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355
Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

Cost benefit assessment of a novel thermal stripping – acid absorption process for ammonia recovery from anaerobically digested dairy manure

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Abstract

Thermal stripping – acid absorption is a novel technology recently developed to recover ammonia as marketable ammonium sulfate granules from anaerobic digester effluent. Taking a large-size dairy farm in New York State, USA, as an example, this study evaluates the costs and benefits of ammonia recovery from a recirculation line of mesophilic anaerobic digesters. Option 1 is the baseline without ammonia recovery. Option 2 is to draw digester effluent at 28% of the liquid manure loading rate, heat to 101 °C for ammonia recovery, and return the ammonia-recovered dairy manure to the digesters. Under option 2, the returned hot manure eliminates the need to heat the digesters. Option 3 is similar to Option 2, but the recirculation rate is only 14% of the manure loading rate. In this case, additional heating is needed for the digesters. Engineering unit cost and revenue models are developed for the thermal stripping – acid absorption process. Options 2 and 3 have benefit/cost ratios of 1.90 and 1.86, respectively. Option 2 produces greater net present value (NPV) ($1.34 million) than Option 2 ($0.72 million), while Option 1 yields a negative NPV (−$0.23 million). Ammonia recovery on this farm can create 1.5–3 jobs. Labor costs account for 62–70% of the total operating costs. Option 2 can generate a benefit of $0.018/L manure digestate or $0.50/d/cow. Any uncertainties relating to NPV and benefit/cost ratio are mainly associated with the sale price of ammonium sulfate and hourly wage rate.

Key words: ammonia recovery, anaerobic digestion, cost-benefit analysis, liquid manure, thermal stripping

INTRODUCTION

Liquid dairy manure, a mixture of as-excreted manure, used bedding and wastewater, is rich in nutrients and typically applied to cropland as an organic fertilizer (USDA 2009; ASABE 2010). Many dairy farms, especially large-size operations, generate excess liquid manure that cannot be applied to their own land, on the basis of nutrient application rates. Anaerobic digestion has been increasingly applied to stabilize liquid manure and produce biogas for energy production. However, it converts organic nitrogen to bioavailable ammonia. Because more nitrogen is bioavailable in anaerobically digested dairy manure than in undigested manure, land application rates must be reduced for digested manure and any excess digested manure must be treated further or transported off-site (Nkoa 2014). To facilitate treatment and beneficial use, digester effluent (digestate) is mostly separated into liquid and solid fractions (Fuchs & Drosg 2013). Solid-liquid separation and subsequent treatment, including ammonia removal from the liquid fraction, often adds financial burden to the operation of anaerobic digesters.

Despite steadily rising costs and more stringent regulations for land application, a digestate processing plant is economically viable only in a small number of cases, and the search for improved and more economic approaches continues (Fuchs & Drosg 2013). Recently, instead of removing

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

ammonia, Tao & Ukwuani (2015) developed a technology that couples thermal stripping and acid absorption to produce ammonium sulfate granules from digestate. Aqueous ammonia in digestate is converted to free ammonia by boiling (about 101 °C) at pH 9, which is stripped out of the digestate and absorbed in dilute sulfuric acid, to form ammonium sulfate. When the acid solution is oversaturated, ammonium sulfate granules are produced, which can be sold commercially.

When the ammonia recovery process is applied to an anaerobic digester recirculation line, the need to heat the digesters is eliminated or reduced. Therefore, the integration of ammonia recovery into anaerobic digestion could make energy-intensive thermal stripping viable. Moreover, thermal stripping has several design and operational advantages over what is, currently, the most promising air-stripping ammonia recovery process for manure digestate (Tao & Ukwuani 2015). This paper analyzes cost inputs, cost savings, and potential revenues of ammonia recovery from anaerobically digested dairy manure at a large dairy farm (Twin Birch Dairy LLC), assesses net present value (NPV) and benefit/cost ratio, and explores the sensitivity of both NPV and benefit/cost ratio to various market uncertainties. Cost-benefit analysis helps gauge the most economic form of thermal stripping – acid absorption and allows comparison with other ammonia recovery methods.

METHODOLOGY

Twin Birch Dairy is a dairy farm in central New York State, USA, with 1,100 milking cows. As-excreted manure and used bedding are scraped off the barns' concrete floors, mixed with milking washwater, and treated in two plug-flow anaerobic digesters at mesophilic temperatures (37 °C on average). A combined heat and power system uses the biogas to heat the liquid manure fed to the anaerobic digesters. The digesters are operated in parallel and have a total liquid manure loading rate of 110,000 L/d. Digester effluent passes through a screw press separator. The separated solids are composted, and used for bedding or sold. The separated liquid is stored 2.3 km away and used to irrigate the farm's cropland, which comprises 1,012 hectares of wheat, corn and alfalfa. Most of the cropland – 890 to 1,012 hectares – was irrigated with the separated liquid until 2015.

Three options are proposed for ammonia recovery by the thermal stripping – acid absorption process, involving the two digesters (Figure 1).

- Option 1 is the baseline condition without ammonia recovery. The conceptual design sets the digester feedstock temperature at 20 °C and the total ammonia concentration at 640 mg-N/L, based on

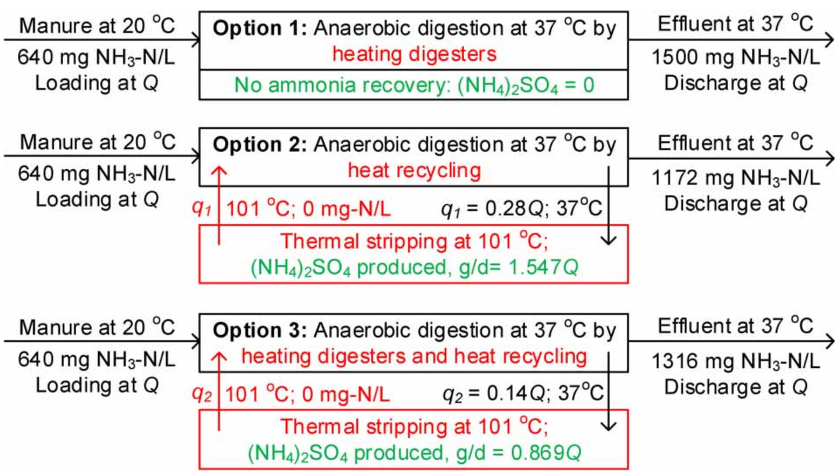

Figure 1 | Options for integrating thermal stripping – acid absorption into anaerobic digestion of liquid dairy manure. Q = manure loading rate to two digesters = 110,000 L/d; q = recirculation rate.

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

the measured ammonia concentration in manure liquor and the manure solids content. The digested dairy manure has an average total ammonia concentration of 1,500 mg-N/L.

- Option 2 is to draw off digester effluent at 28% of the digester loading rate, heat it to 101 °C for ammonia recovery, and return the ammonia-recovered digestate to the anaerobic digesters for heat recycling. Based on water budget and heat balance analysis, recovering ammonia at this recirculation rate eliminates the need to heat the mesophilic digesters and avoids over-heating the mesophilic digesters. Using the regression model developed by Bohnhoff & Converse (1987), it is estimated that the specific heat is 4.014 kJ/kg/°C for digested dairy manure with a total solids concentration of 6.1%, and 3.843 kJ/kg/°C for raw dairy manure with a total solids concentration of 11.3%.
- Option 3 is similar to Option 2, but the recirculation rate is 14% of the digester loading rate and additional digester heating is needed. The resulting digester effluent concentration and amount of ammonium sulfate produced are estimated using mass balance analysis, as in Figure 1.

Because of the shorter hydraulic retention time in the digesters and the enhanced hydrolysis of organic matter due to treatment during thermal stripping under options 2 and 3, relative to Option 1, it is conservatively assumed that the ammonification rate under options 2 and 3 will be the same as that achieved presently – i.e., Option 1.

A stepwise linear approach was used to evaluate the three options (Figure 2). Cost and revenue models were developed for the thermal stripping – acid absorption process, with supporting data from laboratory experiments, conceptual designs, trade journals, and design manuals. The models enable comparison of the ammonia recovery options and assessment of market uncertainties at the conceptual design stage. Calculations of the cost and revenue components, and cash flow were done using Excel spreadsheets.

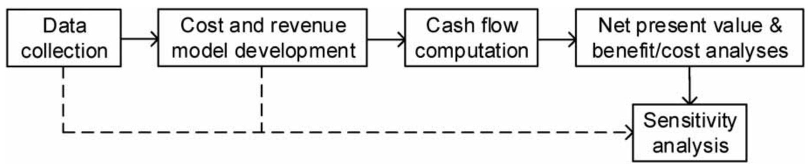

Figure 2 | Process diagram of economic analysis for ammonia recovery from manure digestate.

Models for capital costs

Stripping vessels

The stainless steel stripping vessels considered for this project are kettle re-boilers with demisters for batch operation. Each vessel is 1.52 m in diameter and 0.5 m high, and holds 365 L. Assuming the recirculation rates and complete ammonia recovery in 3-hour batch operations, the process will need 11 stripping vessels in Option 2 and 5 in Option 3. One spare (standby) vessel is added to each option. Cost determination of vessels is governed by the principles of capacity factors and power sizing models, the latter using an exponent value for scale adjustment. Each equipment unit has a unique exponent value representing its scaling level. The cost model for the stripping vessels is given in Equation (1).

$$C_v = C_s V^x N \qquad (1)$$

where C_v = total cost of stripping vessels, \$; C_s = unit cost to purchase steel vessels based on volumetric capacity, \$/L; V = vessel volume, L; N = number of stripping vessels; and x = power sizing factor. A unit cost of \$2.75/L presented by Loh (2002) for stainless steel vessels, was updated using the Marshall &

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

Swift Equipment Cost Index, which is a ratio of the cost index value for the current year over the cost index value in the base year for which the unit price is retrieved (Whitesides 2012). Based on the consumer price indexes for all U.S. urban consumers in 2001 and 2014 (BLS 2015a), the base unit cost (C_s) was adjusted to \$3.68/L. The power sizing factor (x) is 0.70 for boiler packages, forced circulation evaporators, and stainless steel tanks and vessels (Whitesides 2012). A sizing factor of 0.70 was used in this study to estimate the stripping vessel costs.

Centrifugal pumps

Pumps are required to feed digester effluent to the stripping vessels and recycle the hot manure to the anaerobic digester inlets after ammonia recovery. It is proposed that variable-speed centrifugal pumps capable of delivering 174 L/min at 3 m head be used. These will be 370 W (½ hp) submersible dewatering and trash pumps. The capital cost model for the pumps is given in Equation (2). It will take approximately 2 minutes to feed a single batch and 2 minutes to recycle the hot manure with the pump, and it is estimated that four pumps will be needed to run the 10 stripping vessels in Option 2, with only two needed for the 5 vessels in Option 3.

$$C_p = X_i ab \tag{2}$$

where C_p = total capital cost of pumps, \$; X_i = unit cost of a pump based on speed, \$/L/min; a = pump capacity, L/min; and b = number of pumps. Based on the consumer price indexes for all U.S. urban consumers in 2001 and 2014 (BLS 2015a), the unit cost of \$9.05/L/min presented by Loh (2002) was adjusted to a current equivalent of \$12.10/L/min.

Absorption columns

When equipping three stripping vessels with one absorption column for batch operation, it is estimated that each column would be of 0.5 m diameter and 0.8 m height, with a total capacity of 157 L, and hold 98 L of acid solution. Four columns will be required for Option 2 and two for Option 3. Carbon steel or polyethylene columns are typically used to hold sulfuric acid solution. It was proposed to assemble ammonia absorption columns with conical, high-density polyethylene tanks. The retail price is approximately \$150 each.

Models for operational and maintenance costs

Energy demand

Energy demand for ammonia recovery includes (1) that required to heat the stripping vessels, and (2) that for recirculating digestate through the vessels. The energy required for heating comprises (a) that to raise the temperature from the 37 °C of digester effluent to 101 °C for the thermal stripping of ammonia (Equation (3)), and (b) that arising from the latent heat of evaporation of water during thermal stripping (Equation (4)). Heat loss through the stripping vessels and the recirculation lines could be offset by increasing the recirculation rate in practical operations. Thus, additional heating needs to offset heat loss were not considered in this study.

$$E_q = h_v \times (101 - 37) \times q \times 0.278 = 71.4q \tag{3}$$

where E_q = energy required to raise the temperature of manure digestate to boiling inside the stripping vessels, Wh/d; h_v = specific heat of digested dairy manure with a total solids concentration of 6.1% = 4.014 kJ/L/°C (Bohnhoff & Converse 1987); and q = recirculation rate, L/d.

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

$$E_v = h_v \times V_w \times q \times 0.278 = 11.3q \tag{4}$$

where E_v = energy required to maintain boiling due to water evaporation, Wh/d; h_v = latent heat of water evaporation at 100 °C and 760 torr = 2,258 kJ/L (Haynes 2012); V_w = specific volume of water vaporized, L/L; and q = recirculation rate, L/d. The volume of water evaporated in thermal stripping varied between 0.012 and 0.082 L/L-digestate in laboratory experiments without water reflux (Tao & Ukwuani 2015). With a demister to capture mists and sprays, it is assumed that the thermal stripping – acid absorption system will reduce water vapor loss to 0.018 L/L.

Estimates of the energy demand for digestate recirculation are based on the pumps' power rating. It will take approximately 4 minutes, in total, to feed a single batch and recycle the hot manure. Each batch processing event will last for approximately 3 hours, before hot manure is pumped to the digesters (Tao & Ukwuani 2015), and each stripping vessel will be operated for 8 batches per day. The total energy consumed by the pumps, on this basis, is calculated using Equation (5).

$$E_p = 368 \times 0.07 \times 8 \times N = 206N \tag{5}$$

where E_p = energy demand for pumping, Wh/d; 368 = wattage of pumps, W; 0.07 = total time for feeding and recycling for each batch, h; 8 = number of batches in a day; and, N = number of stripping vessels used.

The total energy demand of the ammonia recovery system is the sum of the results from the above three models, as given in Equation (6).

$$C_e = K_e\left(E_q + E_v + E_p\right) \tag{6}$$

where C_e = total energy cost, \$/d; and K_e = unit energy cost. The unit energy cost was \$0.070/kWh on average in 2014 for industrial users in the USA (EIA 2015).

Sulfuric acid

Because of the reaction between sulfuric acid and stripped ammonia, the sulfuric acid solution's normality will decrease over time in a batch. Theoretically, 0.4 L concentrated sulfuric acid is required to form 1 kg ammonium sulfate. The 2013 market value of sulfuric acid was \$55/tonne (ICIS 2014), which was equivalent to \$0.10/L at a specific gravity of 1.84. The rate of sulfuric acid consumption depends on ammonium sulfate production and the cost model is calculated using Equation (7).

$$C_s = 0.4 \times P \times K_s \tag{7}$$

where C_s = cost of sulfuric acid, \$/d; P = production of ammonium sulfate, kg/d; and K_s = unit cost of concentrated sulfuric acid solution, \$/L.

Elevation of feed pH

With thermal stripping at pH 9 in an anaerobic digestion recirculation line, the digester effluent pH will increase from 7.8 by less than 0.06. Laboratory experiments showed that increasing the digestate pH from 7.8 to 9 for ammonia recovery would require 1.33 g-CaO/L-digestate. The unit cost of lime (CaO) is \$70/tonne (Jiang *et al.* 2014). The cost of pH elevation can then be calculated using an equation similar to Equation (7).

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

Labor

The labor required to operate the ammonia recovery system varies with the numbers of stripping vessels and acid absorption columns, which depends on the recirculation rate. Each stripping vessel will operate for 8 batches per day. Each batch operation will last approximately 3 hours, and all stripping vessels and absorption columns will operate in parallel. It is hence estimated that one operator per 8-hour shift will be able to run the stripping vessels (11) and absorption columns (4) in Option 2, including feeding and discharging the stripping vessels, harvesting the ammonium sulfate granules and renewing the sulfuric acid solution. Option 3 will only need one, half-time operator. An hourly wage of $17.94 was used – the national mean hourly wage in 2014 for farm equipment mechanics and service technicians, as reported by the U.S. Department of Labor (BLS 2015b).

Repairs and maintenance

Maintenance and repairs are considered contingency costs. They may arise due to requirements like vessel and pipe cleaning, unclogging, machine oiling, and parts replacement. To secure efficient performance and avoid unnecessary breakdowns, annual maintenance costs were estimated at 5% of total capital costs (Sinnott & Towler 2009).

Compliance cost

With ammonia recovery, the ammonia concentration of the digester effluent will decrease (Figure 1). As a result, a dairy farm may apply more digested manure to its own land with less extra manure to be transported to other farms. In New York State, tankers are used to transport and spread liquid manure. In a survey of dairy farms in the state, Howland & Karszes (2014) reported an average liquid manure application cost of $2.99/m^3. The total included (1) operating costs (labor, fuel, utilities, and repairs); (2) ownership costs (depreciation, interest and insurance); and (3) the costs of custom service provided by an off-farm company.

Howland & Karszes (2014) did not find a significant relationship between liquid manure application cost and distance to field, between 0.7 and 16 km. Twin Birch Dairy sells the separated solids and stores the separated liquid 2.3 km away for irrigation within a further 5–6 km. The compliance cost used was, therefore, estimated by multiplying the volume of digestate to be transported off-site by this unit manure application cost. The latter is lower than, but in the same order of magnitude as, that in Europe for digestate disposal (Fuchs & Drosg 2013). Based on the ammonia concentrations of digester effluent under the three options (Figure 1), it is estimated that Option 1 will need storage for 30,694 L/d more digestate off-site and Option 3 13,462 L/d more, compared to Option 2.

Models for returns from ammonia recovery

In addition to the production of ammonium sulfate granules, the thermal stripping of ammonia may enhance anaerobic digestion due to thermal treatment of particulate organic matter in the recirculated digestate and zero risk of ammonia toxicity to methanogens in the digesters (Tao & Ukwuani 2015). The synergistic effects of integrating ammonia recovery to anaerobic digestion have yet to be quantified. The economic analysis in this study does not take the indirect effects of ammonia recovery on anaerobic digestion into account.

Production of ammonium sulfate

Ammonium sulfate production depends on both the recirculation rate and the digester effluent ammonia concentration (Figure 1). During each 3-hour batch operation, almost all ammonia in the

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

digester effluent could be recovered and it is estimated that ammonium sulfate productivity would be 169.6 kg/d and 95.2 kg/d, respectively, in options 2 and 3.

The granular product contains more than 98% ammonium sulfate (Tao & Ukwuani 2015). It could then be sold either as a nitrogen fertilizer or analytical grade chemical. The wholesale price of analytical grade ammonium sulfate is generally above \$10/kg (VWR 2015), while the price of ammonium sulfate granules as a chemical fertilizer is approximately \$0.2/kg (CRU 2014; VWR 2015). Because of product certification requirements and the limited production scale, the ammonium sulfate recovered from digestate at dairy farms would probably need to be sold through a recognized supplier. Therefore, a manufacturer's price of \$6/kg was assumed for this study. Equation (8) is generalized for ammonium sulfate revenue.

$$R_a = P_a \times E_a \times \left(\frac{132}{28}\right) \times \frac{q}{1000} = 0.0047 P_a E_a q \tag{8}$$

where R_a = revenue generation from ammonium sulfate recovered, \$/d; P_a = unit sale price of ammonium sulfate, \$/kg; E_a = digester effluent ammonia concentration, g-N/L; 132/28 = factor converting from ammonia-N to ammonium sulfate; and q = recirculation rate, L/d.

Savings in heating anaerobic digesters

A heat balance shows that the anaerobic digesters will attain the digestion temperature of 37 °C when the ammonia-recovered hot manure is recycled to the inlet of the digesters at the recirculation rate of Option 2, thus saving the cost of energy for digester heating at $K_e\, E_q$. The savings can be calculated for Option 3, with its lower recirculation rate, similarly.

Assessment of costs and benefits

As a chemical engineering process, the ammonia recovery system is assumed to have a usable life of 10 years (USDA 2007; Sinnott & Towler 2009). To compare the three options, NPVs and benefit/cost ratios were calculated using a net discount rate of 8% (USDA 2007), as in Equations (9) and (10).

$$NPV = \sum_{t=1}^{n} \frac{M_t}{(1 + r/100)^t} - M_0 \tag{9}$$

$$\frac{\text{Benefit}}{\text{Cost ratio}} = \frac{\sum_{t=1}^{n} B_t}{\sum_{t=1}^{n} C_t} \tag{10}$$

where NPV = the net present value, \$; t = the time of cash flow, year; n = project life span, year; r = discount rate, %; M_t = net cash flow in year t, \$/yr; M_o = capital outlay at the beginning of investment, \$; B_t = present value of returns in t, \$/yr; and C_t = present value of operating cost in t, \$/yr.

The NPV and benefit/cost ratio are calculated without consideration of a separate inflation rate. The costs and returns are estimated using current unit costs and revenues instead of predicted prices. Instead, sensitivity analysis was carried out to evaluate the uncertainties associated with the key cost and benefit components.

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

RESULTS AND DISCUSSION

Capital and operating costs, and revenues were calculated for each ammonia recovery option, using the cost and revenue models above, as well as the design and operating parameters. As summarized in Table 1, options 2 and 3 have similarly high benefit/cost ratios. However, the NPV of Option 2 is 1.85 times that of Option 3, while that for Option 1 is negative. Options 2 and 3 both require small amounts of initial investment so, Option 2 is economically better. In addition, options 2 and 3 will create 3 and 1.5 jobs, respectively, operating the ammonia recovery system 24 hours a day. Labor cost is the largest component of the operating cost, accounting for between 61 and 69% of its total.

Table 1 | Estimated costs and benefits for three ammonia recovery options from anaerobically digested dairy manure at Twin Birch Dairy Farm

	Option 1	Option 2	Option 3
Rate of recirculation for ammonia recovery (q), L/d	0	30,694	15,347
Total capital cost, $	**0**	**14,226**	**7,113**
Stripping vessels	0	5,211	2,605
Centrifugal pumps	0	8,416	4,208
Acid absorption columns	0	600	300
Total operating cost, $/yr	**33,497**	**226,307**	**127,995**
Energy	0	64,926	32,460
Sulfuric acid	0	2,476	1,390
Lime to increase pH	0	1,040	520
Labor	0	157,154	78,577
Maintenance and repairs	0	711	356
Compliance cost	33,497	0	14,692
Total revenue, $/yr	**0**	**427,362**	**236,483**
Ammonium sulfate production	0	371,355	208,480
Savings in digester heating	0	56,007	28,003
Annual cash flow, $/yr	−33,497	201,054	108,488
10-year net present value (NPV), $	**−224,771**	**1,334,864**	**720,852**
Benefit/cost ratio	**0.0**	**1.89**	**1.85**

The specific benefit of thermal stripping – acid absorption under Option 2 is \$0.018/L-digestate, \$3.25/kg-$(NH_4)_2SO_4$, or \$0.50/d/cow. The specific operating cost of the process, excluding labor, under Option 2 is \$0.006/L-digestate or \$1.12/kg-$(NH_4)_2SO_4$. This is lower than the optimized values for gas stripping – acid absorption, i.e., \$0.014/L-digestate or \$1.63/kg-$(NH_4)_2SO_4$ (Jiang *et al.* 2014).

The greatest uncertainty in this economic analysis is over the sale price of ammonium sulfate because it can be marketed as either a chemical fertilizer or an analytical grade chemical. The wholesale price of ammonium sulfate granules varies greatly, from \$0.2/kg as a chemical fertilizer to between \$10 and \$30/kg as an analytical grade granular chemical (CRU 2014; VWR 2015). Ammonium sulfate is traded globally and its price, especially as a fertilizer, is affected by transport costs, currency exchange rates, policy decisions and other uncontrollable factors. The variations in NPV and benefit/cost ratio under Option 2 were then determined at different percentage price changes relative to the assumed manufacturer price (\$6/kg), i.e., +400% (\$30/kg), +233% (\$20/kg), +66.7% (\$10/kg), and −96.7% (\$0.2/kg). The NPV will be 0 at \$2.77/kg and the benefit/cost ratio 1 at \$2.74/kg (Figure 3).

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.041

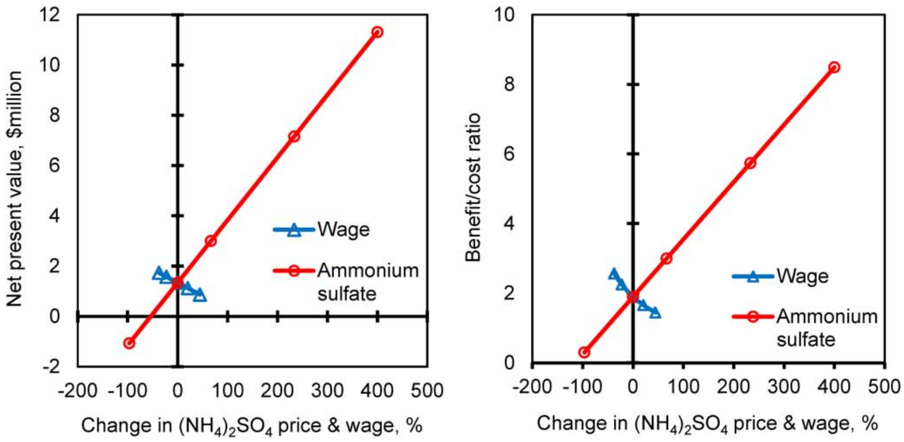

Figure 3 | Strauss plots of NPV and benefit/cost ratio versus changes in the major revenue and cost components at the optimum recirculation rate for ammonia recovery.

The price of sulfuric acid was between $21 and $141/tonne between 2009 and 2014 (ICIS 2014). This level of price variation relative to current prices ($55/tonne) will not result in any significant changes in NPV or benefit/cost ratio because it only accounts for 1.1% of total operating costs (Table 1). The net energy cost – i.e., total energy cost minus savings in digester heating – is only 5.7% of the labor cost for Option 2, so, the sensitivity analysis on the cost components was carried out only in relation to potential changes in labor cost. The hourly wage for farm equipment mechanics and service technicians in the USA varied in 2013, being $11.18 at 10% percentile, $13.86 at 25%, $17.38 at 50%, $21.55 at 75%, and $25.88 at 90% (BLS 2015b). With these variations, the NPV and benefit/cost ratio responded as shown in Figure 3. The NPV will be zero and the benefit/cost ratio 1 at a wage rate of $40.65/h (Figure 3). As indicated by a greater slope of change, the NPV is more sensitive to the ammonium sulfate price than to wage rates. However, it appears that the benefit/cost ratio is equally sensitive to both factors. The hourly wage will probably not reach $41, so, ammonia recovery via thermal stripping – acid absorption will make a profit when ammonium sulfate granules can be sold for $2.77/kg-$(NH_4)_2SO_4$ or more.

CONCLUSIONS

Ammonia recovery via thermal stripping – acid absorption is estimated to be profitable. Although drawing digester effluent at 14 and 28% of the manure loading rate for ammonia recovery yields similar benefit/cost ratios, the higher recirculation rate produces a higher NPV and creates more jobs.

Labor costs account for between 61 and 69% of total operating costs for thermal stripping – acid absorption. Excluding these, the specific operating cost of thermal stripping is substantially lower than that of air-stripping.

The uncertainties in NPV and benefit/cost ratio are mainly associated with the sale price of ammonium sulfate and the hourly wage rate.

ACKNOWLEDGEMENTS

This study was funded by a U.S. EPA grant to Dr. Tao (SU835723). The views expressed are solely those of the authors and do not necessarily reflect those of the Agency. We would like to thank the U.S. Department of State for a Fulbright Foreign Student Program Scholarship to Sohaib Anwar.

Water Practice & Technology Vol 11 No 2
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