Eco-friendly and energy efficient sewage SLUDGE dewaTeRing through novEl nanomAterials and elecTro-osmotic process

SLUDGEtreat

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Table of Contents

List of figures

1. List of 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
WWTP	Wastewater Treatment Plant

2. Case study based on an Italian WWTP

2.1 Environmental assessment

2.1.1 Goal and scope

The case study focuses on a WWTP situated in the Milan metropolitan area, which serves 47,000 population equivalents. This plant has been chosen as a typical medium-size European WWTP, according to a previous analysis reported in Deliverable D2.2. In this plant, the sludge is stabilised with the aerobic stabilisation method. After that, it is dewatered with a belt press (mechanical dewatering). In 2016 it has produced a total of 2300 t of dewatered sludge that were disposed through a multiple-channel approach: 54.8% to landfill, 26.2% to incineration, and 19% to external WWTP for further processing. The average disposal cost was 80 €/wet tonne.

The goal of this study is to assess the feasibility of implementing Electro-dewatering (EDW) upgrade for a medium-sized WWTP following the Life Cycle Assessment (LCA) methodology. In this case study, "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 increase the sludge DS from the initial 3.3% to 40%. 40% was set as the targeting DS due to the requirements of self-sustaining incineration (Outotec Oyj, 2016; Zhang et al., 2017).

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 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).

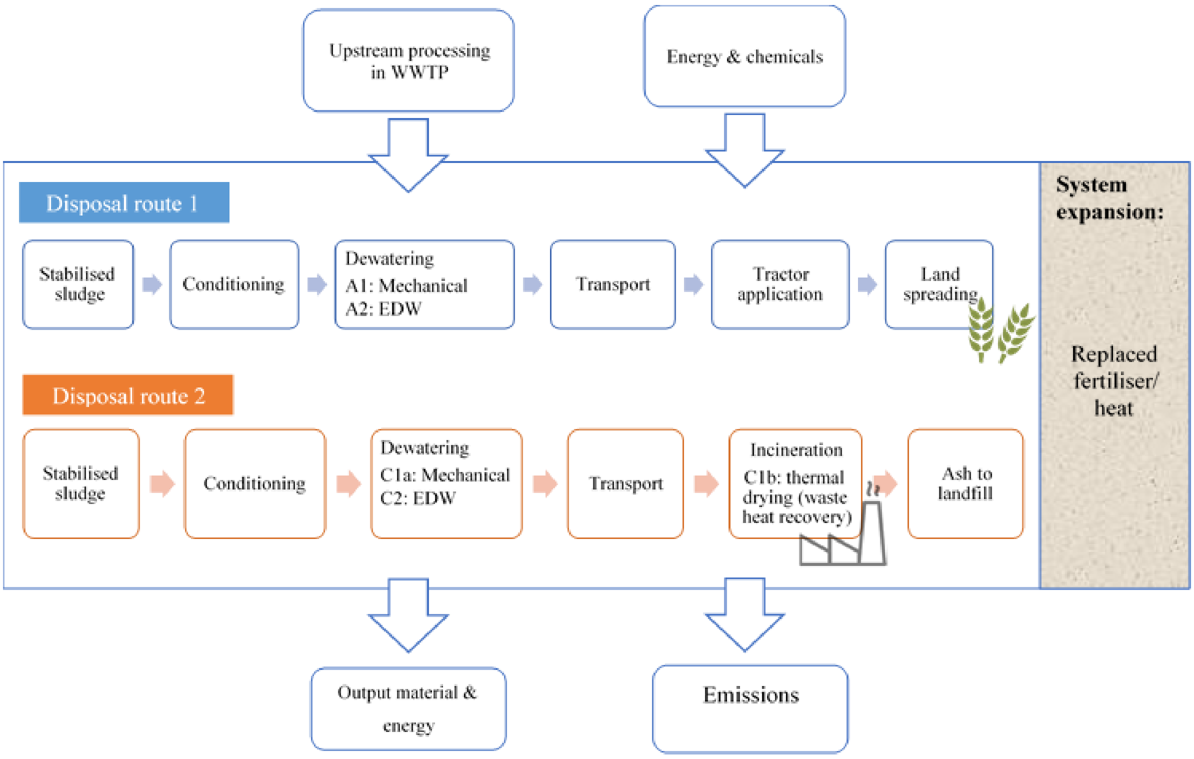

Figure 1 - Overview of system boundaries. Two sludge disposal routes were considered: land spreading (scenarios A1 & A2) and centralised incineration (scenarios C1 & C2). Since the sludge dewatering in C1 occurs in different locations, it is marked with C1a and C1b for clarity. EDW dewatering means the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

In total, four scenarios were thus set up for making comparisons (see Figure 1):

- **A1**: Mechanically-dewatered sludge for land spreading
- **A2**: EDW-dewatered sludge for land spreading
- **C1**: Sludge first mechanically dewatered at WWTPs (C1a), and then thermally dried at the incineration plant (C1b) and used for incineration
- **C2**: 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, the scenario C2 was constructed to consider the further improvement on the efficiency of energy recovery – instead of relying on the integrated on-site thermal dryer, if the sludge on delivery already has suitable DS content (e.g. 40%) to be dumped 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 set as in Italy.

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). They were assessed with the Life Cycle Impact Assessment (LCIA) methods recommended by the "ILCD Handbook" (European commission JRC-IES, 2011).

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 3). Data collection for each life cycle stage is described as follows.

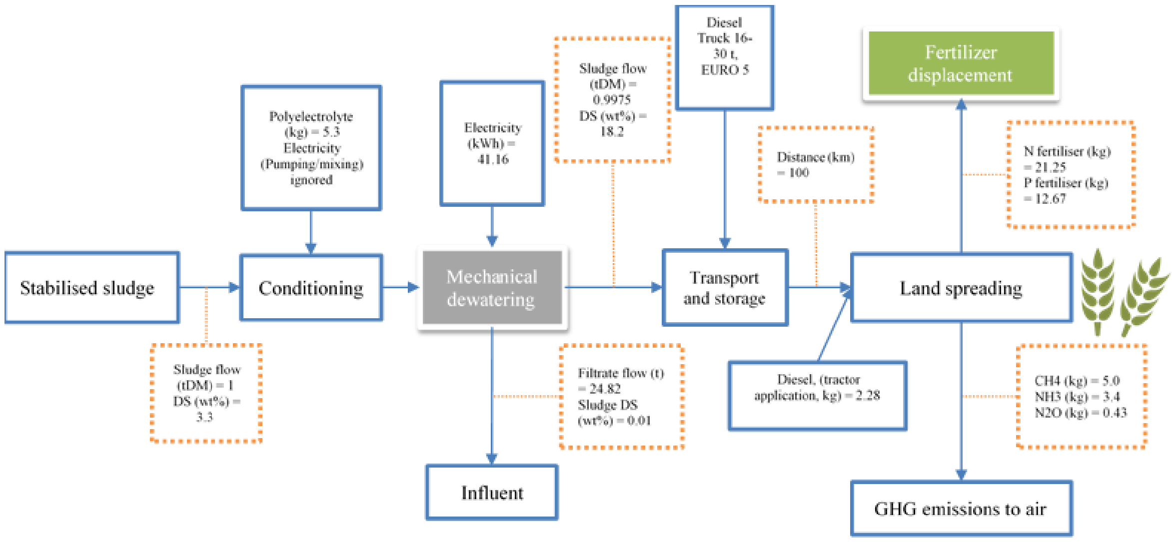

Figure 2 - Mass balance of scenario A1. Mass flow is normalised to the functional unit (1 tDM).

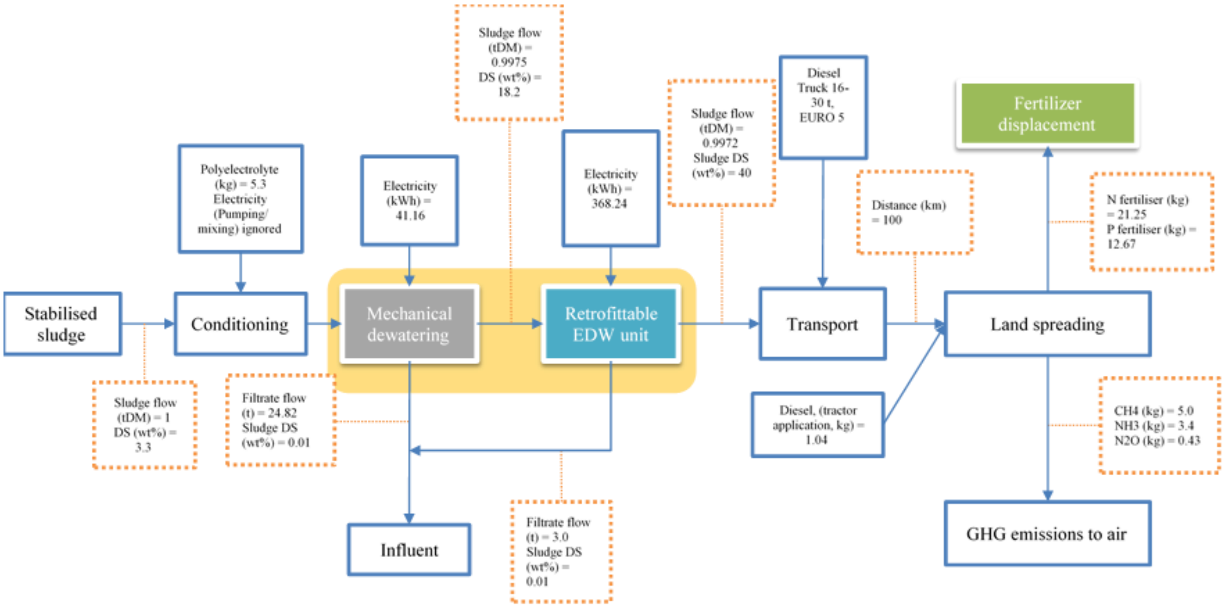

Figure 3 - Mass balance of scenario A2. Mass flow is normalised to the functional unit (1 tDM).

Conditioning

During the conditioning, 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 publications (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

The EDW unit was used to process the mechanically-dewatered sludge, increasing its DS from 18.2% to 40%. The data of sludge volume reduction and specific energy consumption were derived from our lab test following the method described in (Visigalli et al., 2017). The test was carried out at DICA, Politecnico di Milano from January through February of 2017, with samples extracted from the case study WWTP. As a whole system, the EDW dewatering 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 (Heimersson et al., 2017; Mantovi et al., 2005). For the N-fertiliser, the total N was 4.25% of the sludge Dry Mass (DM); a converting 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 factor of 0.7 was used to account for the element mineralisation.

On the other hand, the GHG (Greenhouse Gas) 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 4. 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).

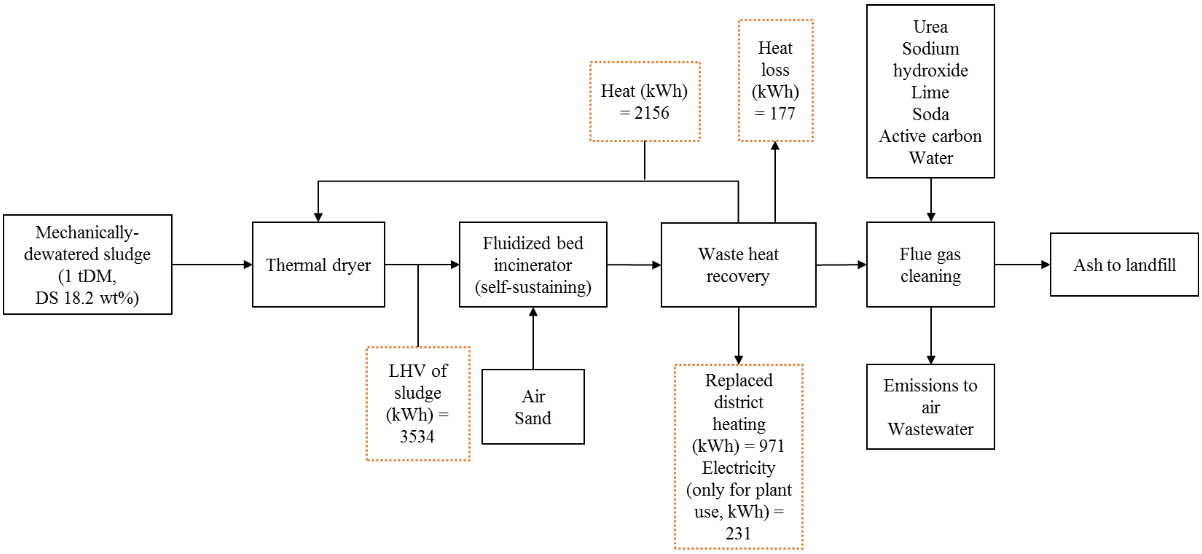

Figure 4 - Energy balance of scenario C1. The data are normalised to the functional unit (1 tDM). In case of scenario C2, the heat used by thermal dryer will be diverted to the district heating.

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 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%.

For thermal drying, the specific energy consumption was taken as 0.72 kWh per kilogram evaporated water, reflecting the best available industrial technology (SUEZ's degremont® water handbook, n.d.). 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. 90% 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 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

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

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

In the case of 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):

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

In the case of 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.

1) **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 represents the situation when the EDW machine is running with improved dewatering efficiency.

2) **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.

3) **EU average case**: The Italian electricity price (for industrial user) is the 2nd highest in the EU-28 – 30% higher than the EU average price (Eurostat, 2017). 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

The EDW machine has a throughput of 0.2 m^3/h. In terms of yearly throughput, it can process 800 t of mechanically-dewatered sludge, which especially suits the needs of small-medium-sized WWTPs.
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	Own data
DS of inlet sludge	18.2%	Extracted from the WWTP
DS of outlet sludge	40%	Own data
Working hours per year	3800 h	Extracted from the WWTP
EDW machine price	Estimate	Estimate
Maintenance cost	Own data	Own data
Machine service life/project period	10 years	Estimate
Machine power*	14.6-18.2 kW	Estimate
Electricity price for industrial users, all taxes included, Italy	0.148 €/kWh	(Eurostat, 2017)
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	Extracted from real cases of Italy, also applicable to other EU markets (Bertanza et al., 2015)

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

2.3 LCIA results

2.3.1 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 5 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.

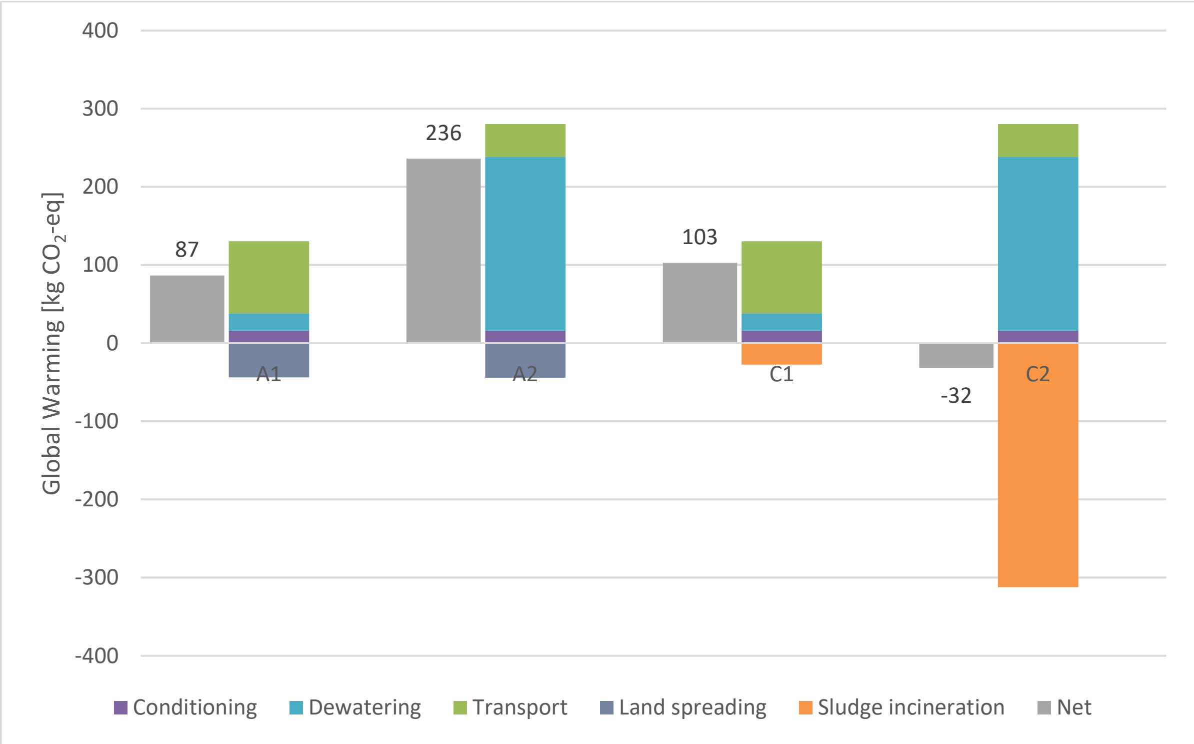

Figure 5 - Global Warming (IPCC 2013, 100a) for the four scenarios considered. Refer to the text for detailed scenario descriptions.

It can be 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 cut 50 kg CO_2-eq in 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).

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 C2.

2.3.2 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 %).

The LCIA results for the land spreading route (A1 & A2) are depicted in Figure 6. The data labels over the bar end indicate the net impact values.

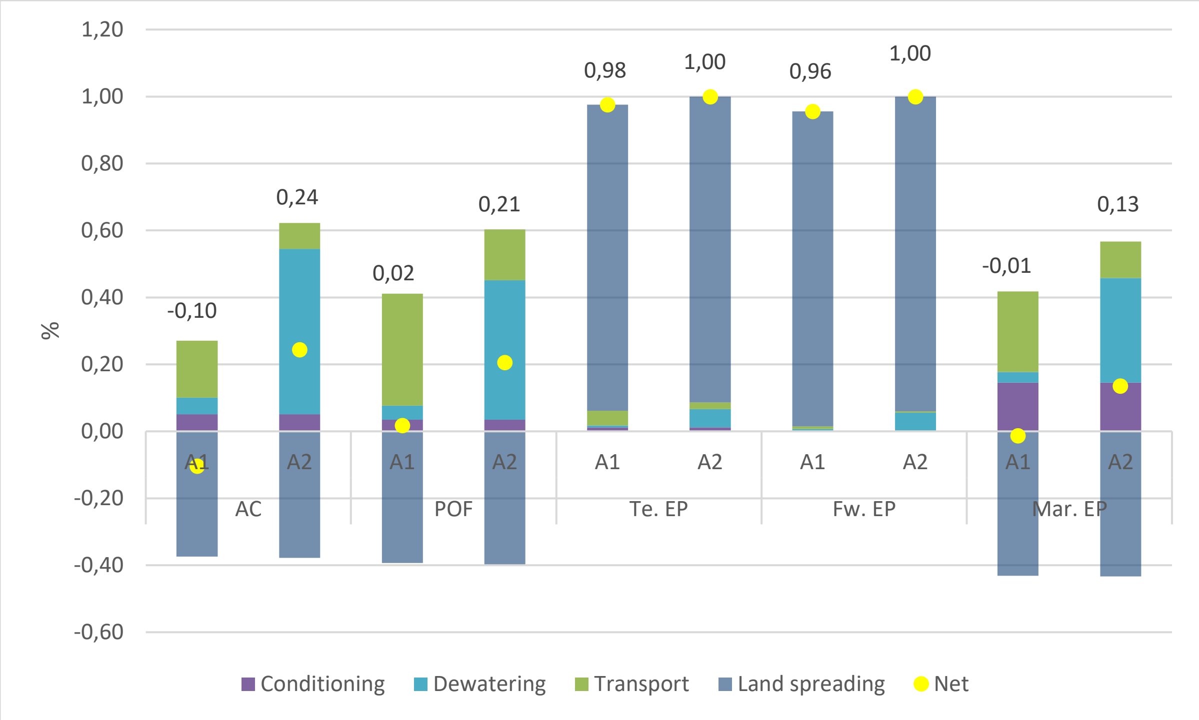

Figure 6 - LCIA results (normalised to percentage) for the scenarios of A1 & A2. Refer to the text for detailed scenario descriptions. Acidification abbreviated as AC, Photochemical Ozone Formation as POF, Terrestrial, Freshwater and Marine Eutrophication as Te. EP, Fw. EP and Mar. EP, respectively. Data labels over the bar end indicate the net impact values.

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, therefore 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, 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 7. The data labels over the bar end indicate the net impact values. Because of the EDW upgrade, the system's net impact drops 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).

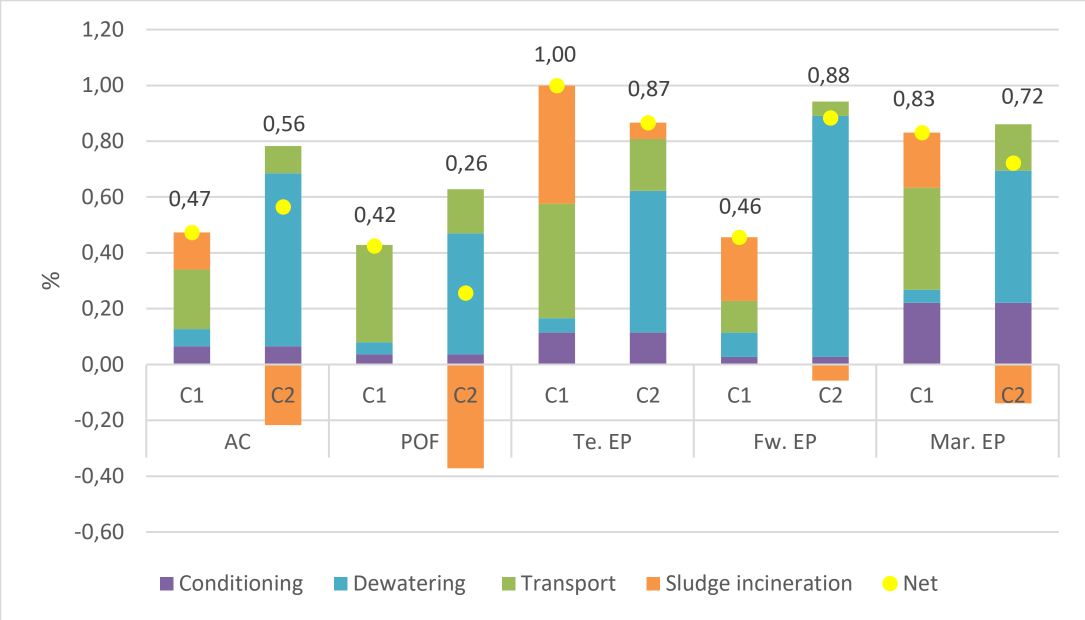

Figure 7 - LCIA results (normalised to percentage) for the scenarios of C1 and C2. Refer to the text for detailed scenario descriptions. Acidification abbreviated as AC, Photochemical Ozone Formation as POF, Terrestrial, Freshwater and Marine Eutrophication as Te. EP, Fw. EP and Mar. EP, respectively. Data labels over the bar end indicate the net impact values.

Regarding the AC, moving from C1 to C2 will increase the impact 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, 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).

2.3.3 Results of the sensitivity analysis

The LCIA results of the sensitivity analysis about 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	molc 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	molc 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

2.4 Economic profitability

The incremental ROI for implementing the EDW upgrade is depicted in Figure 8. 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 15.10%. Thus, a reference line at ROI 15.10% is added to facilitate the evaluation. The break-even values at ROI 15.1% are reported in the annotation box in the figure.

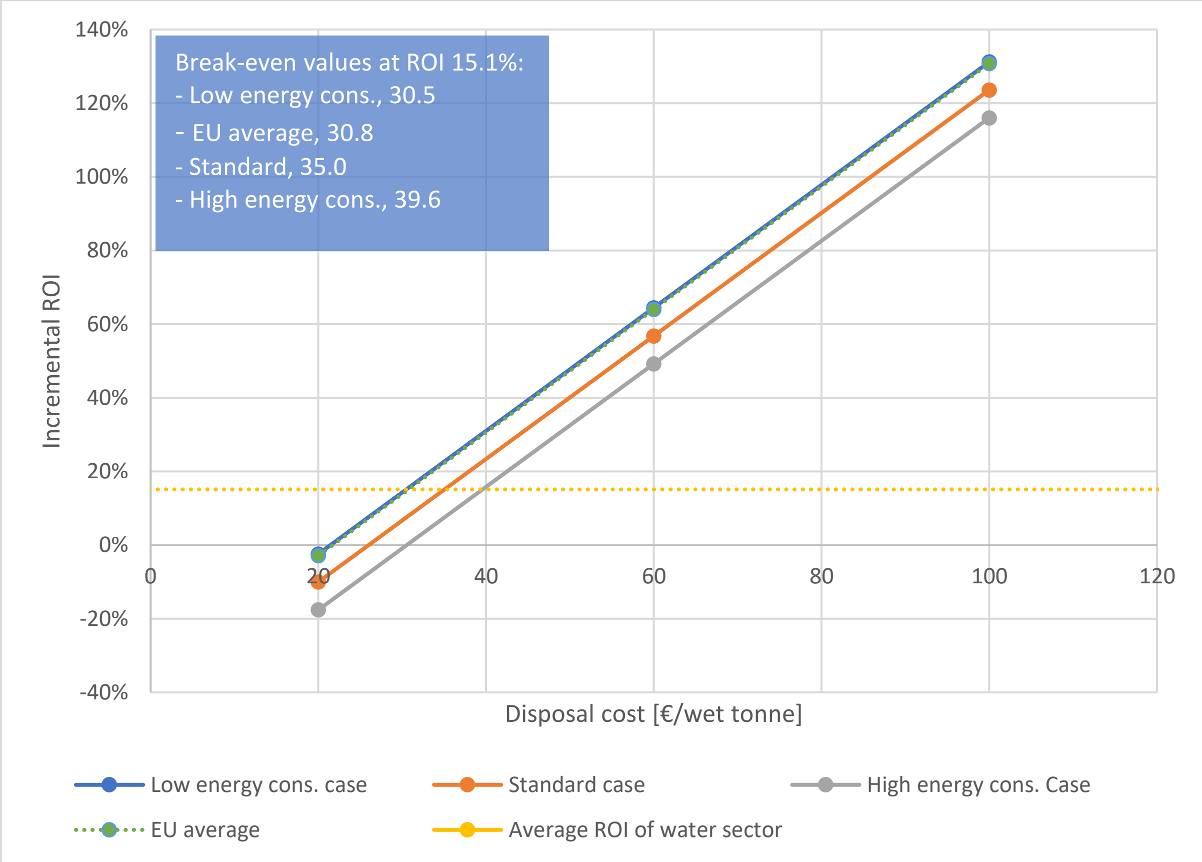

Figure 8 - Incremental Return On Investment (ROI) as a function of disposal cost at 20, 60, 100 €/wet tonne. The reference line at ROI 15.10% represents the average ROI of water sector. Refer to the text for detailed case descriptions.

It can be 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. Based on our recent survey of some WWTPs in the Lombardy region of Italy, the sludge disposal cost for agriculture use (both land spreading and composting, at DS 25%) is 47-57 €/wet tonne including transport. 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 the annual capital charge taking 21%, the consumables taking 17% (mainly the anode consumption), and the fixed cost of production taking 5% (maintenance cost). 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 so that the WWTP will enjoy a good profit after implementing the EDW.

2.5 Summary

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).

The LCIA results give a holistic view of the sludge management scenarios concerned. 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 Assessment of the 1st version of prototype EDW machine

Unlike the abovementioned case study, this assessment focuses on the actual prototype EDW machine developed in this project. It consists of two sections, mechanical dewatering section and EDW section. It is designed to process liquid sludge, and the targeting outlet DS is 25%.

3.1 Environmental impact assessment

This assessment is based on the preliminary test with the prototype EDW machine as reported in Deliverable D4.2a. The results of Test No.4 were used (see Table 4) since in this trial the outlet DS of sludge reached at 26.6%, matching the targeting DS 25%.

Table 4 - Data derived from the preliminary test with the prototype EDW machine.

DS of raw sludge [%]	Outlet DS [%] when EDW switched off	Outlet DS [%] when EDW switched on	DS improvement [%]	Specific energy consumption [Wh/kg water removed]	Machine power [kW]
4.3	21.7	26.6	4.9	13.9	0.89

Set the reference flow as 1000 kg liquid sludge at DS 4.3% before feeding into the prototype machine. The relationship between DS improvement and mass of sludge to be disposed is depicted in Figure 9.

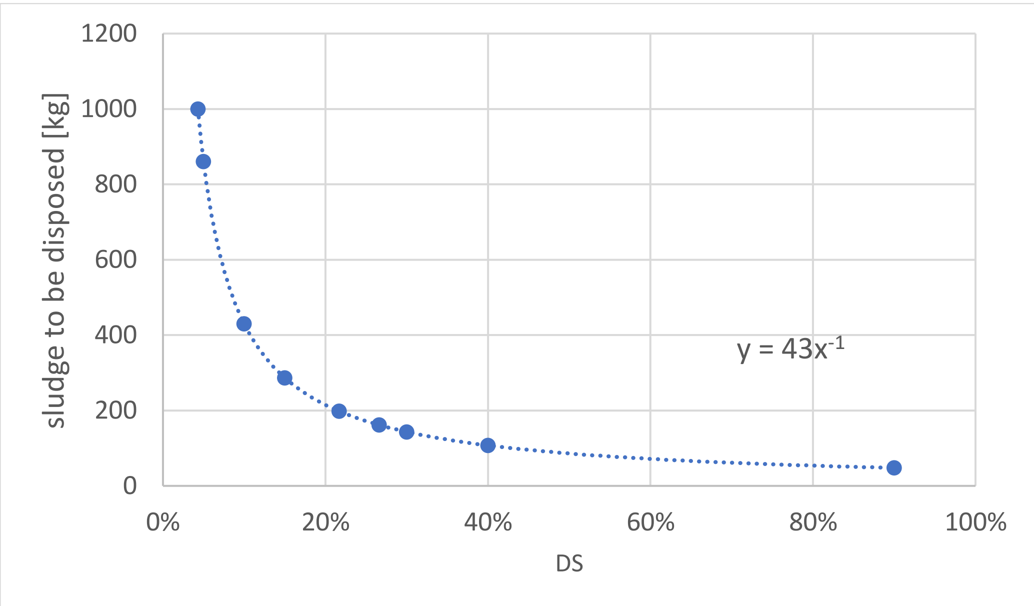

Figure 9 - Mass of sludge to be disposed as a function of DS improvement.

When the EDW section is switched on, the DS is increased from 21.7% to 26.6%.
Hence, the sludge volume reduction (i.e. mass reduction) is

$$198.2 \text{ kg} - 161.7 \text{ kg} = 36.5 \text{ kg}$$

In terms of percentage, it corresponds to 18% reduction.
To remove this amount of water, the energy input to the EDW section will be

$$36.5 \text{ kg} \times 13.9 \frac{\text{Wh}}{\text{kg}} = 507.35 \text{ Wh}$$

Because the targeting outlet DS is 25%, the incineration route is out of question. Alternatively, we focus on the land spreading route.
For a quick calculation, we only look at those life cycle stages having influence on the trade-off relationship: dewatering (additional energy input, incremental impacts), transport and tractor application (decremental impacts due to sludge volume reduction). The assessment was carried out using the same methods as discussed in the previous LCA study (ICLD midpoints impact categories).
The LCIA results are summarised in Table 5. To ease the comparison, the incremental impacts are listed against with the decremental ones. It can be seen that the impacts of the two groups are in the same magnitude and the decremental values are greater than the incremental ones except for the impact of freshwater EP. This implies that when the EDW section is switched on, the system's overall impacts will be lowered. Particularly, the reduction effect is more remarkable in the impact category of POF.

Table 5 - LCIA results of the influential life cycle stages.

Impact category	Unit	EDW energy consumption (incremental)	Transport and tractor application (decremental)
GW (IPCC 100a)	kg CO_2-eq	2.76E-01	6.20E-01
AC	molc H^+-eq	1.39E-03	2.68E-03
POF	kg NMVOC-eq	5.57E-04	2.45E-03
Terrestrial EP	molc N-eq	1.83E-03	8.08E-03
Freshwater EP	kg P-eq	6.80E-05	4.92E-05
Marine EP	kg N-eq	1.76E-04	7.42E-04

3.2 Economic assessment

For the economic assessment, the same performance indicator incremental ROI was used. Data derived from the preliminary test with the prototype EDW machine were used as input (see Table 4).
A sensitivity analysis was introduced by considering the following cases:

- **Prototype**: The Italian electricity price and the upper limit of the EDW machine investment cost 19059.67 € were used.
- **EU average**: The Italian electricity price was replaced with the EU average electricity price, 0.114 €/kWh. The EDW machine investment cost was at 19059.67 €.
- **Reduced investment cost**: It was assumed that after launching the machine, the market demand is strong, the production flow is enhanced, and consequently the EDW machine investment cost can be reduced to 15000 €.

The Incremental ROI of using EDW machine as a function of disposal cost is illustrated in Figure 10. The break-even values for achieving the average ROI of water sector 15.10% are 45.7, 50.5, and 51.3 €/wet tonne, which correspond to the cases of "reduced investment cost", "EU average" and "prototype", respectively. These values overlap with the current Italian market disposal cost, 47-57 €/wet tonne for the land spreading route. This means that a good profitability cannot always be guaranteed. To improve the situation, it is beneficial to increase the outlet DS. For example, when the outlet DS is lifted to 40%, the break-even cost can be

lowered to 35.0 €/wet tonne (see Figure 8). As pointed out in Deliverable D4.2a, the 2nd version of prototype machine will be extended in length to allow for a longer EDW treatment time.
Besides, it can be found that the slope of "reduced investment cost" is greater than that of "EU average". This implies that reducing the machine investment cost will enable more dramatic change to the incremental ROI than lowering the electricity price.

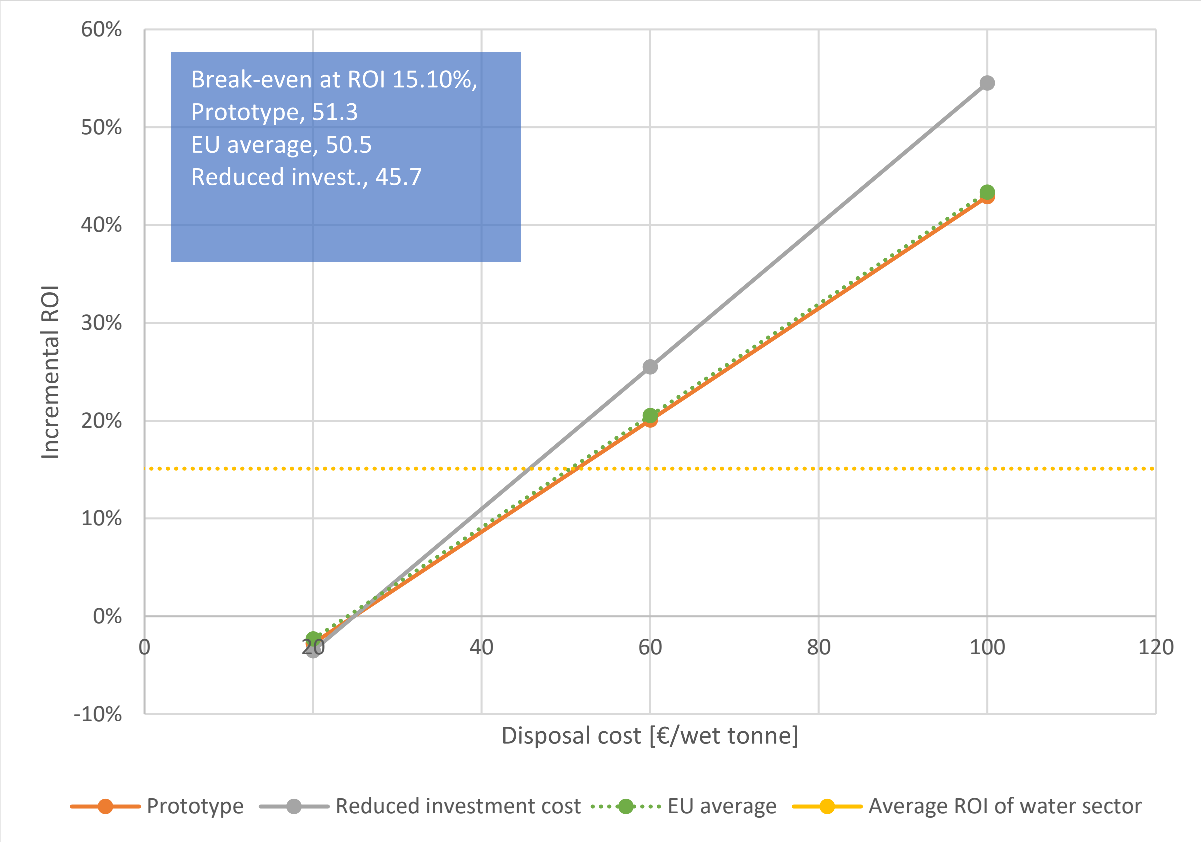

Figure 10 - Incremental Return On Investment (ROI) as a function of sludge disposal cost at 20, 60, 100 €/wet tonne. The break-even values with the average ROI of waster sector (15.10%) are indicated in the annotation box.

3.3 Summary

The results indicate that the prototype EDW machine enables to improve the WWTP's environmental profile, reducing most of the impacts except the freshwater EP. However, it cannot guarantee a good profitability for all the WWTPs that implement the EDW machine, as it requires the market disposal cost to be above 51.3 €/wet tonne. Therefore, for the 2nd version of prototype machine, it is advised to extend the machine length to reach a greater outlet DS.
Also, the data quality should be improved for future assessment. As seen from the test results reported in Deliverable D4.2a, large variations exist. It is therefore advised to optimise the machine operating parameters and conduct test under continuous working mode. And then extract data and update them in the LCA model and profitability model.

4 Conclusions

This deliverable involves two studies. The first study, case study of WWTP, represents the ideal situation where the EDW machine is implemented. While the second study, it focuses on the actual prototype EDW machine.

Regarding the incineration route in the first study, the GW impact results indicate that it is advantageous to implement the EDW upgrade (i.e. moving from C1 to C2). 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. So, the net effect is that the 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 other indicators, e.g. POF, terrestrial and marine EP. The economic analysis shows that under current Italian market situation, the EDW upgrade will generate very attractive ROI (>15.10%) for small-medium-sized WWTPs regardless of disposal routes.

In the second study, the assessment provides guidelines for improving the machine's design from the perspective of environmental and economic performance. The outlet DS 26.6% enables to reduce most of the environmental impact indicators except the freshwater EP. However, with such outlet DS, the economic profitability cannot always be guaranteed. Therefore, for the next version of machine design, it is advised to extend the machine length to allow for a longer EDW treatment time and hence increase the outlet DS of sludge.

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