heat extraction capacity HEC = 150 kW was chosen for the reference scenario (Figure 2). This value resulted in a heat extraction $Q_{extracted} = 705\ MWh_{th}.year^{-1}$ (76% of Q_{max}) and left room for a sensitivity analysis considering higher and lower HECs.

The operation costs ($C_{operation}$, Equation (4), Figure 2(a)) were considered to arise mainly from the power needed to operate the compressor system of the heat pump; this can be seen as a *best case* scenario, as further costs are expected depending on how far heat is delivered; that is, pumping. At this stage, this is more a feasibility study. The operation costs can be determined directly from the extractable heat ($Q_{extracted}$) obtained through simulation, the assumed COP (i.e. 3.85) and the electricity price (EP). Under the above-specified conditions, this resulted in 29.9 thousand euros per year operation costs. The savings ($C_{savings}$, Equation (3), Figure 2(a)), reflecting the substitution of fuel to supply the heating requirements that would now be delivered by the heat pump ($Q_{delivered}$) amounted to 32.8 thousand euros per year. Note that aeration efficiency is expected to improve in periods where heat is being extracted from the basin, as lower temperatures mean higher oxygen solubility. This effect on the energy requirement for aeration (electricity), which implies an additional advantage for heat extraction scenarios, has not been accounted for in this paper.

The maintenance costs ($C_{maintenance}$, Equation (5), Figure 2(a)) were 2.4 thousand euros per year, deriving from the 79.2 thousand euro investment cost (Equation (6); Figure 2(a)). All in all, a positive net-cash-flow was obtained (453 €.$year^{-1}$, Equation (2), Figure 2(b)). Nevertheless, no internal rate of return could be found; that is, the

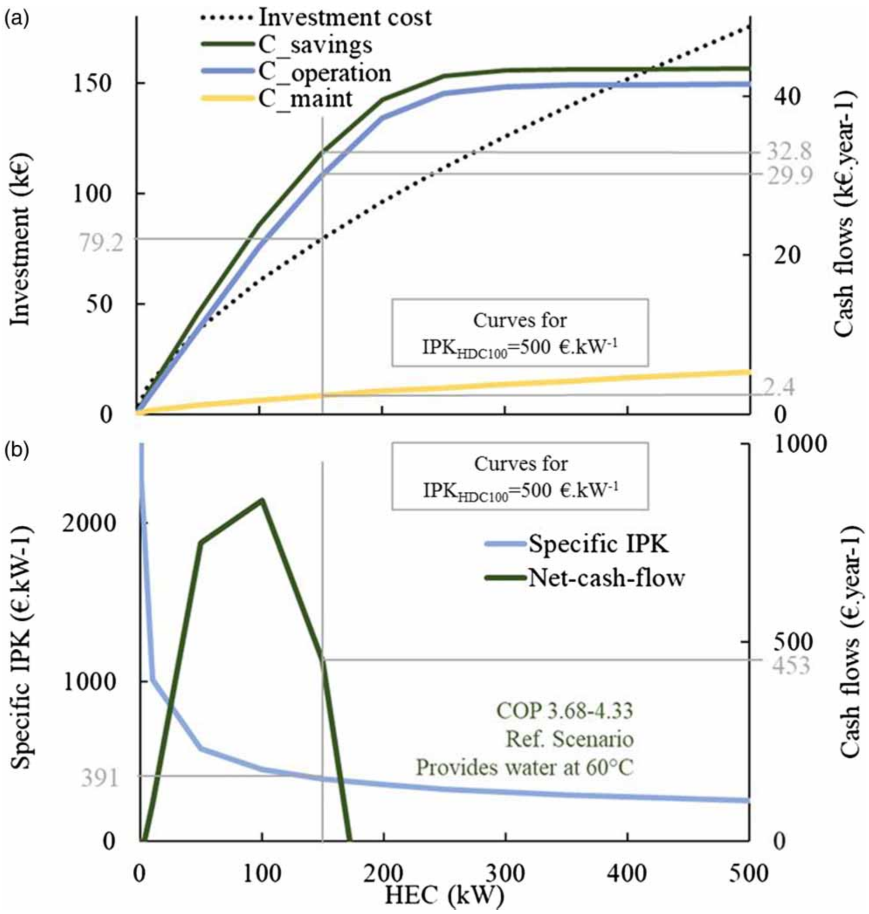

Figure 2 | Economic evaluation at different heat extraction capacities (HEC) considering $IPK_{HDC100} = 500$ €.kW^{-1}. (a) Savings, operation and maintenance values; (b) investment per kW (IPK) at different HEC, including the effect of scale economics, and the corresponding net-cash-flow. Grey line marks the reference scenario (HEC = 150 kW; see Table 1).

investment costs are not recovered within the lifetime of the installation (15 years), for this reference scenario. With a 0% interest rate, the simple payback time for this reference scenario would be 175 years (investment/net-cash-flow).

Sensitivity analysis

Heat extraction capacity (HEC) and the coefficient of performance (COP)

At first, as the HEC increases (Figure 3(a) and 3(b)), the net-cash-flow increases as a greater amount of heat is extracted from the system – economies of scale further favour larger installations. Then, a maximum cash flow is reached as the increase in maintenance costs starts outweighing the savings obtained with the heat pump, as maintenance costs follow heat pump size (HEC) and not the actual time in operation. After this point (maximum net-cash-flow), increasing the capacity of the system decreases the net-cash-flow. The higher the COP, the higher the maximum net-cash-flow obtained (Figure 3(a) and 3(b)), and the higher the HEC at which it is obtained – higher COP values mean a higher ratio between heat delivered and electricity power required to transfer it. For an $IPK_{HDC100} = 500$ €.kW^{-1}, no economically favourable heat pump size was found (Figure 3(c)), in the reference case providing water at 60 °C, corresponding with a COP of 3.68–4.33. In order to reach an actual internal rate of return, the COP needs to be increased by decreasing the temperature of water to be provided (Figure 3(c)). It is also important to note that the maximum net-cash-flow is not obtained at the same heat pump size (HEC) as the highest internal rate of return (Figure 3(a) and 3(c); 3(b) and 3(d)). For example (Figure 3(a) and 3(c)), for a system providing water at 40 °C (COP 5.96–7.59), the maximum net-cash-flow (12,468 €.year^{-1}) is obtained at an HEC = 250 kW; while the highest internal rate of return is obtained at an HEC of 100–150 kW. In most of the cases, an HEC = 100 kW showed a peaking rate of return (Figure 3(c) and

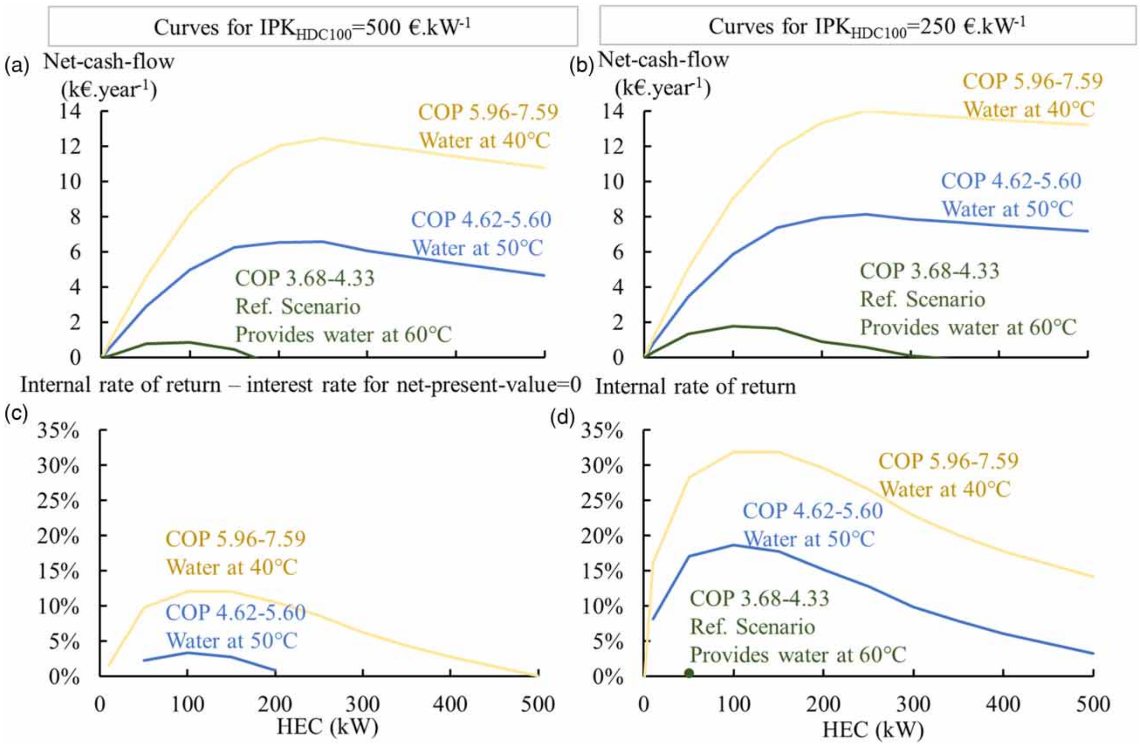

Figure 3 | (Top) Net-cash-flows as a function of the HEC at different COP values. (Bottom) Internal rate of return; this at specific investment costs of $IPK_{HDC100} = 500$ and 250 €.kW^{-1} [left and right, respectively].

3(d)), which would translate into an extraction of 55% of the available heat (Q_{max}).

Investment costs (IPK_{HDC100})

As expected, the investment costs have an important effect on the economics of the system (Figure 3(c) vs. 3(d)). Higher investment costs per unit power installed translate into a lower range of economically feasible uses for the recovered heat, as one would have to try to achieve higher COP values, and thus provide lower temperature water in this case. For an $IPK_{HDC100} = 750$ €.kW^{-1}, only the case providing water at 40 °C (COP 5.96–7.59) showed some windows for economically feasible application of heat pumps in this system (data not shown).

Electricity price (EP)

Lower electricity prices favor the economics of heat pump applications. On the one hand, electricity prices have been relatively constant since 2009 in the Euro area (Eurostat 2011; Somesmo 2015; Eurostat 2017a), averaging 120 €.MWh^{-1} (max. +6.5% min. −9.3%) and without a clear trend to decrease significantly. Nonetheless, it is important to mention that electricity values that result in a positive economic evaluation of the heat pump installation can be encountered; for example, 109 €.MWh^{-1} as in 2009 in the Eurozone (Eurostat 2011; Figure 4(c)). On the other hand, electricity production onsite could be an option. For example, for photovoltaic installations, the levelised cost of electricity (generation) can already range from 54–84 €.MWh^{-1} for large installations (Mayer 2015). With a price for electricity of 84 €.MWh^{-1}, the application of a heat pump for production of water at 60 °C seems achievable (COP 3.68–4.33; Figure 4(a)). However, this electricity price might not be achievable at the scale of this application, and the direct use of solar energy for water heating might be a better alternative (as most heat is available during the summer).

Fuel price (FP)

The higher the fuel price, the better economic expectation of heat pump implementations, as the monetary savings due to the replaced heat source increase. Gas (heat) prices that result in a positive economic evaluation of the heat pump installation can be encountered; for example, 45.6 €.MWh^{-1} as in 2013 (Somesmo 2015; Figure 4(b)).

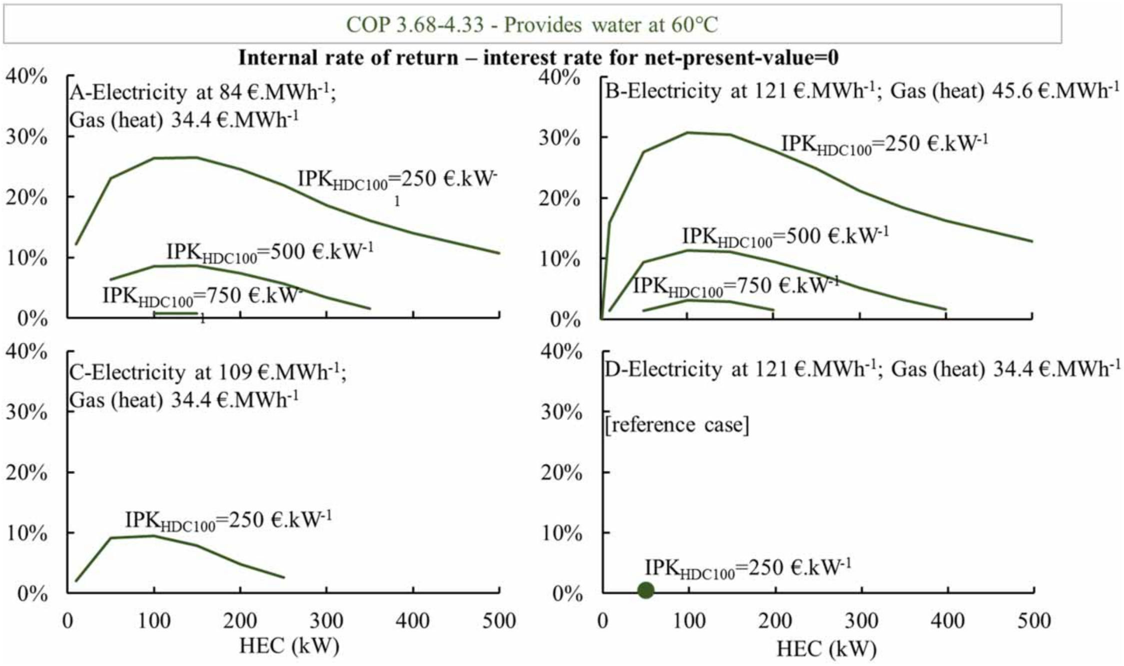

Figure 4 | Electricity and heat prices effects on the internal rate of return (interest rate for a net-present-value = 0). Electricity prices: 121 €.MWh^{-1} (Euro-area year 2017), 109 €.MWh^{-1} (2009), 84 €.MWh^{-1} (production on site); Gas (heat) prices: 34.4 €.MWh^{-1} (2017), 45.6 €.MWh^{-1} (2013).

Nonetheless, heat and electricity prices are not completely independent from each other; in this case, even if the actual electricity price of that year was used (126 €.MWh^{-1}; Somesmo 2015), a positive economic evaluation is encountered (data not shown). Comparing Figure 3(a)–3(d), one can observe that the economics of the heat pump installation depend more on possible heat prices than on electricity prices – considering current prices. Therefore, an installation would be certainly more appealing in regions with relatively high fuel (heat) prices.

Perspectives

Even though positive net-cash-flows can be obtained through the heat recovery from the aerobic treatment of highly concentrated wastewater, limitations were encountered when evaluating the economic feasibility of such operation. In the results presented above, it became obvious that the production of warm water ($T_{warmwater} = 60$ °C; $T_{basin,average} = 20$–28 °C;COP = 3.68–4.33) is not economically attractive. Even more when one considers that in reality, the system will have lower performance (heat losses from heat source to heat sink, pumping costs, fouling prevention costs, etc.). Lower water-temperature production systems (i.e. 40 °C – COP = 5.96–7.59), display stronger economic outputs. Nonetheless, at these water temperatures, the applicability is very limited to very specific applications (e.g. warming up swimming pools; INNERS 2015). Furthermore, most of the heat is available during the summer months, when it might be more worthwhile to obtain warm water from solar energy systems.

Nonetheless, heat pumps to recover heat from wastewater are applied in many countries due to relatively higher energy utilization efficiency and environmental protection (Hepbasli *et al.* 2014), when compared to conventional systems. Furthermore, heat pumps can show lower operating costs than other operational systems (Liu *et al.* 2014) and be economically favorable with subsidies (Chae & Kang 2013). Heat from wastewater can also be recovered close to its source (e.g. shower water in buildings), an idea that wants to be brought forward to the market (Meggers & Leibundgut 2011). This has already been realized in countries such as Sweden (Lindström 1985); its economic potential has also been observed to largely depend on the relative heating costs of alternative fuels such as oil and gas (McCarty *et al.* 2011). For the particular case of aerobic treatment of manure, the treatment basin can require cooling during the summer to prevent high temperatures that could hamper biological activity. This is the reason why it was assumed that heat was taken directly from the basin in this study. Note that cooling as such also requires energy, which was not taken into account in this study but would add benefit to the heat extraction scenario. In cases with milder temperatures, it could be more advisable to extract heat from the effluent stream in order to avoid decreasing the temperature below the minimum level required for biological activity. An example is the treatment of municipal wastewater, which has lower organic carbon and nitrogen concentrations, resulting in less biological heat production and thus lower temperatures.

In this paper, the COP was dependent on the assumed temperature of the water provided. The higher this temperature, the lower the COP (Figure 3), The COP also depends on the temperature at which heat is extracted (Figure S1), the lower this temperature is, the lower the COP. It is therefore expected that in municipal wastewater treatment plants, with lower temperatures, heat extraction extractions would not be economically attractive.

CONCLUSIONS

The economics of the application of a heat pump for heat recovery from a wastewater treatment plant dealing with highly concentrated wastewater (30 kg COD.m^{-3}; 4.5 kg NH_4-N.m^{-3}; 57.9 m^3.d^{-1}) have been assessed through simulation.

- Economically viable heat recovery from the system is difficult and highly dependent on the coefficient of performance (COP) of the heat pump.
- If water at 60 °C needs to be obtained (COP = 3.68 to 4.33), different factors would have to change to achieve economic viability (e.g. higher fuel-heat prices, lower electricity prices).
- The best economical performance of heat recovery was achieved when approximately 55% of the available heat was recovered from the system. Higher heat extraction, requires a heat pump with a larger heat extraction capacity, resulting in maintenance costs that surpass the monetary savings, and lower heat extraction benefits less from economics of scale.
- With current energy prices, economic feasibility of heat pump installations appears to be more dependent on fuel (heat) prices than electricity prices.

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REFERENCES

Chae, K.-J. & Kang, J. 2013 Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. *Energy Conversion and Management* **75**, 664–672.

Corbala-Robles, L., Volcke, E. I. P., Samijn, A., Ronsse, F. & Pieters, J. G. 2016 Effect of foam on temperature prediction and heat recovery potential from biological wastewater treatment. *Water Research* **95**, 340–347.

Corbala-Robles, L., Sastafiana, W. N. D., Van linden, V., Volcke, E. I. P. & Schaubroeck, T. 2018 Life cycle assessment of biological pig manure treatment versus direct land application – a trade-off story. *Resources, Conservation and Recycling* **131**, 86–98.

Croteau, R. & Gosselin, L. 2015 Correlations for cost of ground-source heat pumps and for the effect of temperature on their performance. *International Journal of Energy Research* **39**, 433–438.

Dogniaux, R., Lemoine, M. & Sneyers, R. 1978 Année-type moyenne pour le traitement de problémes de capitation d'énergie solaire [Typical reference year for treatment of solar energy captation problems]. *Institut Royal Météorologique de Belgique, Bruxelles, Misc. sér. B, no. 45*.

Ekama, G. A. & Wentzel, M. C. 2008 Chapter No. 5: Nitrogen removal. In: *Biological Wastewater Treatment: Principles, Design and Modelling* (M. C. M. van Loosdrecht, M. Henze, G. A. Ekama & D. Brdjanovic, eds). IWA Publishing.

EMERSON 2011 Industrial heat pumps (EmersonClimate, Trans.) (pp. 1–16). USA: EMERSON climate technologies.

Eurostat 2011 *Electricity and Natural gas Price Statistics*. Retrieved January 29, 2018, from http://ec.europa.eu/eurostat/documents/38154/41386/SEarticle2011S1.pdf/505395ff-d855-47f2-98f0-99d899968b25.

Eurostat 2017a *Electricity Price Statistics*. Retrieved January 29, 2018, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Notes.

Eurostat 2017b *Natural gas Price Statistics*. Retrieved January 29, 2018, from http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics.

Evans, M. R., Svoboda, I. F. & Baines, S. 1982 Heat from aerobic treatment of piggery slurry. *Journal of Agricultural Engineering Research* **27** (1), 45–50.

Green, D. & Perry, R. 2007 *Perry's Chemical Engineers' Handbook*, 8th edn. McGraw-Hill Education.

Hepbasli, A., Biyik, E., Ekren, O., Gunerhan, H. & Araz, M. 2014 A key review of wastewater source heat pump (WWSHP) systems. *Energy Conversion and Management* **88**, 700–722.

Hughes, D. F. 1984 Extraction of energy from an aerobic farm waste lagoon. *Journal of Agricultural Engineering Research* **29** (2), 133–139.

INNERS 2015 *Innovative Energy Recovery Strategies in the Urban Water Cycle*. INNERS, Zwolle.

IPU n.d. CoolPack (Version 1.5) [Computer software]. Retrieved February 26, 2018, from http://www.en.ipu.dk/Indhold/refrigeration-and-energy-technology/coolpack.aspx.

Lindström, H. O. 1985 Experiences with a 3.3 MW heat pump using sewage water as heat source. *Journal of Heat Recovery Systems* **5** (1), 33–38.

Liu, Z., Ma, L. & Zhang, J. 2014 Application of a heat pump system using untreated urban sewage as a heat source. *Applied Thermal Engineering* **62** (2), 747–757.

Mayer, J. N. 2015 *Current and Future Cost of Photovoltaics*. Retrieved January 29, 2018, from https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/AgoraEnergiewende_Current_and_Future_Cost_of_PV_Feb2015_web.pdf.

McCarty, P. L., Bae, J. & Kim, J. 2011 Domestic wastewater treatment as a net energy producer–can this be achieved? *Environmental Science & Technology* **45** (17), 7100–7106.

Meggers, F. & Leibundgut, H. 2011 The potential of wastewater heat and exergy: decentralized high-temperature recovery with a heat pump. *Energy and Buildings* **43** (4), 879–886.

Nishihata, H. 2013 *Heat Pumps – Technology Brief: IEA-ETSAP and IRENA*.

Somesmo 2015 *Half-yearly Electricity and gas Prices 2014 Semester 2*. Retrieved December 2015 http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Half-yearly_electricity_and_gas_prices_2014semester2.png.

Svoboda, I. F. & Evans, M. R. 1987 Heat from aeration of piggery slurry. *Journal of Agricultural Engineering Research* **38** (3), 183–192.

VLM 2015 *Mestrapport 2015 Over de Mestproblematiek in Vlaanderen*. Vlaamse Land Maatschappij. https://www.vlm.be/nl/SiteCollectionDocuments/Publicaties/mestbank/Mestrapport%202015.pdf.

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