Nutrient and energy recovery from pig manure and sludge: Economic optimization using a new process model library

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INTRODUCTION

In order to hasten the implementation of optimal, cost-effective and sustainable treatment trains for resource recovery from bio-wastes, a nutrient recovery model (NRM) library has recently been developed and validated at steady state (Vaneeckhaute *et al.*, 2018a). It includes dynamic mathematical process models for anaerobic digestion (biogas recovery), struvite crystallization (phosphorus recovery), and NH_3 stripping and acidic air scrubbing (ammonium sulfate recovery). The models are based on detailed chemical solution speciation and reaction kinetics. To facilitate numerical solution, a highly efficient PHREEQC-WEST (DHI) software interface has been established and verified. Important generic insights in the interactions between process inputs and outputs were obtained through global sensitivity analyses. Based on the results, it was possible to define an optimal sequence of unit processes in a treatment train for energy and nutrient recovery aiming at the production of high-quality fertilizers from bio-waste at minimal cost (Figure 1).

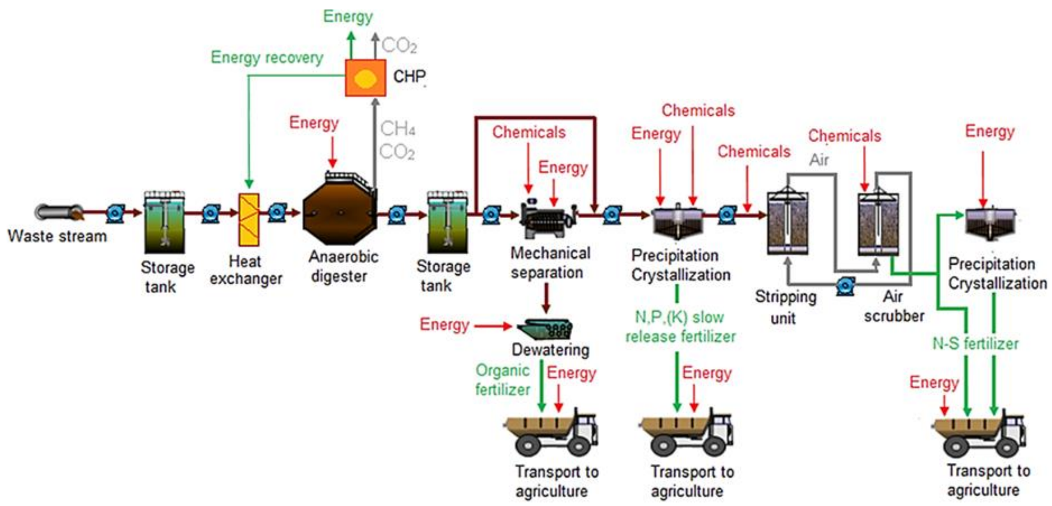

Figure 1. Treatment train for recovery of energy (CHP = combined heat & power generation), organic solid fertilizer, ammonium sulfate (N/S) and struvite (N/P/(K)) fertilizers from waste (Vaneeckhaute *et al.*, 2018b).

This paper presents the use of the NRM library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource recovery and minimal energy and chemical requirements. An economic analysis was programmed in the process model library, and the operational settings of the above treatment train were optimized for pig manure as a case study.

MATERIAL AND METHODS

The operational settings of the configured treatment train (Figure 1) were optimized in order to maximize resource recovery and minimize energy and chemical requirements in a cost-effective way. The operational envelope involves: i) the operational temperature, liquid flow rate, and amount of alkalinity dosing for the anaerobic digester, ii) the fraction of non-settleable precipitates and particulate organics for the phase separation unit, iii) the amount of base dosing, the concentration of seed material in the input flow, and precipitate extraction rate for the precipitation unit, iv) the operational temperature and gas flow rate for the stripping unit, and v) the acid dose and liquid recycle flow rate for the scrubbing unit. The operational costs for the optimized scenario were then calculated and included in the overall economic balance, in addition to labor, material and maintenance costs, revenues from CO_2-emission reduction credits, as well as capital costs.

Capital costs (including equipment and construction costs) for each unit process were obtained from technology providers who delivered design reactor dimensions for the treatment train set-up. The complete treatment train was also implemented in CAPDET (Symantec, 2014) in order to estimate other important direct and indirect construction costs, not included in the unit process cost estimations, such as land costs (agricultural land was assumed), legal costs, inspection costs, costs for lab and administration buildings, and miscellaneous costs.

RESULTS AND DISCUSSION

Assuming an average discount rate of 6% and a depreciation period of 20 years for all unit processes (Symantec, 2014), except for the NH_3 stripping unit, for which a depreciation period of eight years was assumed, the nutrient recovery project presented above would have a positive net present value (NPV) in year 7 of operation in the best case. This value is at the lower end of the range of payback times for existing anaerobic digestion plants without nutrient recovery in the US, i.e. 6.9-8.9 years based on a survey of 24 plants. The NPV after 20 years amounted to about 3.5 M \$, resulting in average net financial benefits of ± 2 \$ m^{-3} manure yr^{-1} (40 \$ ton^{-1} total solids (TS) yr^{-1}) over 20 years.

The internal rate of return (IRR), i.e. the discount rate that makes the NPV equal to zero, after 20 years in this case was 18%, which is about the same as the estimated best-case IRR (including subsidies) after 20 years for an operational full-scale resource recovery facility in the Netherlands, i.e. 19-21% (Gebrezgabher *et al.*, 2010). In the worst-case scenario, the IRR after 20 years was only 5%. Based on the analysis (worst vs. best case), it can be stated that the feasibility of implementing a resource recovery project depends greatly on the heat recovery potential, the marketing potential of the fertilizers, as well as the subsidies obtained. For instance, when accounting for an income of 40 \$ ton^{-1} net saved CO_2-equivalents instead of the conservative US carbon prices (15 \$ ton^{-1}), the IRR would be around 26% and 14% in the best and worst case, respectively, resulting in a revenue of 1.3-3.4 \$ m^{-3} manure y^{-1} (25-70 \$ ton^{-1} TS y^{-1}) averaged over 20 years.

CONCLUSIONS

This paper presents the use of a new nutrient recovery model (NRM) library to establish the operational settings of a sustainable and cost-effective treatment scenario with maximal resource recovery and minimal energy and chemical requirements. To this end, an economic analysis was programmed in the process model library and the operational settings of a pre-configured treatment train were optimized for pig manure as a case study. Under the optimized conditions and assumptions made, potential financial benefits for a large-scale anaerobic digestion and nutrient recovery project were estimated at an average of ± 2 m^{-3} y^{-1}, equivalent to 40 \$ ton^{-1} total solids y^{-1}, over 20 years. Results indicate that subsidies, fertilizer marketing potential and heat balances are key factors determining the feasibility of resource recovery projects. Hence, process and design engineers should focus on the optimization of heat balances in the configuration of future integrated nutrient and energy recovery facilities. Fertilizer regulations and subsidies should be adjusted accordingly.

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