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233 Estimation of marginal costs at anaerobic digestion

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Abstract

Anaerobic digestion (AD) is commonly used to treat organic waste due to its robustness and ability to recover energy and material. During its operation, the incoming waste treated by an AD can change either in quantity, composition, or both. This change can have economic implication at which the average cost of treating waste will change. This paper provides means to assess the economic consequences of waste diversion with regards to existing AD. The method was then applied to a case study including AD with co-generation of heat and power. Baseline and four scenarios were developed to assess the economic impact of waste diversion using dairy manure, municipal food waste (MFW), and biosludge as feedstock. The feedstocks for baseline were dairy manure and municipal food waste. There were two waste diversions involving the reduction of manure input and MFW input with the application of six scenarios in regard to this diversion. Negative marginal costs (-6.95 to -4.56 €/ton diluted waste) were obtained in S1 and S4 at which the reduction of certain type of waste was not compensated by other type of waste. Positive marginal costs (2.39 to 2.53 €/ton diluted waste) were found when the input reduction was compensated by other type of waste to produce same amount of methane as shown in baseline scenario. The results implied that the quantity and composition of the incoming waste affected the marginal cost differently. Calculating marginal cost can provide comprehensive view concerning waste diversion and new waste management solution that mainly includes only environmental assessment. This can be used as well for future reference to support decision making and adjusting gate fee.

Keywords: Cost, anaerobic digestion, biogas, waste diversion, waste management

Introduction

There is a paradigm shift in municipal waste management that initially focused on maintaining public health and protecting the environment to resource recovery (Vergara & Tchobanoglous, 2012). In Europe, improved waste management has reduced the amount of waste going into landfill despite the increase in waste generation (Evangelisti, Lettieri, Borello, & Clift, 2014). It includes sourced-separated collection and applying suitable technology that can treat different type of waste safely resulting material and energy recovery as well as volume reduction. One of the technologies is anaerobic digestion (AD) that has been used to treat organic waste. Biological process involving different types of bacteria with the absence of oxygen occurs in AD so that organic matter is converted into biogas and digestate. AD provides benefits due to its robustness in handling high organic loading rate, its ability to treat waste without pre-treatment, and its products such as biogas and digestate (Appels et al., 2011). Biogas generated by AD contains methane for around 65% making it suitable for renewable energy source whereas the digestate has high nutrient and can be used as fertilizers (Appels et al., 2011; Evangelisti et al., 2014).

Although AD provides benefits in treating biowaste, the technology requires high monetary investment with a long technical lifespan (Edwards, Burn, Crossin, & Othman, 2018). During its operation, progress can occur in the society and government causing changes in the socio-economic condition, regulation, and environmental requirement. For example, regulation change such as landfill ban can prevent food waste from being landfilled and it must divert to existing AD. These changes will alter the quantity and composition of organic waste treated by AD implying an economic implication in the post-design costs of AD. Post-design cost including marginal costs and average cost. The first one refers to the supplementary cost related to additional quantity of something (e.g., the change in total cost of AD to treat an extra ton of waste), while average cost represents the cost resulted from dividing total cost in running AD facility by total waste input (Martinez-Sanchez et al., 2016; Massarutto, 2015).

As a suitable technology to treat organic waste, AD is widely used as shown by the increase in total capacity in Europe. Its capacity was 120000 ton per year in 1990, and it has increased into almost 9 million tons per year in 2015 (European Bioplastics, 2015). It shows the importance of AD and the economic consequence regarding its operation should be understood. To anticipate the unexpected cost with regards to waste diversion, this study aims at developing an approach to calculate economic consequences of waste diversion in existing AD facilities that can be used as basis in decision making. The applicability of the approach is tested using a hypothetical case study of AD facility. The aim of the study is achieved through specific objectives: i) define cost item of AD facility, and ii) identify marginal costs related to diversions of different waste composition.

Materials and methods

The basis of marginal cost concept at existing waste facilities was adopted from work developed by Martinez-Sanchez et al. (2016):

a. Assessing the average costs of baseline situation of AD based on waste parameter. The cost items were defined as fixed costs, effluent handling costs, energy and consumable costs, and revenue.
b. Defining marginal change that was represented by different scenarios. These scenarios illustrating various waste quantity and composition.
c. Assessing the average costs of various scenarios where marginal change occurs.
d. Estimating the marginal cost as the difference between average costs in baseline situation (a) and the alternative scenarios (c).

Case study

This hypothetical case study was used to illustrate the financial implication of waste diversion at AD. The AD was assumed to have maximum throughput of 88000 ton/year with its design of 12% total solids (TS), 20 days of hydraulic retention time (HRT) and operating period of 8000 hours per year. Pre-treatment facility that has throughput of 22000 ton/year was used for MFW. Figure 1 shows the sketch of AD digestion flow that produce heat, electricity and biosolids to sale (dashed boxes). Table 1 shows elemental composition, total solids (TS), and volatile solids (VS) of dairy manure (Akyürek, 2019; Chen, Rojas-Downing, Zhong, Saffron, & Liao, 2015; Tsai, Huang, & Lin, 2019), MFW (Arafat & Jijakli, 2013; Zhang, Lee, & Jahng, 2011), and biosludge (Nielfa, Cano, & Fdz-Polanco, 2015; Saarela, 2018).

Table 1 composition of the feedstocks

Feedstock	Dairy manure	Municipal food waste (MFW)	Biosludge
C (% dw)	33.07	44.99	5.4
H (% dw)	4.87	6.43	9.1
O (% dw)	58.53	28.76	36.4
N (% dw)	2.9	3.3	0.6
VS (g/kg)	79	170	56.9
TS (%)	13	31	20

The baseline scenario comprises of dairy manure and MFW as feedstocks, and waste diversion will cause the input of dairy manure decreasing for 5%. The scenarios to illustrate marginal cost were: i) no reaction to the waste diversion (S1), ii) increasing the input of MFW (S2), iii) using biosludge to replace dairy manure (S3). Another diversion involved the decrease amount of MFW input by 12% causing the CH_4 production equalled with 5% reduction manure input. The scenarios regarding the second diversion were: i) no reaction to the diversion (S4), ii) increasing the input of dairy manure (S5), iii) using biosludge to replace MFW (S6). In the scenario S2, S3, S5, and S6 the addition of MFW, dairy manure or biosludge would maintain the CH_4 production at the same level as baseline scenario.

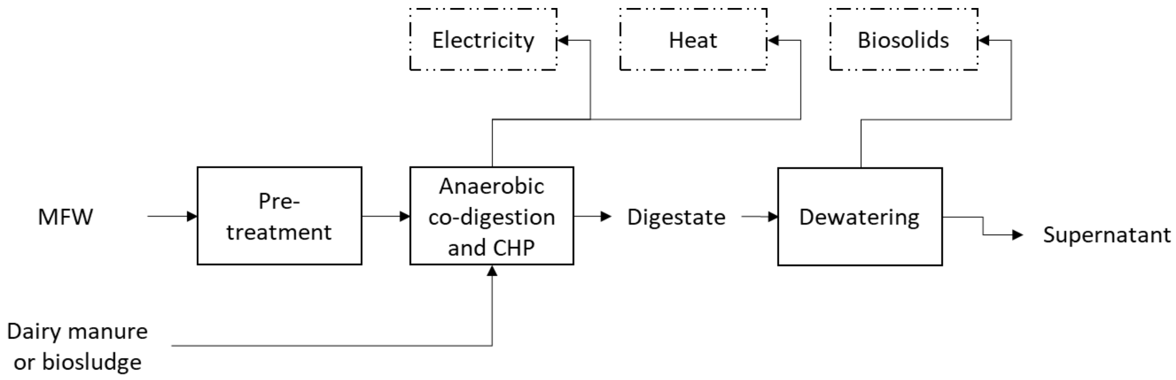

Figure 1 The sketch of AD flow

Cost model

The average cost calculation consisted of fixed cost (FC), effluent handling cost (EC), energy consumption and consumables cost (ECC), and revenue (Rev) as shown by equation (1). The cost was then divided by usage rate (UR) which equalled to the annual waste input that has been diluted for digestion process. The reference year was 2020 and the result was expressed in monetary unit per ton diluted waste (12% TS) in the AD (€/ton diluted waste). The cost unit for each parameter was based on Finnish or European condition.

$$Average\ cost = \frac{FC + EC + ECC + Rev}{UR} \quad (1)$$

Fixed cost

Annual fixed cost included amortisation of capital cost (CAPEX), annual maintenance cost (MC), annual insurance cost (IC), and annual labour cost (LC). CAPEX comprised of land cost, planning and design, building and civil work, process equipment and other contingency cost for pre-treatment facility and AD facility (Martinez-Sanchez, Kromann, & Astrup, 2015). The amortisation of CAPEX was obtained by converting the total capital cost into annuities using interest rate (4.6%) and the lifetime of the technology (25 years). It was reported that an AD (300000 ton/year) and a mechanical pre-treatment facility for municipal organic waste (30000 ton/year) cost for about 20.6

M€ and 5.8 M€, respectively (Martinez-Sanchez et al., 2015). To adjust the known cost of a facility into a specific capacity, the rule of 0.6 can be used as shown by equation (2) (Serna, 2018):

$$\frac{Cost_1}{Cost_2} = \left(\frac{Cap_1}{Cap_2}\right)^{0.6} \qquad (2)$$

where Cap_1 and Cap_2 are the capacity of first and second equipment meanwhile $Cost_1$ and $Cost_2$ are the cost of first and second equipment, respectively. Adjustment to reference year may be needed and can be performed using the Marshall and Swift index as shown by equation (3):

$$\frac{C_1}{C_2} = \left(\frac{I_1}{I_2}\right) \qquad (3)$$

where $C_{1,}$ and $C_{2,}$ show the calculated cost at year 2020 and the reference price, whereas I_1 and I_2 are the index at year 2020 and at the reference year, respectively. Annual insurance and maintenance costs were assumed to be 1.5% and 3% of CAPEX, respectively (Martinez-Sanchez et al., 2015). The number of employees were assumed to be 8 and the average salary was 25 €/hour. Equation (4) shows the formula of fixed cost (FC):

$$FC = CAPEX + MC + IC + LC \qquad (4)$$

Effluent handling cost

The effluent cost (EC) was related to the handling of supernatant and biosolids as shown by equation (5). Cost in treating supernatant was a product of supernatant (m_{sp}) and price of treating a unit mass of supernatant (P_{sp}). Meanwhile, the cost of handling biosolids was obtain by multiplying biosolids (m_{bs}) and price of treating a unit mass of biosolids (P_{bs}).

$$EC = m_{sp}.P_{sp} + m_{bs}.P_{bs} \qquad (5)$$

The system has TS reduction rate of 50% and water content in biosolids of 17% (Chen et al., 2015; Remy, 2018), whereas the price in treating supernatant and biosolids are 0.68 €/ton supernatant and 26 €/ ton biosolids, respectively (Edwards et al., 2018).

Energy consumption and consumables

Energy consumption and consumables (ECC) comprises of expenses for the electricity, natural gas, water, and activated carbon as shown by equation (6) . The water consumption related to the dilution was required to adjust the TS of the waste into 12%. The consumption of electricity and natural gas were 0.031 % of biogas produced and 0.036 % of biogas produced, respectively, with additional electricity of 9.16 kWh/ton feedstock was required for dilution of MFW due to its high content of TS (Evangelisti et al., 2014). Activated carbon required by MFW was about 0.0082 ton/ton feedstock, whereas manure and biosludge consume 0.0015 ton/ ton feedstock (Chen et al., 2015).

$$ECC = W.P_w + AC.P_{ac} + El.P_{el} + NG.P_{ng} \quad (6)$$

$$W = Waste\ diluted\ weight - Feedstock\ weight$$

$$Waste\ diluted\ weight = Feedstock\ weight.\frac{TS_{act}}{TS_d}$$

where $W, AC, El,$ and NG are the consumption of water, activated carbon, electricity, and natural gas, respectively. Meanwhile $P_w, P_{ac}, P_{el},$ and P_{ng} refer to price of water, activated carbon, electricity, and natural gas. It was estimated that: electricity costed 0.066 €/kWh, natural gas costed 0.032 €/kWh, activated carbon costed 0.94 €/kg, and water costed 0.4 €/m^3 (Ecoinvent Centre, 2019; Eurostat, 2020a, 2020b). To calculate the water required for dilution, estimation of the weight of diluted waste was needed. It could be calculated using the information regarding the feedstock weight, the actual TS of the feedstock (TS_{act}) and the TS design (TS_d)

Revenues

The revenues were obtained from the sale of heat, electricity and biosolids (pressed digestate). The amount of heat and electricity generated depend on CH_4 produced. To estimate CH_4 potential, laboratory test is usually performed. However, the process takes time and can be costly. This study employs stoichiometric equation based on elemental composition of the feedstocks by taking into account carbon (C), oxygen (O), hydrogen (H), and nitrogen (N). Boyles equation shows the chemical reaction occurred as shown by equation (7) (Nielfa et al., 2015):

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} - \frac{b}{4} + \frac{3c}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} - \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3$$

$$BMP_{th} = \frac{22.4\left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)}{12n + a + 16b + 14c} \quad (7)$$

with BMP_{th} indicates theoretical methane generated by certain feedstocks in AD. The constant of each element such as n, a, b, c are obtained from dividing the mass of each element in grams (**Table 1**) by its relative mass.

Additivity method was applied to estimate the total theoretical methane production by estimating methane potential from individual feedstocks and summing them up. The value of 0.8 was used to adjust the methane production model under ideal condition to the realistic condition (Achinas & Euverink, 2016). This method did not take into account synergistic or inhibitory effect that may potentially occur in co-digestion process. Holliger, Fruteau de Laclos, & Hack (2017) reported that the difference of methane potential in laboratory experiment between mixed substrates and additivity of individual substrates were not significant.

The energy recovery system employs CHP assuming that electricity efficiency was 32%, heat efficiency was 50% (Evangelisti et al., 2014),and the energy content of methane was 10 kWh/m^3 (World Nuclear Association, 2016). Equation (8) shows the revenue from AD.

$$Rev = Electricity.SP_{el} + Heat.SP_h + Biosolids.SP_b \quad (8)$$

where SP_{el}, SP_h, SP_b are selling price of electricity (0.066 €/kWh), heat (0.027 €/kWh) and biosolids (5 €/ton), respectively (Corden et al., 2019; Eurostat, 2020a; Helen ltd, 2021).

Marginal costs

The marginal cost is defined as the additional cost in treating organic waste using AD with regards to a change in waste quantity. The change in waste quantity was represented by different scenarios, and the marginal cost was calculated using equation (9).

$$Marginal_{cost} = \frac{Average\ cost_{scenario} \cdot m_{scenario} - Average\ cost_{baseline} \cdot m_{baseline}}{m_{scenario} - m_{baseline}} \quad (9)$$

at which $m_{scenario}$ and $m_{baseline}$ indicate the quantity of waste treated (diluted to 12% TS) in various scenarios and baseline, respectively.

Sensitivity analysis

Sensitivity analysis was performed to identify the consequences of input parameters on the results. It was carried out by applying perturbation analysis at which each input parameter was increased by 10% one at a time while keeping other parameters as the same as the baseline values. The results of perturbation analysis was used to calculate (SR) which indicated the ratio of two relative changes as shown by equation (10) (Clavreul, Guyonnet, & Christensen, 2012).

$$SR = \frac{\frac{\Delta\, result}{initial\ result}}{\frac{\Delta\, parameter}{initial\ parameter}} \tag{10}$$

Results and Discussion

Average cost of anaerobic digestion

Calculation on methane potential using elemental composition and stoichiometry showed that dairy manure, MFW, and biosludge could generate for about 178.37 ml CH_4/g VS, 458.29 ml CH_4/g VS, and 267.81 ml CH_4/g VS, respectively. The total methane generated in the baseline scenario was about 1.26 Mm^3 in a year. It was translated into average cost of treating waste using AD for about 27.62 €/ton diluted waste (Table 2), meanwhile the gross costs were around 33.36 €/ton diluted waste. The major costs contribution was from fixed cost. Within fixed cost, the highest contributions were from labour costs and annual capital costs for about 66% and 33%, respectively. The costs related to energy consumption, water and consumables were minor compared the whole cost items, meanwhile the total revenue from selling electricity, heat, and biosolids brought revenue for about 5.74 €/ton diluted waste.

Table 2 Average cost of baseline system

Cost item	Value (€/ton diluted waste)
Annual fixed cost:	
• Labour cost	19.76
• Insurance cost	0.15
• Maintenance cost	0.29
• Amortization capital cost	9.79
Energy consumption, water, and consumables	0.89
Effluent handling	
• Supernatant handling	0.6
• Biosolids handling	1.88
Revenue	
• Electricity sale	-3.28
• Heat sale	-2.1
• Biosolids sale	-0.36
Total average cost	27.62

The average cost of treating waste using AD was correspond well with other studies, such as ones performed by Edwards et al. (2018) and (WRAP, 2018). The denominator unit in other study might be different, because the other study seemed to use monetary unit per ton waste input instead of diluted waste, nevertheless, our results were still similar and fell in between their ranges.

Marginal cost

Waste diversion was illustrated by decreasing dairy manure input for about 5% and in another case, decreasing MFW input by 12%. In S1 and S4 where there were no reaction to the decrease, energy production would decrease as well. Meanwhile in S2, S3, S5, and S6 there were additional input of different feedstocks to maintain the energy production as equal as baseline scenario. The study assumed the use capacity of the AD was not 100% but ranging from 88-96%. Table 3 summarises the input and output of all scenarios.

Table 3 Summary of inputs and outputs for each scenario

Scenario	Feedstock (ton/year)			Use capacity (%)	Energy produced (MWh)		Diluted waste (ton)	Biosolids (ton)
	Dairy manure	MFW	Biosludge		Electricity	Heat		
Baseline	63522	4701	0	92	4036.3	6306.7	80960	5853
S1	60346	4701	0	88	3893.1	6082.9	77519	5604
S2	60346	5275	0	90	4036.3	6306.7	79003	5711
S3	60346	4701	2937	94	4036.3	6306.7	82414	5958
S4	63522	4126	0	90	3893.1	6082.9	79476	5745
S5	66699	4126	0	94	4036.3	6306.7	82917	5994
S6	63522	4126	2937	96	4036.3	6306.7	84371	6099

Although energy production in S2, S3, S5, and S6 were the same as baseline, the quantity of feedstock input and diluted waste were varied. It was affected by different TS and CH_4 potential in each of the feedstock. Higher TS will require more water to dilute the waste in order to achieve the TS design (12%). Meanwhile, feedstock with higher CH_4 potential will limit the input due to its high energy content.

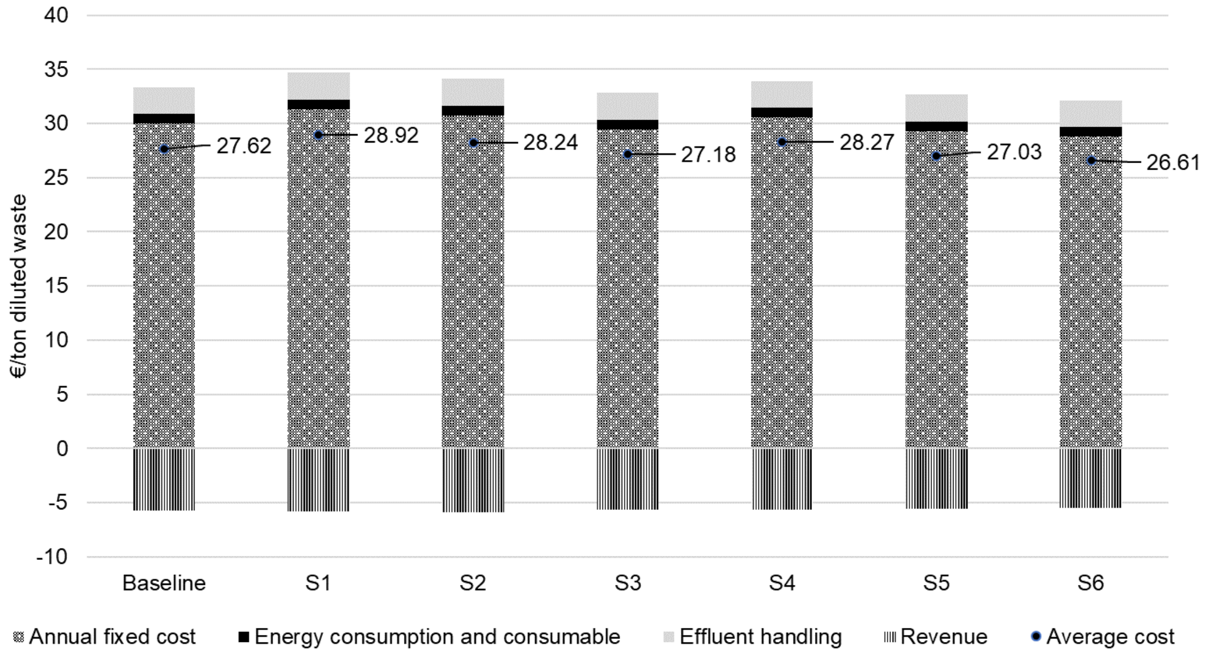

Figure 2 Average cost of baseline and alternative scenarios

Figure 2 shows average costs of baseline and alternative scenarios. S1, S2, and S4 resulted higher average costs compared to the baseline, meanwhile S3, S5, and S6 produced lower average costs. The average costs and the quantity of the waste were used to estimate marginal costs as shown in Figure 3. For the marginal cost, same pattern occurred in the case of reduction of manure input and MFW. The marginal costs were negative when the diversion was not followed by reaction (S1 and S4), and the marginal costs were positive when the diversion was followed by the reaction through additional waste input (S2, S3, S5, S6). When the manure input was reduced by 5% and the MFW input was reduced by 12%, the CH_4 generation was the same for around 1.21 Mm^3 CH^4. However, the value of marginal costs was different at which reducing MFW resulted lower cost for about 78% than reducing manure input. The reduction of manure input corresponded to a decrease of 3176 ton manure feedstock that is relatively higher compared to diversion of MFW that was translated into a reduction of 574 ton MFW feedstock. This stark difference was caused by the content of CH_4 in the feedstocks.

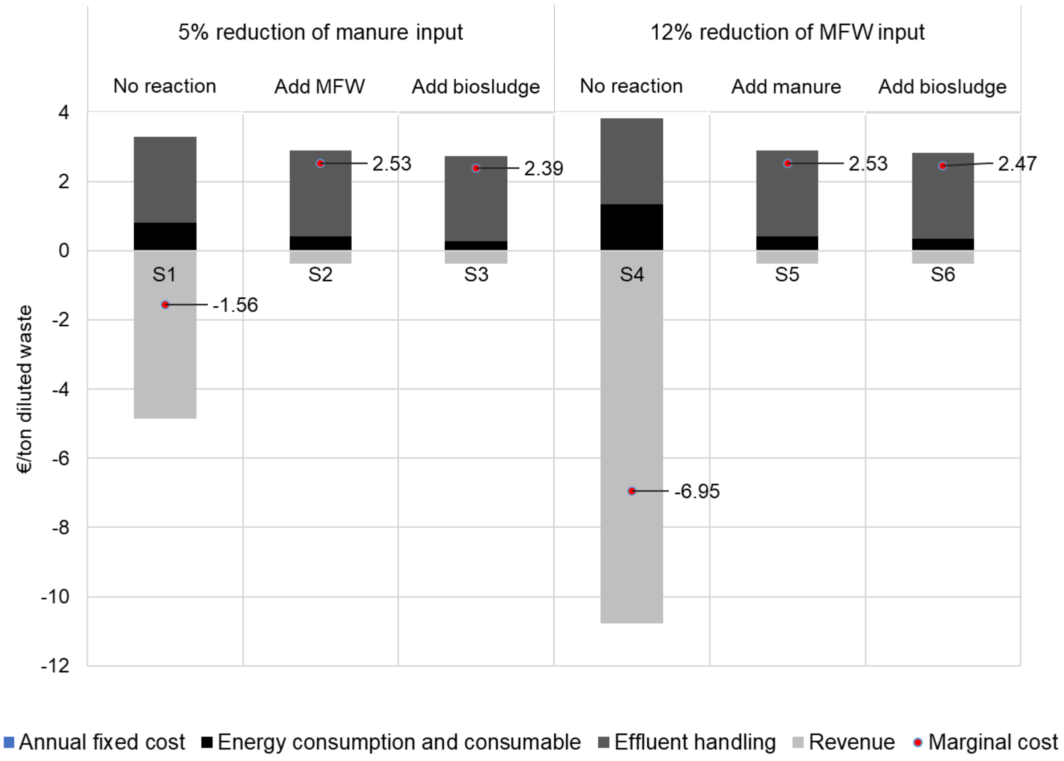

Figure 3 Marginal cost of waste diversion in AD

S2 and S5 resulted same marginal cost. The proportion of dairy manure and MFW in S2 and S5 were 84:16 and 87:13, respectively. Nevertheless, the production of CH_4 was equal and feedstock types were similar. This might explain the similarity in the marginal cost values. In S3 and S6, to maintain CH4 production, the diversion was aided by biosludge addition for about 2937 ton in both scenarios. These additions resulted positive marginal costs that were only slightly different in between S3 and S6.

Sensitivity analysis

Figure 4 shows the results of perturbation analysis with x axis indicates the SR. The parameters included were only the ones that gave results larger than ± 0.025. If an SR has value of 0.025, it shows that when the value of parameter is increased by 10%, the result will increase by 2.5%. The SR results ranging from -0.18 up to 0.72. Positive SR indicates linear correlation at which an increase value of the parameter will drive the cost higher, whereas the opposite correlation is indicated by SR with negative values. For the positive SR, the most sensitive parameters were number of employee and labour cost (0.72) followed by interest rate (0.37) and CAPEX (0.35). For the negative one, 10% increase in LHV of CH_4 will drive down the cost by 18%

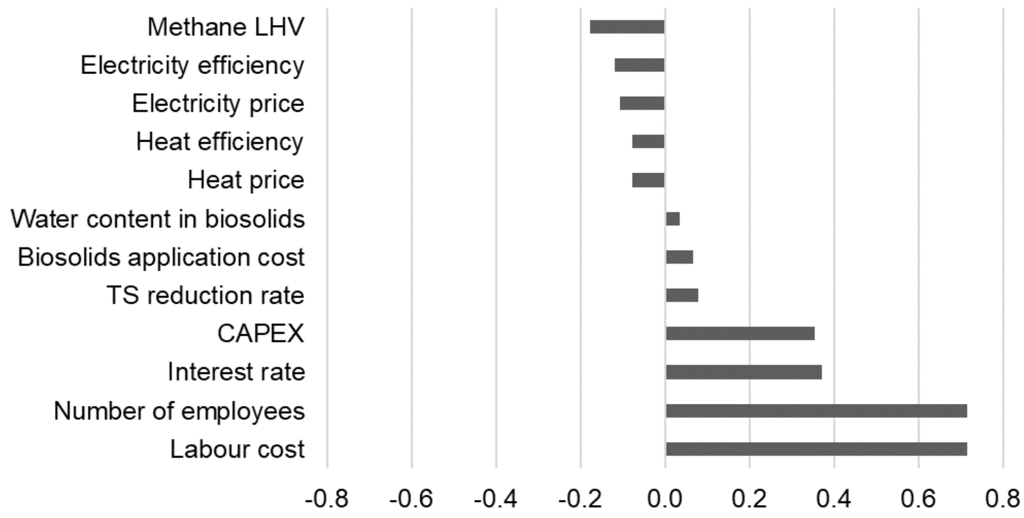

Figure 4 Sensitivity ratio among input parameters

Limitations and implications

The study on the marginal cost of existing AD was done using secondary data. Assessing CH_4 potential through experiment can provide more accurate results although it takes time and can be expensive. Meanwhile, the use of secondary data and stoichiometry are quicker. Although it can result more uncertainties, conducting CH_4 assessment using stoichiometry can gauge the potential economic consequences and anticipate it when diversion strategy is applied.

Gate fee is levied to usually offset cost of opening, operating, and closing the facility. The value may change based on the cost incurred regarding the facility. The marginal costs due to waste diversion may be aided by an adjustment of gate fee, accordingly, this study did not include gate fee as one of cost items.

The results of S1 and S4 showed the importance of waste composition. The marginal cost of diverting waste in both scenarios were difference although S1 and S4 producing the same amount of CH_4. Each waste type has different level of TS and methane potential that limits the input quantity into the AD. This study only simulated few scenarios that limit the knowledge on how the system will behave, whereas many other waste types can be treated and diverted to and from AD.

Conclusions

This study developed marginal costs estimation caused by waste diversion in AD. The model was then applied in case study showing its applicability. This study illustrated that costs calculation involve various costs items that can be categorized into fixed costs, energy and consumables, effluent handling, and revenue. The variety of cost items can affect the result and increase uncertainty of the study. The case study showed that marginal costs can be positive or negative depending on the waste being diverted and a reaction towards the diversion. It was also shown that marginal and average costs were highly influenced by waste quantity and types. The approach used in this study can be applied to assess cost change with regards to waste diversion that will help waste strategy development.

References

Achinas, S., & Euverink, G. J. W. (2016). Theoretical analysis of biogas potential prediction from agricultural waste. *Resource-Efficient Technologies*, *2*(3), 143–147. https://doi.org/10.1016/j.reffit.2016.08.001

Akyürek, Z. (2019). Sustainable valorization of animal manure and recycled polyester: Co-pyrolysis synergy. *Sustainability (Switzerland)*, *11*(8). https://doi.org/10.3390/SU11082280

Appels, L., Lauwers, J., Degrve, J., Helsen, L., Lievens, B., Willems, K., … Dewil, R. (2011). Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renewable and Sustainable Energy Reviews*, *15*(9), 4295–4301. https://doi.org/10.1016/j.rser.2011.07.121

Arafat, H. A., & Jijakli, K. (2013). Modeling and comparative assessment of municipal solid waste gasification for energy production. *Waste Management*, *33*(8), 1704–1713. https://doi.org/10.1016/j.wasman.2013.04.008

Chen, R., Rojas-Downing, M. M., Zhong, Y., Saffron, C. M., & Liao, W. (2015). Life cycle and economic assessment of anaerobic co-digestion of dairy manure and food waste. *Industrial Biotechnology*, *11*(2), 127–139. https://doi.org/10.1089/ind.2014.0029

Clavreul, J., Guyonnet, D., & Christensen, T. H. (2012). Quantifying uncertainty in LCA-modelling of waste management systems. *Waste Management*, *32*(12), 2482–2495. https://doi.org/10.1016/j.wasman.2012.07.008

Corden, C., Bougas, K., Cunningham, E., Tyrer, D., Kreißig, J., ..., & Crookes, M. (2019). *Digestate and compost as fertilisers: Risk assessment and risk management options*. Retrieved from https://ec.europa.eu/environment/chemicals/reach/pdf/40039 Digestate and Compost RMOA - Final report i2_20190208.pdf

Ecoinvent Centre. (2019). Ecoinvent 3.6. Retrieved May 10, 2020, from https://www.ecoinvent.org/database/ecoinvent-36/ecoinvent-36.html

Edwards, J., Burn, S., Crossin, E., & Othman, M. (2018). Life cycle costing of municipal food waste management systems: The effect of environmental externalities and transfer costs using local government case studies. *Resources, Conservation and Recycling*, *138*, 118–129. https://doi.org/10.1016/j.resconrec.2018.06.018

European Bioplastics. (2015). *Anaerobic digestion fact sheet*. Retrieved from https://docs.european-bioplastics.org/publications/bp/EUBP_BP_Anaerobic_digestion.pdf

Eurostat. (2020a). Electricity price statistics. Retrieved June 25, 2020, from https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Further_Eurostat_information

Eurostat. (2020b). Natural gas price statistics. Retrieved June 25, 2020, from https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics

Evangelisti, S., Lettieri, P., Borello, D., & Clift, R. (2014). Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. *Waste Management*, *34*(1), 226–237. https://doi.org/10.1016/j.wasman.2013.09.013

Helen ltd. (2021). Open district heat. Retrieved July 21, 2021, from https://www.helen.fi/en/companies/heating-for-companies/open-district-heat

Holliger, C., Fruteau de Laclos, H., & Hack, G. (2017). Methane Production of Full-Scale Anaerobic Digestion Plants Calculated from Substrate's Biomethane Potentials Compares Well with the One Measured On-Site. *Frontiers in Energy Research*, *0*(JUN), 12. https://doi.org/10.3389/FENRG.2017.00012

Martinez-Sanchez, V., Hulgaard, T., Hindsgaul, C., Riber, C., Kamuk, B., & Astrup, T. F. (2016). Estimation of marginal costs at existing waste treatment facilities. *Waste Management*, *50*, 364–375. https://doi.org/10.1016/j.wasman.2016.02.032

Martinez-Sanchez, V., Kromann, M. A., & Astrup, T. F. (2015). Life cycle costing of waste management systems: Overview, calculation principles and case studies. *Waste Management*, *36*, 343–355. https://doi.org/10.1016/J.WASMAN.2014.10.033

Massarutto, A. (2015). Economic aspects of thermal treatment of solid waste in a sustainable WM system. *Waste Management*, *37*, 45–57. https://doi.org/10.1016/j.wasman.2014.08.024

Nielfa, A., Cano, R., & Fdz-Polanco, M. (2015). Theoretical methane production generated by the co-digestion of organic fraction municipal solid waste and biological sludge. *Biotechnology Reports*, *5*(1), 14–21. https://doi.org/10.1016/j.btre.2014.10.005

Remy, F. (2018). *Potential for the anaerobic digestion of municipal solid waste (MSW) in the city of Curitiba, Brazil*. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-226313

Saarela, J. (2018). *Biogas as an important part of the sustainable development in our society*. Retrieved from https://www.energyweek.fi/wp-content/uploads/2017/09/7.-Stormossen_Energy-Regulation_VEW18_20180320_v0a.pdf

Serna, R. (2018). Minerals and recycling equipment design. Retrieved June 18, 2020, from https://mycourses.aalto.fi/pluginfile.php/641946/mod_resource/content/1/EquipDesign-Part2.pdf

Tsai, W. T., Huang, P. C., & Lin, Y. Q. (2019). Characterization of biochars produced from dairy manure at high pyrolysis temperatures. *Agronomy*, *9*(10). https://doi.org/10.3390/AGRONOMY9100634

Vergara, S. E., & Tchobanoglous, G. (2012). Municipal solid waste and the environment: A global perspective. *Annual Review of Environment and Resources*, *37*, 277–309. https://doi.org/10.1146/annurev-environ-050511-122532

World Nuclear Association. (2016). Heat values of various fuels. Retrieved July 20, 2021, from http://www.world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

WRAP. (2018). *Comparing the costs of alternative waste treatment options*. Retrieved from https://www.wrap.org.uk/sites/files/wrap/WRAP Gate Fees 2018_exec+extended summary report_FINAL.pdf

Zhang, L., Lee, Y. W., & Jahng, D. (2011). Anaerobic co-digestion of food waste and piggery wastewater: Focusing on the role of trace elements. *Bioresource Technology*, *102*(8), 5048–5059. https://doi.org/10.1016/j.biortech.2011.01.082