Distributed and micro generation from biogas and agricultural application of sewage sludge: Comparative environmental performance analysis using life cycle approaches

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Abstract

The Feed-In-Tariff scheme in the UK has generated attractive economics in the investment for anaerobic digestion (AD) to convert sewage sludge into biogas and digested sludge for energy and agricultural applications, respectively. The biogas is a source of biomethane to replace natural gas in the gas grid system. Biogas can be utilised to generate combined heat and power (CHP) on-site, at household micro and distributed or community scales. These biogas CHP generation options can replace the equivalent natural gas based CHP generation options. Digested sludge can be transformed into fertiliser for agricultural application replacing inorganic N:P:K fertiliser. Biogas and digested matter yields are inter-dependent: when one increases, the other decreases. Hence, these various options need to be assessed for avoided life cycle impact potentials, to understand where greatest savings lie and in order to rank these options for informed decision making by water industries. To fill a gap in the information available to industry dealing with wastewater, the avoided emissions by various AD based technologies, in primary impact potentials that make a difference between various systems, have been provided in this paper.

1 m^3 biogas can save 0.92 m^3 natural gas. An average UK household (with a demand of 2 kWe) requires 180000 MJ or 5000 m^3 or 4.76 t biogas per year, from 15.87 t sewage sludge processed through AD. The proton exchange membrane fuel cell (PEM FC) is suitable

for building micro-generations; micro gas turbine (GT), solid oxide fuel cell (SOFC) and SOFC-GT hybrid are suitable for distributed generations upto 500 kWe and occasionally over 500 kWe; engine and ignition engine above 1 MWe. These CHP technologies can be ranked from the lowest to the highest impacts per unit energy production: PEM FC is the environmentally most benign option, followed by SOFC, SOFC-GT, Engine or Micro GT and Ignition engine (with the highest impact potential), respectively. In terms of avoided global warming, acidification and photochemical ozone creation potentials, compared to equivalent natural gas based systems, the biogas based PEM FC micro-generation and Micro GT distributed systems achieve the greatest avoided emissions with the most cost-effectiveness. Application of digested sludge as fertiliser has more toxicity impacts, however, has greater avoided emissions in acidification and photochemical ozone creation potentials on the basis of inorganic N:P:K fertiliser, compared to the biogas production for the natural gas grid system.

Keywords: wastewater treatment, decentralised generation, biomethane, activated sludge processing, CHP generation, combined Monte Carlo simulation and LCA.

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1. Introduction

There are economic incentives in sewage sludge utilisation for distributed and micro-generation of combined heat and power (CHP), following the introduction of Feed-In-Tariff (FIT) scheme in the UK [1-3]. The distributed systems at community scale are meant to generate few hundred kilowatts to few megawatts of electricity, while the household micro-generation systems are designed to produce 1-4 kilowatts of electricity [2]. The FIT scheme offers the payment for each unit of renewable electricity generation using the technologies shown in the scheme. Thus the scheme enables reduction in import of electricity by facilitating self-generation and export of additional electricity to the electricity grid system. The various payments under the FIT scheme applicable to sewage sludge utilisation in the UK are shown in **Table 1.** These payments create economic incentives for water companies to invest in anaerobic digestion (AD) and CHP plant installations in the UK [2]. However, there remains the most important question to be answered for industries: in which sequence the following technologies to invest on to achieve greatest emission cuts or avoided impact potentials from the plant, biogas to natural gas grid system, on-site biogas based CHP generation and fertiliser production from digested sludge. Additionally, it will be extremely useful to identify most important or sensitive environmental impact categories to evaluate, as LCA is a data intensive exercise. LCA results may be affected by data uncertainty and variability and must be resolved by stochastic Monte Carlo simulations and scenario analysis. This papers answers to these most critical research questions, comprehensively.

A number of studies have been undertaken to find technical solutions for alternative products from solid organic wastes, biogas, cleaner liquid fuel and residual solids for agricultural applications [4-11]. Further, **Table 1** shows the CHP technologies for utilising biogas from the AD plant. The FIT rates shown are applicable to the AD plant installations. For CHP plant installations, a separate FIT rate of 11 pence per kilowatt-hour is applied.

Table 1

Though economic incentives in energy application of sewage sludge through the AD process have been enhanced by such schemes, these solid organics can also be used as fertilisers. Their agricultural application could be environmentally more benign. The latter application however, is associated with some inorganic and heavy metal emissions to soil that eventually are released to the atmosphere and water [12-13].

One driver for alternative energy application of sewage sludge is that their growing quantities in landfills are causing emissions to water and air. Concerns over health and environmental protection are growing as increasing number of contaminants are emitted to water resources previously considered clean. Hence, other usages of sewage sludge, such as energy generation must also be assessed for environmental sustainability. Life cycle costs and primary life cycle assessments (LCA) of various waste water treatment and biogas production processes have been published [14-20]. However, comparative environmental performance analysis using LCA, in terms of avoided emissions, between biogas based on-site distributed and micro CHP generation technologies has not been published. Also, environmental impact potential tradeoffs between biogas production and digested sludge production from sewage sludge via AD need to be established. Thus the aim of this paper is to prioritise primary impact characterisations that make a difference in the selection of the technologies and thereby rank these technologies according to avoided primary impact potential evaluations. Furthermore, Monte Carlo simulation has been carried out to show the probability distributions of impact characterisations and also to determine the most sensitive primary impact characterisations for the wastewater AD system. All the primary impact potentials, acidification (AP), eutrophication (EP), freshwater aquatic ecotoxicity (FAETP), global warming over 100 years (GWP), human toxicity (HTP), marine aquatic ecotoxicity (MAETP), ozone layer depletion (ODP), photochemical ozone creation (POCP) and terrestrial ecotoxicity (TETP) have been evaluated comprehensively, for recommending the most important ones.

2. Process description

Waste water is collected by sewer system and transported to a treatment process. The process configuration comprising primary and secondary treatments along with the operating inventory data is shown in **Fig. 1**. The two main sludge streams collected as a feedstock from the primary and secondary treatment process units are the primary sludge and activated sludge. If there is a large quantity of phosphorous compounds present after the secondary treatment, a tertiary phosphate precipitation process unit is used before releasing water to river or reserve. These process units are common in a waste water treatment plant and can be excluded from the systems to be analysed for comparative LCA.

Fig. 1

The system under consideration shown within the boundary in **Fig. 1** is discussed as follows. The sludge feedstocks are taken to an AD process unit, where micro-organisms in the absence oxygen destroy or decompose the nutrients and produce a gas stream rich in methane and a nutrient rich residual stream. Upon scrubbing with water for further removal of impurities from the gas followed by drying, biogas consisting of methane and carbon dioxide as the main components and nutrient rich digested matter are produced. The two most commonly used physical absorption processes, the Rectisol^{TM} and Selexol^{TM} technologies, can be used for the removal of H_2S, COS, HCN, NH_3, nickel and iron carbonyls, mercaptans, naphthalene, organic sulphides, etc. to a trace level in the biogas, before its injection to the gas grid system. The solvent is regenerated at a higher temperature by temperature swing and metallic sulphur is recovered from the sour gas by the Claus process, where hydrogen sulphide rich gases are partially combusted with a limited amount of air to produce sulphur dioxide, so that a reaction between unreacted hydrogen sulphide and sulphur dioxide can take place to form metallic sulphur. Impurities such as hydrocarbons in the feed gas are also combusted and the products of combustion can interact to form gaseous sulphur containing by-products. The gas clean up processes required to maintain the impurity levels to less than ppm level for trouble free operation of the electrodes of the fuel cells are discussed in detail elsewhere [21-22]. There is an alternative route to AD and that is to directly produce sludge flake upon drying and pressing, implemented by Thames Water [23]. This is a highly combustible source of energy and can be mixed with other biomass fuels in thermo-chemical processes (e.g. gasification, pyrolysis). This process is discussed elsewhere [24].

3. Methodology

The LCA (International Organisation for Standards, ISO standards 14040, 14041 and 14044 [25-27]) methodology was adopted to establish comparative LCA results between systems. An LCA study has four main stages: the goal and scope definition and inventory analysis are discussed in this section; impact assessment and interpretation are included in the following section on results and discussions. The LCA was undertaken in GaBi 6.0 using Ecoinvent 2.0 inventory databases [13].

3.1. Goal and scope definition

The system boundary, process operating inventory data including the detailed inventory of ash and metal disposed to the landfill, per day basis, are shown in **Fig. 1**. The original information obtained from Thames Water was reconciled into the data shown in **Fig. 1**. For comparison between various systems, in terms of avoided impacts compared to the equivalent fossil based systems, a functional unit of 1 ton of sewage sludge AD processing into 315 Nm^3 or 0.3 ton or 11340 MJ of biogas (calorific value = 36 MJ per m^3) and 0.7 ton of digested matter production has been considered. The following system boundaries are considered for various technology options:

1. To establish avoided emissions by biogas to replace natural gas in the gas grid system, cradle to gate systems that include raw material acquisition through operation to reuse, recovery and recycle of AD, gas clean-up and storage and digested matter to fertiliser

production processes and sewage sludge acquisition through processing to biogas production upto the plant gate and digested matter production through to application in agriculture are considered. Consideration of this system also helps to: 1) Identify environmentally the most benign biogas combustion technology for CHP generation that gives lowest impact potentials as well as highest avoided impacts compared to its equivalent natural gas based CHP generation technology. To establish this, the biogas combustion process must be separately analysed from the biogas cradle to gate system. When both are separately established, their impact potentials can be aggregated to give the impact potentials of the cradle to grave systems. 2) To develop heuristics and recommendations for product chain expansion within an industrial site based on LCA results (e.g. upto the biogas production vs. biogas use in CHP generation within an industrial site).

2. For biogas distributed and micro-generation options, cogeneration processes converting biogas into electricity and heat generation are separately considered, shown in **Fig. 2** (gate to grave or end use of biogas). Hence, aggregation of assessments of the cradle to gate and the gate to grave systems of biogas on the same basis results in biogas cradle to grave systems' assessments, from raw material acquisition through conversion to end use.

The distributed and micro-generation systems include the electricity generation process to utilise biogas from storage and the heat recovery steam generation process utilising the exhaust gas from the electricity generation process. The life cycle phases (y-axis) of these two processing steps (x-axis) for distributed and micro CHP generation comprise the material of construction, manufacturing and end of life reuse and recycle, shown in **Fig. 2**.

3.2. Inventory analysis

At the end of the processing steps, the exhaust emissions to the atmosphere from the various CHP processes will comprise the biogenic carbon dioxide, carbon monoxide (due to incomplete combustion) and unconverted methane, some nitrogen and sulphur oxides and dust particles, shown in **Table 2**.

Fig. 2

Table 2

All systems include digested matter to fertiliser production and agricultural use within the system boundary. Hence all cases are analysed for sensitivity of impact potentials to biogas flowrate to determine tradeoffs in impact potentials between sewage sludge's energy and agricultural applications.

Various CHP generation process technologies for electricity and heat generations from 11340 MJ of biogas are shown as follows.

1. Proton exchange membrane fuel cell 2 kWe (**PEM FC**): Electricity: 3628.8 MJ; Heat: 6237 MJ.

2. Solid oxide fuel cell 125 kWe (**SOFC**): Electricity: 5330 MJ; Heat: 3742 MJ.

3. SOFC-GT fuel cell 180 kWe (**SOFC-GT**): Electricity: 6577 MJ; Heat: 2495 MJ.

4. Micro gas turbine 100 kWe (**Micro GT**): Electricity: 3402 MJ; Heat: 5103 MJ.

5. Biogas engine (**Engine**): Electricity: 2952 MJ; Heat: 5026 MJ.

6. Ignition biogas engine (**Ignition**): Electricity: 3502 MJ; Heat: 5714 MJ.

Furthermore, for UK households, the following observations can be made. Based on the assumption of 2 kWe consumption per UK household, and 8000 operating hours per year, the total per household electricity demand is 57600 MJ y^{-1}. Hence, each household would require

180000 MJ or 5000 m^3 or 4.76 t biogas per year, from 15.87 t sewage sludge processed through AD.

The primary impact characterisations of the AD plant infrastructure over a life time of 30 years for processing 1 t of sewage sludge (using GaBi 6.0 and Ecoinvent 2.0 databases [12-13]) are shown in **Table 3**.

Table 3

4. Results and Discussions

4.1. Impact assessment

Biogas conversion into CHP generation

The systems under consideration are the biogas use in CHP generation. The primary impact characterisations of the six potential CHP technology options identified for converting 315 Nm^3 biogas (per t of sewage sludge processing) into CHP generation, Engine, Ignition, Micro GT, PEM FC, SOFC and SOFC-GT are compared in **Table 4**. These impact potentials shown result only from the utilisation of biogas from plant gate to CHP generation (end use).

The fuel cell processes have lower environmental impacts than engine or GT based processes. It is clear, that PEM FC provides the lowest primary impacts in all categories compared to any other option. The CHP technology options can be ranked by the impact potentials, from the lowest to the highest impact potentials, as follows:

PEM FC (lowest impact potential) < SOFC < SOFC-GT < Engine or Micro GT < Ignition (highest impact potential)

Between Engine and Micro GT, the situation is win-win, as only some (not all) environmental impact characterisations improved from Engine to Micro GT. As **Table 1** lists, for ≤ 250 kWe electricity generation, PEM FC is suitable for residential micro-generations; while Micro GT, SOFC and SOFC-GT are suitable for distributed generations upto 500 kWe and occasionally over 500 kWe; Engine and Ignition above 1 MWe, respectively. Because of the lower environmental impacts per MJ of output energy generation, the PEM FC is selected for the micro-generation system and the rest for distributed generation system evaluations. In each case, the digested matter is used for agricultural purposes. The final impact potentials from the various options are reported for the above basis as well as a function of the standard deviations from the base yields.

AD system for biogas production for the natural gas grid system and digested matter production for agricultural application

The system boundary under consideration includes the AD process, biogas production and storage and digested matter production and application in agriculture. **Fig. 3** shows the impacts from individual processes under various categories. For example, the AD infrastructure, digested matter application in agriculture and biogas at the plant gate result in 1.96, -264 and -574 kg CO_2 equivalent per t of sewage sludge processing, respectively. The negative sign indicates biogenic carbon capture in the products, assigned by energy allocation. It is obvious that biogas production for the grid system has more greenhouse gas savings compared to digested matter application in agriculture. The latter also causes more AP, EP, FAETP, HTP, MAETP and TETP, due to accumulation of nutrients and eventually leaching into water bodies and emissions to air. As expected, biogas results in more POCP than the digested matter. POCP results from volatile organic compounds' reactions with NO_x in the presence of sunlight producing ozone and photochemical pollutants, such as peroxyacetyl nitrate, formaldehyde and acetic acid in the lower atmosphere. These pollutants and ozone in the lower atmosphere are responsible for urban smog and ground level ozone formation and are classified under photochemical ozone creation potential.

Fig. 3

Impact characterisation of the integrated AD and CHP system for micro-generation and digested matter production for agriculture

The system boundary under consideration includes the AD process, biogas production, storage and combustion in PEM FC processes and digested matter production and application in agriculture. Further, 315 Nm^3 biogas produced is transformed into electricity and heat using cogeneration PEM FC process. The electricity and heat energies thus produced from the cogeneration plant are 3628.8 MJ and 6237 MJ, respectively, from 11340 MJ of biogas. **Fig. 4** shows the impacts from individual processes under most important impact categories, GWP, AP and POCP. Note that the impacts from the PEM FC process on the same basis are also shown in **Table 4**.

Fig. 4

Table 4

Impact characterisation of the integrated AD and CHP system for distributed generation and digested matter production for agriculture

The system boundary under consideration includes the AD process, biogas production, storage and combustion in SOFC processes and digested matter production and application in agriculture. Further, 315 Nm^3 biogas produced is transformed into electricity and heat using cogeneration SOFC process. The electricity and heat energies thus produced from the cogeneration plant are 5330 MJ and 3742 MJ, respectively, from 11340 MJ of biogas. Taking account of the increases in the GWP by 634.17 kg CO_2 equivalent, AP by 0.022 kg SO_2 equivalent and POCP by 0.0046 kg ethylene equivalent, due to combustion of the biogas in SOFC, shown in **Table 4,** the net GWP from the cradle to grave SOFC based distributed generation system is –202 kg CO_2 equivalent, AP is 0.098 kg SO_2 equivalent and POCP becomes 0.012 kg ethylene equivalent, respectively. Similarly, the GWP, AP and POCP of SOFC-GT, Engine and Ignition, shown in **Table 4,** will be added to the cradle to gate system, to obtain the respective cradle to grave systems' impact potentials.

Table 4

4.2 Interpretation

Comparison of impacts between biogas based micro and distributed generation systems and equivalent natural gas based systems

The following natural gas based systems processing 11340 MJ of natural gas with calorific value of 39 MJ per m^3 are considered in order to establish the avoided emissions by the corresponding biogas based systems, shown in **Table 5**. The primary impact categories selected out for comparison are the GWP, AP and POCP, because the CHP technology options influence these categories. The other impact characterisations have the same values for the cradle to gate and cradle to grave biogas systems.

Table 5

Processing of 11340 MJ of natural gas through the following systems into electricity and heat generations was considered.

1. Proton exchange membrane fuel cell 2 kWe (**PEM FC**): Electricity: 4205 MJ; Heat: 2825 MJ.

2. Solid oxide fuel cell 125 kWe (**SOFC**): Electricity: 5962 MJ; Heat: 3643 MJ.

3. SOFC-GT fuel cell 180 kWe (**SOFC-GT**): Electricity: 6997 MJ; Heat: 3093 MJ.

4. Micro gas turbine 100 kWe (**Micro GT**): Electricity: 4173 MJ; Heat: 5226 MJ.

Thus, in terms of avoided GWP by the AD plant, with respect to corresponding natural gas based CHP system, the following sequence is preferred:

Micro generation (PEM FC) (highest avoided GWP) > Distributed generation (Micro GT) > Distributed generation (SOFC) > Distributed generation (SOFC-GT) > Grid system (lowest avoided GWP).

In terms of avoided AP by the AD plant, the following sequence is preferred:

Micro generation (PEM FC) (highest avoided AP) > Distributed generation (SOFC) > Distributed generation (SOFC-GT) > Grid system > Distributed generation (Micro-GT) (lowest avoided AP).

In terms of avoided POCP by the AD plant, the following sequence is preferred:

Micro generation (PEM FC) (highest avoided POCP) > Distributed generation (SOFC) > Distributed generation (Micro-GT) > Distributed generation (SOFC-GT) > Grid system (lowest avoided POCP).

Comparison of impacts between digested matter and inorganic fertilisers for agricultural application

A comparison of environmental impact potentials between production options from sewage sludge is depicted in **Fig. 5**. The N:P:K fertiliser cradle to grave systems in EU have as low as 0.06 kg CO_2 equivalent emission per kg of fertiliser production, with modern technologies and 0.39 kg CO_2 equivalent emission per kg of fertiliser production on an average [28]. Thus, the avoided GWP by the use of digested matter in agriculture is only 0.44-0.77 kg CO_2 equivalent per kg, compared to the biogas production, 3 kg CO_2 equivalent per kg. The avoided AP and POCP by the use of digested matter in the place of inorganic fertiliser are more, 0.01186 kg SO_2 equivalent per kg and 0.00093 kg ethylene equivalent, compared to 0.00169 kg SO_2 equivalent per kg and 0.000249 kg ethylene equivalent for the biogas application to the grid system, respectively. In all toxicity characterisations, the digested sludge in agricultural application has more impact than inorganic fertilisers.

Fig. 5

Monte Carlo simulation combined LCA (MCLCA)

Analysis of probability distributions of impact potentials with respect to independent variables can be undertaken for a multi-variable decision making problem by the use of MCLCA. With MCLCA important impact characterisations can be selected out to make a choice between various technologies. In Monte Carlo simulation, independent variables within their specified standard deviations from their base values can be randomly selected during a simulation run. All the primary impact characterisations are calculated for the selected set of values of independent variables. At the end of Monte Carlo simulation runs, the chances of occurrence of each impact characterisation by a certain percentage are counted. The impact potentials that can be reduced show wider distribution of chances of occurrence, in contrary to narrow distributions otherwise.

Fig. 6 shows the steps involved in Monte Carlo simulation. The Monte Carlo simulation comprises three main steps:

1. selection of standard deviation and probability distribution function for each uncertain and independent variable;

2. Monte Carlo simulation runs;

3. calculation of chances of occurrence of each model predicted impact characterisation after a large number of simulation runs.

Fig. 6

LCA is data intensive. In addition, dispersed data set makes MCLCA computationally intensive. Additionally, there lies uncertainty in primary raw material and energy flow data or inventory analysis due to spatial and time averages and due to operational data averages, generally used in LCA. Monte Carlo simulation allows consideration of standard deviations in independent process variables in order to predict entire probability distributions of impact potentials. Large number of Monte Carlo simulation runs ensures that the probability distributions of impact potentials can be made more accurate. Monte Carlo simulation runs ~5000, as shown in the IPCC Guidelines [29] is recommended to obtain robust probability distribution curves of impact potentials.

The standard deviation shows the normalised deviation of a dispersed dataset from its average or mean value. Equation 1 shows the formula for calculating the standard deviation of n data points: x_1, x_2, x_3, … x_{n-1}, x_n, with respect to their average.

$$\sigma = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{n}}$$ equation 1

The values of independent variables are generated using given probability distribution function for each variable. The simplest form of probability distribution function is the uniform probability distribution function. Three other most common forms of probability distribution functions are the normal or Gaussian, lognormal and triangular.

Normal or Gaussian probability distribution function =

$$f(x_i) = \frac{1}{\sqrt{2\,\pi\,\sigma^2}} \exp(-\frac{(x_i - \bar{x})^2}{2\,\sigma^2})$$ equation 2

A sewage sludge AD plant can be operated to maximise the output energy generation via biogas production. Alternatively, the digested matter yield can be increased for agricultural application. The biogas and digested matter yields are related by the mass balance for a given sewage sludge mass throughput through an AD plant. Hence, one of the mass yields of biogas and digested matter can be considered as an independent variable and the other can be shown as a function of the independent variable. The following example and data analysis show a systematic decision making about the transfer coefficient of sewage sludge for energy generation against agricultural application. The problem can be formulated for sensitivity analysis, Monte Carlo simulations, etc. and solved in a spreadsheet environment or any other software supporting such analyses. The data have been extracted in sufficient detail to enable problem solutions in a spreadsheet environment.

The following variables are defined for sensitivity analysis. Equations 3-5 are shown to vary F_ADC, F_electricity and F-digested as a function of the independent variable, F_biogas.

F_biogas: Volumetric flowrate of biogas in Nm^3.

F_ADC: Number of AD plants based on the Ecoinvent 2.0 database to process 315 Nm^3 biogas.

$$F\_ADC = F\_biogas \times \frac{1.15 \times 10^{-5}}{315} \qquad \text{equation 3}$$

F_electricity: Electrical energy output from the micro or distributed generation systems in MJ.

As shown earlier, PEM FC system generates 3628.8 MJ electricity from 315 Nm^3 biogas. Hence, F_electricity will proportionally change according to F_biogas (equation 4a). The correlations in equations 4b-f are to proportionally vary F_electricity with respect to F_biogas.

For PEM FC based system, $F\_electricity = F\_biogas \times \frac{3628.8}{315}$ equation 4a

For SOFC based system, $F\_electricity = F\_biogas \times \frac{5330}{315}$ equation 4b

For SOFC-GT based system, $F\_electricity = F\_biogas \times \frac{6577}{315}$ equation 4c

For Micro GT based system, $F\_electricity = F\_biogas \times \frac{3402}{315}$ equation 4d

For Engine based system, $F\_electricity = F\_biogas \times \frac{2952}{315}$ equation 4e

For Ignition based system, $F\_electricity = F\_biogas \times \frac{3502}{315}$ equation 4f

F-digested: Digested sludge mass flowrate in kg.

F-digested = 1000 – F_biogas × $\frac{(1000-700)}{315}$ equation 5

On the basis of 1000 kg of sewage sludge conversion in AD into 700 kg of digested sludge production, 300 kg or 315 Nm^3 of biogas is produced. This biogas mass balance correlation is shown in equation 5.

The value of F_biogas can be varied between –25% and +25% standard deviation from the base value of 315 Nm^3 and all other flows can be changed according to Equations 3-5 and their effects on environmental impacts can be examined. The number of simulation runs is set to 5000. Equation 2 shows the Gaussian correlation in terms of mean, standard deviation and values of the variable (x_i), where x = F_biogas. A Monte Carlo algorithm works on the principle of random number generations. In MCLCA case, a set values of all uncertain and independent variables is randomly selected during one simulation run. Then the LCA model estimations are performed in a usual deterministic way. Reduction in each environmental impact characterisation is noted. After a large number of simulation runs the chances of occurrence of each environmental impact characterisation by a certain percentage are accounted. Using the following specifications, the characteristics of the probability distribution curves of the impact potentials obtained using MCLCA in GaBi 6.0 are shown in **Table 6**. The chances or likelihoods of occurrence in percentages of each impact potential with respect to standard deviations from its mean value are shown in **Table 7**.

Probability distribution function for the independent variable (F_biogas) = Gaussian distribution.

Number of Monte Carlo simulation runs = 5000

Number of clusters to show estimated results = 9

Deviation in estimated results from their base values = –25% and +25%

The chosen case study = Biogas Micro generation (PEM FC based)

Thus, the GWP reduction by 10 and 25 percentiles results in net GWP of –187.13 and –144.52 kg CO_2 equivalent, respectively (**Table 6**). The range from 25% reduction to 25% increase in impact characterisations has been divided into 9 clusters. Positive percentage ranges indicate reduction and negative percentage ranges indicate increase in each impact characterisation. Each row in **Table 7** shows the likelihoods or chances of occurrence in percentages of each impact characterisation, totalling to 100, for various standard deviations from the mean values shown in columns. **Fig. 7** shows the probability distributions (y-axis) of the two most and two least sensitive impact potentials with respect to their standard deviations from their mean values (x-axis). The probability distributions could be due to data uncertainty as well as variations in independent variable. These are to show to what extent an output impact potential could deviate from its mean value due to variations in input parameters. Narrower the probability distribution of an impact characterisation less likelihood is its change from its mean value. All toxicity impacts are less likely to be affected by data uncertainty or deviations in process variables. MAETP and EP especially remain unaffected as a result of process variability and data uncertainty, hence are the least sensitive impact characterisations. The MCLCA also reveals that the most important (sensitive) primary impact characterisations are GWP and POCP showing wider probability distributions.

Table 6

Table 7

Fig. 7

4.3 Recommendations

Sewage sludge AD is encouraged by the need to significantly cut down atmospheric emissions, save fossil resources and utilise wastes as a resource to energy generation and soil nutrients enrichment. Every m^3 of biogas generated from sewage sludge AD can save 0.92 m^3 of natural gas and can reduce GWP by 0.0793 kg CO_2 equivalent per MJ of biogas generation from the plant (Table 5). The following strategies for technology selection can be prioritised.

1. If natural gas is used as fuel for on-site generation of heat (e.g. for dryer, furnace, space heating etc.) and electricity (to drive process equipment), the natural gas should be replaced by biogas, as this will significantly cut down the plant's atmospheric emissions. PEMFC micro-generation can cut down 0.12 kg CO_2 equivalent emission per MJ of energy generation (Table 5). Depending on the scale requirement and capital availability, various CHP options could be used. For distributed systems, micro GT, SOFC-GT and SOFC are the most to least cost-effective options respectively, saving 0.0982, 0.0916 and 0.0951 kg CO_2 equivalent per MJ of energy generation (Table 5), respectively. Hence, micro-GT should be the selected distributed CHP system from both economic and environmental perspectives. Fig. 8 shows the relative placements of the various biogas based cradle to grave CHP systems, in terms of cost per unit energy production vs. avoided emissions compared to equivalent natural gas based systems, on 0 to 1 scale. For the avoided emissions, 0-1 bounds are placed by biogas to grid (no combustion) and PEMFC systems (absolute values are shown in Table 5), whilst for the cost per unit energy production 0-1 bounds are placed by biogas to grid (no combustion) and SOFC systems (0-2250 $ per kW), respectively. The options below the diagonal, PEMFC and Micro-GT exhibit higher avoided impacts at relatively lower costs, e.g. compared to SOFC and SOFC-GT systems. Hence, the desired systems should have high x-axis value (avoided environmental impact) and be placed below the diagonal and closer to the x-axis (low or zero cost).

Fig. 8

2. Biogas could be transmitted to adjacent industrial facilities for CHP generation, if there is space constraint for on-site generation of CHP, provided the transmission causes less than (0.0916 – 0.0793) or 0.0123 kg CO_2 equivalent per MJ of energy generation (differential impacts between cradle to grave and cradle to gate biogas systems).

3. If the above two options are not feasible within the AD plant, biogas can be injected to natural gas grid system to reduce emission from the AD plant.

4. Biogas production also avoids toxicity and aqueous emission impacts otherwise would have resulted from sewage sludge disposal to landfill. Sludge disposal can only be undertaken in controlled and managed soil, to maintain or increase biogenic carbon, while enriching soil quality and productivity.

5. Increase in biogas and decrease in digested sludge would result in lesser avoided POCP and AP, but save on all other impact categories. Both POCP and AP can be improved by improving the engine or CHP process performance to reduce NO_x, SO_x and volatile organic compound (VOC) emissions. Their emissions can be reduced by reducing the amount of excess air and air preheat temperature, recirculating the flue gas, injecting water / steam, by staging air and fuel or even by using oxygen for the combustion process. However, such strategies lower the efficiency of the combustion process. Adsorption of the exhaust gas from the CHP process can help reducing the emissions for cleaner process operations.

5. Conclusions

This study analyses the environmental sustainability of sewage sludge application in energy generation and agricultural processes. One driver for energy application of sewage sludge other than agriculture is that their growing quantities in landfills eventually evolve to the environment. Hence, other usages of sewage sludge, such as energy generation through micro CHP generation, distributed community CHP generation and the gas grid system were assessed by comparative LCA, considering primary impact characterisations that make a difference in the selection of technologies. An integrated Monte Carlo simulation and LCA framework was proposed for sensitivity analysis of biogas yields on the environmental impact characterisations and to determine the sensitive primary impact characterisations. Though all the primary impact characterisation potentials were determined, the GWP and POCP were identified as the key environmental performance indicators that can differentiate between technologies. The biogas production for the grid system has more greenhouse gas savings compared to digested matter application in agriculture. The latter also causes more EP, FAETP, HTP, MAETP and TETP, due to accumulation of nutrients and eventually leaching into water bodies and emissions to air. The biogas production results in more POCP and AP than the digested matter, due to volatile organic compound contents. Hence, by energy application of sewage sludge, most of the primary environmental impacts can be reduced and natural gas can be saved. As can be noted, from the calorific values of the biogas and natural gas, 1 m^3 biogas can save 0.92 m^3 natural gas. In terms of avoided GWP, AP and POCP, biogas based PEM FC micro system is most beneficial compared to the equivalent natural gas based systems.

The integrated Monte Carlo simulation and LCA shows that the most sensitive primary impact characterisations are GWP, POCP and AP, evident from wider probability distributions. The EP and MAETP have least standard deviations or narrow probability distributions and thus are the least sensitive impact categories. Digested matter production is primarily responsible for EP and MAETP impacts.

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