Manuscript Number: JCLEPRO-D-18-04015R2

Title: Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Article Type: Original article

Keywords: Electro-dewatering; Sludge management; Life cycle assessment; Return on investment; Industrial application; WWTP

Corresponding Author: Professor Roberto Canziani,

Corresponding Author's Institution: Politecnico di Milano

First Author: Hai Zhang

Order of Authors: Hai Zhang; Lucia Rigamonti; Simone Visigalli; Andrea Turolla; Paolo Gronchi; Roberto Canziani

Abstract: The objective of this study is to evaluate the feasibility of implementing electro-dewatering (EDW) as an add-on unit to the existing conventional dewatering units with the aim of increasing the final dry solids content and reducing the subsequent handling and energy costs of sewage sludge management. The assessment was carried out by focusing on a case study, a small wastewater treatment plant (WWTP) in the Milan metropolitan area. Various indicators were used to evaluate the environmental impact and economic performance. Primary data, such as operating data from the case study WWTP and economic data from an EDW equipment manufacturer, were extracted and used in the modelling. Four scenarios were set up and compared, which address the current and future sludge management schemes in Italy.

The results suggest that it is environmentally and economically feasible to implement the EDW upgrade if the sludge disposal follows the incineration route. More specifically, when small WWTPs deliver their EDW-dewatered sludge to a centralised incineration facility, this will enable to reduce the global warming impact of the system up to 135 kg CO2-eq. per dry tonne of sludge. In addition, good profitability (incremental return on investment > 15.1%) can be obtained when the market disposal cost is above 30.5-39.6 € per wet tonne of sludge. Based on our recent market survey, the sludge disposal price is well above the break-even values.

Detailed response to reviewers

Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Hai Zhang [a], Lucia Rigamonti [a], Simone Visigalli [a], Andrea Turolla [a], Paolo Gronchi [b], Roberto Canziani [a, *]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

Dear reviewers,
Thank you for taking time to review this manuscript. We really appreciate your valuable comments and suggestions and have carried out revisions accordingly. A point-to-point answer is provided below to address the questions raised in the reviewing and the locations where the revisions are made.

Reviewer #1:
Having read the revised article, I recommend what follows:

1. Have the article edited by a native English speaker and provide the relative certificate.
The article was revised by a native English speaker, Dr. Sam Skinner, from the University of Melbourne. Details about him are reported at https://pursuit.unimelb.edu.au/individuals/sam-skinner.

2. Is any policy supporting the need for your research?
Yes, it is. The following discussions have been added to the manuscript:

"To comply with the EU's strategy in circular economy, sludge is being disposed with two major routes: nutrient recovery by applying in agriculture land and energy recovery by incineration (Papa et al., 2017). In either of these routes, it is favourable to increase the DS (Dry Solids) content of sludge. For example, a minimum DS of 40% is required for incineration in fluidized bed incinerator and DS 90% for cement kiln incineration (Abuşoğlu et al., 2017)."
P3 L6-11 (Page number, Line number in the manuscript with marked changes).

"…and, if properly managed, it can reduce the concentration of heavy metals and organic pollutants in the dewatered sludge (Tuan and Sillanpää, 2010), the limits of which are regulated by the EU directive 86/278/EEC and member state's regulations (Mininni et al., 2015)."
P3 L33-36

"…in accordance with the Water Policy Directive 2000/60/EC (European Commission, 2000), it is necessary to take account of recovery of costs for water services, including environmental and resources, i.e. economic analysis is required. As WWTP is an important constituent of water services, the upgrading project should comply with this policy (Bertanza et al., 2018)."
P5 L2-6

3. Have scenario description preceded by a clear statement of the purpose of the comparative study.
The following parts have been added to the manuscript:

“To help justify the advantages of EDW upgrade, it is compared with the mechanical dewatering equipment used by the WWTP. […] In total, four scenarios were set up-to allow for comparison of the options (see Figure 1):”
P6 L23-36

4. Please describe each scenario individually.
The manuscript has been revised accordingly.
P7 L1-20

5. "This is because at present stage sludge for agriculture use (including land spreading and composting)" (Page 5, lines 23-24): please clearly define the "fertilizer displacement" scenarios: is the cake composted before spreading?
The manuscript has been revised accordingly. This term has been defined in the text, as reported:

“…sludge for land spreading (i.e. sludge is applied to arable land as fertiliser without composting treatment)”
P6 L24-25

6. As in the incineration scenario, you should define the area for land spreading.
In this regard, more information has been added to the manuscript:

“The ashes generated from the flue gas treatment are treated to make them inert and are sent to a landfill for hazardous waste, located in Italy. “
P11 L12-14

7. Explain the rationale behind impact category selection: what does "close relevance"(!) mean?
This point has been clarified in the manuscript, as reported:

“These impact categories were selected for their close relevance to the system under study (Tomei et al., 2016), in relation to the following elements:
(1) the end use of sludge: the emissions of land spreading and incineration are directly related to GW, AC and EP;
(2) EDW is an energy intensive process and a major advantage of using EDW is to reduce the fuel consumption in the road transport stage. In this context, GW, POF, AC and EP are directly related to consumption of fossil fuels.”
P7 L34-P8 L5

8. Table 2: please explain data sources; especially:
- own data: experimental data?
The manuscript has been revised accordingly.

P14 Table 2

“The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers.“
P13 L36-P14 L2

“The machine power was calculated on the basis of lab testing results from Politecnico di Milano.”
P14 L4-5

- data extracted from WWTP: can you mention any collaboration with plant operator?

Yes, the manuscript was updated. One paragraph was modified to properly introduced the case study WWTP. Please, see P6 L10-16. In particular, the sentence “Sludge samples were extracted from this WWTP for the lab-scale EDW test.” was added.
Another mention can be found at P9 L5-6. This WWTP belongs to the CAP holding group, which has been explicitly mentioned in the acknowledgement.

- estimate: based on what?

More information has been added in this regard.

“The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers. “
P13 L36-P14 L2

“The machine power was calculated on the basis of lab testing results from Politecnico di Milano.”
P14 L4-5

- extracted from real cases of Italy, also applicable to other EU markets (Bertanza et al., 2015b): what's the source?

The manuscript has been revised accordingly.

A reference has been added.

P15 Table 2

In the beginning of the “SLUDGEtreat” project, we carried out this market analysis by visiting some WWTPs and interviewing the responsible persons. The sludge disposal price was a key data to be collected. Details about this assessment are reported in “Díaz, C., García, G., Canziani, R., Ferrari, G., 2015. Preliminary market analysis – review: Annex 1. Collected Data from some Visits to WWTPs in Italy [WWW Document]. URL https://sludgetreat.eu/wp-content/uploads/2016/11/D2.2-Annex-I-Data-from-some-visits-to-WWTPs-Italy-2015.pdf (accessed 16.2.18)”

9. Does your study have any limitations??? How could research limitations could be addressed?
The discussion about research limitations has been added.

“The present study has its limitations, such as the lab-scale EDW data (e.g. the outlet DS and the specific energy consumption) were used since the prototype machine was not ready to conduct testing with actual sludge samples. However, the robustness of the results was assessed with two sensitivity analyses, and this allowed us to draw some solid conclusions for the EDW upgrade. Once more data become available, they can be updated in the models to generate more accurate results. Also, more indicators can be incorporated into the decision-making matrix, in particular the social aspects (e.g. employment, income, access to services, public health and safety, etc.).”
P20 L3-9

10. Conclusions: this section should discuss the policy and research implications of your study.
A paragraph has been added in relation to this comment.

“The EU Directive 86/278/EEC was adopted more than 30 years ago. In order to keep it updated with the societal changes, it is currently under review by the European Commission to address emerging issues, in particular in relation to the use of sludge for agriculture. It has been anticipated that the limits of heavy metals will be lowered. In addition to that, limits for organic micropollutants and microbial indicators of pathogens will be introduced. In this context, the advantage of EDW could possibly be further strengthened. However, to date, there are limited data to support the effectiveness of EDW on reducing these contaminants, which could constitute a future research development. “
P20 L10-16

Reviewer #2:

Reviewer#2 comments,

The paper shows significant improvements. The authors modified and greatly improved the article. However, important information suggested by this reviewer has been met only partially, therefore some revision is still needed.
I think the manuscript has interesting results and can be published by the Journal of Cleaner Production, however care, acuity, precision, consistency, zeal, commitment must be taken, so that the results are described by an attractive text around it. The authors are very stubborn. When reviewers require that a review be performed, it must be performed and not rebutted (refused), otherwise the manuscript will be rejected. I almost rejected the manuscript in this second review, but I believe the authors can improve, just follow what was asked by this Reviewer#2.

We are really sorry for this trouble. At that time, we were too worried about the word limit set by the journal (8000), so that we compressed the content a lot. But in this revised version, all the comments and advices from the reviewer have been integrated in the text.

KEY QUESTION 1: I have one key question for the authors: What is the difference between this present manuscript and the other papers that have been published by the same authors? It would be better explaining this topic in the body text of the manuscript with some details. Nowadays, some unintentional and or intentional plagiarism could be taken from other already published work. Please, do not reply only to this Reviewer#2, also include your reply text in the main body text of the manuscript.
In our opinion, there is a strong difference in the focus of this manuscript with respect to our published articles, essentially consisting in the scope of the investigation, that is addressed to the assessment of environmental and economic aspects in the present case. In order to clarify the rationale to the readers, the manuscript has been revised accordingly, as it follows:

"Our previous publications (Visigalli et al., 2017a/b) focus on the technical issues of EDW, investigating the factors that influence the system's performance, while in the present study, the emphasis is placed on the environmental and economic assessment."
P5 L34-37 (Page number, Line number in the manuscript with marked changes).

The publication list is attached below:
- Gronchi, P., Canziani, R., Brenna, A., Visigalli, S., Colominas, C., Montalà, F., Cot, V., Stradi, A., Ferrari, G., Diaz, C., Fuentes, G.G., Georgiadis, A., 2017. Electrode surface treatments in sludge electro-osmosis dewatering. Mater. Manuf. Process. 32, 1265–1273. doi:10.1080/10426914.2017.1279313
- Visigalli, S., Turolla, A., Gronchi, P., Canziani, R., 2017a. Performance of electro-osmotic dewatering on different types of sewage sludge. Environ. Res. 157, 30–36. doi:10.1016/j.envres.2017.05.015
- Visigalli, S., Turolla, A., Zhang, H., Gronchi, P., Canziani, R., 2017b. Assessment of pressure-driven electro-dewatering as a single-stage treatment for stabilized sewage sludge. J. Environ. Chem. Eng. doi:10.1016/j.jece.2017.11.034

KEY QUESTION 2: What are the weaknesses, limitations, restrictions and weak points of this research carried out by the authors? Please, do not reply only to this Reviewer#2, also include your reply text in the main body text of the manuscript.
In this regard, a paragraph has been added to the conclusion section.

"The present study has its limitations, such as the lab-scale EDW data (e.g. the outlet DS and the specific energy consumption) were used since the prototype machine was not ready to conduct testing with actual sludge samples. However, the robustness of the results was assessed with two sensitivity

analyses, and this allows us to draw some solid conclusions for the EDW upgrade. Once more data become available, they can be updated in the models to generate more accurate results. Also, more indicators can be incorporated into the decision-making matrix, in particular the social aspects (e.g. employment, income, access to services, public health and safety, etc.)."
P20 L3-9

KEY QUESTION 3: What are insights, scientific contributions, benefits, strengths, novelties and originalities of this research carried out by the authors? Please, do not reply only to this Reviewer#2, also include your reply text in the main body text of the manuscript.
One of the main original contributions is that we have analysed the barriers that retard the industrial application of EDW. This aspect has been clearly stated by modifying the manuscript:

"Although many promising results have been reported and the mechanisms behind the EDW phenomenon are relatively well understood (Mahmoud et al., 2010), it seems that it takes long time for EDW to make its full swing in the industrial application in WWTPs. Several reasons are… "
P4 L1-36

Moreover, to accommodate the characteristics of EDW upgrade, we have proposed a method which is especially suitable for evaluating small modification projects implemented in WWTPs, which is novel in the research of sludge management practices. Such aspect has been evidenced in the manuscript:

"In this case, a model demonstrating the relationship between the profitability of the upgrading project and the disposal cost will be useful to cover a wide scope of market situations. Therefore, in this study, the economic assessment was carried out following the method from chemical engineering design (Towler and Sinnott, 2013). It focuses on the EDW upgrade itself rather than the scenarios as previously discussed in the LCA. It also gives more flexibility in sensitivity analysis and the results can be easily communicated to the WWTPs managers (Zhao et al., 2016)."
P12 L26-31

We have reported many primary data about EDW machine, which could be useful for other researchers in this field, as explicated in the following paragraph of the manuscript:

"The industrial prototype is currently under development (screw press-based machine), it is therefore possible to extract some primary economic data from the machine manufacturer (X2 Solutions Srl, also one of the project consortiums). The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers."
P13 L34-P14 L2

Finally, the assessment provides evidences to support the industrial application of EDW, giving positive implications to WWTP operator and policy-makers to adopt this novel process, as summarized in the conclusion section (P19 L25-P20 L2).

KEY QUESTION 4: What are the Technological Innovations, Policy Implications, Challenges and Implications of the realization of that work carried out by the authors? Please, do not reply only to this Reviewer#2, also include your reply text in the main body text of the manuscript.

To accommodate the characteristics of EDW upgrade, we have proposed a method which is especially suitable for evaluating small modification projects implemented in WWTPs, which is novel in the research of sludge management practices. The same paragraph cited in KEY QUESTION 3 (P12 L26-31) was modified to highlight this aspect.

The assessment gives positive implications to policy-makers, as clearly stated in the paper.

"The LCIA results give a holistic view of the sludge management scenarios. The EDW dewatering stage consumes large amount of electricity, causing significant increases in the impact indicators; on the other hand, it contributes to reduce the overall system's impacts in the downstream life cycle stages, e.g. reduced impacts in the transport stage due to sludge volume reduction and reduced impact in the disposal stage (replaced fertiliser/heat). This implies that policy-making of sludge management should encompass life cycle thinking, encouraging solutions that enable to reduce the overall environmental impacts, and avoiding shifting environmental burdens from one life cycle stage to another."
P17 L4-10

The biggest challenge is to fill the data gap. In particular, we have addressed two aspects of EDW upgrade (environmental profile and economic profitability). The difficulty was managed by using multiple data collection methods, such as extracting data from WWTP and EDW machine manufacturer, acquiring data with experiments, searching in publications and reports from the industry and consulting companies. These aspects are discussed in different parts of the manuscript.

KEY QUESTION 5: What are the technological recommendations and insights from your results? The policy implications of this work should be presented in a clearer way in the discussion section.
More discussion about technological recommendations has been added.

"In order to achieve an overall positive energy valorisation in the sludge to energy route, it is essential to increase the sludge DS to have a suitable LHV (Arlabosse et al., 2012). EDW machine is very competitive for working in the DS range of 15-40%. In this range, it is more energy efficient than thermal dryer, and at the same time it can maintain a higher productivity than solar dryer (Umwelt Bundesamt, 2013). Besides, it requires less space to implement the upgrading project than solar dryer, which is highly welcomed by those small WWTPs situated near big cities."
"For going beyond DS 40%, as seen from some commercial solution providers (e.g. ACE, Korea), thermal dryer powered by waste heat or solar dryer can be arranged after the EDW unit. In such way, different methods can team up as a complete drying solution to provide the best energy efficiency and productivity."
P19 L3-12

More discussion about policy implications has been added.

"Regulation and policy-making in sludge management can be another important aspect to consider. In terms of disposal methods, landfill will be progressively phased out in the EU (Mininni et al., 2015). In recent years, opposition to direct use of sludge in agriculture has intensified due to consumer's demand on food safety and quality (e.g. organic farming). This has led to the situation that the percentage of sludge for incineration is growing in the EU (Eurostat, 2017a)."
P18 L34-P19 L3

"The EU Directive 86/278/EEC was adopted more than 30 years ago. In order to keep it updated with the societal changes, it is currently under review by the European Commission to address emerging issues, in particular in relation to the use of sludge for agriculture. It has been anticipated that the limits of heavy metals will be lowered. In addition to that, limits for organic micropollutants and microbial indicators of pathogens will be introduced. In this context, the advantage of EDW could possibly be further strengthened. However, to date, there are limited data to support the effectiveness of EDW on reducing these contaminants, which could constitute a future research development."
P20 L10-16

Important Issues: It is extremely recommended that in the all of the sections of the manuscript each referenced work should be accompanied by a brief description of the key results and main conclusions. In this way, the inclusion of the cited work in the manuscript can be better justified. Remove clusters of references, i.e., use 1 citation per 1 claim only.
For example remove the clusters:

"According to the data source (Eurostat, 2017a; Heimersson et al., 2017), in 2010, the EU Wastewater Treatment Plants (WWTPs) needed to handle over 10 million 5 tonnes of sludge (in dry mass) for disposal to agricultural land, composting sites, incineration plants and landfill sites". Remove this cluster!

"Therefore, improvement in sludge dewatering holds a great potential to reduce the WWTP's operating cost and its environmental impacts. Electro-dewatering (EDW) in combination with mechanical compression is shown to be effective in increasing the sludge DS content and thus decreasing the quantity/volume of sludge requiring disposal. In the meanwhile, EDW can maintain a better energy efficiency than thermal drying until reaching the DS of 38-45% (Olivier et al., 2015; Yu et al., 2017).

Remove this cluster!

Etc., etc., etc.

The manuscript has been thoroughly revised.

"In the past decade, much research has been carried out in the field of EDW and the majority of them are focused on how to optimise operating parameters in relation to energy efficiency. For example, two factors, mechanical pressure and electrical voltage, were investigated in the work of Mahmoud et al. (2011). In accordance with the authors, after optimising the operating conditions it was possible to save 25% energy as compared with thermal drying. In another example (Tuan and Sillanpää, 2010), it was found that freeze/thaw conditioning could greatly improve the sludge dewaterability and a higher sludge loading led to a lower DS in the final cake. Because of the strong correlation, some researchers concluded that electrical current could work as an indicator for the kinetics of EDW dewatering (Olivier et al., 2015), which is supported by the results from Visigalli et al. (2017a). More recently, in order to study the effect of sludge type on EDW dewatering performance, sludge samples were collected from four WWTPs and treated with a lab-scale EDW device (Visigalli et al., 2017b). It was shown that for the good-matching sludge (i.e. sludge gives good response to the EDW treatment), DS 39.3% was achieved in the final cake."

P3 L18-30

"In recent years, a decision support system built on technical, economic and environmental performances is gaining popularity and being practiced by the researchers in this field (Bertanza et al., 2015a). Basically, to evaluate the environmental performances, it follows the concept of Life Cycle Assessment (LCA), which is an international standard-based methodology (ISO14040 and ISO14044) and enables to evaluate a product's environmental impacts by considering all its life cycle stages, starting from raw material extraction, manufacturing, use/reuse until final disposal (Gourdet et al., 2017). LCA has been applied in the field of sludge management since the year 2000 (Yoshida et al., 2013). The relevant studies have concentrated on the followings topics: identifying hotspots in WWTPs, assessing upgrading options for the treatment lines (Zhang et al., 2017) and selecting the most suitable sludge management schemes (Buonocore et al., 2016). For instance, in the study of Li et al. (2017), five different anaerobic digestion configurations were assessed with environmental and economic indicators, and the authors identified sludge organic content and the biogas yield as the most influential factors. In another study (Gourdet et al., 2017), by comparing between different scenarios, it was found that increasing the biodegradation rate of volatile solids and the biogas production was the most effective method to lower the system's environmental impacts. Also, as recognised in the same study, the consumption of $FeCl_3$ (a chemical that is used to reduce the phosphorus contained in the return liquors from thickening and dewatering stages) was identified as a hotspot for the system's environmental profile. Besides, LCA is also a useful tool for working out proper waste management policies. As demonstrated by the case study of Righi et al. (2013), a scenario composed of anaerobic digestion and composting had the best environmental performance and thus was recommended to the policy-makers."

P5 L9-29

Also, what was requested by the Reviewer#2 was not answered by the authors:

1) All units used in the body of text must be units of the International System of Units (meter, kilogram, second, joule (or kWh), ampere, Kelvin, etc.).
The manuscript has been revised.

2) The abbreviation of "tonne" in English is "ton" and not "t".
The manuscript has been revised.
In the abbreviation list, “tonne” is abbreviated as “ton” and this has also been updated in the text.

3) After "eq" always include a "dot" for abbreviation.
*The correct way of citing the Life cycle impact assessment midpoint results is:
Acidification Potential -> AP: correct form is "kg SO2-eq." and not "kg SO2 eq". (or percentage (%) if they want).
Eutrophication Potential -> EP: correct form is "kg PO4-3-eq." and not "kg PO-4 eq". (or percentage (%) if they want).
Fresh Water Aquatic Ecotoxicity Potential -> FAETP: correct form is "kg 1,4 DCB-eq." and not "kg 1,4 DCB eq". (or percentage (%) if they want).
Global Warming Potential -> GWP: correct form is "kg CO2-eq." and not "kg CO2 eq". (or percentage (%) if they want).
Human Toxicity Potential -> HTP: correct form is "kg 1,4 DCB-eq." and not "kg 1,4 DCB eq". (or percentage (%) if they want).
Marine Water Aquatic Ecotoxicity Potential -> MAETP: correct form is "kg 1,4 DCB-eq." and not "kg 1,4 DCB eq". (or percentage (%) if they want).
Ozone Layer Depletion Potential -> ODP: correct form is "kg CFC 11-eq." and not "kg CFC 11 eq". (or percentage (%) if they want).
Photochemical Oxidant Formation Potential -> POFP: correct form is "kg C2H4-eq." and not "kg C2H4 eq". (or percentage (%) if they want).
Terrestrial Ecotoxicity Potential -> TETP: correct form is "kg 1,4 DCB-eq." and not "kg 1,4 DCB eq". (or percentage (%) if they want).
The manuscript has been revised.
This has also been updated in the abbreviation list: “Equivalent” is abbreviated as “eq.”

4) The paper has just 7910 words in total. The paper has good results but the authors have space to write more about the methodological issues and technological bottlenecks (bibliographic review) found in the application of this new approach. Please dear authors, extend the manuscript including more references on the subject and improving mainly the Introduction and Methodology sections, and if possible include more results.
The part of bibliography review has been extended. More references have been included.

“In recent years, a decision support system built on technical, economic and environmental performances is gaining popularity and being practiced by the researchers in this field (Bertanza et al., 2015a). Basically, to evaluate the environmental performances, it follows the concept of Life Cycle Assessment (LCA), which is an international standard-based methodology (ISO14040 and ISO14044) and enables to evaluate a product’s environmental impacts by considering all its life cycle stages, starting from raw material extraction, manufacturing, use/reuse until final disposal (Gourdet et al., 2017). LCA has been applied in the field of sludge management since the year 2000 (Yoshida et al., 2013). The relevant studies have concentrated on the followings topics: identifying hotspots in WWTPs, assessing upgrading options for the treatment lines (Zhang et al., 2017) and selecting the most suitable sludge management schemes (Buonocore et al., 2016). For instance, in the study of Li et al. (2017), five different anaerobic digestion configurations were assessed with environmental and economic indicators, and the authors identified sludge organic content and the biogas yield as the most influential factors. In another study (Gourdet et al., 2017), by comparing between different scenarios, it was found that increasing the biodegradation rate of volatile solids and the biogas production was the most effective method to lower the system’s environmental impacts. Also, as recognised in the same study, the consumption of FeCl3 (a chemical that is used to reduce the phosphorus contained in the return liquors from thickening and dewatering stages) was identified as a hotspot for the system's environmental profile. Besides, LCA is also a useful tool for working out proper waste management policies. As demonstrated by the case study of Righi et al. (2013), a scenario composed of anaerobic digestion and composting had the best environmental performance and thus was recommended to the policy-makers."

A list of new citations is attached below:

- Abuşoğlu, A., Özahi, E., İhsan Kutlar, A., Al-jaf, H., 2017. Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production. J. Clean. Prod. 142, 1684–1692. doi:10.1016/J.JCLEPRO.2016.11.121
- Buonocore, E., Mellino, S., De Angelis, G., Liu, G., Ulgiati, S., 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecol. Indic. doi:10.1016/J.ECOLIND.2016.04.047
- Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M., 2017. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. J. Clean. Prod. 143, 1123–1136. doi:10.1016/J.JCLEPRO.2016.12.007
- Li, H., Jin, C., Zhang, Z., O'Hara, I., Mundree, S., 2017. Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. Energy 126, 649–657. doi:10.1016/J.ENERGY.2017.03.068
- Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della Casa, C., 2013. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J. Clean. Prod. 44, 8–17. doi:10.1016/J.JCLEPRO.2012.12.004
- Rocha, M.H., Capaz, R.S., Lora, E.E.S., Nogueira, L.A.H., Leme, M.M.V., Renó, M.L.G., Olmo, O.A. del, 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis. Renew. Sustain. Energy Rev. 37, 435–459. doi:10.1016/J.RSER.2014.05.036
- Díaz, C., García, G., Canziani, R., Ferrari, G., 2015. Preliminary market analysis – review: Annex 1. Collected Data from some Visits to WWTPs in Italy [WWW Document]. URL https://sludgetreat.eu/wp-content/uploads/2016/11/D2.2-Annex-I-Data-from-some-visits-to-WWTPs-Italy-2015.pdf (accessed 16.2.18)
- European Communities, 2000. DIRECTIVE 2000/60/EC. Off. J. Eur. Communities. URL https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF (accessed 9.6.18).
- Bertanza, G., Canato, M., Laera, G., 2018. Towards energy self-sufficiency and integral material recovery in waste water treatment plants: Assessment of upgrading options. J. Clean. Prod. 170, 1206–1218. doi:10.1016/J.JCLEPRO.2017.09.228

The methodology part has been extended.

"The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. The experimental setup and protocol were based on our previous publications (Visigalli et al., 2017b). In brief, sludge samples were treated between the electrodes (anode DSA/Ti MMO, cathode stainless steel AISI 304) that were connected a DC power supply (GBC, 34121070 bench scale generator). A constant mechanical pressure 300 kPa was applied throughout the 25-min EDW treatment. The evolution of electric current and mass of filtrate were recorded and used for calculating the specific energy consumption.
Two sets of parameters were tested:
1) cake thickness (unit in mm): 15, 20, 25;
2) electrical potential (unit in V): 10, 15, 20.
Each combination was tested in two replicates. The data giving the best dewatering performance (in terms of DS improvement and productivity) were used in the assessment, that is lower cake thickness (15 mm) combined with higher voltage (20 V). Accordingly, this parameter combination caused the highest specific energy consumption. From an early publication (Olivier et al., 2015), it is known that EDW can maintain superior energy efficiency over thermal drying until reaching DS 45%. Therefore, we can assume that the parameter combination "15 mm-20 V" gives the best dewatering performance despite the increased specific energy consumption.

For industrial application, it is also important to consider machine's productivity. For example, solar dryer is very energy efficient, but its productivity is very low. In the case of EDW, the operating parameters should ensure a good productivity, i.e. the shortest time to reach a target DS. To address this issue, a target DS was set as 25% and the relevant data were extracted and compared. The results show that the combination of "15 mm-20 V" gives the best productivity, which is in line with the dewatering performance as discussed previously. As a consequence, the data generated from this operating parameter combination were used in the assessment. The detailed results are provided in Supporting Information (Section SI-2)."

Finally, the discussion about LCIA methods has been added in Supporting Information (Section SI-1).

5) Please, in the Introduction section is required a continuous body text, without itenization, as follow: "1) Relatively high energy consumption: Regarding this point, an early research (Mahmoud et al., 2010) suggests that EDW may find better application in dewatering/drying some high value products, e.g. foods and pharmaceuticals rather than sewage sludge. According to a latest publication (Zhang et al., 2017), the electricity consumption measured on an industrial EDW setup was 0.123 kWh per kilogram water removed.
2) Problem with anode material: It is well known that anode is the core part of an EDW system. It has high cost and in the meanwhile it is subjected to high wearing caused by harsh electrochemical corrosion and abrasion (Gronchi et al., 2017). According to the data source (Zhang et al., 2017), by considering the anode cost and its service 1 life, it can be translated as 4.23 € per tonne removed water. On the other hand, as widely recognised, finding the suitable replacement material is one of the key issues for promoting EDW to the industry users.
3) Reliability under continuous working mode: Periodic cathode cleaning is needed to maintain the system's efficiency/productivity. In accordance with the relevant study (Zhang et al., 2017), stepwise pressure has prolonged this period to 15 days, and this is acceptable for many industrial users.
4) Competition with other engineering options: This is especially applicable to the situation of large WWTPs, as for them there are different engineering options to choose from to dry the sludge. For example, if a WWTP is integrated with a Combined Heat and Power (CHP) system, it is possible to utilise the waste heat/low-grade heat from the CHP to dry the sludge up to DS 90% (Mills et al., 2014). In fact, low temperature dryer can be powered by various types of on-site waste heat (e.g. co-generation, heating and air conditioning systems) as long as these heat sources are stable and have a minimum temperature of 90°C (SUEZ's degremont® water handbook, 2017). In another example (Yoshida et al., 2014), the WWTP is integrated with an on-site incinerator so that the heat generated from the incinerator can be used to dry the sludge. Therefore, these large WWTPs may show less interest in EDW."
The manuscript has been revised.
P4 L5-28

6) Where are the novelties, originalities, research gaps and new insights of the realization of this paper?
To accommodate the characteristics of EDW upgrade, we have proposed a method which is especially suitable for evaluating small modification projects implemented in WWTPs, which is novel in the research of sludge management practices. The same paragraph cited in KEY QUESTION 3 and 4 (P12 L26-31) was modified to highlight this aspect.

The assessment provides evidence for implementing the EDW upgrade, as stated in the conclusions:

"The economic analysis shows that under current market situation in Italy, the EDW upgrade will generate very attractive ROI (>15.10%) for small WWTPs regardless of disposal routes. This is because:
(1) the current market price for sludge disposal in Italy (47-78 €/wet tonne) is well above the break-even values (30.5-39.6 €/wet tonne);
(2) upper limit data have been used to stress the calculation, e.g. the Italian electricity price, which is 30% higher than the EU average case."
P19 L29-35

7) It is recommended that in the Introduction Section each referenced work must be accompanied by a brief description of the key results and main conclusions. In this way the inclusion of the cited work in the manuscript can be better justified. There may be exceptions in which multiple referenced works can be used at the same time in presenting important information, but it should be minimized as much as possible. Every single work must be described and summarized in few lines. I am not telling to the authors reproduce again (duplicate) a paper, I just said to summarize in a few lines.
The whole introduction section has been thoroughly revised considering this comment.

8) Methodology section should be enlarged, explaining the details of the study. The realization of a study of Life Cycle Assessment (LCA) predicts that many details, hypotheses, value adoptions, conditions of transportation, data base of inputs and outputs, fuel data base, electricity data base, fertilizers, emissions factors, product disposal, disposal scenarios, etc. are assumed, therefore a better detailing (specification, particularization, etc.) should be provided as the study was conducted. The journal limit could be enlarged, since they already know the authors know how to write and there is a technical-scientific basis in what is being written. Life cycle assessment manuscripts need theoretical and scientific background to portray everything that is being considered in the scope of work.
This section has been enlarged.

"Scenario A1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press). After that, the dewatered sludge cakes (DS 18.2%) are transported by truck to agricultural fields and applied using a tractor. After applying, sludge gradually becomes available to the crops. In this process, it also releases GHG emissions to the air.
Scenario A2: it follows a similar land spreading route as described in A1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will be increased to 40%. In this case, A2 represents the EDW upgrading scenario and it will be compared with the reference scenario A1.
Scenario C1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press) by each individual WWTP. After that, the dewatered sludge cakes (DS 18.2%) from each individual WWTP are transported by truck to a centralised incineration facility. Subsequently, the cakes are mixed and dried with a disc dryer (thermal drying) to reach DS 40% and then they are fed into a fluidized bed furnace. The waste heat is recovered. After material recovery from the ashes, the residues are sent to landfill for hazardous waste.
Scenario C2: it follows a similar incineration route as described in C1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will reach 40% and the thermal drying treatment occurred in the incineration plant will be omitted. In this case, C2 represents the EDW upgrading scenario and it will be compared with the reference scenario C1."
P7 L1-20

"Some data (e.g. the outlet DS and the specific energy consumption) need to be obtained with experiment test. The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. The experimental setup and protocol were based on our previous publications (Visigalli et al., 2017b). In brief, sludge samples were treated between the electrodes (anode DSA/Ti MMO, cathode stainless steel AISI 304) that were connected a DC power supply (GBC, 34121070 bench scale generator). A constant mechanical pressure 300 kPa was applied throughout the 25-min EDW treatment. The evolution of electric current and mass of filtrate were recorded and used for calculating the specific energy consumption.
Two sets of parameters were tested:
(1) cake thickness (unit in mm): 15, 20, 25;
(2) electrical potential (unit in V): 10, 15, 20.
Each combination was tested in two replicates. The data giving the best dewatering performance (in terms of DS improvement and productivity) were used in the assessment, that is lower cake thickness (15 mm) combined with higher voltage (20 V). Accordingly, this parameter combination caused the highest specific energy consumption. From an early publication (Olivier et al., 2015), it is known that EDW can maintain superior energy efficiency over thermal drying until reaching DS 45%. Therefore,

we can assume that the parameter combination “15 mm-20 V” gives the best dewatering performance despite the increased specific energy consumption.
For industrial application, it is also important to consider machine’s productivity. For example, solar dryer is very energy efficient, but its productivity is very low. In the case of EDW, the operating parameters should ensure a good productivity, i.e. the shortest time to reach a target DS. To address this issue, a target DS was set as 25% and the relevant data were extracted and compared. The results show that the combination of “15 mm-20 V” gives the best productivity, which is in line with the dewatering performance as discussed previously. As a consequence, the data generated from this operating parameter combination were used in the assessment. The detailed results are provided in Supporting Information (Section SI-2).”
P9 L1-30

The discussion about LCIA methods has been added in Supporting Information (Section SI-1). An additional sensitivity analysis has been added (P12 L4-7) and the results are reported (P18 L1-10).

9) This sentence could be included in the body text of the manuscript: "As reported in two review papers (references are attached below, LCA applied to wastewater treatment), there are big discrepancies in the LCIA results. The authors attribute this to the variations in the following aspects: data source (WWTPs treating water of different contamination levels with different removal efficiencies), process configuration, system boundaries, geographical area, functional unit and LCIA method. This makes it difficult to compare the results from different studies. Most of the studies stay with comparing scenarios."
This sentence has been added.
P16 L35-P17 L3

10) Where the inventory data of the analyzed scenarios in the paper were extracted? Data were collected in the field or data were extracted from the literature? The authors could talk more about inventory data: time coverage, geographic coverage, technological coverage, accuracy and precision (measurement of variability of inventory data using statistical methods), completeness (percentage of measured data and percentage of estimated data), data consistency (degree of data compatibility and uniformity with a population of interest), reproducibility, sources of data collection and uncertainties.
The manuscript has been revised.

More information about data source has been added.
“The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. The experimental setup and protocol were based on our previous publications (Visigalli et al., 2017b)…
…Each combination was tested in two replicates. The data giving the best dewatering performance (in terms of DS improvement and productivity) were used in the assessment”
P9 L4-29

The detailed results are provided in Supporting Information (Section SI-2).

“The lower heating value (LHV) of the dewatered sludge was calculated according to the handbook of wastewater solids incineration systems (Water Environment Federation - Incineration Task Force, 2009). The value was 3534 kWh/tDM at DS 40%. “
P10 L35-P11 L1

The detailed calculation is provided in Supporting Information (Section SI-4).

“The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers. The machine power was calculated on the basis of lab testing results from Politecnico di Milano.”
P13 L36-P14 L5

11) The results section like the other previous sections is also quite short, with little information and little detail in the comments and explanations. The authors could add more information to the readers.
The section has been enlarged.

An additional sensitivity analysis has been added at (P12 L4-7) and the results are reported at
(P18 L1-10).

The lab-scale EDW testing results are provided in Supporting Information (Section SI-2).

Besides, more discussion has been added.

“Several environmental indicators and economic performance indicators have been assessed. As seen from the results, the EDW upgrade could not give a uniform performance in all these indicators. To assist decision-making, the indicators can be ranked according to their importance or specific needs of a WWTP (e.g. goal to reduce a specific indicator). In this case, a scoring exercise can be helpful (Mills et al., 2014). Furthermore, more aspects can be incorporated in the scoring matrix to improve decision-making. For example, in the studies by Bertanza et al. (2016) and Tomei et al. (2016), technical feasibility (sub-categories such as reliability, flexibility/modularity, complexity and integration with existing structures), administrative aspects and normative constraints, and social aspects have been incorporated. In another example (Mills et al., 2014), tax incentives as a risk factor has been added.”
P18 L24-33

12) Conclusions: The conclusions are overly short. It has only 430 words and it should be at least 600-700 words. Beside that the conclusions are very poor. I would expect some managerial insights and general comments. Conclusions should be more pertinent. Novel insights that arise from the calculations carried out in the paper. There is potential for this in the paper. Conclusion can go deeper, it would be more interesting if the authors focus more on the significance of their findings regarding the importance of the interrelationship between the obtained results and the literature, and the barriers to do it.
This section has been extended. Now it has 650 words.

13) References: Cite ALL OF THESE references in your work.

-Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. Journal of Cleaner Production, 143:1123-1136, 2017. -Larsen, J.D., Hoeve, M., Nielsen, S., Scheutz, C. Life cycle assessment comparing the treatment of surplus activated sludge in a sludge treatment reed bed system with mechanical treatment on centrifuge. Journal of Cleaner Production, 185:148-156, 2018.
-Buonocore, E., Mellino, S., De Angelis, G., Liu, G., Ulgiati, S. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecological Indicators, article in press.
-Abusoglu, A., Ozahi, E., Kutlar, A.I., Al-jaf, H. Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production. Journal of Cleaner Production, 142:1684-1692, 2017.
-Rocha, M.H., Capaz, R.S., Lora, E.E.S., Nogueira, L.A.H., Leme, M.M.V., Renó, M.L.G., Almazán, O.O. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis. Renewable and Sustainable Energy Reviews, 37, 435-459, 2014.
-Li, H., Jin, C., Zhang, Z., Ohara, I., Mundree, S. Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. Energy, 126:649-657, 2017.
-Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della Casa, C. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. Journal of Cleaner Production, 44:8-17, 2013.
All the references have been added.

Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Hai Zhang [a], Lucia Rigamonti [a], Simone Visigalli [a], Andrea Turolla [a], Paolo Gronchi [b], Roberto Canziani [a, *]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

*Corresponding Author
E-mail: roberto.canziani@polimi.it
Telephone: (+39) 02 2399 6410

Keywords: Electro-dewatering; Sludge management; Life cycle assessment; Return on investment; Industrial application; WWTP

Word count: 9673

Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Hai Zhang [a], Lucia Rigamonti [a], Simone Visigalli [a], Andrea Turolla [a], Paolo Gronchi [b], Roberto Canziani [a, *]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

[b] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

*Corresponding Author

E-mail: roberto.canziani@polimi.it

Telephone: (+39) 02 2399 6410

Keywords: Electro-dewatering; Sludge management; Life cycle assessment; Return on investment; Industrial application; WWTP

Word count: 9673

Abbreviations

AC	Acidification
CHP	Combined Heat and Power
DM	Dry Mass
DS	Dry Solids
EDW	Electro-dewatering
EP	Eutrophication
eq.	Equivalent
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas
GW	Global Warming
LHV	Lower Heating Value
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
POF	Photochemical Ozone Formation
ROI	Return On Investment
ton	tonne
WWTP	Wastewater Treatment Plant

Abstract

The objective of this study is to evaluate the feasibility of implementing electro-dewatering (EDW) as an add-on unit to the existing conventional dewatering units with the aim of increasing the final dry solids content and reducing the subsequent handling and energy costs of sewage sludge management. The assessment was carried out by focusing on a case study, a small wastewater treatment plant (WWTP) in the Milan metropolitan area. Various indicators were used~~, including~~ to evaluate the environmental impact ~~indicators~~ and economic performance ~~indicators~~. Primary data, such as operating data from the case study WWTP and economic data from an EDW equipment manufacturer, were extracted and used in the modelling. Four scenarios were set up and compared, which address~~ing~~ the current and future sludge management schemes in Italy.

The results suggest that it is environmentally and economically feasible to implement the EDW upgrade if the sludge disposal follows the incineration route. More specifically, when small WWTPs deliver their EDW-dewatered sludge to a centralised incineration facility, this will enable to reduce the global warming impact of the system up to 135 kg CO_2-eq. per dry tonne of sludge. In addition, good profitability (incremental return on investment > 15.1%) can be obtained when the market disposal cost is above 30.5-39.6 € per wet tonne of sludge. Based on our recent market survey, the sludge disposal price is well above the break-even values.

1 Introduction

The generation of sewage sludge is experiencing a steady growth in the European Union (EU; European Commission, 2016). ~~According to the data source (Eurostat, 2017a; Heimersson et al., 2017), in 2010, t~~The EU wastewater treatment plants (WWTPs) ~~have~~ dealt with ~~needed to handle~~ over 10 million tons of sludge (in dry mass) ~~for disposal to agricultural land, composting sites, incineration plants and landfill sites~~ in 2010 (Eurostat, 2017a). To comply with the EU's strategy for a circular economy, sludge is being disposed ~~with~~ of via two major routes: nutrient recovery by ~~applying~~ application to agricultural land and energy recovery by incineration (Papa et al., 2017). In either of these routes, it is favourable to increase the dry solid (DS) content of sludge. For example, a minimum DS of 40% is required for incineration in a fluidized bed incinerator and a DS of 90% for cement kiln incineration (Abuşoğlu et al., 2017). However, ~~in many WWTPs, sludge is being disposed at an average Dry Solids (DS) content of 20% (i.e. the sludge cake contains 80% of water),~~ due to the limits of mechanical dewatering that cannot remove the water bound to the colloidal solids in the sludge matrix (Mahmoud et al., 2010~~; Vesilind, 1994~~), the mechanically-dewatered sludge can only reach an average DS of 20%. Hence, additional thermal drying is needed, which consumes a significant amount of energy.

~~Therefore, improvement in sludge dewatering holds a great potential to reduce the WWTP's operating cost and its environmental impacts.~~

Electro-dewatering (EDW) in combination with mechanical compression is shown to be effective in increasing the sludge DS content and thus decreasing the quantity/volume of sludge requiring disposal. ~~In the meanwhile,~~ EDW can also maintain a better energy efficiency than thermal drying until reaching a DS of 38–45% (Olivier et al., 2015~~; Yu et al., 2017~~). In the past decade, much research has been carried out in the field of EDW and the majority of the studies are focused on how to optimise operating parameters in relation to energy efficiency. For instance, two factors, mechanical pressure and electrical voltage, were investigated in the work of Mahmoud et al. (2011). According to the authors, after optimising the operating conditions it was possible to save 25% energy compared with thermal drying. Therefore, EDW ~~improvement in sludge dewatering~~ holds great potential to reduce the WWTP operating costs and environmental impacts.

~~, polyelectrolyte dosage, different working modes (constant electrical voltage/constant electrical current), and sludge properties (e.g. type/nature, pH, and electrical conductivity; Guo et al., 2017; Mahmoud et al., 2011; Olivier et al., 2015; Tuan and Sillanpää, 2010; Visigalli et al., 2017a, 2017b).~~

Apart from being an effective dewatering technique, EDW also brings additional benefits during the treatment as it causes pathogen inactivation (Navab Daneshmand et al., 2012), and, if properly managed, it can reduce the concentration of heavy metals and organic pollutants in the dewatered sludge (Tuan and Sillanpää, 2010), the limits of which are regulated by the EU Directive 86/278/EEC and member states' regulations (Mininni et al., 2015).

Although many promising results have been reported and the mechanisms behind the EDW phenomenon are relatively well understood (Mahmoud et al., 2010), it ~~seems that it~~ has taken a long time for EDW to ~~make its full swing in the~~ be fully adopted for industrial application in WWTPs. Several reasons are behind this:

(1) Relatively high energy consumption: Regarding this point, an early ~~research~~ study (Mahmoud et al., 2010) suggests that EDW may find better application in dewatering/drying some high value products, e.g. foods and pharmaceuticals rather than sewage sludge. According to a latest publication (Zhang et al., 2017), the electricity consumption measured on an industrial EDW setup was 0.123 kWh per kilogram of water removed.

(2) Problems with anode material: It is well known that the anode is the core part of an EDW system. It has a high cost and ~~in the meanwhile~~ it is subjected to high wearing caused by harsh electrochemical corrosion and abrasion (Gronchi et al., 2017). According to ~~the~~ one data source (Zhang et al., 2017), by considering the anode cost and its service life, it can be translated ~~as~~ into 4.23 € per tonne of water removed. ~~On the other hand, as~~ It is widely recognised that finding the suitable replacement material is one of the key issues for promoting EDW to the industry users.

(3) Reliability under continuous working mode: Periodic cathode cleaning is needed to maintain the ~~system's~~ efficiency and productivity of the system. In accordance with a relevant study (Zhang et al., 2017), stepwise pressure has prolonged this period to 15 days, and this is acceptable for many industrial users.

(4) Competition with other engineering options: This is especially applicable to the situation of large WWTPs where there are different engineering options to choose from to dry the sludge. For example, if a WWTP is integrated with a combined heat and power (CHP) system, it is possible to utilise the waste heat/low-grade heat from the CHP to dry the sludge up to DS of 90% (Mills et al., 2014). In fact, a low temperature dryer can be powered by various types of on-site waste heat (e.g. co-generation, heating and air conditioning systems) as long as these heat sources are stable and have a minimum temperature of 90°C (SUEZ's Degremont, 2017). In another example (Yoshida et al., 2014), the WWTP is integrated with an on-site incinerator so that the heat generated from the incinerator can be used to dry the sludge. Therefore, large WWTPs may show less interest in EDW.

The doubts and uncertainties presented in the points 1-3 can be resolved with a comprehensive economic assessment. This is one of the objectives of this study. ~~While about the~~ For point 4, we should not ignore the large number of small WWTPs (< 100,000 population equivalents). For instance, currently there are about 60 WWTPs in the Milan metropolitan area and half of them are small WWTPs. Normally, they do not have suitable and stable on-site heat sources to power a low-temperature dryer, or the throughput of low-temperature dryer cannot satisfy the sludge production rate. In this case, EDW upgrade could be a good solution to increase their sludge dryness ~~and~~, thus reducing the ~~plant's~~ operating costs of the plant.

To evaluate the feasibility of EDW upgrade, it is important to provide measures from various perspectives. Firstly, in accordance with the Water Policy Directive 2000/60/EC (European Commission, 2000), it is necessary to take into account the recovery of costs for water services, including environmental and resources, i.e. economic analysis is required. As a WWTP is an important constituent of water services, the upgrading project should comply with this policy (Bertanza et al., 2018).

In recent years, a decision support system built on technical, economic and environmental performances is gaining popularity and being practiced by the researchers in this field (Bertanza et al., 2015a~~; MacDonald et al., 2018; Mills et al., 2014; Tomei et al., 2016~~). Basically, to evaluate the environmental performances, it follows the concept of Life Cycle Assessment (LCA), which is an international standard-based methodology (ISO14040 and ISO14044) and provides the ability to evaluate a product's environmental impacts by considering all its life cycle stages, starting from raw material extraction, manufacturing, use/reuse until final disposal (Gourdet et al., 2017). LCA has been applied in the field of sludge management since 2000 (Yoshida et al., 2013). The relevant studies have concentrated on the followings topics: identifying hotspots in WWTPs, assessing upgrading options for the treatment lines (Zhang et al., 2017) and selecting the most suitable sludge management schemes (Buonocore et al., 2016). For instance, in the study of Li et al. (2017), five different anaerobic digestion configurations were assessed with environmental and economic indicators, and the authors identified sludge organic content and biogas yield as the most influential factors. In another study (Gourdet et al., 2017), by comparing different scenarios, it was found that increasing the biodegradation rate of volatile solids and the biogas production was the most effective method to reduce the environmental impacts. Also, the same study recognised that the consumption of $FeCl_3$ (a chemical that is used to reduce the phosphorus contained in the return liquors from thickening and dewatering stages) was identified as a hotspot in the system's environmental profile. Besides, LCA is also a useful tool for working out proper waste management policies. As demonstrated by the case study of Righi et al. (2013), a scenario composed of anaerobic digestion and composting had the best environmental performance and was recommended to the policy-makers.

~~Therefore, in this study, we follow this idea and carry out an assessment focusing on the EDW upgrade.~~ The objective of this study is to evaluate the feasibility of implementing EDW as an add-on unit to the existing conventional dewatering, which serves to increase the final DS content and reduce the subsequent handling and energy costs of sewage sludge management. The assessment was carried out by focusing on a case study, a small WWTP in the Milan metropolitan area. Based on the comparisons between different scenarios~~sludge management options~~, we attempt~~aim~~ to identify the most suitable market to implement the EDW upgrade. Our previous publications focused on the technical issues of EDW (Visigalli et al., 2017a/b) by investigating the factors that influence the system's performance. Whereas, in the present study, the emphasis is placed on the environmental and economic assessment.

2 Methods

2.1 Environmental assessment

2.1.1 Goal and scope

The goal of this study is to assess the feasibility of implementing an EDW upgrade for a small WWTP following the ~~Life Cycle Assessment (~~LCA~~)~~ methodology. Here, "EDW upgrade/EDW dewatering" indicates that the EDW unit is a retrofittable add-on module arranged after the existing mechanical dewatering facility. As a whole system, it enables ~~to~~ an increase to the sludge DS from the initial 3.3% to 40%. 40% was set as the target DS due to the requirements of self-sustaining incineration (Outotec Oyj, 2016~~; Zhang et al., 2017~~).

The case study focuses on a small WWTP situated in the Milan metropolitan area, which serves 47,000 population equivalents. In this plant, the sludge is stabilised with the aerobic stabilisation method. After that, it is dewatered with a belt press (mechanical dewatering). Sludge samples were extracted from this WWTP for the lab-scale EDW test. In 2016, the plant ~~has~~ produced a total of 2300 tons of dewatered sludge that was disposed through a multiple-channel approach: 54.8% to landfill, 26.2% to incineration, and 19% to an external WWTP for further processing. The average disposal cost was 80 €/wet tonne.

The Functional Unit (FU) was defined as the treatment and disposal of 1 dry tonne of sludge (denoted as 1 tDM) coming from the upstream stabilisation stage.

The system boundaries are depicted in Figure 1, including all of the processing stages taking place after sludge stabilisation (i.e. conditioning, dewatering, and transport) up to the final disposal stage (land spreading or incineration and ash to landfill).

(Figure 1)

To help justify the advantages of the EDW upgrade, it was compared with the mechanical dewatering equipment used by the WWTP. Moreover, two sludge disposal routes were considered: sludge for land spreading (i.e. sludge is applied to arable land as fertiliser without composting treatment) and sludge for incineration. This is because ~~at present stage~~ sludge for agriculture use currently ~~(including land spreading and composting)~~ accounts for the biggest share in sludge end use in Italy (Eurostat, 2017a~~; Papa et al., 2017~~). It is widely used for its low cost. However, it is susceptible to policy changes, e.g. increasingly stringent contaminants limits (Mininni et al., 2015). Seeing that it is no longer permitted in Switzerland and discouraged in Netherlands and Germany, this has raised significant concerns among the Italian WWTP operators, and our recent survey of some WWTPs in the Lombardy region found that many of the WWTPs were using more than one disposal routes in case that the policy tightens (Díaz et al., 2015). The other disposal route, sludge disposed to a centralised incinerator, represents the future scheme of sludge management as it enables to lower the disposal cost and cope with the challenges and risks associated with sludge for agriculture use.

In total, four scenarios were set up ~~for making~~to allow for comparison of the options (see Figure 1):

Scenario A1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press). After that, the dewatered sludge cakes (DS 18.2%) are transported by truck to agricultural fields and applied using a tractor. After application, sludge gradually becomes available to the crops. In this process, it also releases GHG emissions to the air.

Scenario A2: it follows a similar land spreading route as described in A1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will be increased to 40%. In this case, A2 represents the EDW upgrading scenario and it will be compared with the reference scenario A1. ~~EDW-dewatered sludge for land spreading~~

Scenario C1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press) by each individual WWTP. After that, the dewatered sludge cakes (DS 18.2%) from each individual WWTP are transported by truck to a centralised incineration facility. Subsequently, the cakes are mixed and dried with a disc dryer (thermal drying) to reach DS 40% and then they are fed into a fluidized bed furnace. The waste heat is recovered. After material recovery from the ashes, the residues are sent to landfill for hazardous waste.

Scenario C2: it follows a similar incineration route as described in C1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will reach 40% and the thermal drying treatment occurred in the incineration plant will be omitted. In this case, C2 represents the EDW upgrading scenario and it will be compared with the reference scenario C1.~~ EDW-dewatered sludge at WWTPs for incineration~~

~~Between the scenarios (A1 versus A2, C1 versus C2), the difference only lies in the dewatering stage. The mechanical dewatering as concerned in A1 and C1 (reference scenarios) reflects the current state of the art; while the EDW dewatering as concerned in A2 and C2 is the upgrading option under assessment.~~

~~Especially, t~~The scenario C2 was constructed to consider the further improvement ~~on~~ to the efficiency of energy recovery~~ - instead of relying on the integrated on-site thermal dryer, ~~. The reliance on the integrated on-site thermal dryer is removed. If the delivered sludge ~~on delivery~~ already has a suitable DS content (e.g. 40%) to be ~~dumped~~ loaded into the incinerator, it would boost the incinerator's productivity and more heat could be diverted to the local district heating network compared to scenario C1.

SimaPro 8.4 was used to model the scenarios. Database ecoinvent V3 (allocation, recycled content system model) was used with priority for the background systems. The geographic boundary was specified to be the Italian border.

Six impact categories were assessed: Global Warming (GW), Acidification (AC), Photochemical Ozone Formation (POF), and terrestrial, freshwater and marine Eutrophication (EP). These impact categories were selected for their close relevance to the system under study (~~Mills et al., 2014; ~~Tomei et al., 2016~~; Yoshida et al., 2013~~), in relation to the following elements:

(1) the end use of sludge: the emissions of land spreading and incineration are directly related to GW, AC and EP;

(2) EDW is an energy intensive process and a major advantage of using EDW is to reduce the fuel consumption in the road transport stage. In this context, GW, POF, AC and EP are directly related to consumption of fossil fuels.

The impact categories were assessed with the Life Cycle Impact Assessment (LCIA) methods recommended by the "ILCD Handbook" (European commission JRC-IES, 2011). A detailed list of methods used is provided in Supplementary Information (Section SI-1).

The toxicity issues in relation to sludge for agriculture use (e.g. heavy metals, pathogens, organic pollutants and other contaminants) were not considered. Also, the benefits of improved soil properties and crop productivity were discounted because there is a lack of proper characterization model to quantify them. In fact, further risk assessment is ~~more~~ needed to address the associated risks and benefits. For example, ~~field studies are good examples (~~Alvarenga et al. (2017) conducted soil and plant analysis on the sludge-amended fields; Mantovi et al. (2005) carried out a 12-year field study to compare the difference between mineral fertilisers and sludge.

Cases of multi-functionality were solved by expanding the system boundaries to include avoided primary productions due to material recovery from waste (European Commission JRC-IES, 2010; Finnveden et al., 2009). In this case study, the avoided products are fertiliser and heat.

2.1.2 Environmental data inventory

As a common practice in this research area (Corominas et al., 2013~~; Mills et al., 2014; Tomei et al., 2016; Yoshida et al., 2013~~), the construction and demolition of infrastructure were excluded; biogenic CO_2 emission was regarded as climate neutral (Houillon and Jolliet, 2005~~; Tomei et al., 2016~~).

The LCA modelling was assisted with mass balance calculations (see Figure 2 and Figure SI-1 in Supplementary Information). Data collection for each life cycle stage is described as follows.

(Figure 2)

Conditioning

During the sludge conditioning, a polyelectrolyte is used. The polyelectrolyte dosage, 5.30 kg/tDM, was taken from the WWTP's operating data. Polyelectrolyte was modelled with acrylonitrile (a raw material for producing acrylamide polymers) following the relevant literature (~~Tomei et al., 2016;~~ Yoshida et al., 2014).

Mechanical dewatering

The mechanical dewatering data, energy consumption (41.16 kWh/tDM) and sludge DS improvement (3.3% to 18.2%), were extracted from the WWTP. The Italian electricity data (database ecoinvent V3) was used.

EDW dewatering

~~Our previous publications focus on the technical issues of EDW, investigating the factors that influence the system's performance. While in the present study, the emphasis is placed on the~~

~~environmental and economic assessment, but s~~Some data (e.g. the outlet DS and the specific energy consumption) needed to be obtained from experiments.

~~The data of sludge volume reduction and specific energy consumption were derived from our lab test following the method described in (Visigalli et al., 2017b).~~ The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. The experimental setup and protocol were based on our previous publications (Visigalli et al., 2017b). In brief, sludge samples were treated between the electrodes (anode DSA® by De Nora and cathode stainless steel AISI 304) that were connected to a DC power supply (GBC, 34121070 bench scale generator). A constant mechanical pressure of 300 kPa was applied throughout the 25-min EDW treatment. The evolution of electric current and mass of filtrate were recorded and used for calculating the specific energy consumption.

Two sets of parameters were tested:

(1) cake thickness (unit in mm): 15, 20, 25;

(2) electrical potential (unit in V): 10, 15, 20.

Each combination was tested in two replicates. The data giving the best dewatering performance (in terms of DS improvement and productivity) were used in the assessment, that is lower cake thickness (15 mm) combined with higher voltage (20 V) ~~gives the best DS improvement in each sludge case~~. Accordingly, this parameter combination caused the highest specific energy consumption. From an early publication (Olivier et al., 2015), it is known that EDW can maintain superior energy efficiency over thermal drying until reaching DS 45%. Therefore, we can assume that the parameter combination “15 mm-20 V” gives the best dewatering performance despite the increased specific energy consumption.

For industrial application, it is also important to consider the productivity of the machine. For example, a solar dryer is very energy efficient, but its productivity is very low. In the case of EDW, the operating parameters should ensure good productivity, i.e. the shortest time to reach a target DS. To address this issue, a target DS was set at 25% and the relevant data were extracted and compared. The results show that the combination of “15 mm-20 V” gives the best productivity, which is in line with the dewatering performance as discussed previously. As a consequence, the data generated from this operating parameter combination were used in the assessment. The detailed results are provided in Supplementary Information (Section SI-2).

Based on the experiment data, it was assumed that the EDW unit was used to process the mechanically-dewatered sludge, increasing its DS from 18.2% to 40%. As a whole system, the EDW upgrade consumed 409.40 kWh/tDM for increasing the sludge DS from 3.3% to 40%. The Italian electricity data (database ecoinvent V3) was used.

It seems that there is a limitation for extrapolating the lab-scale device data to industrial application. However, in accordance with the data reported by Zhang et al. (2017), from the lab scale device (anode area 0.13 m^2) to the industrial scale machine (anode area 47.52 m^2) under continuous working mode, only negligible discrepancy was found between the specific energy consumptions.

Transport

It was assumed that the dewatered sludge was transported for 100 km (Truck 16-30 t, vehicle emission EURO 5) to reach the storage site/incineration plant. The storage related input and output were discounted due to lack of data (Heimersson et al., 2016).

Tractor application

It was assumed that the sludge cake was applied in agriculture land using a tractor, which consumed 0.5 L diesel per wet tonne of sludge (Møller et al., 2009).

Land spreading

The fertiliser replacement rates are based on the relevant studies. The nutrient concentrations of dewatered sludge were based on the data from Mantovi et al. (2005), and the conversion factors were extracted from the study of Heimersson et al., (2017). For the N-fertiliser, the total N was 4.25% of the sludge Dry Mass (DM); a ~~converting~~ conversion factor of 0.5 was used to account for the element mineralisation (subsequently becomes available for crop uptake). For the P-fertiliser, the total P was 1.81% of the sludge DM; a ~~converting~~ conversion factor of 0.7 was used to account for the element mineralisation.

~~On the other hand, t~~The greenhouse gas (GHG) emissions associated with the life cycle stage of land spreading were calculated following the relevant references: CH_4, 5kg/tDM (~~Heimersson et al., 2016;~~ Penman et al., 2000); NH_3, 8% total N of sludge applied (~~Heimersson et al., 2016;~~ Remy and Jekel, 2008); N_2O, 1% of total N of sludge applied (Tomei et al., 2016). The emissions to soil and water were extracted from the study of Lombardi et al. (2017).

Incineration

The incineration plant configuration with energy balance calculation (scenario C1) is illustrated in Figure 3. It is based on a reference case, in which a centralised incineration plant is responsible for processing sludge from over 70 small WWTPs in the region (Outotec Oyj, 2016).

(Figure 3)

It was assumed that the plant was equipped with a waste heat recovery system of thermal efficiency of 95% (Murakami et al., 2009). The energy (biogenetic) produced by the system was utilised in such a way that the electricity was only for the plant's self-use, part of the heat was used to power the thermal dryer to increase the sludge DS content from 18.2% to 40% (having the same DS improvement as the "EDW upgrade"), and the rest of the heat is distributed through the local district heating network (output to the outside of system boundaries). Combustion air preheating was excluded ~~for~~ because it is not needed in the scheme considered.

The lower heating value (LHV) of the dewatered sludge was calculated according to the handbook of wastewater solids incineration systems (Water Environment Federation - Incineration Task Force, 2009). The value was 3534 kWh/tDM at DS 40%. The detailed calculation is provided in Supplementary Information (Section SI-4).

For thermal drying, the specific energy consumption was taken as 0.72 kWh per kilogram of water evaporated, reflecting the best available industrial technology (SUEZ's Degremont, 2017). The resulting value was 2155.57 kWh/tDM.

The output energy flow was modelled as replaced heat generated from fossil fuel sources (co-generation using natural gas), aiming to reflect the possible impact to the Italian energy consumption structure. ~~At current stage c.a.~~Currently, approximately 90% of energy consumption in Italy is fossil fuel-based (Deloitte, 2015). This represents the scenario C1.

In the case of scenario C2, the heat previously used for thermal drying will be saved and completely diverted to the district heating, i.e. more output to the outside of the system.

The ashes generated from the flue gas treatment are treated to make them inert and are ~~, after material recovery (sand, gravel, sodium chloride, etc.), the residues are~~sent to a landfill for hazardous waste, located in Italy.

The incineration related material and energy inputs and emissions were extracted from the relevant study with necessary adaptions (Lombardi et al., 2017).

The key inventory items are summarised in Table 1. The data are normalised to the FU (1 tDM).

Table 1. Inventory of data for the LCA (normalised to the FU, 1 tDM).

Inventory item	**Unit**	**Amount**
Polyelectrolyte (modelled with Acrylonitrile)	kg	5.30
Electricity, medium voltage, IT (mechanical dewatering, belt press)	kWh	41.16
Electricity, medium voltage, IT (EDW dewatering)	kWh	409.40
Energy consumption for sludge thermal drying	kWh	2155.57
Sludge for land spreading		
N-fertiliser replacement (ammonium nitrate)	kg	21.25
P-fertiliser replacement (superphosphate)	kg	12.67
GHG emissions due to sludge application in the fields		
Methane (CH_4)	kg	5.0
Ammonia (NH_3)	kg	3.4
Nitrous oxide (N_2O)	kg	0.43
Sludge for incineration		
Replaced heat (C1)	kWh	971
Replaced heat (C2)	kWh	3127

2.1.3 Sensitivity analysis

As stated in the introduction, energy consumption is a critical factor for promoting EDW to the industrial users. At the same time, very often the energy data contains big variations when treating sludge from different sources. In this case, the robustness of the results was analysed. The energy consumption of EDW dewatering stage was varied by ±25% with respect to the lab testing data.

2.2 Economic assessment

2.2.1 Assessment method and indicators

To assess the economic performance of the~~ upgrading ~~upgrade options for the WWTP, previous studies have utilised the life cycle costing method (~~Bertanza et al., 2015; ~~Tomei et al., 2016). In this method, the results are presented as a cost gap in each life cycle stage (i.e. the difference between the reference scenario and upgrading scenario): a negative gap means the upgrading option is economically favourable. The total cost gap is an aggregated result of all the life cycle stages. In this way, it is possible to identify the most critical life cycle stages (i.e. hotspots) but the downside is that the results are restricted to the scenarios concerned in the study.

Apart from assessment method, it is also important to select appropriate economic performance indicators. ~~For large chemical engineering project (e.g. to build a WWTP or to implement large modifications), n~~Net present value (Mills et al., 2012) and internal rate of return (Mills et al., 2014) are usually used for large chemical engineering projects (e.g. building a WWTP or implementing large modifications). However, they are not suitable for evaluating small project, such as the EDW upgrade concerned in the present study, which only requires a short execution time and a relatively small investment. In this case, more suitable indicators are needed: ~~For EDW upgrade, c~~cost saving stems from sludge volume reduction and sludge disposal cost for an EDW upgrade. However, sludge disposal costs currently ~~varies ~~vary greatly from country to country and from region to region, depending on the local circumstances, such as regulations, disposal routes and subcontractors. According to the data source (Bertanza et al., 2015b), the disposal cost within the EU ranges from 20 to 100 €/wet tonne. In this case, a model demonstrating the relationship between the profitability of the upgrading project and the disposal cost will be useful to cover a wide scope of market situations. Therefore, ~~in this study, ~~the economic assessment in this study was carried out following the method of Towler and Sinnott (2013). It focuses on the EDW upgrade itself rather than the scenarios as previously discussed in the LCA. It also gives more flexibility in sensitivity analysis and the results can be easily communicated to the WWTPs managers (Zhao et al., 2016).

The first indicator, incremental Return On Investment (ROI), was calculated with Equation 1 (Towler and Sinnott, 2013):

$$\text{Incremental Return On Investment} = \frac{\text{Incremental Profit}}{\text{Incremental Investment}} \times 100\% \qquad (1)$$

In the case of the EDW upgrade, the incremental investment refers to the EDW machine's investment cost (one piece of EDW machine, including the cost of installation and shipping). It was assumed that the upgrade caused no changes to the working capital. The incremental profit was calculated from the difference between the cost saving in sludge disposal and the cash cost of production.

The second indicator, total cost of production, was calculated with Equation 2 (Towler and Sinnott, 2013):

$$\text{Total Cost of Production} = \text{Cash Cost of Production} + \text{Annual Capital Charge} \qquad (2)$$

In the case of the EDW upgrade, the cash cost of production is the sum of variable production cost (e.g. consumables and EDW electricity use) and fixed production cost (e.g. labour and maintenance). The annual capital charge is the annualized investment of EDW machine over the project period (i.e. the service life of the EDW machine) at a certain interest rate.

2.2.2 Sensitivity analysis

EDW is an energy intensive process. Energy consumption and energy price can have a strong influence on the project's profitability. Therefore, a sensitivity analysis was carried out to address the following cases.

Low energy consumption case: The "low energy consumption case" was modelled as the EDW unit energy consumption dropping by 25% with respect to the "standard case" (lab testing results) while holding the DS improvement constant. ~~It~~ This case represents the situation when the EDW machine is running with improved dewatering efficiency. This is a practical consideration. In fact, nowadays there are a few examples of industrial EDW systems on the market, e.g. the "ELODE" from ACE (Korea) and the "EKG" from Electrokinetic (UK) (Zhang et al., 2017). However, all of them are belt press-based. ~~By~~ In contrast, our EDW prototype machine is screw press-based, and it is expected that the dewatering efficiency will be improved. This is because the shearing effect of the screw would mitigate the curst development on the anode, which has been recognised as the major limit to the EDW dewatering efficiency in a latest study (Yu et al., 2017).

High energy consumption case: The "high energy consumption case" was modelled as the EDW unit energy consumption increasing by 25% with respect to the "standard case" while holding the DS improvement constant. This corresponds to the situation of treating the poor-EDW-response sludge. This is also a practical consideration ~~as~~ because in our previous studies we have noticed that sludge from different WWTPs showed different responses to the EDW treatment, depending on the sludge nature and its upstream processes (Visigalli et al., 2017b).

EU average case: The Italian electricity price (for industrial user) is the ~~2nd~~ second highest in the EU, being 28 – 30% higher than the EU average price (Eurostat, 2017b). Thus, an additional case was added by considering the EU average electricity price (0.114 €/kWh) and is denoted as "EU average".

2.2.3 Economic data inventory

In our project (Visigalli et al., 2017b), we aim to scale up the lab-scale EDW device for industrial applications. The industrial prototype is currently under development (screw press-based machine), it is therefore possible to extract some primary economic data from the machine manufacturer (X2 Solutions Srl, who is also one of the project consortiums). The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers.

The EDW machine has a throughput of 0.2 m^3/h. In terms of yearly throughput, it can process 800 tons of mechanically-dewatered sludge, which especially suits the needs of small WWTPs. The machine power was calculated on the basis of lab testing results from Politecnico di Milano.

As a first assumption, the EDW machine will be distributed and used in the Italian market. Therefore, the Italian market data were used for the calculation, including the cost of shipping and installation, maintenance, labour, tax rate, interest rate, and electricity price.

To be consistent with the previous LCA study, the input sludge DS was set as 18.2% and the output DS as 40%.

The data used for the economic assessment and their sources are summarised in Table 2.

Table 2. Inventory of data for the economic assessment.

Item	**Value**	**Source**
Machine capacity	0.2 m^3/h	EDW machine manufacturer
DS of inlet sludge	18.2%	Extracted from WWTP
DS of outlet sludge	40%	Experimental data
Working hours per year	3800 h	Extracted from WWTP
EDW machine price	Estimate	EDW machine manufacturer
Maintenance cost	Estimate	EDW machine manufacturer
Machine service life/project period	10 years	EDW machine manufacturer
Machine power*	14.6-18.2 kW	Experimental data
Electricity price for industrial users, all taxes included, Italy	0.148 €/kWh	Eurostat (2017b)
Interest rate (before taxes), water sector	8.74%	KPMG (2015)
Tax rate, Italy	27.90%	Deloitte (2017)
Sludge disposal cost (including transport)	20-100 €/wet tonne of sludge	Díaz et al. (2015), Bertanza et al. (2015b)

* The power value is given in ranges, as it includes the variations of energy consumption considered in the sensitivity analysis.

3 Results and discussions

3.1 LCIA results

3.1.1 Global Warming

GW is regarded as the most important impact category in sludge management (Mills et al., 2014). It is also the most frequently communicated one (Yoshida et al., 2013). It directly affects a WWTP's profit via the regulator's incentives/tax charges (Mills et al., 2014). Figure 4 shows the GW impact for the four scenarios considered in this study. The net impact is calculated as the sum of the impacts from all the life cycle stages including the credits (either replaced fertilisers or replaced heat) and it is indicated with a data label.

(Figure 4)

It ~~can be~~was found that the scenario C2 gives the best performance. The system's net GW impact of C2 drops to -32 kg CO_2-eq., in contrast to 87 kg CO_2-eq. of A1 and 103 kg CO_2-eq. of C1. This is for two reasons:

(1) though the EDW upgrade itself induces a big percentage of impact (223 kg CO_2-eq.) due to its electricity consumption, it enables a greater credit to the system (-312 kg CO_2-eq.) by displacing the fossil fuel-based district heat;

(2) the EDW upgrade also enables sludge volume reduction by 55%, which in turn contributes to cutting 50 kg CO_2-eq. ~~in~~ during the transport stage. This result is in line with the findings reported in the study of Gourdet et al. (2017), in which the sludge DS was identified as one of the most sensitive parameters in the dewatering stage and it produced the greatest variability to GW impact through its influence on the transport stage (emissions e.g. CO_2, N_2O, SF_6, and CH_4).

In fact, further reduction is possible. For example, in C1 we have used the data of the best available technology in thermal drying – 30-50% more efficient than the average cases (SUEZ's Degremont, 2017). This means that when we move from C1 to C2, less replaced heat has been considered in the calculation.

It should be noted that the Italian electricity data have been used in the current calculation. In 2012, over 68% of Italy's electricity generation was fossil fuel-based (14% by hydropower and 13% by renewable sources; Deloitte, 2015), which is a relatively high percentage within the EU. Therefore, an additional scenario was constructed to reflect the average EU case, in which the Italian electricity data was replaced with the "country-mix" electricity data of the EU (ENTSO-E). The results indicate that the GW impact of C2 can be further reduced to -57 kg CO_2-eq.

On the other hand, the scenario A2 is the worst performer in this impact category. If we move from A1 to A2, the indicator will increase significantly, from 87 to 236 kg CO_2-eq. This is mainly attributed to the use of electricity of EDW in the meanwhile its effect on sludge volume reduction (reduced fuel consumption in transport and field tractor application) is not big enough to offset the GW impact induced by the EDW itself.

In conclusion, ~~if a WWTP's objective is to cut off its GW impact,~~ the current analysis provides strong support for implementing the EDW upgrade~~, either moving from A1 to C2, or moving from C1 to~~ (moving to C2) if a WWTP's objective is to reduce its GW impact.

3.1.2 Other impact categories

The LCIA results of other impact categories strongly depend on the disposal routes. So, they were plotted in two respective figures according to the disposal routes. Also, the results were normalised against the greatest absolute net value for each impact category to make them share a common y-axis (in %). Figures plotted with absolute impact values can be found in Supplementary Information (section SI-5).

The LCIA results for the land spreading route (A1 & A2) are depicted in Figure 5. The data labels over the bar end indicate the net impact values.

(Figure 5)

The life cycle stage of land spreading is shown as an aggregated result, which sums the impact of the emissions (to air, soil and water) and the credit to the system (inorganic fertiliser replacement). It behaves differently in different impact categories. For example, for the indicators of AC, POF and marine EP, the effect of the credit is stronger than the emissions, and, as a consequence, the net outcome is negative; whereas for the other impact categories (terrestrial and freshwater EP), the emissions become dominant, accounting for over 90% of the overall system's impact. In accordance with a more detailed study (Yoshida et al., 2018), the fate of phosphorus (P) strongly influences the freshwater EP, while the fate of nitrogen (N) has greater impact on the terrestrial EP and marine EP. The electricity consumption of EDW accounts for a very large percentage in the indicators of AC, POF and marine EP. ~~In the meanwhile, t~~The "trade-off" (i.e. the reduced impacts in the stages of transport and field tractor application due to sludge volume reduction) is not big enough to offset the EDW electricity consumption itself. So, the net outcome is that the EDW upgrade increases the impacts in these categories.

The impacts for the incineration disposal route (C1 & C2) are depicted in Figure 6. The data labels over the bar end indicate the net impact values. ~~Because of~~The EDW upgrade results in ~~the system's~~ net impact drops reduction in the following impact categories: POF, terrestrial EP and marine EP. Especially, the drop is more remarkable in the POF – 40% less than the case of C1. Furthermore, if the Italian electricity data are replaced with the ENTSO-E data, 65% reduction can be achieved in the POF. The reduction mainly comes from the trade-off effect of those life cycle stages using fossil fuel, e.g. transport (diesel) and avoided heat production (natural gas-powered CHP plant, IT market, ecoinvent V3).

(Figure 6)

~~Regarding the AC, m~~Moving from C1 to C2 will increase the impact to AC by 20% despite the credit coming from the replaced heat. While for the impact of freshwater EP, the EDW dewatering accounts for nearly 90% of the impact of C2. However, if we look at the absolute value (see Supplementary Information, Figure SI-5), moving from C1 to C2 corresponds to an increase from 0.03 to 0.06 kg P-eq., which is less than 6% of the land spreading cases, which is in line with the results reported in the study of Lombardi et al. (2017).

In fact, there are discrepancies between the LCIA results reported from different publications (Corominas et al., 2013; Yoshida et al., 2013), which can be attributed to the variations in the following aspects: data source (WWTPs treating water of different contamination levels with different removal efficiencies), process configuration, system boundaries, geographical area, functional unit and LCIA method. This makes it difficult to compare the results from different studies. Instead, most of the studies stay with comparing scenarios.

The LCIA results give a holistic view of the sludge management scenarios. The EDW dewatering stage consumes large amount of electricity, causing significant increases in the impact indicators; on the other hand, it contributes to reduce the overall system's impacts in the downstream life cycle stages, e.g. reduced impacts in the transport stage due to sludge volume reduction and reduced impact in the disposal stage (replaced fertiliser/heat). This implies that sludge management should encompass the life cycle thinking, encouraging solutions that enable to reduce the overall environmental impacts, and avoiding shifting the environmental burdens from one life cycle stage to another.

3.1.3 Results of the sensitivity analysis

The LCIA results of the sensitivity analysis ~~about~~ of the EDW energy consumption are listed in Table 3. Generally, the variation of the EDW energy consumption has no significant influence on the conclusions derived from comparing the scenarios (i.e. A1 versus A2 and C1 versus C2). The only exception is that if the EDW energy consumption decreases by 25%, the AC impact of C2 will be less than that of C1.

Table 3. LCIA results of the life cycle stage of EDW dewatering. The EDW energy consumption is varied by ±25% (corresponding to the results of Min and Max, respectively) with respect to the lab testing data (corresponding to the results of Mean).

Impact category	Unit	Min	Mean	Max	Difference from mean
GW (IPCC 100a)	kg CO_2-eq.	1.73E+02	2.23E+02	2.73E+02	5.00E+01
AC	mol H^+-eq.	8.72E-01	1.13E+00	1.38E+00	2.53E-01
POF	kg NMVOC-eq.	3.49E-01	4.50E-01	5.51E-01	1.01E-01
Terrestrial EP	mol N-eq.	1.15E+00	1.48E+00	1.81E+00	3.32E-01
Freshwater EP	kg P-eq.	4.25E-02	5.49E-02	6.72E-02	1.23E-02
Marine EP	kg N-eq.	1.10E-01	1.42E-01	1.74E-01	3.20E-02

3.2 Economic profitability

The incremental ROI for implementing the EDW upgrade is depicted in Figure 7. Three representative points of disposal cost (20, 60 and 100 €/wet tonne) were selected to establish the relationship between the incremental ROI and the disposal cost. According to the data source (Investopedia, 2015), the average ROI of water sector is 15.1%. Thus, a reference line at ROI 15.1% is added to facilitate the evaluation. The break-even values at ROI 15.1% are reported in the annotation box in the figure.

(Figure 7)

It ~~can be~~was observed that most of the ROI developments are above the reference line, which implies that all ~~the~~ four cases considered can enjoy good profitability with the EDW upgrade. More specifically, an attractive ROI is attainable for the low energy consumption case, EU average case, standard case and high energy consumption case when the sludge disposal cost is above 30.5, 30.8, 35.0, and 39.6 €/wet tonne, respectively.

The sludge disposal cost for agriculture use (both land spreading and composting, at DS 25%) is 47-57 €/wet tonne including transport based on our recent survey of some WWTPs in the Lombardy region of Italy (Díaz et al., 2015). In the case of disposal to incineration (at DS 80-90%), 66-78 €/wet tonne is common. Therefore, the incremental ROI generated from the EDW upgrade is very attractive, especially if one considers that the disposal cost is projected to increase, driven by the increasingly stringent discharge limit on the sludge for agriculture use, and the increasing fuel price for transport (Mininni et al., 2015).

The EU average case performs close to the low energy consumption case, suggesting that the EDW upgrade is applicable to other EU markets and may give better economic performance than in Italy.

The results of total cost of production indicate that the cost of electricity accounts for the biggest share~~, being~~ (57%) with contributions from the annual capital charge (21%), the consumables (17%, mainly the anode consumption), and the fixed cost of production (5%, for the cost of maintenance). This confirms the concerns associated with using EDW, e.g. relatively high energy consumption and expensive anode replacement. However, the cost saving from sludge volume reduction is much greater than the total cost of production, such that the WWTP will enjoy a good profit after implementing the EDW.

3.3 Selecting drying methods

Several environmental ~~indicators~~ impact and economic performance indicators have been assessed. As seen from the results, the EDW upgrade could not give a uniform performance in all these indicators. ~~To assist decision-making, t~~The indicators can be ranked according to their importance or specific needs of a WWTP (e.g. goal to reduce a specific indicator) to assist decision-making. In this case, a scoring exercise can be helpful (Mills et al., 2014). Furthermore, more aspects can be incorporated in the scoring matrix to improve decision-making. For example, in the studies by Bertanza et al. (2016) and Tomei et al. (2016), technical feasibility (sub-categories such as reliability, flexibility/modularity, complexity and integration with existing structures), administrative aspects and normative constraints, and social aspects have been incorporated. In another example (Mills et al., 2014), tax incentives as a risk factor has been added.

Regulation and policy-making in sludge management can be another important aspect to consider. In terms of disposal methods, landfill will be progressively phased out in the EU (Mininni et al., 2015). In recent years, opposition to direct use of sludge in agriculture has intensified due to consumer's demand on food safety and quality (e.g. organic farming). This has led to ~~the situation that the~~a growing percentage of sludge ~~for incineration~~being incinerated ~~is growing~~ in the EU (Eurostat, 2017a). In order to achieve an overall positive energy valorisation in the sludge to energy route, it is essential to increase the sludge DS to have a suitable LHV (Arlabosse et al., 2012). An EDW machine is very competitive for working in the DS range of 15-40%. In this range, it is more energy efficient than thermal dryer, and at the same time it can maintain a higher productivity than a solar dryer (Umwelt Bundesamt, 2013). Besides, it requires less space to implement the upgrading project than a solar dryer, which is highly welcomed by those small WWTPs situated near big cities.

A thermal dryer powered by waste heat or solar dryer can be arranged after the EDW unit to go beyond DS 40%, as seen from some commercial solution providers (e.g. ACE). In such way, different methods can team up as a complete drying solution to provide the best energy efficiency and productivity.

4 Conclusions

In this study, the feasibility of implementing EDW as an add-on unit to the existing conventional dewatering was evaluated with environmental impact and economic profitability indicators.

In the environmental assessment, four scenarios were setup and compared (A1, A2, C1 and C2, as depicted in Figure 1). ~~As for the incineration route, t~~The results show that ~~considering the GW impact,~~ it is advantageous to implement the EDW upgrade (i.e. moving from C1 to C2) when considering the GW impact for the incineration route. Though the EDW itself is responsible for a big share of the impact, it enables to generate a much bigger credit to the system. ~~In the meanwhile,~~ The effect of sludge volume reduction also helps to lower the system’s impact in the transport stage. The net effect is that GW impact of C2 will drop from 103 to -32 kg CO_2-eq., which is a significant reduction. Additionally, the EDW upgrade also contributes to ~~lower~~ reducing other indicators, e.g. POF, terrestrial and marine EP.

~~As for the land spreading route, t~~The EDW upgrade (i.e. moving from A1 to A2) will ~~indeed~~ increase all the studied impact indicators for the land spreading route. This is mainly because the benefits associated with the sludge volume reduction (55%) ~~is~~ are not big enough to offset the impacts induced by the EDW electricity use.

The economic analysis shows that under current market situation in Italy, the EDW upgrade will generate very attractive ROI (>15.1%) for small WWTPs regardless of disposal routes. This is because:

(1) the current market price for sludge disposal in Italy (47-78 €/wet tonne) is well above the break-even values (30.5-39.6 €/wet tonne);

(2) upper limit data have been used to stress the calculation, e.g. the Italian electricity price, which is 30% higher than the EU average case.

In summary, ~~in the case of sludge disposal for incineration, the~~ EDW upgrade is highly recommended as it offers good environmental performance and economic profitability in the case of sludge disposal for incineration. While in the case of sludge for land spreading, the environmental impacts of EDW upgrade could be reduced by carefully selecting an intermediate outlet DS point.

The present study has its limitations, such as the lab-scale EDW data (e.g. the outlet DS and the specific energy consumption) were used since the prototype machine was not ready to conduct testing with actual sludge samples. However, the robustness of the results was assessed with two sensitivity analyses, and this allowed us to draw some solid conclusions for the EDW upgrade. Once more data become available, they can be updated in the models to generate more accurate results. Also, more indicators can be incorporated into the decision-making matrix, in particular the social aspects (e.g. employment, income, access to services, public health and safety, etc.).

The EU Directive 86/278/EEC was adopted more than 30 years ago. In order to keep it updated with the societal changes, it is currently under review by the European Commission to address emerging issues, in particular in relation to the use of sludge for agriculture. It has been anticipated that the limits of heavy metals will be lowered. In addition to that, limits for organic micropollutants and microbial indicators of pathogens will be introduced. In this context, the advantage of EDW could possibly be further strengthened. However, to date, there are limited data to support the effectiveness of EDW on reducing these contaminants, which could constitute a future research development.

Acknowledgements

This research leading to these results has received funding from the European Union’s Seventh Framework Programme under grant agreement No. 611593 the “SLUDGEtreat” project, and the LIFE Programme under grant agreement No. ENV/IT/000039 the “ELECTRO-SLUDGE” project. The authors wish to thank Cap Holding Group for supplying the sludge samples and Industrie De Nora Spa for providing the DSA® anodes ~~DSA electrode~~. The valuable support of Dr. Sam Skinner in proof reading is gratefully acknowledged by the authors.

Supplementary information

Supplementary information related to this article can be found at https://.

References

Abuşoğlu, A., Özahi, E., İhsan Kutlar, A., Al-jaf, H., 2017. Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production. J. Clean. Prod. 142, 1684–1692. doi:10.1016/J.JCLEPRO.2016.11.121

Alvarenga, P., Palma, P., Mourinha, C., Farto, M., Dôres, J., Patanita, M., Cunha-Queda, C., Natal-da-Luz, T., Renaud, M., Sousa, J.P., 2017. Recycling organic wastes to agricultural land as a way to improve its quality: A field study to evaluate benefits and risks. Waste Manag. 61, 582–592. doi:10.1016/j.wasman.2017.01.004

Arlabosse, P., Ferrasse, J.-H., Lecomte, D., Crine, M., Dumont, Y., Léonard, A., 2012. Efficient

Sludge Thermal Processing: From Drying to Thermal Valorization, in: Modern Drying Technology. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, pp. 295–329. doi:10.1002/9783527631681.ch8

Bertanza, G., Canato, M., Laera, G., 2018. Towards energy self-sufficiency and integral material recovery in waste water treatment plants: Assessment of upgrading options. J. Clean. Prod. 170, 1206–1218. doi:10.1016/J.JCLEPRO.2017.09.228

Bertanza, G., Baroni, P., Canato, M., 2016. Ranking sewage sludge management strategies by means of Decision Support Systems: A case study. Resour. Conserv. Recycl. 110, 1–15. doi:10.1016/j.resconrec.2016.03.011

Bertanza, G., Canato, M., Heimersson, S., Laera, G., Salvetti, R., Slavik, E., Svanström, M., 2015a. Techno-economic and environmental assessment of sewage sludge wet oxidation. Environ. Sci. Pollut. Res. 22, 7327–7338. doi:10.1007/s11356-014-3378-6

Bertanza, G., Canato, M., Laera, G., Tomei, M.C., 2015b. Methodology for technical and economic assessment of advanced routes for sludge processing and disposal. Environ. Sci. Pollut. Res. 22, 7190–7202. doi:10.1007/s11356-014-3088-0

Buonocore, E., Mellino, S., De Angelis, G., Liu, G., Ulgiati, S., 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecol. Indic. doi:10.1016/J.ECOLIND.2016.04.047

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: State of the art. Water Res. 47, 5480–5492. doi:10.1016/j.watres.2013.06.049

Deloitte, 2017. Corporate Tax Rates 2017 [WWW Document]. URL https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Tax/dttl-tax-corporate-tax-rates.pdf (accessed 10.9.17).

Deloitte, 2015. Energy market reform in Europe [WWW Document]. URL https://www2.deloitte.com/global/en/pages/energy-and-resources/articles/energy-market-reform-europe.html (accessed 1.19.18).

Díaz, C., García, G., Canziani, R., Ferrari, G., 2015. Preliminary market analysis – review: Annex 1. Collected Data from some Visits to WWTPs in Italy [WWW Document]. URL https://sludgetreat.eu/wp-content/uploads/2016/11/D2.2-Annex-I-Data-from-some-visits-to-WWTPs-Italy-2015.pdf (accessed 16.2.18)

European Commission, 2016. Sewage Sludge [WWW Document]. URL http://ec.europa.eu/environment/waste/sludge/ (accessed 9.6.17).

European commission JRC-IES, 2011. International reference life cycle data system (ILCD) handbook, 1st ed. European Union, Luxemburg. doi:10.2788/33030

European Commission JRC-IES, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance., First. ed. European

Union, Luxembourg. doi:10.2788/38479

European Commission, 2000. DIRECTIVE 2000/60/EC. Off. J. Eur. Communities. URL https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF (accessed 9.6.18).

Eurostat, 2017a. Sewage sludge production and disposal [WWW Document]. URL http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ww_spd&lang=en (accessed 10.4.17).

Eurostat, 2017b. Electricity price for non-household comsumers, first half of 2017 [WWW Document]. URL http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Further_Eurostat_information (accessed 9.27.17).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. doi:10.1016/J.JENVMAN.2009.06.018

Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M., 2017. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. J. Clean. Prod. 143, 1123–1136. doi:10.1016/J.JCLEPRO.2016.12.007

Gronchi, P., Canziani, R., Brenna, A., Visigalli, S., Colominas, C., Montalà, F., Cot, V., Stradi, A., Ferrari, G., Diaz, C., Fuentes, G.G., Georgiadis, A., 2017. Electrode surface treatments in sludge electro-osmosis dewatering. Mater. Manuf. Process. 32, 1265–1273. doi:10.1080/10426914.2017.1279313

Guo, X., Wang, Y., Wang, D., 2017. Permanganate/bisulfite (PM/BS) conditioning-horizontal electro-dewatering (HED) of activated sludge: Effect of reactive Mn(III) species. Water Res. 124, 584–594. doi:10.1016/j.watres.2017.08.027

Heimersson, S., Svanström, M., Cederberg, C., Peters, G., 2017. Improved life cycle modelling of benefits from sewage sludge anaerobic digestion and land application. Resour. Conserv. Recycl. 122, 126–134. doi:10.1016/j.resconrec.2017.01.016

Heimersson, S., Svanström, M., Laera, G., Peters, G., 2016. Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems. Int. J. Life Cycle Assess. 21, 1197–1212. doi:10.1007/s11367-016-1095-8

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. J. Clean. Prod. 13, 287–299. doi:10.1016/J.JCLEPRO.2004.02.022

Investopedia, 2015. What average annual total return does the utilities sector generate? [WWW Document]. URL http://www.investopedia.com/ask/answers/071415/what-average-annual-total-return-does-utilities-sector-generate.asp (accessed 10.3.17).

KPMG, 2015. Cost of Capital Study 2015: Value enhancement in the interplay of risks and returns [WWW Document]. URL https://assets.kpmg.com/content/dam/kpmg/pdf/2016/01/kpmg-cost-of-capital-study-2015.pdf (accessed 9.22.17).

Li, H., Jin, C., Zhang, Z., O'Hara, I., Mundree, S., 2017. Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. Energy 126, 649–657. doi:10.1016/J.ENERGY.2017.03.068

Lombardi, L., Nocita, C., Bettazzi, E., Fibbi, D., Carnevale, E., 2017. Environmental comparison of alternative treatments for sewage sludge: An Italian case study. Waste Manag. 69, 365–376. doi:10.1016/j.wasman.2017.08.040

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2011. Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects. Water Res. 45, 2795–2810. doi:10.1016/j.watres.2011.02.029

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2010. Electrical field: A historical review of its application and contributions in wastewater sludge dewatering. Water Res. 44, 2381–2407. doi:10.1016/j.watres.2010.01.033

Mantovi, P., Baldoni, G., Toderi, G., 2005. Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: Effects of long-term application on soil and crop. Water Res. 39, 289–296. doi:10.1016/j.watres.2004.10.003

Mills, N., Pearce, P., Farrow, J., Thorpe, R., Kirkby, N., 2012. Life Cycle Assessment of Advanced Anaerobic Digestion Process Configurations for Sewage Sludge - A UK Perspective, in: 4th Symposium of Energy from Waste. Elsevier, Venice.

Mills, N., Pearce, P., Farrow, J., Thorpe, R.B., Kirkby, N.F., 2014. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Manag. 34, 185–195. doi:10.1016/j.wasman.2013.08.024

Mininni, G., Blanch, A.R., Lucena, F., Berselli, S., 2015. EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. Environ. Sci. Pollut. Res. 22, 7361–7374. doi:10.1007/s11356-014-3132-0

Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–824. doi:10.1177/0734242X09344876

Murakami, T., Suzuki, Y., Nagasawa, H., Yamamoto, T., Koseki, T., Hirose, H., Okamoto, S., 2009. Combustion characteristics of sewage sludge in an incineration plant for energy recovery. Fuel Process. Technol. 90, 778–783. doi:10.1016/J.FUPROC.2009.03.003

Navab Daneshmand, T., Beton, R., Hill, R.J., Gehr, R., Frigon, D., 2012. Inactivation mechanisms of bacterial pathogen indicators during electro-dewatering of activated sludge biosolids. Water Res. 46, 3999–4008. doi:10.1016/j.watres.2012.05.009

Olivier, J., Conrardy, J.B., Mahmoud, A., Vaxelaire, J., 2015. Electro-dewatering of wastewater sludge: An investigation of the relationship between filtrate flow rate and electric current. Water Res. 82, 66–77. doi:10.1016/j.watres.2015.04.006

Outotec Oyj, 2016. SUSTAINABLE SEWAGE SLUDGE INCINERATION FOR ZÜRICH CANTON (Newsletter) [WWW Document]. URL https://www.outotec.com/company/media/news/2016/sustainable-sewage-sludge-incineration-for-zurich-canton/ (accessed 11.16.17).

Papa, M., Foladori, P., Guglielmi, L., Bertanza, G., 2017. How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy. J. Environ. Manage. 198, 9–15. doi:10.1016/j.jenvman.2017.04.061

Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., 2000. Good practice guidance and uncertainty management in national greenhouse gas inventories. Institute of Global Environmental Strategies (IGES).

Remy, C., Jekel, M., 2008. Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. Water Sci. Technol. 58, 1555. doi:10.2166/wst.2008.533

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della Casa, C., 2013. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J. Clean. Prod. 44, 8–17. doi:10.1016/J.JCLEPRO.2012.12.004

Rocha, M.H., Capaz, R.S., Lora, E.E.S., Nogueira, L.A.H., Leme, M.M.V., Renó, M.L.G., Olmo, O.A. del, 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis. Renew. Sustain. Energy Rev. 37, 435–459. doi:10.1016/J.RSER.2014.05.036

SUEZ’s degremont® water handbook, 2017. low temperature sludge drying system – Evaporis^{TM} LT [WWW Document]. URL https://www.suezwaterhandbook.com/degremont-R-technologies/sludge-treatment/drying/low-temperature-sludge-drying-system-Evaporis-LT (accessed 12.12.17).

SUEZ’s degremont® water handbook, 2017. Drying unit energy consumption [WWW Document]. URL https://www.suezwaterhandbook.com/processes-and-technologies/dewatered-sludge-treatment/drying/drying-unit-energy-consumption (accessed 1.15.18).

Tomei, M.C., Bertanza, G., Canato, M., Heimersson, S., Laera, G., Svanström, M., 2016. Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants. J. Clean. Prod. 112, 3106–3115. doi:10.1016/j.jclepro.2015.10.017

Towler, G.P., Sinnott, R.K., 2013. Chemical engineering design : principles, practice, and economics of plant and process design, 2nd ed. Butterworth-Heinemann.

Tuan, P.A., Sillanpää, M., 2010. Migration of ions and organic matter during electro-dewatering of anaerobic sludge. J. Hazard. Mater. 173, 54–61. doi:10.1016/j.jhazmat.2009.08.046

Umwelt Bundesamt, 2013. Sewage sludge management in Germany [WWW Document]. URL https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/sewage_sludge_management_in_germany.pdf (accessed 1.15.18).

~~Vesilind, P.A., 1994. The role of water in sludge dewatering. Water Environ. Res. 66, 4–11. doi:10.2175/WER.66.1.2~~

Visigalli, S., Turolla, A., Gronchi, P., Canziani, R., 2017a. Performance of electro-osmotic dewatering on different types of sewage sludge. Environ. Res. 157, 30–36. doi:10.1016/j.envres.2017.05.015

Visigalli, S., Turolla, A., Zhang, H., Gronchi, P., Canziani, R., 2017b. Assessment of pressure-driven electro-dewatering as a single-stage treatment for stabilized sewage sludge. J. Environ. Chem. Eng. doi:10.1016/j.jece.2017.11.034

Water Environment Federation - Incineration Task Force, 2009. Wastewater solids incineration systems: WEF Manual of Practice No. 30. WEF press - McGraw-Hill Professional.

Yoshida, H., Christensen, T.H., Scheutz, C., 2013. Life cycle assessment of sewage sludge management: A review. Waste Manag. Res. 31, 1083–1101. doi:10.1177/0734242X13504446

Yoshida, H., Clavreul, J., Scheutz, C., Christensen, T.H., 2014. Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant. Water Res. 56, 292–303. doi:10.1016/j.watres.2014.03.014

Yoshida, H., ten Hoeve, M., Christensen, T.H., Bruun, S., Jensen, L.S., Scheutz, C., 2018. Life cycle assessment of sewage sludge management options including long-term impacts after land application. J. Clean. Prod. 174, 538–547. doi:10.1016/J.JCLEPRO.2017.10.175

Yu, W., Yang, J., Wu, X., Gu, Y., Xiao, J., Yu, J., Shi, Y., Wang, J., Liang, S., Liu, B., Hou, H., Hu, J., 2017. Study on dewaterability limit and energy consumption in sewage sludge electro-dewatering by in-situ linear sweep voltammetry analysis. Chem. Eng. J. 317, 980–987. doi:10.1016/j.cej.2017.02.137

Zhang, S., Yang, Z., Lv, X., Zhi, S., Wang, Y., Li, Q., Zhang, K., 2017. Novel electro-dewatering system for activated sludge biosolids in bench-scale, pilot-scale and industrial-scale applications. Chem. Eng. Res. Des. 121, 44–56. doi:10.1016/j.cherd.2017.02.035

Zhao, X., Jiang, G., Li, A., Wang, L., 2016. Economic analysis of waste-to-energy industry in China. Waste Manag. 48, 604–618. doi:10.1016/J.WASMAN.2015.10.014

Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Hai Zhang [a], Lucia Rigamonti [a], Simone Visigalli [a], Andrea Turolla [a], Paolo Gronchi [b], Roberto Canziani [a, *]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

*Corresponding Author
E-mail: roberto.canziani@polimi.it
Telephone: (+39) 02 2399 6410

Keywords: Electro-dewatering; Sludge management; Life cycle assessment; Return on investment; Industrial application; WWTP

Word count: 9673

Abbreviations

AC	Acidification
CHP	Combined Heat and Power
DM	Dry Mass
DS	Dry Solids
EDW	Electro-dewatering
EP	Eutrophication
eq.	Equivalent
EU	European Union
FU	Functional Unit
GHG	Greenhouse Gas
GW	Global Warming
LHV	Lower Heating Value
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
POF	Photochemical Ozone Formation
ROI	Return On Investment
ton	tonne
WWTP	Wastewater Treatment Plant

Abstract

The objective of this study is to evaluate the feasibility of implementing electro-dewatering (EDW) as an add-on unit to the existing conventional dewatering units with the aim of increasing the final dry solids content and reducing the subsequent handling and energy costs of sewage sludge management. The assessment was carried out by focusing on a case study, a small wastewater treatment plant (WWTP) in the Milan metropolitan area. Various indicators were used to evaluate the environmental impact and economic performance. Primary data, such as operating data from the case study WWTP and economic data from an EDW equipment manufacturer, were extracted and used in the modelling. Four scenarios were set up and compared, which address the current and future sludge management schemes in Italy.

The results suggest that it is environmentally and economically feasible to implement the EDW upgrade if the sludge disposal follows the incineration route. More specifically, when small WWTPs deliver their EDW-dewatered sludge to a centralised incineration facility, this will enable to reduce the global warming impact of the system up to 135 kg CO_2-eq. per dry tonne of sludge. In addition, good profitability (incremental return on investment > 15.1%) can be obtained when the market disposal cost is above 30.5-39.6 € per wet tonne of sludge. Based on our recent market survey, the sludge disposal price is well above the break-even values.

1 Introduction

The generation of sewage sludge is experiencing a steady growth in the European Union (EU; European Commission, 2016). The EU wastewater treatment plants (WWTPs) dealt with over 10 million tons of sludge (in dry mass) in 2010 (Eurostat, 2017a). To comply with the EU's strategy for a circular economy, sludge is being disposed of via two major routes: nutrient recovery by application to agricultural land and energy recovery by incineration (Papa et al., 2017). In either of these routes, it is favourable to increase the dry solid (DS) content of sludge. For example, a minimum DS of 40% is required for incineration in a fluidized bed incinerator and a DS of 90% for cement kiln incineration (Abuşoğlu et al., 2017). However, due to the limits of mechanical dewatering that cannot remove the water bound to the colloidal solids in the sludge matrix (Mahmoud et al., 2010), the mechanically-dewatered sludge can only reach an average DS of 20%. Hence, additional thermal drying is needed, which consumes a significant amount of energy.

Electro-dewatering (EDW) in combination with mechanical compression is shown to be effective in increasing the sludge DS content and thus decreasing the quantity/volume of sludge requiring disposal. EDW can also maintain a better energy efficiency than thermal drying until reaching a DS of 38–45% (Olivier et al., 2015). In the past decade, much research has been carried out in the field of EDW and the majority of the studies are focused on how to optimise operating parameters in relation to energy efficiency. For instance, two factors, mechanical pressure and electrical voltage, were investigated in the work of Mahmoud et al. (2011). According to the authors, after optimising the operating conditions it was possible to save 25% energy compared with thermal drying. Therefore, EDW holds great potential to reduce the WWTP operating costs and environmental impacts.

Apart from being an effective dewatering technique, EDW also brings additional benefits during the treatment as it causes pathogen inactivation (Navab Daneshmand et al., 2012), and, if properly managed, it can reduce the concentration of heavy metals and organic pollutants in the dewatered sludge (Tuan and Sillanpää, 2010), the limits of which are regulated by the EU Directive 86/278/EEC and member states' regulations (Mininni et al., 2015).

Although many promising results have been reported and the mechanisms behind the EDW phenomenon are relatively well understood (Mahmoud et al., 2010), it has taken a long time for EDW to be fully adopted for industrial application in WWTPs. Several reasons are behind this:

<u>(1) Relatively high energy consumption</u>: Regarding this point, an early study (Mahmoud et al., 2010) suggests that EDW may find better application in dewatering/drying some high value products, e.g. foods and pharmaceuticals rather than sewage sludge. According to a latest publication (Zhang et al., 2017), the electricity consumption measured on an industrial EDW setup was 0.123 kWh per kilogram of water removed.

<u>(2) Problems with anode material</u>: It is well known that the anode is the core part of an EDW system. It has a high cost and it is subjected to high wearing caused by harsh electrochemical corrosion and abrasion (Gronchi et al., 2017). According to one data source (Zhang et al., 2017), by considering the

anode cost and its service life, it can be translated into 4.23 € per tonne of water removed. It is widely recognised that finding the suitable replacement material is one of the key issues for promoting EDW to the industry users.

(3) Reliability under continuous working mode: Periodic cathode cleaning is needed to maintain the efficiency and productivity of the system. In accordance with a relevant study (Zhang et al., 2017), stepwise pressure has prolonged this period to 15 days, and this is acceptable for many industrial users.

(4) Competition with other engineering options: This is especially applicable to the situation of large WWTPs where there are different engineering options to choose from to dry the sludge. For example, if a WWTP is integrated with a combined heat and power (CHP) system, it is possible to utilise the waste heat/low-grade heat from the CHP to dry the sludge up to DS of 90% (Mills et al., 2014). In fact, a low temperature dryer can be powered by various types of on-site waste heat (e.g. co-generation, heating and air conditioning systems) as long as these heat sources are stable and have a minimum temperature of 90°C (SUEZ's Degremont, 2017). In another example (Yoshida et al., 2014), the WWTP is integrated with an on-site incinerator so that the heat generated from the incinerator can be used to dry the sludge. Therefore, large WWTPs may show less interest in EDW.

The doubts and uncertainties presented in the points 1-3 can be resolved with a comprehensive economic assessment. This is one of the objectives of this study. For point 4, we should not ignore the large number of small WWTPs (< 100,000 population equivalents). For instance, currently there are about 60 WWTPs in the Milan metropolitan area and half of them are small WWTPs. Normally, they do not have suitable and stable on-site heat sources to power a low-temperature dryer, or the throughput of low-temperature dryer cannot satisfy the sludge production rate. In this case, EDW upgrade could be a good solution to increase their sludge dryness, thus reducing the operating costs of the plant.

To evaluate the feasibility of EDW upgrade, it is important to provide measures from various perspectives. Firstly, in accordance with the Water Policy Directive 2000/60/EC (European Commission, 2000), it is necessary to take into account the recovery of costs for water services, including environmental and resources, i.e. economic analysis is required. As a WWTP is an important constituent of water services, the upgrading project should comply with this policy (Bertanza et al., 2018).

In recent years, a decision support system built on technical, economic and environmental performances is gaining popularity and being practiced by the researchers in this field (Bertanza et al., 2015a). Basically, to evaluate the environmental performances, it follows the concept of Life Cycle Assessment (LCA), which is an international standard-based methodology (ISO14040 and ISO14044) and provides the ability to evaluate a product's environmental impacts by considering all its life cycle stages, starting from raw material extraction, manufacturing, use/reuse until final disposal (Gourdet et al., 2017). LCA has been applied in the field of sludge management since 2000 (Yoshida et al., 2013). The relevant studies have concentrated on the followings topics: identifying hotspots in WWTPs, assessing upgrading options for the treatment lines (Zhang et al., 2017) and selecting the most suitable sludge management schemes (Buonocore et al., 2016). For instance, in the study of Li et al. (2017), five different anaerobic digestion configurations were assessed with environmental and economic indicators, and the authors identified sludge organic content and biogas yield as the most influential factors. In another study (Gourdet et al., 2017), by comparing different scenarios, it was found that increasing the biodegradation rate of volatile solids and the biogas production was the most effective method to reduce the environmental impacts. Also, the same study recognised that the consumption of $FeCl_3$ (a chemical that is used to reduce the phosphorus contained in the return liquors from thickening and dewatering stages) was identified as a hotspot in the system's environmental profile. Besides, LCA is also a useful tool for working out proper waste management policies. As demonstrated by the case study of Righi et al. (2013), a scenario composed of anaerobic digestion and composting had the best environmental performance and was recommended to the policy-makers.

The objective of this study is to evaluate the feasibility of implementing EDW as an add-on unit to the existing conventional dewatering, which serves to increase the final DS content and reduce the subsequent handling and energy costs of sewage sludge management. The assessment was carried out by focusing on a case study, a small WWTP in the Milan metropolitan area. Based on the comparisons between different scenarios, we attempt to identify the most suitable market to implement the EDW upgrade. Our previous publications focused on the technical issues of EDW (Visigalli et al., 2017a/b) by investigating the factors that influence the system's performance. Whereas, in the present study, the emphasis is placed on the environmental and economic assessment.

2 Methods

2.1 Environmental assessment

2.1.1 Goal and scope

The goal of this study is to assess the feasibility of implementing an EDW upgrade for a small WWTP following the LCA methodology. Here, "EDW upgrade/EDW dewatering" indicates that the EDW unit is a retrofittable add-on module arranged after the existing mechanical dewatering facility. As a whole system, it enables an increase to the sludge DS from the initial 3.3% to 40%. 40% was set as the target DS due to the requirements of self-sustaining incineration (Outotec Oyj, 2016).

The case study focuses on a small WWTP situated in the Milan metropolitan area, which serves 47,000 population equivalents. In this plant, the sludge is stabilised with the aerobic stabilisation method. After that, it is dewatered with a belt press (mechanical dewatering). Sludge samples were extracted from this WWTP for the lab-scale EDW test. In 2016, the plant-produced a total of 2300 tons of dewatered sludge that was disposed through a multiple-channel approach: 54.8% to landfill, 26.2% to incineration, and 19% to an external WWTP for further processing. The average disposal cost was 80 €/wet tonne.

The Functional Unit (FU) was defined as the treatment and disposal of 1 dry tonne of sludge (denoted as 1 tDM) coming from the upstream stabilisation stage.

The system boundaries are depicted in Figure 1, including all of the processing stages taking place after sludge stabilisation (i.e. conditioning, dewatering, and transport) up to the final disposal stage (land spreading or incineration and ash to landfill).

(Figure 1)

To help justify the advantages of the EDW upgrade, it was compared with the mechanical dewatering equipment used by the WWTP. Moreover, two sludge disposal routes were considered: sludge for land spreading (i.e. sludge is applied to arable land as fertiliser without composting treatment) and sludge for incineration. This is because sludge for agriculture use currently accounts for the biggest share in sludge end use in Italy (Eurostat, 2017a). It is widely used for its low cost. However, it is susceptible to policy changes, e.g. increasingly stringent contaminants limits (Mininni et al., 2015). Seeing that it is no longer permitted in Switzerland and discouraged in Netherlands and Germany, this has raised significant concerns among the Italian WWTP operators, and our recent survey of some WWTPs in the Lombardy region found that many of the WWTPs were using more than one disposal routes in case that the policy tightens (Díaz et al., 2015). The other disposal route, sludge disposed to a centralised incinerator, represents the future scheme of sludge management as it enables to lower the disposal cost and cope with the challenges and risks associated with sludge for agriculture use.

In total, four scenarios were set up to allow for comparison of the options (see Figure 1):

Scenario A1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press). After that, the dewatered sludge cakes (DS 18.2%) are transported by truck to agricultural fields and applied using a tractor. After application, sludge gradually becomes available to the crops. In this process, it also releases GHG emissions to the air.

Scenario A2: it follows a similar land spreading route as described in A1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will be increased to 40%. In this case, A2 represents the EDW upgrading scenario and it will be compared with the reference scenario A1.

Scenario C1: stabilised sludge is conditioned with polyelectrolyte and then dewatered with mechanical dewatering equipment (belt press) by each individual WWTP. After that, the dewatered sludge cakes (DS 18.2%) from each individual WWTP are transported by truck to a centralised incineration facility. Subsequently, the cakes are mixed and dried with a disc dryer (thermal drying) to reach DS 40% and then they are fed into a fluidized bed furnace. The waste heat is recovered. After material recovery from the ashes, the residues are sent to landfill for hazardous waste.

Scenario C2: it follows a similar incineration route as described in C1. The only difference lies in the dewatering stage, in which mechanical dewatering is replaced with the EDW upgrade, and consequently the outlet DS will reach 40% and the thermal drying treatment occurred in the incineration plant will be omitted. In this case, C2 represents the EDW upgrading scenario and it will be compared with the reference scenario C1.

The scenario C2 was constructed to consider the further improvement to the efficiency of energy recovery. The reliance on the integrated on-site thermal dryer is removed. If the delivered sludge already has a suitable DS content (e.g. 40%) to be loaded into the incinerator, it would boost the incinerator's productivity and more heat could be diverted to the local district heating network compared to scenario C1.

SimaPro 8.4 was used to model the scenarios. Database ecoinvent V3 (allocation, recycled content system model) was used with priority for the background systems. The geographic boundary was specified to be the Italian border.

Six impact categories were assessed: Global Warming (GW), Acidification (AC), Photochemical Ozone Formation (POF), and terrestrial, freshwater and marine Eutrophication (EP). These impact categories were selected for their close relevance to the system under study (Tomei et al., 2016), in relation to the following elements:

(1) the end use of sludge: the emissions of land spreading and incineration are directly related to GW, AC and EP;

(2) EDW is an energy intensive process and a major advantage of using EDW is to reduce the fuel consumption in the road transport stage. In this context, GW, POF, AC and EP are directly related to consumption of fossil fuels.

The impact categories were assessed with the Life Cycle Impact Assessment (LCIA) methods recommended by the "ILCD Handbook" (European commission JRC-IES, 2011). A detailed list of methods used is provided in Supplementary Information (Section SI-1).

The toxicity issues in relation to sludge for agriculture use (e.g. heavy metals, pathogens, organic pollutants and other contaminants) were not considered. Also, the benefits of improved soil properties and crop productivity were discounted because there is a lack of proper characterization model to quantify them. In fact, further risk assessment is needed to address the associated risks and benefits. For example, Alvarenga et al. (2017) conducted soil and plant analysis on the sludge-amended fields; Mantovi et al. (2005) carried out a 12-year field study to compare the difference between mineral fertilisers and sludge.

Cases of multi-functionality were solved by expanding the system boundaries to include avoided primary productions due to material recovery from waste (European Commission JRC-IES, 2010; Finnveden et al., 2009). In this case study, the avoided products are fertiliser and heat.

2.1.2 Environmental data inventory

As a common practice in this research area (Corominas et al., 2013), the construction and demolition of infrastructure were excluded; biogenic CO_2 emission was regarded as climate neutral (Houillon and Jolliet, 2005).

The LCA modelling was assisted with mass balance calculations (see Figure 2 and Figure SI-1 in Supplementary Information). Data collection for each life cycle stage is described as follows.

(Figure 2)

Conditioning

During the sludge conditioning, a polyelectrolyte is used. The polyelectrolyte dosage, 5.30 kg/tDM, was taken from the WWTP's operating data. Polyelectrolyte was modelled with acrylonitrile (a raw material for producing acrylamide polymers) following the relevant literature (Yoshida et al., 2014).

Mechanical dewatering

The mechanical dewatering data, energy consumption (41.16 kWh/tDM) and sludge DS improvement (3.3% to 18.2%), were extracted from the WWTP. The Italian electricity data (database ecoinvent V3) was used.

EDW dewatering

Some data (e.g. the outlet DS and the specific energy consumption) needed to be obtained from experiments. The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. The experimental setup and protocol were based on our previous publications (Visigalli et al., 2017b). In brief, sludge samples were treated between the electrodes (anode DSA® by De Nora and cathode stainless steel AISI 304) that were connected to a DC power supply (GBC, 34121070 bench scale generator). A constant mechanical pressure of 300 kPa was applied throughout the 25-min EDW treatment. The evolution of electric current and mass of filtrate were recorded and used for calculating the specific energy consumption.

Two sets of parameters were tested:

(1) cake thickness (unit in mm): 15, 20, 25;

(2) electrical potential (unit in V): 10, 15, 20.

Each combination was tested in two replicates. The data giving the best dewatering performance (in terms of DS improvement and productivity) were used in the assessment, that is lower cake thickness (15 mm) combined with higher voltage (20 V). Accordingly, this parameter combination caused the highest specific energy consumption. From an early publication (Olivier et al., 2015), it is known that EDW can maintain superior energy efficiency over thermal drying until reaching DS 45%. Therefore, we can assume that the parameter combination "15 mm-20 V" gives the best dewatering performance despite the increased specific energy consumption.

For industrial application, it is also important to consider the productivity of the machine. For example, a solar dryer is very energy efficient, but its productivity is very low. In the case of EDW, the operating parameters should ensure good productivity, i.e. the shortest time to reach a target DS. To address this issue, a target DS was set at 25% and the relevant data were extracted and compared. The results show that the combination of "15 mm-20 V" gives the best productivity, which is in line with the dewatering performance as discussed previously. As a consequence, the data generated from this operating parameter combination were used in the assessment. The detailed results are provided in Supplementary Information (Section SI-2).

Based on the experiment data, it was assumed that the EDW unit was used to process the mechanically-dewatered sludge, increasing its DS from 18.2% to 40%. As a whole system, the EDW upgrade consumed 409.40 kWh/tDM for increasing the sludge DS from 3.3% to 40%. The Italian electricity data (database ecoinvent V3) was used.

It seems that there is a limitation for extrapolating the lab-scale device data to industrial application. However, in accordance with the data reported by Zhang et al. (2017), from the lab scale device (anode area 0.13 m^2) to the industrial scale machine (anode area 47.52 m^2) under continuous working mode, only negligible discrepancy was found between the specific energy consumptions.

Transport

It was assumed that the dewatered sludge was transported for 100 km (Truck 16-30 t, vehicle emission EURO 5) to reach the storage site/incineration plant. The storage related input and output were discounted due to lack of data (Heimersson et al., 2016).

Tractor application

It was assumed that the sludge cake was applied in agriculture land using a tractor, which consumed 0.5 L diesel per wet tonne of sludge (Møller et al., 2009).

Land spreading

The fertiliser replacement rates are based on the relevant studies. The nutrient concentrations of dewatered sludge were based on the data from Mantovi et al. (2005), and the conversion factors were extracted from the study of Heimersson et al., (2017). For the N-fertiliser, the total N was 4.25% of the sludge Dry Mass (DM); a conversion factor of 0.5 was used to account for the element mineralisation (subsequently becomes available for crop uptake). For the P-fertiliser, the total P was 1.81% of the sludge DM; a conversion factor of 0.7 was used to account for the element mineralisation.

The greenhouse gas (GHG) emissions associated with the life cycle stage of land spreading were calculated following the relevant references: CH_4, 5kg/tDM (Penman et al., 2000); NH_3, 8% total N of sludge applied (Remy and Jekel, 2008); N_2O, 1% of total N of sludge applied (Tomei et al., 2016). The emissions to soil and water were extracted from the study of Lombardi et al. (2017).

Incineration

The incineration plant configuration with energy balance calculation (scenario C1) is illustrated in Figure 3. It is based on a reference case, in which a centralised incineration plant is responsible for processing sludge from over 70 small WWTPs in the region (Outotec Oyj, 2016).

(Figure 3)

It was assumed that the plant was equipped with a waste heat recovery system of thermal efficiency of 95% (Murakami et al., 2009). The energy (biogenetic) produced by the system was utilised in such a way that the electricity was only for the plant's self-use, part of the heat was used to power the thermal dryer to increase the sludge DS content from 18.2% to 40% (having the same DS improvement as the "EDW upgrade"), and the rest of the heat is distributed through the local district heating network (output to the outside of system boundaries). Combustion air preheating was excluded because it is not needed in the scheme considered.

The lower heating value (LHV) of the dewatered sludge was calculated according to the handbook of wastewater solids incineration systems (Water Environment Federation - Incineration Task Force, 2009). The value was 3534 kWh/tDM at DS 40%. The detailed calculation is provided in Supplementary Information (Section SI-4).

For thermal drying, the specific energy consumption was taken as 0.72 kWh per kilogram of water evaporated, reflecting the best available industrial technology (SUEZ's Degremont, 2017). The resulting value was 2155.57 kWh/tDM.

The output energy flow was modelled as replaced heat generated from fossil fuel sources (co-generation using natural gas), aiming to reflect the possible impact to the Italian energy consumption structure. Currently, approximately 90% of energy consumption in Italy is fossil fuel-based (Deloitte, 2015). This represents the scenario C1.

In the case of scenario C2, the heat previously used for thermal drying will be saved and completely diverted to the district heating, i.e. more output to the outside of the system.

The ashes generated from the flue gas treatment are treated to make them inert and are-sent to a landfill for hazardous waste, located in Italy.

The incineration related material and energy inputs and emissions were extracted from the relevant study with necessary adaptions (Lombardi et al., 2017).

The key inventory items are summarised in Table 1. The data are normalised to the FU (1 tDM).

Table 1. Inventory of data for the LCA (normalised to the FU, 1 tDM).

Inventory item	**Unit**	**Amount**
Polyelectrolyte (modelled with Acrylonitrile)	kg	5.30
Electricity, medium voltage, IT (mechanical dewatering, belt press)	kWh	41.16
Electricity, medium voltage, IT (EDW dewatering)	kWh	409.40
Energy consumption for sludge thermal drying	kWh	2155.57
Sludge for land spreading		
N-fertiliser replacement (ammonium nitrate)	kg	21.25
P-fertiliser replacement (superphosphate)	kg	12.67
GHG emissions due to sludge application in the fields		
Methane (CH_4)	kg	5.0
Ammonia (NH_3)	kg	3.4
Nitrous oxide (N_2O)	kg	0.43
Sludge for incineration		
Replaced heat (C1)	kWh	971
Replaced heat (C2)	kWh	3127

2.1.3 Sensitivity analysis

As stated in the introduction, energy consumption is a critical factor for promoting EDW to the industrial users. At the same time, very often the energy data contains big variations when treating sludge from different sources. In this case, the robustness of the results was analysed. The energy consumption of EDW dewatering stage was varied by ±25% with respect to the lab testing data.

2.2 Economic assessment

2.2.1 Assessment method and indicators

To assess the economic performance of the upgrade options for the WWTP, previous studies have utilised the life cycle costing method (Tomei et al., 2016). In this method, the results are presented as a cost gap in each life cycle stage (i.e. the difference between the reference scenario and upgrading scenario): a negative gap means the upgrading option is economically favourable. The total cost gap is an aggregated result of all the life cycle stages. In this way, it is possible to identify the most critical life cycle stages (i.e. hotspots) but the downside is that the results are restricted to the scenarios concerned in the study.

Apart from assessment method, it is also important to select appropriate economic performance indicators. Net present value (Mills et al., 2012) and internal rate of return (Mills et al., 2014) are usually used for large chemical engineering projects (e.g. building a WWTP or implementing large modifications). However, they are not suitable for evaluating small project, such as the EDW upgrade concerned in the present study, which only requires a short execution time and a relatively small investment. In this case, more suitable indicators are needed: cost saving stems from sludge volume reduction and sludge disposal cost for an EDW upgrade. However, sludge disposal costs currently vary greatly from country to country and from region to region, depending on the local circumstances, such as regulations, disposal routes and subcontractors. According to the data source (Bertanza et al., 2015b), the disposal cost within the EU ranges from 20 to 100 €/wet tonne. In this case, a model demonstrating the relationship between the profitability of the upgrading project and the disposal cost will be useful to cover a wide scope of market situations.

Therefore, the economic assessment in this study was carried out following the method of Towler and Sinnott (2013). It focuses on the EDW upgrade itself rather than the scenarios as previously discussed in the LCA. It also gives more flexibility in sensitivity analysis and the results can be easily communicated to the WWTPs managers (Zhao et al., 2016).

The first indicator, incremental Return On Investment (ROI), was calculated with Equation 1 (Towler and Sinnott, 2013):

$$\text{Incremental Return On Investment} = \frac{\text{Incremental Profit}}{\text{Incremental Investment}} \times 100\% \qquad (1)$$

In the case of the EDW upgrade, the incremental investment refers to the EDW machine's investment cost (one piece of EDW machine, including the cost of installation and shipping). It was assumed that the upgrade caused no changes to the working capital. The incremental profit was calculated from the difference between the cost saving in sludge disposal and the cash cost of production.

The second indicator, total cost of production, was calculated with Equation 2 (Towler and Sinnott, 2013):

$$\text{Total Cost of Production} = \text{Cash Cost of Production} + \text{Annual Capital Charge} \qquad (2)$$

In the case of the EDW upgrade, the cash cost of production is the sum of variable production cost (e.g. consumables and EDW electricity use) and fixed production cost (e.g. labour and maintenance). The annual capital charge is the annualized investment of EDW machine over the project period (i.e. the service life of the EDW machine) at a certain interest rate.

2.2.2 Sensitivity analysis

EDW is an energy intensive process. Energy consumption and energy price can have a strong influence on the project's profitability. Therefore, a sensitivity analysis was carried out to address the following cases.

Low energy consumption case: The "low energy consumption case" was modelled as the EDW unit energy consumption dropping by 25% with respect to the "standard case" (lab testing results) while holding the DS improvement constant. This case represents the situation when the EDW machine is running with improved dewatering efficiency. This is a practical consideration. In fact, nowadays there are a few examples of industrial EDW systems on the market, e.g. the "ELODE" from ACE (Korea) and the "EKG" from Electrokinetic (UK) (Zhang et al., 2017). However, all of them are belt press-based. In contrast, our EDW prototype machine is screw press-based, and it is expected that the dewatering efficiency will be improved. This is because the shearing effect of the screw would mitigate the curst development on the anode, which has been recognised as the major limit to the EDW dewatering efficiency in a latest study (Yu et al., 2017).

High energy consumption case: The "high energy consumption case" was modelled as the EDW unit energy consumption increasing by 25% with respect to the "standard case" while holding the DS improvement constant. This corresponds to the situation of treating the poor-EDW-response sludge. This is also a practical consideration because in our previous studies we have noticed that sludge from different WWTPs showed different responses to the EDW treatment, depending on the sludge nature and its upstream processes (Visigalli et al., 2017b).

EU average case: The Italian electricity price (for industrial user) is the second highest in the EU, being 28 – 30% higher than the EU average price (Eurostat, 2017b). Thus, an additional case was added by considering the EU average electricity price (0.114 €/kWh) and is denoted as "EU average".

2.2.3 Economic data inventory

In our project (Visigalli et al., 2017b), we aim to scale up the lab-scale EDW device for industrial applications. The industrial prototype is currently under development (screw press-based machine), it is therefore possible to extract some primary economic data from the machine manufacturer (X2 Solutions Srl, who is also one of the project consortiums). The EDW machine price and service life were estimated by this manufacturer, based on their existing product lines, the prototype built for this project and the relevant information from their suppliers.

The EDW machine has a throughput of 0.2 m^3/h. In terms of yearly throughput, it can process 800 tons of mechanically-dewatered sludge, which especially suits the needs of small WWTPs. The machine power was calculated on the basis of lab testing results from Politecnico di Milano.

As a first assumption, the EDW machine will be distributed and used in the Italian market. Therefore, the Italian market data were used for the calculation, including the cost of shipping and installation, maintenance, labour, tax rate, interest rate, and electricity price.

To be consistent with the previous LCA study, the input sludge DS was set as 18.2% and the output DS as 40%.

The data used for the economic assessment and their sources are summarised in Table 2.

Table 2. Inventory of data for the economic assessment.

Item	**Value**	**Source**
Machine capacity	0.2 m^3/h	EDW machine manufacturer
DS of inlet sludge	18.2%	Extracted from WWTP
DS of outlet sludge	40%	Experimental data
Working hours per year	3800 h	Extracted from WWTP
EDW machine price	Estimate	EDW machine manufacturer
Maintenance cost	Estimate	EDW machine manufacturer
Machine service life/project period	10 years	EDW machine manufacturer
Machine power*	14.6-18.2 kW	Experimental data
Electricity price for industrial users, all taxes included, Italy	0.148 €/kWh	Eurostat (2017b)
Interest rate (before taxes), water sector	8.74%	KPMG (2015)
Tax rate, Italy	27.90%	Deloitte (2017)
Sludge disposal cost (including transport)	20-100 €/wet tonne of sludge	Díaz et al. (2015), Bertanza et al. (2015b)

* The power value is given in ranges, as it includes the variations of energy consumption considered in the sensitivity analysis.

3 Results and discussions

3.1 LCIA results

3.1.1 Global Warming

GW is regarded as the most important impact category in sludge management (Mills et al., 2014). It is also the most frequently communicated one (Yoshida et al., 2013). It directly affects a WWTP's profit via the regulator's incentives/tax charges (Mills et al., 2014). Figure 4 shows the GW impact for the four scenarios considered in this study. The net impact is calculated as the sum of the impacts from all the life cycle stages including the credits (either replaced fertilisers or replaced heat) and it is indicated with a data label.

(Figure 4)

It was found that the scenario C2 gives the best performance. The system's net GW impact of C2 drops to -32 kg CO_2-eq., in contrast to 87 kg CO_2-eq. of A1 and 103 kg CO_2-eq. of C1. This is for two reasons:

(1) though the EDW upgrade itself induces a big percentage of impact (223 kg CO_2-eq.) due to its electricity consumption, it enables a greater credit to the system (-312 kg CO_2-eq.) by displacing the fossil fuel-based district heat;

(2) the EDW upgrade also enables sludge volume reduction by 55%, which in turn contributes to cutting 50 kg CO_2-eq. during the transport stage. This result is in line with the findings reported in the study of Gourdet et al. (2017), in which the sludge DS was identified as one of the most sensitive parameters in the dewatering stage and it produced the greatest variability to GW impact through its influence on the transport stage (emissions e.g. CO_2, N_2O, SF_6, and CH_4).

In fact, further reduction is possible. For example, in C1 we have used the data of the best available technology in thermal drying – 30-50% more efficient than the average cases (SUEZ's Degremont, 2017). This means that when we move from C1 to C2, less replaced heat has been considered in the calculation.

It should be noted that the Italian electricity data have been used in the current calculation. In 2012, over 68% of Italy's electricity generation was fossil fuel-based (14% by hydropower and 13% by renewable sources; Deloitte, 2015), which is a relatively high percentage within the EU. Therefore, an additional scenario was constructed to reflect the average EU case, in which the Italian electricity data was replaced with the "country-mix" electricity data of the EU (ENTSO-E). The results indicate that the GW impact of C2 can be further reduced to -57 kg CO_2-eq.

On the other hand, the scenario A2 is the worst performer in this impact category. If we move from A1 to A2, the indicator will increase significantly, from 87 to 236 kg CO_2-eq. This is mainly attributed to the use of electricity of EDW in the meanwhile its effect on sludge volume reduction (reduced fuel consumption in transport and field tractor application) is not big enough to offset the GW impact induced by the EDW itself.

In conclusion, the current analysis provides strong support for implementing the EDW upgrade (moving to C2) if a WWTP's objective is to reduce its GW impact.

3.1.2 Other impact categories

The LCIA results of other impact categories strongly depend on the disposal routes. So, they were plotted in two respective figures according to the disposal routes. Also, the results were normalised against the greatest absolute net value for each impact category to make them share a common y-axis (in %). Figures plotted with absolute impact values can be found in Supplementary Information (section SI-5).

The LCIA results for the land spreading route (A1 & A2) are depicted in Figure 5. The data labels over the bar end indicate the net impact values.

(Figure 5)

The life cycle stage of land spreading is shown as an aggregated result, which sums the impact of the emissions (to air, soil and water) and the credit to the system (inorganic fertiliser replacement). It behaves differently in different impact categories. For example, for the indicators of AC, POF and marine EP, the effect of the credit is stronger than the emissions, and, as a consequence, the net outcome is negative; whereas for the other impact categories (terrestrial and freshwater EP), the emissions become dominant, accounting for over 90% of the overall system's impact. In accordance with a more detailed study (Yoshida et al., 2018), the fate of phosphorus (P) strongly influences the freshwater EP, while the fate of nitrogen (N) has greater impact on the terrestrial EP and marine EP. The electricity consumption of EDW accounts for a very large percentage in the indicators of AC, POF and marine EP. The "trade-off" (i.e. the reduced impacts in the stages of transport and field tractor application due to sludge volume reduction) is not big enough to offset the EDW electricity consumption itself. So, the net outcome is that the EDW upgrade increases the impacts in these categories.

The impacts for the incineration disposal route (C1 & C2) are depicted in Figure 6. The data labels over the bar end indicate the net impact values. The EDW upgrade results in net impact drops reduction in the following impact categories: POF, terrestrial EP and marine EP. Especially, the drop is more remarkable in the POF – 40% less than the case of C1. Furthermore, if the Italian electricity data are replaced with the ENTSO-E data, 65% reduction can be achieved in the POF. The reduction mainly comes from the trade-off effect of those life cycle stages using fossil fuel, e.g. transport (diesel) and avoided heat production (natural gas-powered CHP plant, IT market, ecoinvent V3).

(Figure 6)

Moving from C1 to C2 will increase the impact to AC by 20% despite the credit coming from the replaced heat. While for the impact of freshwater EP, the EDW dewatering accounts for nearly 90% of the impact of C2. However, if we look at the absolute value (see Supplementary Information, Figure SI-5), moving from C1 to C2 corresponds to an increase from 0.03 to 0.06 kg P-eq., which is less than 6% of the land spreading cases, which is in line with the results reported in the study of Lombardi et al. (2017).

In fact, there are discrepancies between the LCIA results reported from different publications (Corominas et al., 2013; Yoshida et al., 2013), which can be attributed to the variations in the following aspects: data source (WWTPs treating water of different contamination levels with different removal efficiencies), process configuration, system boundaries, geographical area, functional unit and LCIA method. This makes it difficult to compare the results from different studies. Instead, most of the studies stay with comparing scenarios.

The LCIA results give a holistic view of the sludge management scenarios. The EDW dewatering stage consumes large amount of electricity, causing significant increases in the impact indicators; on the other hand, it contributes to reduce the overall system's impacts in the downstream life cycle stages, e.g. reduced impacts in the transport stage due to sludge volume reduction and reduced impact in the disposal stage (replaced fertiliser/heat). This implies that sludge management should encompass the life cycle thinking, encouraging solutions that enable to reduce the overall environmental impacts, and avoiding shifting the environmental burdens from one life cycle stage to another.

3.1.3 Results of the sensitivity analysis

The LCIA results of the sensitivity analysis of the EDW energy consumption are listed in Table 3. Generally, the variation of the EDW energy consumption has no significant influence on the conclusions derived from comparing the scenarios (i.e. A1 versus A2 and C1 versus C2). The only exception is that if the EDW energy consumption decreases by 25%, the AC impact of C2 will be less than that of C1.

Table 3. LCIA results of the life cycle stage of EDW dewatering. The EDW energy consumption is varied by ±25% (corresponding to the results of Min and Max, respectively) with respect to the lab testing data (corresponding to the results of Mean).

Impact category	Unit	Min	Mean	Max	Difference from mean
GW (IPCC 100a)	kg CO_2-eq.	1.73E+02	2.23E+02	2.73E+02	5.00E+01
AC	mol H^+-eq.	8.72E-01	1.13E+00	1.38E+00	2.53E-01
POF	kg NMVOC-eq.	3.49E-01	4.50E-01	5.51E-01	1.01E-01
Terrestrial EP	mol N-eq.	1.15E+00	1.48E+00	1.81E+00	3.32E-01
Freshwater EP	kg P-eq.	4.25E-02	5.49E-02	6.72E-02	1.23E-02
Marine EP	kg N-eq.	1.10E-01	1.42E-01	1.74E-01	3.20E-02

3.2 Economic profitability

The incremental ROI for implementing the EDW upgrade is depicted in Figure 7. Three representative points of disposal cost (20, 60 and 100 €/wet tonne) were selected to establish the relationship between the incremental ROI and the disposal cost. According to the data source (Investopedia, 2015), the average ROI of water sector is 15.1%. Thus, a reference line at ROI 15.1% is added to facilitate the evaluation. The break-even values at ROI 15.1% are reported in the annotation box in the figure.

(Figure 7)

It was observed that most of the ROI developments are above the reference line, which implies that all four cases considered can enjoy good profitability with the EDW upgrade. More specifically, an attractive ROI is attainable for the low energy consumption case, EU average case, standard case and high energy consumption case when the sludge disposal cost is above 30.5, 30.8, 35.0, and 39.6 €/wet tonne, respectively.

The sludge disposal cost for agriculture use (both land spreading and composting, at DS 25%) is 47-57 €/wet tonne including transport based on our recent survey of some WWTPs in the Lombardy region of Italy (Díaz et al., 2015). In the case of disposal to incineration (at DS 80-90%), 66-78 €/wet tonne is common. Therefore, the incremental ROI generated from the EDW upgrade is very attractive, especially if one considers that the disposal cost is projected to increase, driven by the increasingly stringent discharge limit on the sludge for agriculture use, and the increasing fuel price for transport (Mininni et al., 2015).

The EU average case performs close to the low energy consumption case, suggesting that the EDW upgrade is applicable to other EU markets and may give better economic performance than in Italy.

The results of total cost of production indicate that the cost of electricity accounts for the biggest share (57%) with contributions from the annual capital charge (21%), the consumables (17%, mainly the anode consumption), and the fixed cost of production (5%, for the cost of maintenance). This confirms the concerns associated with using EDW, e.g. relatively high energy consumption and expensive anode replacement. However, the cost saving from sludge volume reduction is much greater than the total cost of production, such that the WWTP will enjoy a good profit after implementing the EDW.

3.3 Selecting drying methods

Several environmental impact and economic performance indicators have been assessed. As seen from the results, the EDW upgrade could not give a uniform performance in all these indicators. The indicators can be ranked according to their importance or specific needs of a WWTP (e.g. goal to reduce a specific indicator) to assist decision-making. In this case, a scoring exercise can be helpful (Mills et al., 2014). Furthermore, more aspects can be incorporated in the scoring matrix to improve decision-making. For example, in the studies by Bertanza et al. (2016) and Tomei et al. (2016), technical feasibility (sub-categories such as reliability, flexibility/modularity, complexity and integration with existing structures), administrative aspects and normative constraints, and social aspects have been incorporated. In another example (Mills et al., 2014), tax incentives as a risk factor has been added.

Regulation and policy-making in sludge management can be another important aspect to consider. In terms of disposal methods, landfill will be progressively phased out in the EU (Mininni et al., 2015). In recent years, opposition to direct use of sludge in agriculture has intensified due to consumer’s demand on food safety and quality (e.g. organic farming). This has led to growing percentage of sludge being incinerated in the EU (Eurostat, 2017a).

In order to achieve an overall positive energy valorisation in the sludge to energy route, it is essential to increase the sludge DS to have a suitable LHV (Arlabosse et al., 2012). An EDW machine is very competitive for working in the DS range of 15-40%. In this range, it is more energy efficient than thermal dryer, and at the same time it can maintain a higher productivity than a solar dryer (Umwelt Bundesamt, 2013). Besides, it requires less space to implement the upgrading project than a solar dryer, which is highly welcomed by those small WWTPs situated near big cities.

A thermal dryer powered by waste heat or solar dryer can be arranged after the EDW unit to go beyond DS 40%, as seen from some commercial solution providers (e.g. ACE). In such way, different methods can team up as a complete drying solution to provide the best energy efficiency and productivity.

4 Conclusions

In this study, the feasibility of implementing EDW as an add-on unit to the existing conventional dewatering was evaluated with environmental impact and economic profitability indicators.

In the environmental assessment, four scenarios were setup and compared (A1, A2, C1 and C2, as depicted in Figure 1). The results show that it is advantageous to implement the EDW upgrade (i.e. moving from C1 to C2) when considering the GW impact for the incineration route. Though the EDW itself is responsible for a big share of the impact, it enables to generate a much bigger credit to the system. The effect of sludge volume reduction also helps to lower the system's impact in the transport stage. The net effect is that GW impact of C2 will drop from 103 to -32 kg CO_2-eq., which is a significant reduction. Additionally, the EDW upgrade also contributes to reducing other indicators, e.g. POF, terrestrial and marine EP.

The EDW upgrade (i.e. moving from A1 to A2) will increase all the studied impact indicators for the land spreading route. This is mainly because the benefits associated with the sludge volume reduction (55%) are not big enough to offset the impacts induced by the EDW electricity use.

The economic analysis shows that under current market situation in Italy, the EDW upgrade will generate very attractive ROI (>15.1%) for small WWTPs regardless of disposal routes. This is because:

(1) the current market price for sludge disposal in Italy (47-78 €/wet tonne) is well above the break-even values (30.5-39.6 €/wet tonne);

(2) upper limit data have been used to stress the calculation, e.g. the Italian electricity price, which is 30% higher than the EU average case.

In summary, EDW upgrade is highly recommended as it offers good environmental performance and economic profitability in the case of sludge disposal for incineration. While in the case of sludge for land spreading, the environmental impacts of EDW upgrade could be reduced by carefully selecting an intermediate outlet DS point.

The present study has its limitations, such as the lab-scale EDW data (e.g. the outlet DS and the specific energy consumption) were used since the prototype machine was not ready to conduct testing with actual sludge samples. However, the robustness of the results was assessed with two sensitivity analyses, and this allowed us to draw some solid conclusions for the EDW upgrade. Once more data become available, they can be updated in the models to generate more accurate results. Also, more indicators can be incorporated into the decision-making matrix, in particular the social aspects (e.g. employment, income, access to services, public health and safety, etc.).

The EU Directive 86/278/EEC was adopted more than 30 years ago. In order to keep it updated with the societal changes, it is currently under review by the European Commission to address emerging issues, in particular in relation to the use of sludge for agriculture. It has been anticipated that the limits of heavy metals will be lowered. In addition to that, limits for organic micropollutants and microbial indicators of pathogens will be introduced. In this context, the advantage of EDW could possibly be further strengthened. However, to date, there are limited data to support the effectiveness of EDW on reducing these contaminants, which could constitute a future research development.

Acknowledgements

This research leading to these results has received funding from the European Union's Seventh Framework Programme under grant agreement No. 611593 the "SLUDGEtreat" project, and the LIFE Programme under grant agreement No. ENV/IT/000039 the "ELECTRO-SLUDGE" project. The authors wish to thank Cap Holding Group for supplying the sludge samples and Industrie De Nora Spa for providing the DSA® anodes. The valuable support of Dr. Sam Skinner in proof reading is gratefully acknowledged by the authors.

Supplementary information

Supplementary information related to this article can be found at https://.

References

Abuşoğlu, A., Özahi, E., İhsan Kutlar, A., Al-jaf, H., 2017. Life cycle assessment (LCA) of digested sewage sludge incineration for heat and power production. J. Clean. Prod. 142, 1684–1692. doi:10.1016/J.JCLEPRO.2016.11.121

Alvarenga, P., Palma, P., Mourinha, C., Farto, M., Dôres, J., Patanita, M., Cunha-Queda, C., Natal-da-Luz, T., Renaud, M., Sousa, J.P., 2017. Recycling organic wastes to agricultural land as a way to improve its quality: A field study to evaluate benefits and risks. Waste Manag. 61, 582–592. doi:10.1016/j.wasman.2017.01.004

Arlabosse, P., Ferrasse, J.-H., Lecomte, D., Crine, M., Dumont, Y., Léonard, A., 2012. Efficient Sludge Thermal Processing: From Drying to Thermal Valorization, in: Modern Drying Technology. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, pp. 295–329. doi:10.1002/9783527631681.ch8

Bertanza, G., Canato, M., Laera, G., 2018. Towards energy self-sufficiency and integral material recovery in waste water treatment plants: Assessment of upgrading options. J. Clean. Prod. 170, 1206–1218. doi:10.1016/J.JCLEPRO.2017.09.228

Bertanza, G., Baroni, P., Canato, M., 2016. Ranking sewage sludge management strategies by means of Decision Support Systems: A case study. Resour. Conserv. Recycl. 110, 1–15. doi:10.1016/j.resconrec.2016.03.011

Bertanza, G., Canato, M., Heimersson, S., Laera, G., Salvetti, R., Slavik, E., Svanström, M., 2015a. Techno-economic and environmental assessment of sewage sludge wet oxidation. Environ. Sci. Pollut. Res. 22, 7327–7338. doi:10.1007/s11356-014-3378-6

Bertanza, G., Canato, M., Laera, G., Tomei, M.C., 2015b. Methodology for technical and economic assessment of advanced routes for sludge processing and disposal. Environ. Sci. Pollut. Res. 22, 7190–7202. doi:10.1007/s11356-014-3088-0

Buonocore, E., Mellino, S., De Angelis, G., Liu, G., Ulgiati, S., 2016. Life cycle assessment indicators of urban wastewater and sewage sludge treatment. Ecol. Indic. doi:10.1016/J.ECOLIND.2016.04.047

Corominas, L., Foley, J., Guest, J.S., Hospido, A., Larsen, H.F., Morera, S., Shaw, A., 2013. Life cycle assessment applied to wastewater treatment: State of the art. Water Res. 47, 5480–5492. doi:10.1016/j.watres.2013.06.049

Deloitte, 2017. Corporate Tax Rates 2017 [WWW Document]. URL https://www2.deloitte.com/content/dam/Deloitte/global/Documents/Tax/dttl-tax-corporate-tax-rates.pdf (accessed 10.9.17).

Deloitte, 2015. Energy market reform in Europe [WWW Document]. URL https://www2.deloitte.com/global/en/pages/energy-and-resources/articles/energy-market-reform-europe.html (accessed 1.19.18).

Díaz, C., García, G., Canziani, R., Ferrari, G., 2015. Preliminary market analysis – review: Annex 1. Collected Data from some Visits to WWTPs in Italy [WWW Document]. URL https://sludgetreat.eu/wp-content/uploads/2016/11/D2.2-Annex-I-Data-from-some-visits-to-WWTPs-Italy-2015.pdf (accessed 16.2.18)

European Commission, 2016. Sewage Sludge [WWW Document]. URL http://ec.europa.eu/environment/waste/sludge/ (accessed 9.6.17).

European commission JRC-IES, 2011. International reference life cycle data system (ILCD) handbook, 1st ed. European Union, Luxemburg. doi:10.2788/33030

European Commission JRC-IES, 2010. International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance., First. ed. European Union, Luxembourg. doi:10.2788/38479

European Commission, 2000. DIRECTIVE 2000/60/EC. Off. J. Eur. Communities. URL https://eur-lex.europa.eu/resource.html?uri=cellar:5c835afb-2ec6-4577-bdf8-756d3d694eeb.0004.02/DOC_1&format=PDF (accessed 9.6.18).

Eurostat, 2017a. Sewage sludge production and disposal [WWW Document]. URL http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=env_ww_spd&lang=en (accessed 10.4.17).

Eurostat, 2017b. Electricity price for non-household comsumers, first half of 2017 [WWW Document]. URL http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics#Further_Eurostat_information (accessed 9.27.17).

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in Life Cycle Assessment. J. Environ. Manage. 91, 1–21. doi:10.1016/J.JENVMAN.2009.06.018

Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., Pradel, M., 2017. In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. J. Clean. Prod. 143, 1123–1136. doi:10.1016/J.JCLEPRO.2016.12.007

Gronchi, P., Canziani, R., Brenna, A., Visigalli, S., Colominas, C., Montalà, F., Cot, V., Stradi, A., Ferrari, G., Diaz, C., Fuentes, G.G., Georgiadis, A., 2017. Electrode surface treatments in sludge electro-osmosis dewatering. Mater. Manuf. Process. 32, 1265–1273. doi:10.1080/10426914.2017.1279313

Guo, X., Wang, Y., Wang, D., 2017. Permanganate/bisulfite (PM/BS) conditioning-horizontal electro-dewatering (HED) of activated sludge: Effect of reactive Mn(III) species. Water Res. 124, 584–594. doi:10.1016/j.watres.2017.08.027

Heimersson, S., Svanström, M., Cederberg, C., Peters, G., 2017. Improved life cycle modelling of benefits from sewage sludge anaerobic digestion and land application. Resour. Conserv. Recycl. 122, 126–134. doi:10.1016/j.resconrec.2017.01.016

Heimersson, S., Svanström, M., Laera, G., Peters, G., 2016. Life cycle inventory practices for major nitrogen, phosphorus and carbon flows in wastewater and sludge management systems. Int. J. Life Cycle Assess. 21, 1197–1212. doi:10.1007/s11367-016-1095-8

Houillon, G., Jolliet, O., 2005. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. J. Clean. Prod. 13, 287–299. doi:10.1016/J.JCLEPRO.2004.02.022

Investopedia, 2015. What average annual total return does the utilities sector generate? [WWW Document]. URL http://www.investopedia.com/ask/answers/071415/what-average-annual-total-return-does-utilities-sector-generate.asp (accessed 10.3.17).

KPMG, 2015. Cost of Capital Study 2015: Value enhancement in the interplay of risks and returns [WWW Document]. URL https://assets.kpmg.com/content/dam/kpmg/pdf/2016/01/kpmg-cost-of-capital-study-2015.pdf (accessed 9.22.17).

Li, H., Jin, C., Zhang, Z., O’Hara, I., Mundree, S., 2017. Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. Energy 126, 649–657. doi:10.1016/J.ENERGY.2017.03.068

Lombardi, L., Nocita, C., Bettazzi, E., Fibbi, D., Carnevale, E., 2017. Environmental comparison of alternative treatments for sewage sludge: An Italian case study. Waste Manag. 69, 365–376. doi:10.1016/j.wasman.2017.08.040

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2011. Electro-dewatering of wastewater sludge: Influence of the operating conditions and their interactions effects. Water Res. 45, 2795–2810. doi:10.1016/j.watres.2011.02.029

Mahmoud, A., Olivier, J., Vaxelaire, J., Hoadley, A.F.A., 2010. Electrical field: A historical review of its application and contributions in wastewater sludge dewatering. Water Res. 44, 2381–2407. doi:10.1016/j.watres.2010.01.033

Mantovi, P., Baldoni, G., Toderi, G., 2005. Reuse of liquid, dewatered, and composted sewage sludge on agricultural land: Effects of long-term application on soil and crop. Water Res. 39, 289–296. doi:10.1016/j.watres.2004.10.003

Mills, N., Pearce, P., Farrow, J., Thorpe, R., Kirkby, N., 2012. Life Cycle Assessment of Advanced Anaerobic Digestion Process Configurations for Sewage Sludge - A UK Perspective, in: 4th Symposium of Energy from Waste. Elsevier, Venice.

Mills, N., Pearce, P., Farrow, J., Thorpe, R.B., Kirkby, N.F., 2014. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Manag. 34, 185–195. doi:10.1016/j.wasman.2013.08.024

Mininni, G., Blanch, A.R., Lucena, F., Berselli, S., 2015. EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. Environ. Sci. Pollut. Res. 22, 7361–7374. doi:10.1007/s11356-014-3132-0

Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–824. doi:10.1177/0734242X09344876

Murakami, T., Suzuki, Y., Nagasawa, H., Yamamoto, T., Koseki, T., Hirose, H., Okamoto, S., 2009. Combustion characteristics of sewage sludge in an incineration plant for energy recovery. Fuel Process. Technol. 90, 778–783. doi:10.1016/J.FUPROC.2009.03.003

Navab Daneshmand, T., Beton, R., Hill, R.J., Gehr, R., Frigon, D., 2012. Inactivation mechanisms of bacterial pathogen indicators during electro-dewatering of activated sludge biosolids. Water Res. 46, 3999–4008. doi:10.1016/j.watres.2012.05.009

Olivier, J., Conrardy, J.B., Mahmoud, A., Vaxelaire, J., 2015. Electro-dewatering of wastewater sludge: An investigation of the relationship between filtrate flow rate and electric current. Water Res. 82, 66–77. doi:10.1016/j.watres.2015.04.006

Outotec Oyj, 2016. SUSTAINABLE SEWAGE SLUDGE INCINERATION FOR ZÜRICH CANTON (Newsletter) [WWW Document]. URL https://www.outotec.com/company/media/news/2016/sustainable-sewage-sludge-incineration-for-zurich-canton/ (accessed 11.16.17).

Papa, M., Foladori, P., Guglielmi, L., Bertanza, G., 2017. How far are we from closing the loop of sewage resource recovery? A real picture of municipal wastewater treatment plants in Italy. J. Environ. Manage. 198, 9–15. doi:10.1016/j.jenvman.2017.04.061

Penman, J., Kruger, D., Galbally, I., Hiraishi, T., Nyenzi, B., 2000. Good practice guidance and uncertainty management in national greenhouse gas inventories. Institute of Global Environmental Strategies (IGES).

Remy, C., Jekel, M., 2008. Sustainable wastewater management: life cycle assessment of conventional and source-separating urban sanitation systems. Water Sci. Technol. 58, 1555. doi:10.2166/wst.2008.533

Righi, S., Oliviero, L., Pedrini, M., Buscaroli, A., Della Casa, C., 2013. Life Cycle Assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J. Clean. Prod. 44, 8–17. doi:10.1016/J.JCLEPRO.2012.12.004

Rocha, M.H., Capaz, R.S., Lora, E.E.S., Nogueira, L.A.H., Leme, M.M.V., Renó, M.L.G., Olmo, O.A. del, 2014. Life cycle assessment (LCA) for biofuels in Brazilian conditions: A meta-analysis. Renew. Sustain. Energy Rev. 37, 435–459. doi:10.1016/J.RSER.2014.05.036

SUEZ's degremont® water handbook, 2017. low temperature sludge drying system – Evaporis^{TM} LT [WWW Document]. URL https://www.suezwaterhandbook.com/degremont-R-technologies/sludge-treatment/drying/low-temperature-sludge-drying-system-Evaporis-LT (accessed 12.12.17).

SUEZ's degremont® water handbook, 2017. Drying unit energy consumption [WWW Document]. URL https://www.suezwaterhandbook.com/processes-and-technologies/dewatered-sludge-treatment/drying/drying-unit-energy-consumption (accessed 1.15.18).

Tomei, M.C., Bertanza, G., Canato, M., Heimersson, S., Laera, G., Svanström, M., 2016. Techno-economic and environmental assessment of upgrading alternatives for sludge stabilization in municipal wastewater treatment plants. J. Clean. Prod. 112, 3106–3115. doi:10.1016/j.jclepro.2015.10.017

Towler, G.P., Sinnott, R.K., 2013. Chemical engineering design : principles, practice, and economics of plant and process design, 2nd ed. Butterworth-Heinemann.

Tuan, P.A., Sillanpää, M., 2010. Migration of ions and organic matter during electro-dewatering of anaerobic sludge. J. Hazard. Mater. 173, 54–61. doi:10.1016/j.jhazmat.2009.08.046

Umwelt Bundesamt, 2013. Sewage sludge management in Germany [WWW Document]. URL https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/sewage_sludge_management_in_germany.pdf (accessed 1.15.18).

Visigalli, S., Turolla, A., Gronchi, P., Canziani, R., 2017a. Performance of electro-osmotic dewatering on different types of sewage sludge. Environ. Res. 157, 30–36.

doi:10.1016/j.envres.2017.05.015

Visigalli, S., Turolla, A., Zhang, H., Gronchi, P., Canziani, R., 2017b. Assessment of pressure-driven electro-dewatering as a single-stage treatment for stabilized sewage sludge. J. Environ. Chem. Eng. doi:10.1016/j.jece.2017.11.034

Water Environment Federation - Incineration Task Force, 2009. Wastewater solids incineration systems: WEF Manual of Practice No. 30. WEF press - McGraw-Hill Professional.

Yoshida, H., Christensen, T.H., Scheutz, C., 2013. Life cycle assessment of sewage sludge management: A review. Waste Manag. Res. 31, 1083–1101. doi:10.1177/0734242X13504446

Yoshida, H., Clavreul, J., Scheutz, C., Christensen, T.H., 2014. Influence of data collection schemes on the Life Cycle Assessment of a municipal wastewater treatment plant. Water Res. 56, 292–303. doi:10.1016/j.watres.2014.03.014

Yoshida, H., ten Hoeve, M., Christensen, T.H., Bruun, S., Jensen, L.S., Scheutz, C., 2018. Life cycle assessment of sewage sludge management options including long-term impacts after land application. J. Clean. Prod. 174, 538–547. doi:10.1016/J.JCLEPRO.2017.10.175

Yu, W., Yang, J., Wu, X., Gu, Y., Xiao, J., Yu, J., Shi, Y., Wang, J., Liang, S., Liu, B., Hou, H., Hu, J., 2017. Study on dewaterability limit and energy consumption in sewage sludge electro-dewatering by in-situ linear sweep voltammetry analysis. Chem. Eng. J. 317, 980–987. doi:10.1016/j.cej.2017.02.137

Zhang, S., Yang, Z., Lv, X., Zhi, S., Wang, Y., Li, Q., Zhang, K., 2017. Novel electro-dewatering system for activated sludge biosolids in bench-scale, pilot-scale and industrial-scale applications. Chem. Eng. Res. Des. 121, 44–56. doi:10.1016/j.cherd.2017.02.035

Zhao, X., Jiang, G., Li, A., Wang, L., 2016. Economic analysis of waste-to-energy industry in China. Waste Manag. 48, 604–618. doi:10.1016/J.WASMAN.2015.10.014

Figure 1

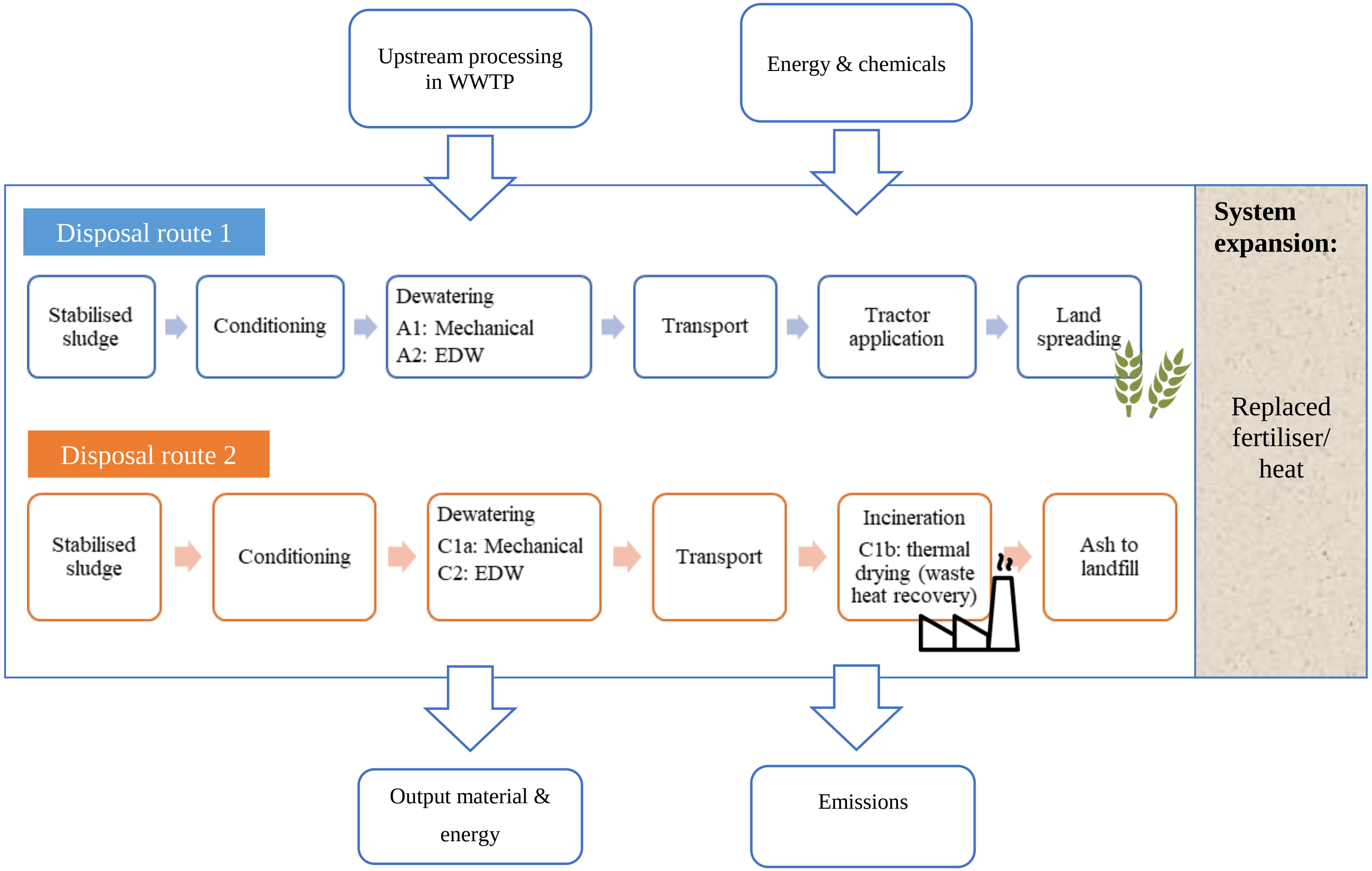

Figure 1. Overview of system boundaries. Two sludge disposal routes were considered: land spreading (scenarios A1 & A2) and centralised incineration (scenarios C1 & C2). Since the sludge dewatering in C1 occurs in different locations, it is marked with C1a and C1b for clarity. EDW dewatering means that the EDW unit is a retrofittable add-on module arranged after the existing mechanical dewatering facility.

Figure 2

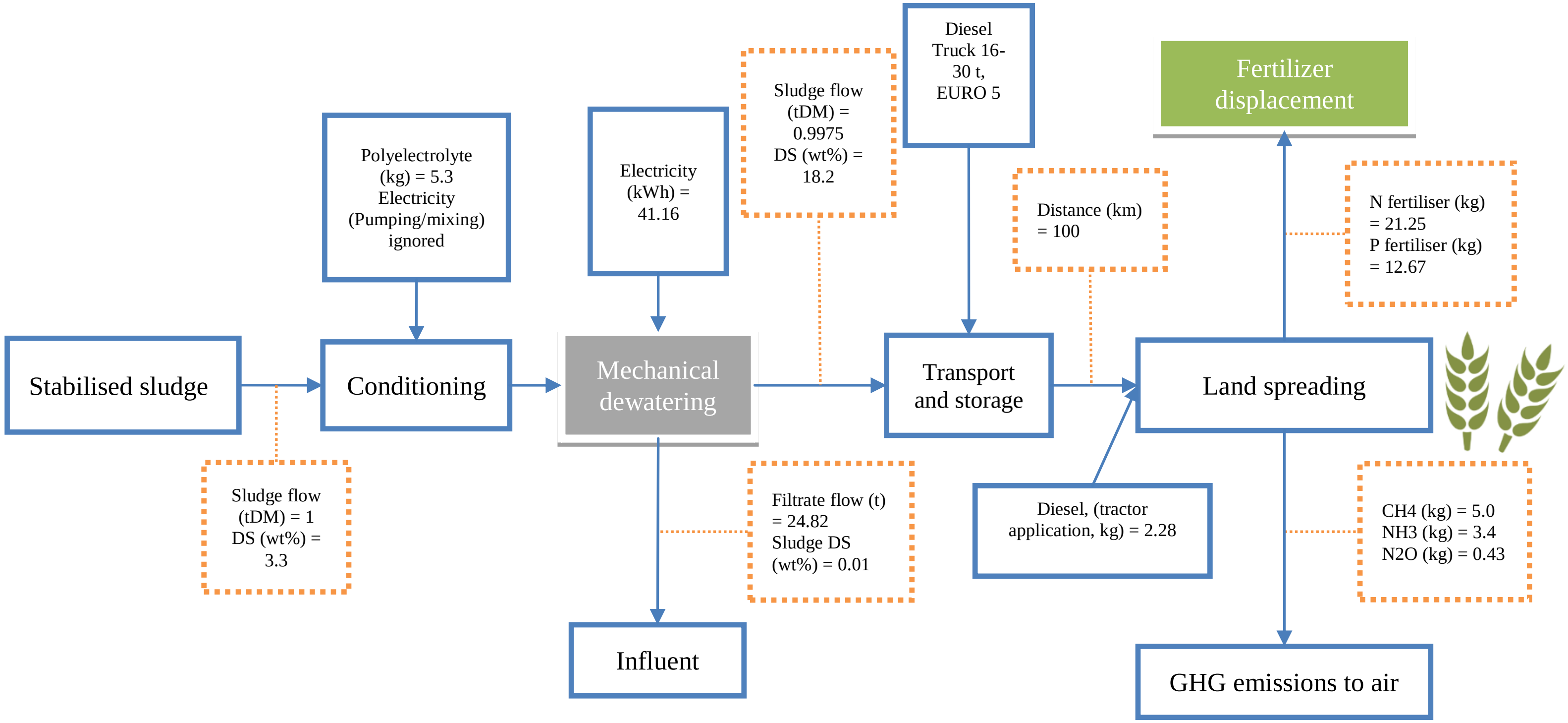

Figure 2. Mass balance of scenario A1. Mass flow is normalised to the functional unit (1 tDM).

Figure 3

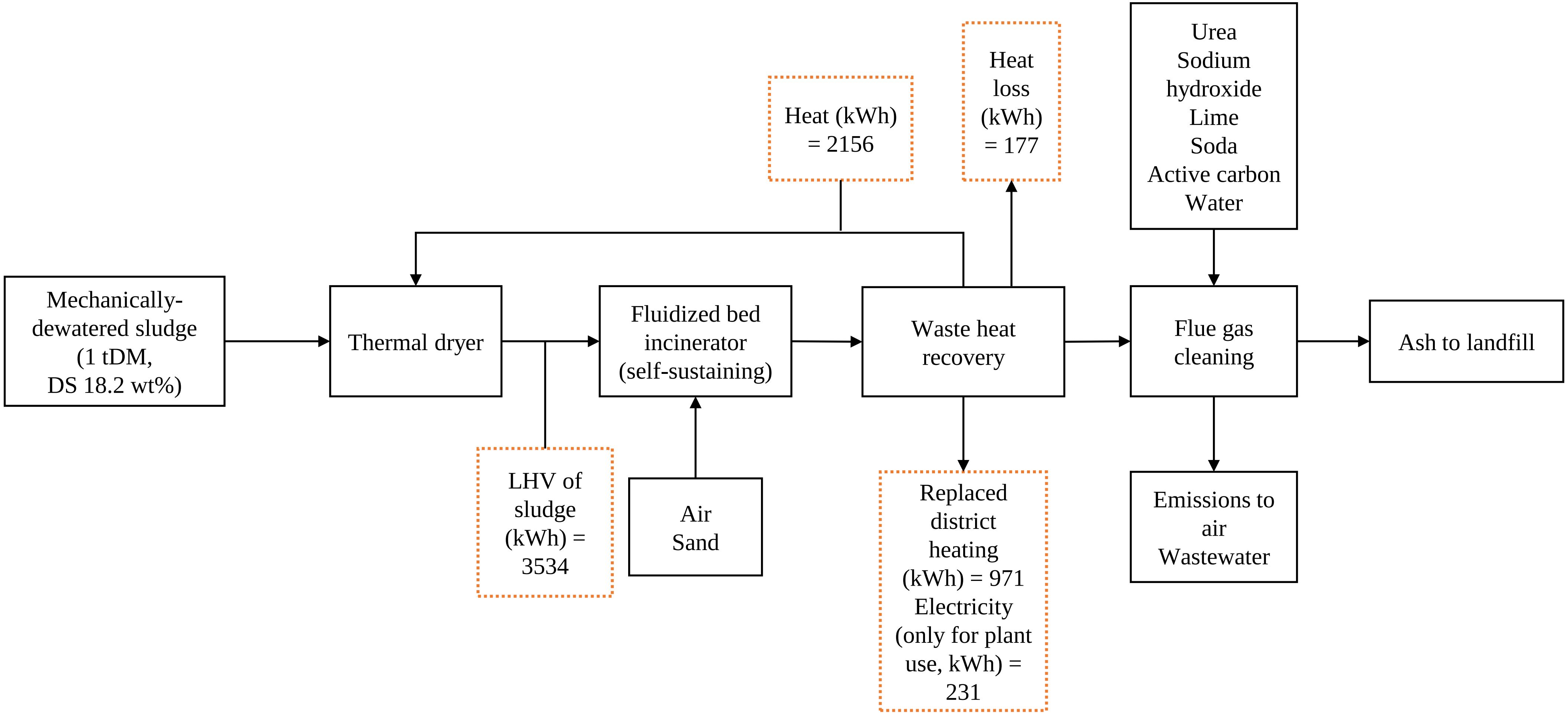

Figure 3. Energy balance of scenario C1. The data are normalised to the functional unit (1 tDM). In case of scenario C2, the heat used by thermal dryer will be diverted to the district heating.

Figure 4

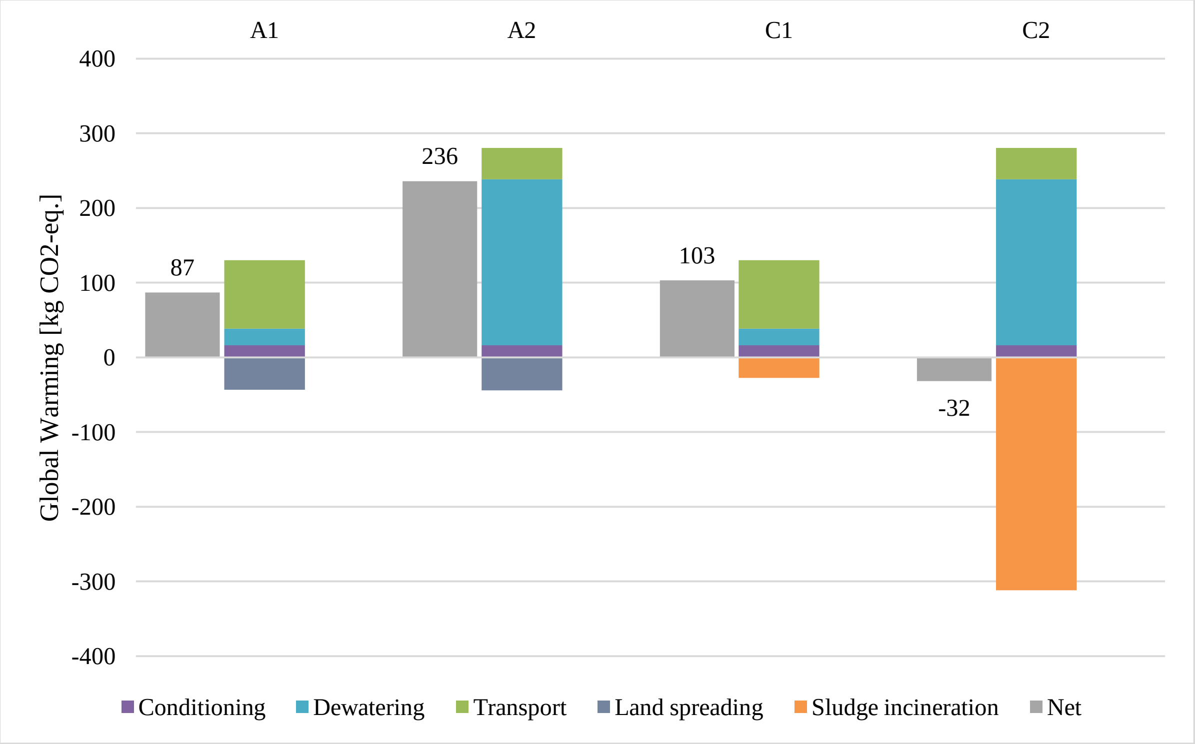

Figure 4. Global Warming (IPCC 2013, 100a) for the four scenarios considered. Refer to the text for detailed scenario descriptions.

Figure 5

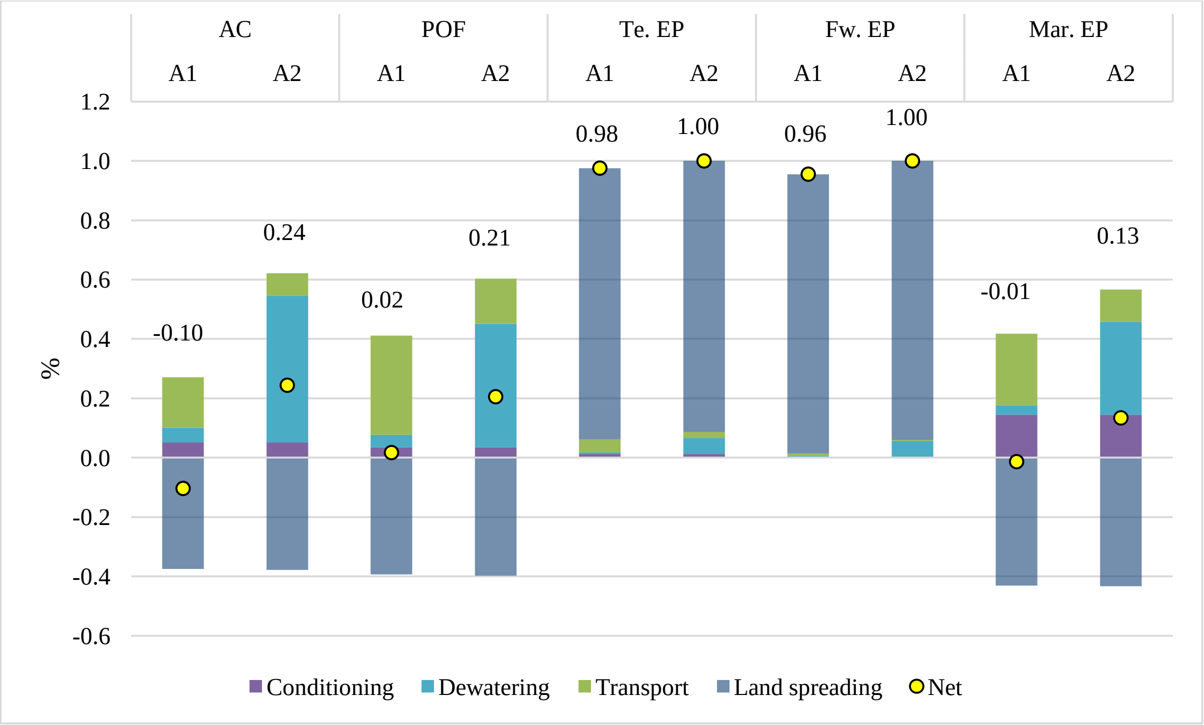

Figure 5. LCIA results (normalised to percentage) for the scenarios of A1 & A2. Refer to the text for detailed scenario descriptions. Acidification abbreviated as AC, Photochemical Ozone Formation as POF, Terrestrial, Freshwater and Marine Eutrophication as Te. EP, Fw. EP and Mar. EP, respectively. Data labels over the bar end indicate the net impact values.

Figure 6

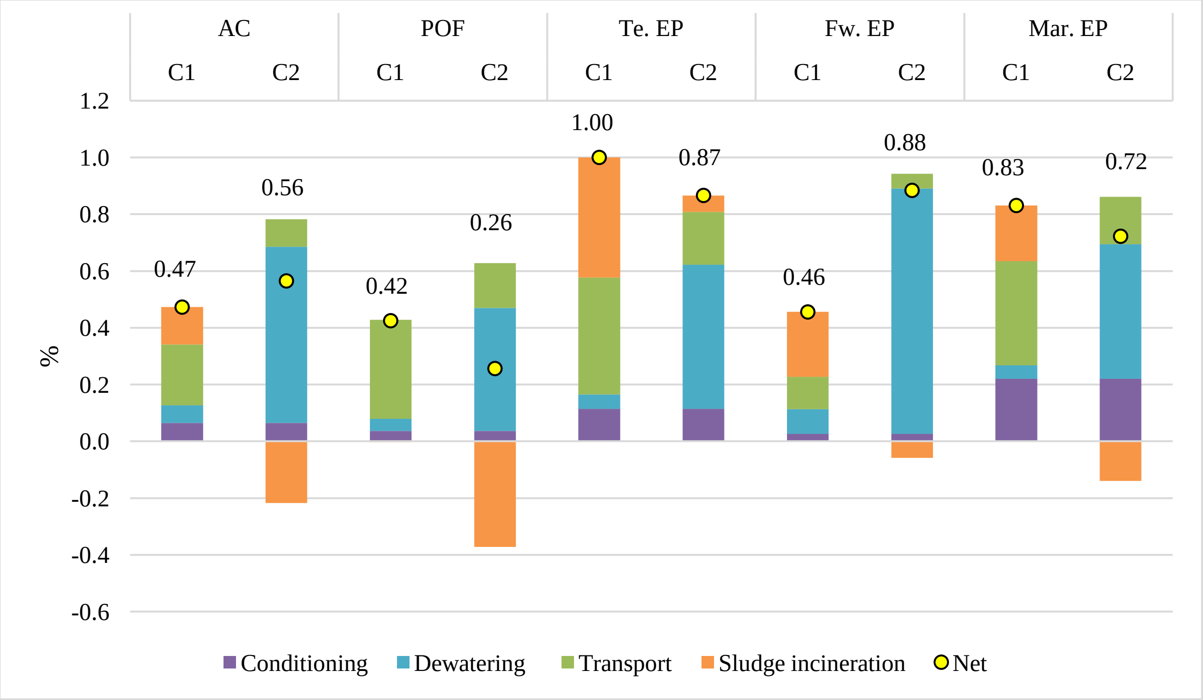

Figure 6. LCIA results (normalised to percentage) for the scenarios of C1 and C2. Refer to the text for detailed scenario descriptions. Acidification abbreviated as AC, Photochemical Ozone Formation as POF, Terrestrial, Freshwater and Marine Eutrophication as Te. EP, Fw. EP and Mar. EP, respectively. Data labels over the bar end indicate the net impact values.

Figure 7

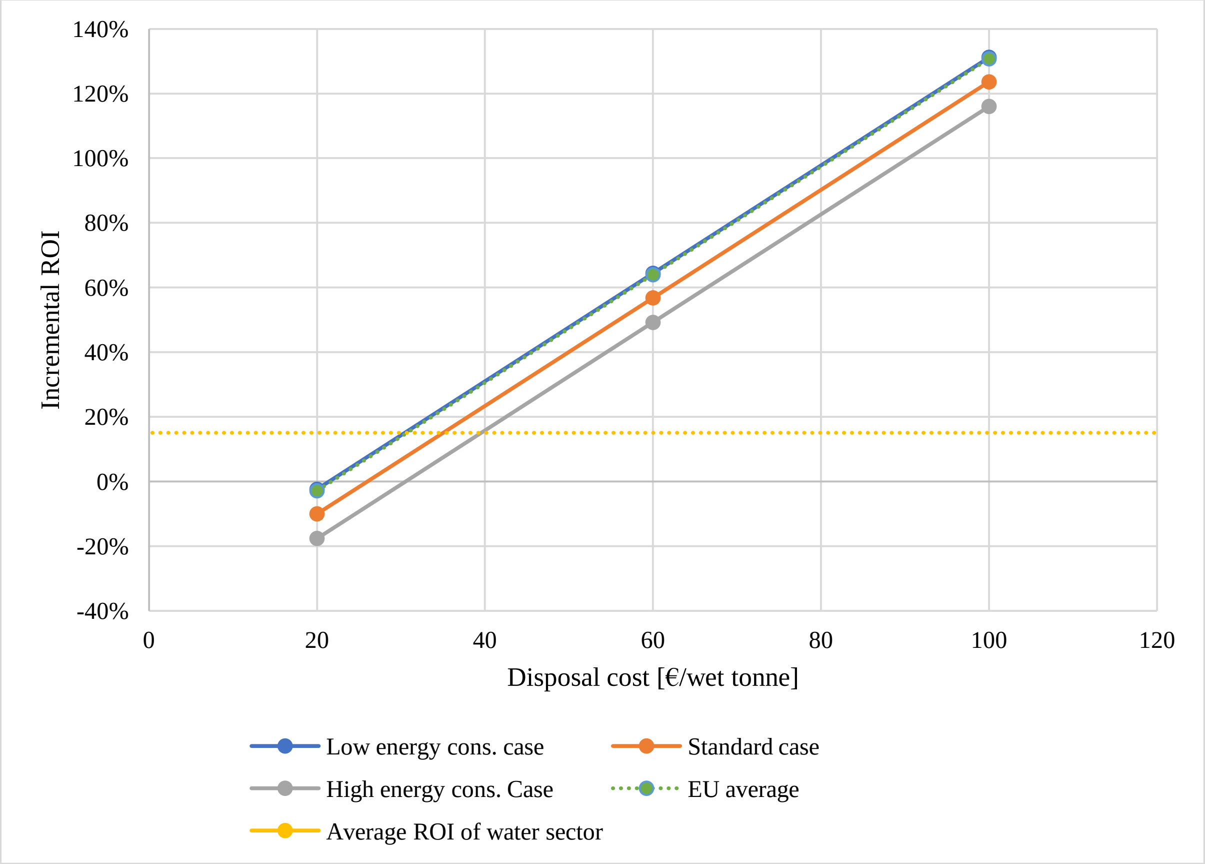

Figure 7. Incremental Return On Investment (ROI) as a function of disposal cost at 20, 60, 100 €/wet tonne. The reference line at ROI 15.1% represents the average ROI of water sector. Refer to the text for detailed case descriptions.

Highlights:

- A case study was carried out by focusing on a small WWTP in Italy
- The EDW upgrade enables significant reduction in global warming in one scenario
- Good economic profitability can be attained for the case study WWTP
- EDW upgrade is recommended for small WWTPs disposing sludge to incineration

Supplementary Information

Environmental and economic assessment of electro-dewatering application to sewage sludge: A case study of an Italian wastewater treatment plant

Hai Zhang [a], Lucia Rigamonti [a], Simone Visigalli [a], Andrea Turolla [a], Paolo Gronchi [b], Roberto Canziani [a, *]

[a] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA) - Environmental Section, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
[b] Politecnico di Milano, Department of Chemistry, Materials and Chemical Engineering, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

SI-1. LCIA methods

The LCIA methods used in this study are summarised in Table SI-1.

Table SI-1. Impact categories and the corresponding LCIA methods used.

Impact category (ILCD midpoint)	What the impact indicator measures	LCIA method	Reference
GW	The radiative forcing over a time horizon of 100 years	IPCC 2013, 100a	(IPCC, 2013)
AC	The change in critical load exceedance of the sensitive area in terrestrial and main freshwater ecosystems, to which acidifying substances deposit	Accumulated Exceedance	(Posch et al., 2008; Seppälä et al., 2006)
POF	The potential contribution to photochemical ozone formation	ReCiPe 2008 V1.05	(Van Zelm et al., 2008)
Terrestrial EP	The change in critical load exceedance of the sensitive area, to which eutrophying substances deposit	Accumulated Exceedance	(Posch et al., 2008; Seppälä et al., 2006)
Freshwater EP	The degree to which the emitted nutrients reaches the freshwater end compartment (phosphorus considered as limiting factor in freshwater)	ReCiPe 2008 V1.05 (EUTRENO model)	(Struijs et al., 2009)
Marine EP	The degree to which the emitted nutrients reaches the marine end compartment (nitrogen considered as limiting factor in marine water)	ReCiPe 2008 V1.05 (EUTRENO model)	(Struijs et al., 2009)

SI-2. Lab-scale EDW test

The EDW test was carried out at DICA, Politecnico di Milano from January through February of 2017. Mechanically-dewatered sludge was sampled from the case study WWTP. The EDW test was performed with a lab-scale device following the method described in our previous publication (Visigalli et al., 2017). The operating parameters were set as cake thickness 15 mm and electrical potential 20 V. The dewatering results are summarised in Table SI-2.

Table SI-2. Lab-scale EDW test results: DS improvement and specific energy consumption.

Inlet DS [%]	Outlet DS [%]	DS improvement [%]	Specific energy consumption [Wh/kg water removed]
16.3	38.1	21.8	116

SI-3. Mass balance of scenario A2

The mass balance of scenario of A2 is depicted in Figure SI-1.

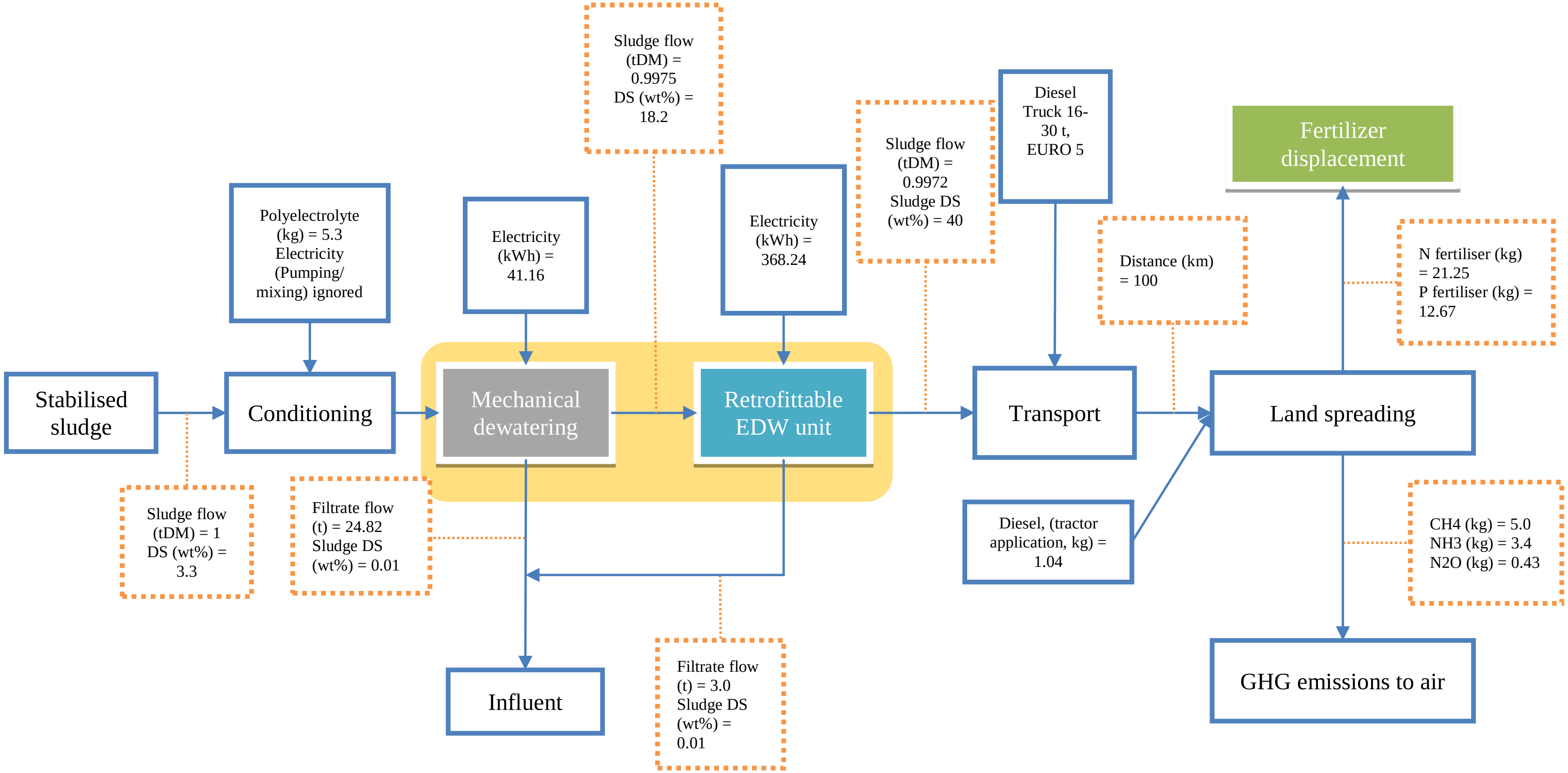

Figure SI-1. Mass balance of scenario A2. Mass flow is normalised to the functional unit (1 tDM).

SI-4. Sludge cake lower heating value (LHV) calculation

In accordance with the reference (Sanin et al., 2011), assuming the composition of Volatile Solids (VS) of sludge to be C5: H7: O2: N1: S0.03, the total molecule weight of the VS (i.e. combustible elements), *TM*, is *TM* = 12 × 5 + 7 × 1 + 2 × 16 + 14 × 1 + 0.03 × 32 = 114.

Carbon percentage, *%C*, in kg C/kg wet sludge, is given by Equation SI.1:

$$\%C = 60/TM * VS/DS * (1-U) \tag{SI.1}$$

where

U = moisture content

VS/DS = volatile solids content

In this case study, the DS is set as 40%, i.e. *U* is 60%.

Based on our lab test, the average VS/DS is 70%.

So, the carbon content *C* is *C* = %*C* × 100

The content of *H*, *O*, *N* and *S* can be calculated in the same way.

The sludge cake LHV (in kcal/kg of wet sludge) can be estimated with the Dulong equation (Equation SI.2; Water Environment Federation - Incineration Task Force, 2009):

$$LHV = 81C + 28.7(H - O/8) + 22.1S - 6U \tag{SI.2}$$

So, substituting in the data gives the LHV of 1216.4 kcal/kg wet sludge, i.e. 5.09 MJ/kg of wet sludge. Normalising the LHV value to the FU gives 5.09 × 1/40% = 12.725 MJ/kgDM = 3534 kWh/tDM.

For sludge mono-incineration, the combustion temperature must be in compliance with the EU regulation, to be in the range of 850-950 °C (Umwelt Bundesamt, 2013). On the other hand, to ensure complete combustion and avoid generating higher emission of NOx, the supplied combustion air must be 40% greater than the oxidation stoichiometry (Water Environment Federation-Incineration Task Force, 2009). The excess air percentage, *e*, is given by Equation SI.3 (Water Environment Federation - Incineration Task Force, 2009):

$$e = \left[\frac{0.97LHV - 40}{T_f - T_0} - 0.38V_{fs} - 0.0332\right] / (0.0033 \cdot V_{as}) \tag{SI.3}$$

where

T_0 = inlet air temperature

T_f = flue gas temperature in the freeboard area of the incinerator

V_{fs} = volume of flue gas

V_{as} = stoichiometry air volume for complete combustion

Hence, set *e* as 140% and then it gives

T_f = 900 °C

This result suggests that the supplied sludge cake can maintain self-sustaining incineration at the assumed DS value (40%), and no preheating unit is needed.

SI-5. LCIA results

The LCIA results for the scenarios considered are presented in Figures from SI-2 to SI-6.

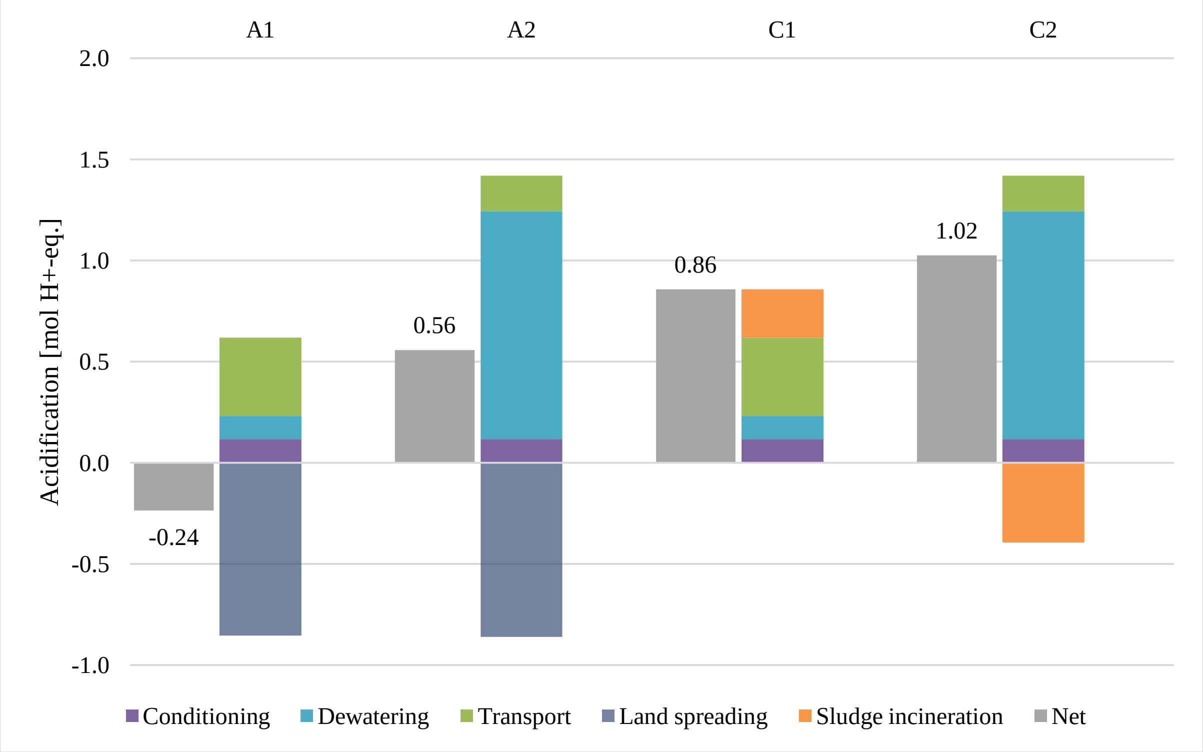

Figure SI-2. Acidification for the four scenarios considered.

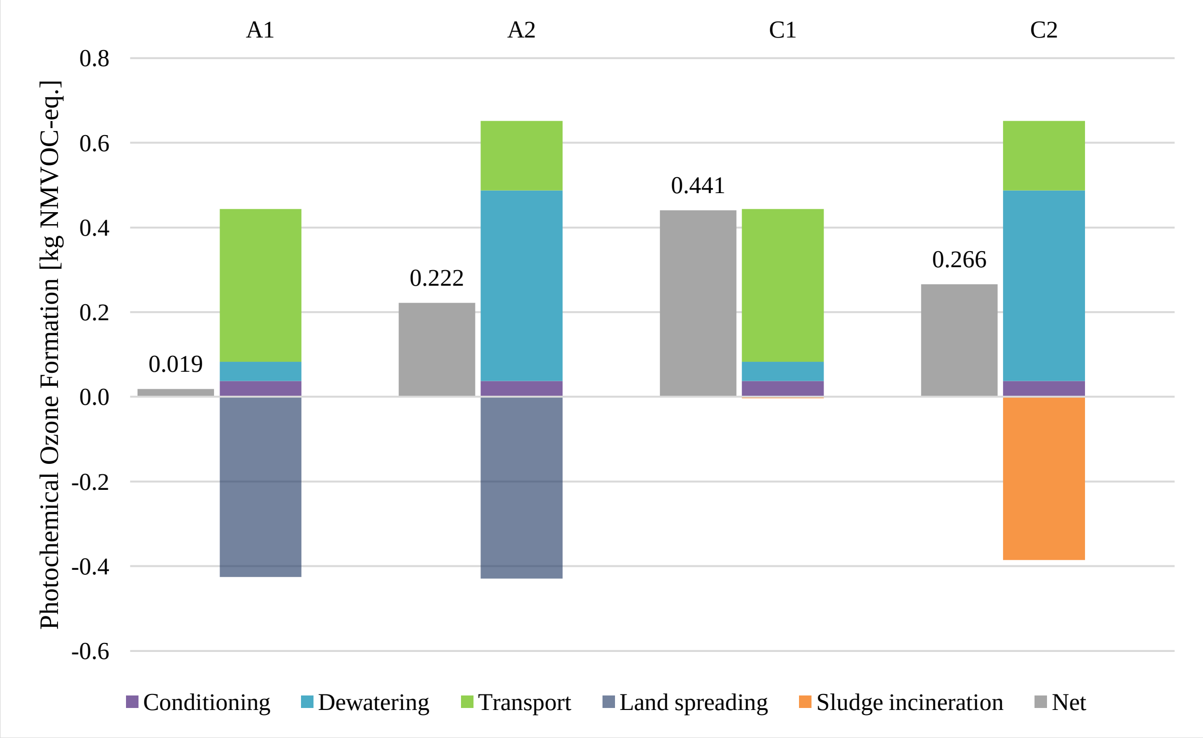

Figure SI-3. Photochemical Ozone Formation for the four scenarios considered.

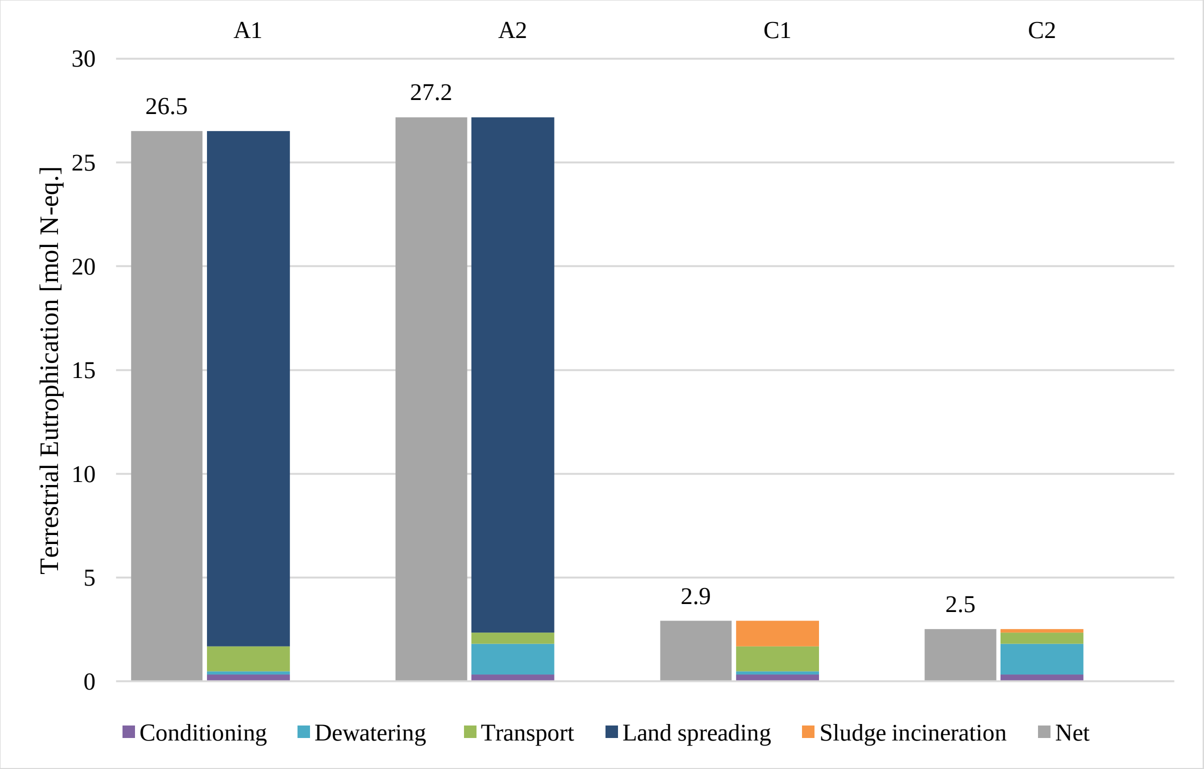

Figure SI-4. Terrestrial Eutrophication for the four scenarios considered.

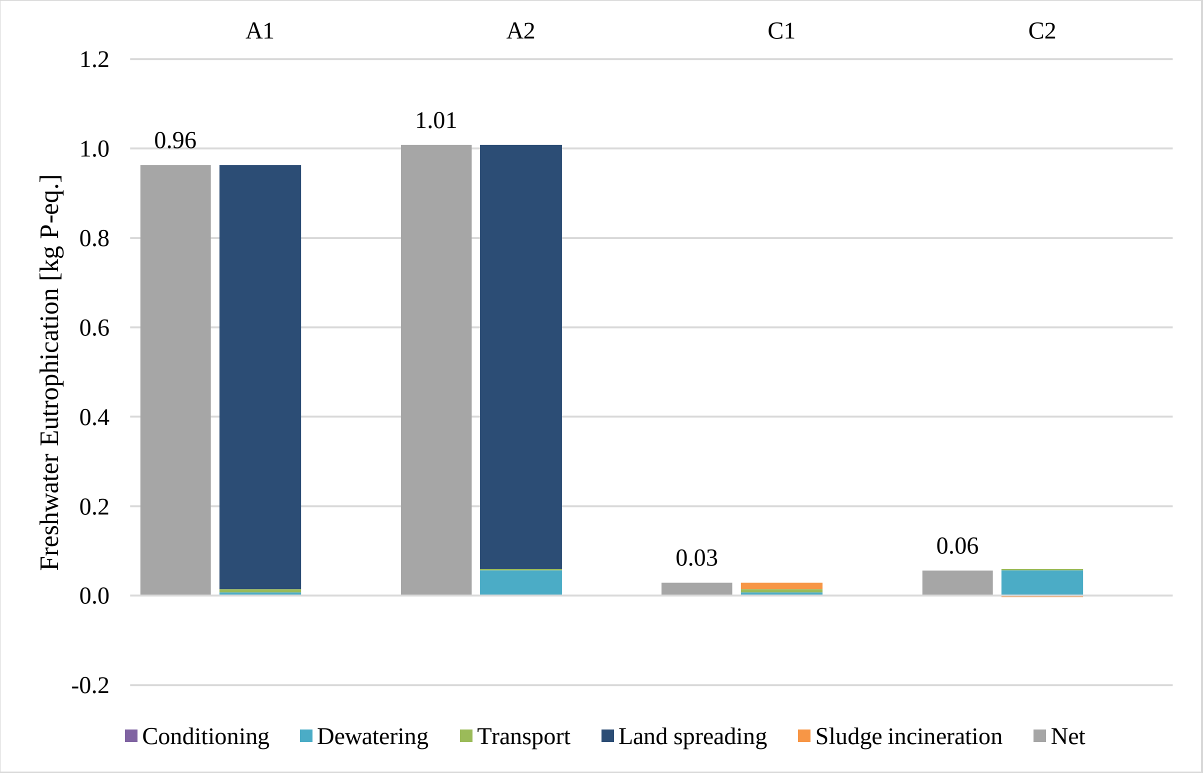

Figure SI-5. Freshwater Eutrophication for the four scenarios considered.

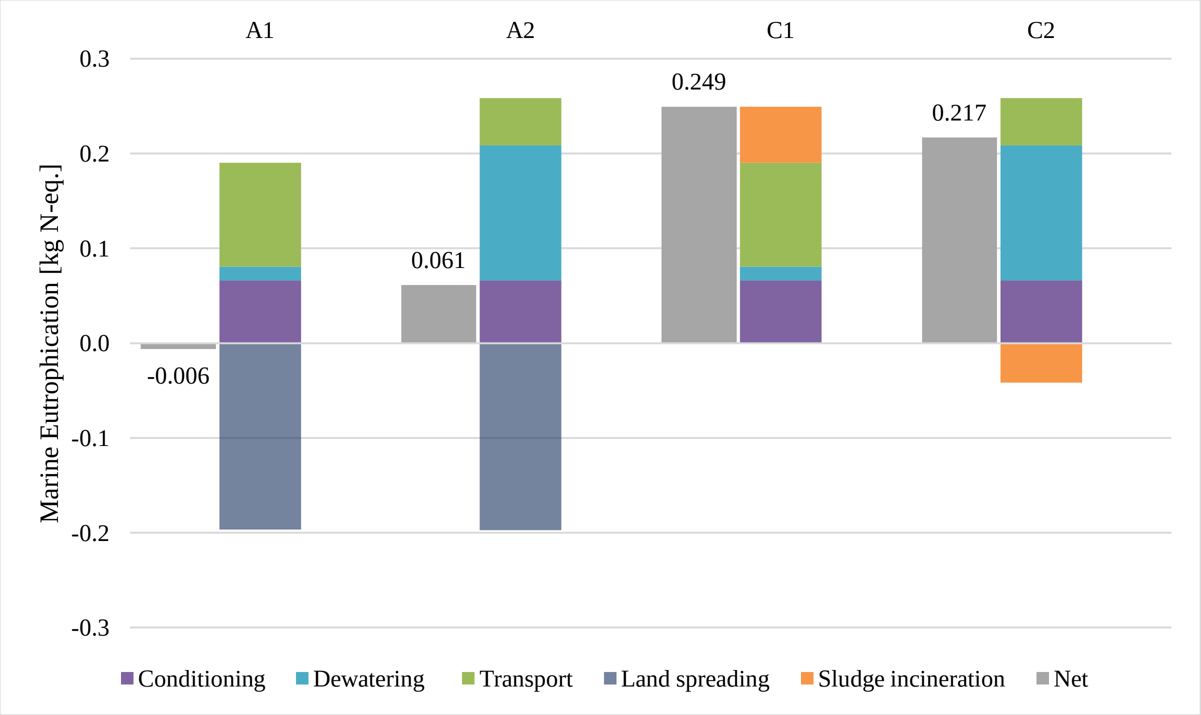

Figure SI-6. Marine Eutrophication for the four scenarios considered.

References

IPCC, 2013. Climate change 2013: The physical science basis [WWW Document]. URL http://www.ipcc.ch/report/ar5/wg1/ (accessed 1.24.18)

Posch, M., Seppälä, J., Hettelingh, J.-P., Johansson, M., Margni, M., Jolliet, O., 2008. The role of atmospheric dispersion models and ecosystem sensitivity in the determination of characterisation factors for acidifying and eutrophying emissions in LCIA. Int. J. Life Cycle Assess. 13, 477–486. doi:10.1007/s11367-008-0025-9

Sanin, F.D., Clarkson, W.W. (William W., Vesilind, P.A., Vesilind, P.A., 2011. Sludge engineering: The treatment and disposal of wastewater sludges. DEStech Publications, Inc.

Seppälä, J., Posch, M., Johansson, M., Hettelingh, J.-P., 2006. Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator (14 pp). Int. J. Life Cycle Assess. 11, 403–416. doi:10.1065/lca2005.06.215

Struijs, J., Beusen, A., van Jaarsveld, H., Huijbregts, M.A.J., 2009. Chapter 6 Eutrophication, in: Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., van Zelm, R. (Eds.), ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterization factors. p. 132.

Umwelt Bundesamt, 2013. Sewage sludge management in Germany [WWW Document]. URL https://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/sewage_sludge_management_in_germany.pdf (accessed 1.15.18).

Van Zelm, R., Huijbregts, M.A.J., den Hollander, H.A., van Jaarsveld, H.A., Sauter, F.J., Struijs, J., van Wijnen, H.J., van de Meent, D., 2008. European characterization factors for human health damage of PM10 and ozone in life cycle impact assessment. Atmos. Environ. 42, 441–453. doi:10.1016/J.ATMOSENV.2007.09.072

Visigalli, S., Turolla, A., Zhang, H., Gronchi, P., Canziani, R., 2017. Assessment of pressure-driven electro-dewatering as a single-stage treatment for stabilized sewage sludge. J. Environ. Chem. Eng. doi:10.1016/j.jece.2017.11.034

Water Environment Federation - Incineration Task Force, 2009. Wastewater solids incineration systems: WEF Manual of Practice No. 30. WEF press - McGraw-Hill Professional.