Method for technical, economic and environmental assessment of advanced sludge processing routes

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ABSTRACT

The legislative framework in force in Europe entails restrictive effluent standards for sensitive areas, and quite severe restrictions on the properties of residual sewage sludge, both for landfill disposal and for agricultural use. Several technologies and management strategies have been proposed and applied in wastewater treatment plants to minimise sludge production and contamination. However, their techno-economic and environmental performance has to be carefully evaluated. The ROUTES project, funded within the EU Seventh Framework programme, aims to find new routes for wastewater treatment and sludge management and thereby guide EU members in their future choices. Within this project, the authors have developed and applied a procedure for techno-economic-environmental assessment of new wastewater and sludge processing lines in comparison to reference plants. The reference plants are model conventional plants that experience different types of problems and the new plants are modified plants in which different innovative technologies have been added to solve these problems. The procedure involves a rating of selected technical issues, estimates of operating costs and an assessment of environmental impacts from a life cycle perspective. This paper reports on the procedure and shows examples of results.

Key words | comparison, cost calculations, life cycle assessment, sludge management, wastewater treatment

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INTRODUCTION

Centralised collection and treatment of wastewater were introduced to avoid odour problems, spreading of diseases and eutrophication. Since then, the management of wastewater treatment plants (WWTPs) and resulting sludges has been under constant development and debate. In particular, the spreading of sludge in agriculture has received widespread public attention due to perceived risks related to the content of pathogens, heavy metals and organic micropollutants (Bengtsson & Tillman 2004; Wang *et al.* 2005). Today, optimal management should minimise costs and risks related to processes, effluent and sludges and maximise value from recoverable resources. This requires that the technical, economic and environmental performance of existing and proposed solutions is assessed, and that new technical developments address current and upcoming concerns.

The EU ROUTES project – 'Novel processing routes for effective sewage sludge management' (www.eu-routes.org; see Braguglia *et al.* (2012) for a project description) – has engaged in process development in wastewater and sludge treatment in order to make it possible to improve the situation in Europe. The technologies that have been assessed and further developed in the project target different common problems in existing wastewater and sludge management, and each has one or several of the following purposes: to minimise sludge production in the waterline; to maximise sludge stability; or to recover resources. Alongside the process development performed in some work packages, techno-economic-environmental assessment has been performed. Model reference WWTPs, set up to represent plants experiencing different and common problems, have been described, and new plants with different technical

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or design solutions have been developed and compared to the reference WWTPs. Techno-economic-environmental assessment activities are performed in two stages in order to provide guidance on the performance and needs of further development in, or after, the project. This paper reports on the first stage of the techno-economic-environmental assessment activities, performed during the first 15 months of the project, and describes the methodology that was developed and applied. The subsequent second stage assessment is influenced by the experience of using the methodology and of assessment results and thus involves a modified assessment methodology applied to modified systems.

The techno-economic-environmental performance of wastewater and sludge management solutions has to consider the specific situation in which it is, or is planned to be, applied since many variables determine the suitability of a particular solution. Each situation has to be considered with its own site-specific technical and environmental preconditions, such as, for instance, sludge disposal costs, distance between the plant and the disposal/recovery site, wastewater characteristics, efficiency of treatment units and machinery, land availability, sensitivity of waters and characteristics of soil. Furthermore, government policies and stakeholder acceptance of particular solutions may depend on the location. Appropriate assumptions therefore strongly depend on the conditions and circumstances at the location of a specific treatment and disposal technology, and on specific political, social and economic situations, and results have to be interpreted based on the assumptions that were made. Although a relatively generic methodology is presented in this paper, any assessment of the kind presented should thus be conducted case by case using relevant data. Some examples of results are shown in this paper but only to illustrate what results may look like, and not to allow for a full understanding of the merits and demerits of the studied WWTP solutions.

METHODS

The methodology used for the assessment of technical, economic and environmental features was inspired by the systems engineering approach. Systems engineering is, according to the International Council on Systems Engineering (INCOSE 2004), 'an interdisciplinary approach and means to enable the realisation of successful systems'. Eisner (2011) points out the need to apply systems thinking, that is, to have a holistic view of development, operation and management of the system. Eisner (2008) also points out the importance of using an iterative assessment approach to be able to refine and converge different performance aspects of the studied system, especially when dealing with large complex systems.

The activities in the techno-economic-environmental assessment in the ROUTES project followed the work process outlined in Figure 1. Even if the process is described as consisting of a number of consecutive actions, in practice,

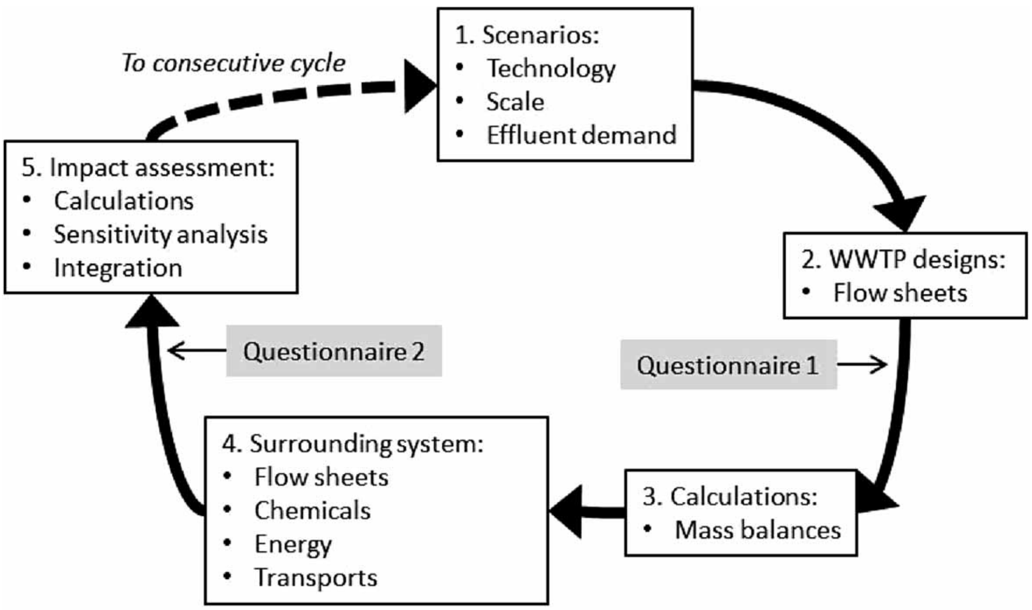

Figure 1 | Work process applied in the first stage of the techno-economic-environmental assessment activities in the ROUTES project.

the techno-economic-environmental assessment was performed using an iterative approach, involving several loops of definition and redefinition of systems, data collection and performance assessment.

Scenario definition

First, different scenarios were defined along with their boundary conditions. In each case, a model reference plant was defined, with different possibilities for the sludge end-of-life. A conventional activated sludge secondary treatment was included in all model reference plants, some after primary settling. Sludges underwent thickening, aerobic or anaerobic stabilization, and dewatering. For each reference plant, one or several new solutions were defined, addressing anticipated problems and with different possibilities for the sludge end-of-life. An overview of the studied cases is shown in Table 1.

The design of the processes of the WWTPs was conducted in such a way that effluent nitrogen (N) and phosphorus (P) concentrations comply with standards for discharge in either sensitive or non-sensitive areas, as defined in EU Directive 91/271/EEC. The effluent standards that were applied are reported in Table 2, along with generic influent characteristics.

Design of technologies and systems

Preliminary design of the treatment units included the development of flow sheets for mass balance calculations, a detailed quantitative characterisation of the water and sludge streams, data collection and calculation of mass balances. Processes located at the WWTP (the foreground system; the focus of technical development activities) were defined and designed in a first step; thereafter, the necessary details of the surrounding system (the background system) relating to transports, chemicals and products replaced by the generated products, were decided on.

Slightly different system boundaries were applied in the techno-economic and environmental assessments. In the techno-economic assessment, the consequence of changing the reference scenario into the new scenario was assessed. For the environmental assessment, this was not seen as sufficient since this assessment also aimed at a dominance analysis, that is, the total impact from each scenario was studied in order to reveal so-called hot spots (dominant activities) in the life cycle. This second approach reveals more details of the larger system that can be used to direct optimisation efforts to where it can have the most significant impact. The drawback, however, of this second approach, is the larger amount of data required and that some differences between scenarios that can be attributed to the specific technologies under study may appear to be insignificant when there are other parts in the life cycle that have a large contribution to the total results. The techno-economic assessment also studied a more narrow system (in terms of life cycle stages) than the environmental assessment, which was performed using a life cycle perspective.

Data collection

For the foreground system, data were generally obtained from research activities in the project or from plant monitoring, while for the background system, literature data were often deemed sufficient. Two different questionnaires were used to gather data from different subprojects within the ROUTES project. For some assessment parameters, generic data were seen as sufficient while for other parameters, data describing local conditions were preferred (as indicated for technical aspects in Table 3).

The new designs and technical solutions applied to these model plants are in different phases of technological development (ranging from laboratory scale to full scale) and therefore, in describing, designing and assessing these, different difficulties relating to, for example, availability, confidentiality and quality of data were experienced.

Impact assessment

For the technical evaluation, the assessment parameters listed in Table 3 were selected to be used. For each main aspect, several different subcategories were defined. Table 3 also indicates what type of data source was utilised in the assessment. Data collected were filled into worksheets that had been prepared for calculations and the results were then analysed. For each subcategory and for both reference WWTP and new solution(s), a score between 1 and 3 (3 being the best and 1 the worst) was attributed. For example, concerning power consumption, the reference plant was given a score of 2 and the score of the new solution was calculated based on the ratio between the power consumption of the new and the reference solution (3 being given when 50% energy saving was achieved and 1 when an increase of power consumption of 50% was declared). The mean value for each aspect was then calculated (final score). Eventually, the mean difference (gap) between the final scores of the new and reference plants was calculated, attributing equal weights to all technical aspects.

Table 1 | Case studies assessed in the first stage of the techno-economic-environmental assessment within the ROUTES project

Case study	Plant capacity (p.e.)[a]	Effluent standard	Primary sedimentation	P removal[b]	Anticipated problems of reference WWTP	Proposed solution in new WWTP design	Sludge end-of-life; reference/new[c]
1.1-1	15,000	Non-sensitive	NO	NO	Aerobically stabilized sludge not suitable for agricultural use because of industrial contamination. Need for decrease of sludge volume.	Sequential batch biofilm granular reactor (SBBGR)	L/L
1.1-2							I/I
1.2-1	15,000	Non-sensitive	YES	NO		Membrane bioreactor (MBR) + side-stream ozonation	L/L
1.2-2							I/I
2.1-1	70,000	Non-sensitive	YES	NO	Overloaded anaerobic digester resulting in poor stabilization and large amount of sludge not suitable for agricultural use. Need for improved sludge quality.	Post aerobic stabilisation	L/A
2.1-2							I/A
2.2-1	30,000	Sensitive	NO	YES	Aerobically stabilized sludge not suitable for agricultural use due to industrial contamination. Need for decrease of sludge volume.	Biological treatment with oxic-anoxic cycles	L/L
2.2-2							I/I
2.3-1	70,000	Sensitive	YES	YES	High N recycle after anaerobic digestion. Need for nitrogen removal; opportunity for N recovery.	Ammonia stripping	L/L
2.3-2							I/I
2.3-3							A/A
2.4-1	70,000	Non-sensitive	NO	NO	WWTP without sludge line. Need to transport sludge in a more efficient way.	Sludge pumping replacing truck transport to centralised treatment plant	L/L
2.4-2							I/I
2.4-3							A/A
3.1-1	500,000	Non-sensitive	YES	NO	Production of anaerobically digested sludge that is not sufficiently hygienized. Need for decrease of sludge volume; opportunity for resource recovery if biodegradability can be increased.	WO + anaerobic digestion of liquid side-stream	L/L
3.1-2							I/L
3.2.1-1	500,000	Sensitive	YES	YES	High production of anaerobically digested sludge that is not well stabilized and not suitable for agricultural use due to industrial contamination. Need for improved sludge quality.	Sludge separation; primary sludge: WO, secondary sludge: Sonolysis + anaerobic mesophilic and thermophilic digestion	L/L (solid WO residue) and A (secondary sludge)
3.2.1-2							I/L (solid WO residue) and A (secondary sludge)

(*continued*)

Table 1 | continued

Case study	Plant capacity (p.e.)[a]	Effluent standard	Primary sedimentation	P removal[b]	Anticipated problems of reference WWTP	Proposed solution in new WWTP design	Sludge end-of-life; reference/new[c]
3.2.2-1						Ultrasound + anaerobic mesophilic and thermophilic digestion	L/L (solid WO residue) and A (secondary sludge)
3.2.2-2							I/L (solid WO residue) and A (secondary sludge)
3.2.3-1						Thermal hydrolysis + anaerobic thermophilic digestion	L/L (solid WO residue) and A (secondary sludge)
3.2.3-2							I/L (solid WO residue) and A (secondary sludge)
3.2.4-1						Ozonation + anaerobic mesophilic digestion + aerobic post-treatment	L/L (solid WO residue) and A (secondary sludge)
3.2.4-2							I/L (solid WO residue) and A (secondary sludge)
3.3-1	500,000	Sensitive	NO	YES	High production of anaerobically digested sludge not suitable for agricultural use due to poor biological stability. Need to improve sludge quality.	Mechanical disintegration by hydrodynamic cavitation	L/A
3.3-2							I/A
3.4-1	500,000	Sensitive	NO	YES	Under-loaded anaerobic digester and high sludge contamination, which makes it unsuitable for agricultural use. Need to utilise spare capacity of digester.	Co-digestion with organic fraction of municipal solid waste	L/L
3.4-2							I/I

[a]Person equivalents; 1 p.e. = 273 litres per day with characteristics as specified in Table 2.
[b]Chemical phosphorus removal by simultaneous precipitation.
[c]L = landfill; I = incineration; A = agricultural use.

Table 2 | Influent and effluent characteristics used in the design of wastewater treatment systems

	Influent[a]	Effluent; non-sensitive recipient		Effluent; sensitive recipient	
		Limit[b]	Design	Limit[b]	Design
COD	500	125	50	125	50
BOD_5	220	25	–	25	–
N_{tot}	40	–	18	15 or 10[c]	10
P_{tot}	5.5	–	–	2 or 1[c]	1
TSS	220	35	20	35	14

Concentrations are given as mg/litre.
[a]Metcalf & Eddy Inc. *et al.* (2004).
[b]EU Directive 91/271/EEC.
[c]Depending on the size of the WWTP; less than or more than 100,000 p.e.

For the economic assessment, the following input parameters were selected for use:

- Cost of personnel.
- Cost of electric energy.
- Cost of raw materials and reagents.
- Cost for reuse or disposal of solid/slurry residues.
- Cost of transportation.
- Ordinary maintenance cost.
- Income from recovered materials.
- Income from electric energy sale.
- Income from thermal energy sale.
- Income from treatment of organic fraction of municipal solid waste.

Table 3 | Technical aspects considered in the technical assessment, along with the type of data used

Main aspect and subcategories		Data source[a]
Reliability of the technology	Reliability of the technology (e.g. in relation to variability of wastewater or sludge characteristics)	L, R
	Number of full-scale applications in the EU	L
Complexity and integration with existing facilities	Requires intervention for integration with existing structures (e.g. hydraulic and electrical connections)	L
	Footprint; all equipment included	L
	Daily work hours for ordinary operation (*Technicians with tertiary education, Specialised workers, and Workers)*	L, R
	Safety standards to be observed	L
Flexibility/Modularity	Possibility of modular implementation (e.g. in case the size has to be progressively increased)	L, R
Residues/Recovered materials	Solid/slurry	R
	Liquid	R
	Gaseous	R
Consumption of raw materials and reagents	Fresh water	R
	Polyelectrolyte	R
	Coagulants	R
	Substrate for denitrification	R
	Pure oxygen	R
	Methane	R
	Other	R
Consumption of electric energy	Quantity	R
Net production of thermal energy	Type of heat vector (e.g. water, steam, oil)	R
	Quantity	R
	Temperature of heat vector	R
Net production of electric energy	Quantity	R
Social and authorisation aspects	Public acceptance	L
	Complexity of authorisation procedures	L

Note that only differences between the reference WWTP and suggested new solution were considered in the data collection.
[a]L = the aspect is site-specific and data therefore reflect local conditions; R = data obtained from research activities or plant monitoring.

All items are site-specific and data that reflected local conditions were therefore gathered as far as possible. Capital cost was ignored due to the risk for the difference between the uncertainty range of well-developed technologies and relatively new technologies to bias the results. The economic comparison was carried out by calculating the difference in operating cost between the new and the reference solution. For the economic assessment, a sensitivity analysis was performed to reveal critical factors. This was done by calculating variations in the final result due to variations of ±10% of the cost items, one by one. For more details on the techno-economic assessment, see Bertanza *et al.* (2012).

The environmental assessment was performed as a life cycle assessment (LCA), as far as possible following international standards ISO 14040:2006, ISO 14044:2006 and the International Life Cycle Data Systems (ILCD) Handbook (European Commission Joint Research Centre 2010). Parameters were selected based on how commonly they are applied in similar LCAs in the literature (e.g. Tarantini *et al.* (2007), Johansson *et al.* (2008), Peters & Rowley (2009)) and based on anticipated data availability:

- Global warming potential (reflecting concerns related to climate change).
- Acidification potential (reflecting issues related to acid rain).
- Eutrophication potential (reflecting impacts of excessive nutrient addition to soil and receiving waters).
- Ozone depletion potential (reflecting the impact on stratospheric ozone; this parameter will, however, not be discussed any further in this paper because the analysis did not provide meaningful results).
- Photochemical ozone creation potential (reflecting the issue of smog formation in urban air).

The listed parameters were evaluated from a life cycle perspective; the environmental impacts from wastewater and sludge treatment as well as the sludge end-of-life, and the production of input materials such as electricity, heat and chemicals and sludge transports were included in the studied system. However, production capital was not included in the first stage LCA as the environmental impacts of the assessed kind are typically small for this part of the system (Corominas *et al.* 2013). Average European conditions were assumed for generic activities such as electricity and transport. In cases where a marketable by-product was generated, a system expansion approach was applied, giving the studied system benefits for the by-products by accounting for avoided production of a similar conventional product. Weighting in order to generate a single-point indicator for environmental impacts was not applied. The Gabi software (from PE International) was used to model the systems and the CML2001 (2010 edition) system was used in the impact assessment.

After data entry and impact assessment, a dominance analysis was made, identifying the environmental hot spots for the studied scenarios and important input parameters to be varied in the sensitivity analysis (see the results presentation below for more details).

RESULTS AND DISCUSSION

Some results are shown in this paper mainly to illustrate the methodology and provide understanding of what types of results can be achieved. It is not the intention to provide a complete and transparent description of the technologies and their performance.

Table 4 summarises results for technical, economic and environmental aspects, derived using the assessment procedure as described in the previous section. A clearly positive outcome (at least 10% improvement) for the new solution has been indicated by grey shaded cells, as an example of how the outcome can be visualised. In general, all of the proposed solutions seem to be suitable for practical application although there are different challenges involved for most of the technologies.

As far as technical aspects are concerned, when the gap is positive, the new solution is preferable to the reference design. For each technical aspect, the maximum attainable gap is +/ − 2. Differences are typically relatively small, ranging from −0.22 to 0.34.

With regard to economic aspects, a positive gap means that an additional cost must be paid when the new solution is applied to an existing WWTP; remember that costs for reconstruction are excluded. The sensitivity analysis revealed the parameters whose variability significantly affects the global result for each studied solution (see Table 4). The most important cost items overall are: sludge disposal, raw materials and reagents, and electric energy. When comparing different strategies within a specific context, a careful evaluation of these parameters should therefore be mandatory, so as to obtain relevant results.

Environmental LCA results are shown in Table 4 for four of the assessed environmental impacts. A positive (+), negative (−), almost equal (difference is less than 10%; ≈) or practically identical (=) performance of the new solution compared to the reference plant is indicated. More detailed

Table 4 | Summary of results from the first techno-economic-environmental assessment within the ROUTES project. When the assessment results indicate that the new solution leads to an improvement of more than 10%, this has been indicated by grey shaded cells

Case study	Technical assessment Technical score (gap)	Economic assessment Cost (gap) €/[p.e. × y]	Economic results sensitive to:	Environmental assessment GWP	AP	EP	POCP	Environmental hot spots and comments
1.1-1	0.29	4.14	Cost of electric energy and for reuse/disposal of residues	–	–	≈	–	Electricity use is a hot spot in the new scenario
1.1-2	0.28	4.14		–	–	≈	–	
1.2-1	−0.22	9.18	Cost of electric energy and maintenance	–	–	–	–	Electricity use is a hot spot in the new scenario
1.2-2	−0.22	9.18		–	–	–	–	
2.1-1	0.23	−5.40	Cost for reuse/disposal of residues and maintenance	+	+	–	+	Lower energy use for new scenario is important for result
2.1-2	−0.06	−5.40		+	+	–	+	
2.2-1	0.09	−1.44	Cost of electric energy and for reuse/disposal of residues	+	+	≈	+	Lower energy use for new scenario is important for result
2.2-2	0.04	−1.44		+	+	≈	+	
2.3-1	0.01	4.01	Cost of raw materials and reagents and income of recovered materials	+	–	≈	–	Sulphuric acid use is a hot spot in the new scenario
2.3-2	−0.21	4.01		+	–	≈	–	
2.3-3	−0.21	4.01		+	–	≈	–	
2.4-1	−0.22	5.29	Cost of electric energy and transportation	–	–	≈	–	Electricity use is a hot spot in the new scenario
2.4-2	−0.22	5.29		–	–	≈	–	
2.4-3	−0.22	5.29		–	–	≈	–	
3.1-1	0.16	−0.89	Cost of raw materials and reagents and for reuse/disposal of residues and income of recovered materials	+	–	–	+	
3.1-2	−0.02	−0.89		≈	+	–	+	
3.2.1-1	0.32	−0.92	Cost of raw materials and reagents and for reuse/disposal of residues	+	–	≈	+	More impact categories need to be assessed
3.2.1-2	0.17	−0.92		≈	+	≈	+	
3.2.2-1	0.30	−0.39	Cost of raw materials and reagents and for reuse/disposal of residues	+	–	≈	+	More impact categories need to be assessed
3.2.2-2	0.16	−0.39		≈	+	≈	+	
3.2.3-1	0.34	−0.40	Cost of raw materials and reagents and for reuse/disposal of residues	+	≈	≈	+	More impact categories need to be assessed
3.2.3-2	0.19	−0.40		+	+	≈	+	
3.2.4-1	0.30	−2.39	Cost of raw materials and reagents and for reuse/disposal of residues	+	+	≈	+	More impact categories need to be assessed
3.2.4-2	0.14	−2.39		≈	+	≈	+	
3.3-1	−0.01	−0.05	Cost of raw materials and reagents and for reuse/disposal of residues	+	=	≈	+	More impact categories need to be assessed
3.3-2	−0.15	−0.05		+	+	≈	+	
3.4-1	– 0.14	– 10.82	Income from electric energy and from treatment of organic fraction of MSW	≈	+	≈	–	The assumption that electricity and heat can be sold is important for the result
3.4-2	– 0.15	– 10.82		+	+	≈	+	

For environmental impacts, a positive (+), negative (–), almost equal (less than 10% difference; ≈) or practically identical (=) performance of the new solution compared to the reference plant is indicated. GWP denotes global warming potential, AP acidification potential, EP eutrophication potential and POCP photochemical oxidant creation potential.

results can be found in Heimersson *et al*. (2013). In the environmental sensitivity analysis, electricity consumption, means of electricity generation and level of leakage of nitrate from agricultural fields were all shown to have a large impact for many studied systems. However, transport distances of dewatered sludge affect results only to a small extent. The eutrophication potential is strongly dependent on emissions to water from the effluent of the WWTP. As P in the effluent is one of the design parameters for the scenarios in sensitive areas, the difference between the new and the reference scenario is typically small – this is thus a result of how the design was made and not an inherent property of the new technology.

There is typically a strong correlation between economic and environmental outcomes. A major reason is the strong correlation between these impacts and electricity use.

For the two technologies that aim at solving problems related to high sludge production volumes for small scale WWTPs, both studied technologies – SBBGR (1.1) and MBR (1.2) – experience challenges related to the electricity use of the new processes. For neither the economic nor the environmental performance is the impact from the higher electricity use off-set by gains from having to landfill or incinerate less sludge. Another technology that appears to be less attractive in the first stage assessment is the pumping of sludge to a centralised treatment plant instead of using lorry transportation (2.4). Also in this case, the impact from higher electricity use exceeds the gain from the avoided transportation. However, new progress within the project made after this initial preliminary assessment indicates higher efficiencies than was assumed and these technologies may therefore perform better in the second stage assessment.

The first stage assessment indicates that biological treatment with oxic-anoxic cycles (2.2) provides an improvement compared to the reference WWTP. Recirculation is decreased along with use of energy, chemicals and sludge amounts, resulting in lower costs and lower environmental impacts. In this case, the gains from introduction of the new technology are larger than the losses.

Some solutions – post aerobic stabilisation (2.1), separate treatment of primary and secondary sludge (3.2) and mechanical disintegration by hydrodynamic cavitation (3.3) – are implemented with the idea that the generated sludge will become suitable for use in agriculture. The assessment shows an overall positive turnout for these solutions. However, the assessment does not yet include some potentially important aspects, such as negative impacts from heavy metals or organic micro-pollutants that end up in soil, or positive impacts such as build-up of organic material and carbon in the soil. An effort will therefore be made to include some of these impacts in the second stage LCA, to provide a more holistic understanding of all important environmental impacts.

Since this assessment has been made of technologies that are under development, the availability of relevant data has in some cases been low. This affects the usefulness of the results, which is a dilemma since the results are aimed at being used in technology development. The first assessment clearly points to some hot spots to focus on in further technical development efforts and also to changes that can be made to the WWTP designs. The lessons learned from the techno-economic-environmental assessment feed into the second phase assessment in the ROUTES project. The new assessment will dig deeper into the problem areas identified in the first stage assessment. Modified designs that address the identified hotspots are being made and the assessment methodology itself is being modified. For example, a risk of double-counting between technical, economic and environmental aspects has been identified and this will be addressed mainly by a clearer focus on aspects that have an actual technical impact (for those who operate the plant) in the technical assessment.

The second stage assessment is not only aimed at being used internally within the project but also aims at providing useful input to decision-making in Europe on different levels. Therefore, an effort will be made to cover the areas that many stakeholders see as important in decision-making around wastewater treatment and sludge management, and to interpret assessment results in light of the differing priorities of different stakeholders. A stakeholder questionnaire has already been directed towards project partners and members of the board of end-users to provide input to these considerations.

In these types of assessments, it is in principle possible to use weighting factors in order to arrive at one single number based on which the different plant designs can be compared. However, because of the subjectivity of such a procedure, it has to be made with caution, preferably testing the outcome of applying values of different stakeholder groups as an input to a more comprehensive understanding of the results (Rowley *et al*. 2012). This could be made in the second stage assessment.

The applied methodology for techno-economic-environmental assessment has proven to be useful, although some parts have required a large work effort because of the early stage of technology development for some studied technologies.

CONCLUSIONS

A methodology for technical-economic-environmental assessment, influenced by a systems engineering approach and to be used in comparisons between WWTPs, has been developed and successfully applied. In general, none of the proposed solutions can be discarded based on the results so far; however, some technologies have been shown to have particular challenges that need to be solved if they are to be interesting for implementation. Many aspects should be evaluated based on site-specific circumstances and constraints. In a second stage assessment, both the methodology and the assessed systems are modified based on the experiences and results from the first stage assessment. The new methodology will consider, for example, the risk of double-counting between the different areas assessed and the need for inclusion of more environmental aspects for a more complete understanding of environmental impacts.

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