"MFC4Sludge": Microbial fuel cell technologies for combined wastewater sludge treatment and energy production

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4	Fraunhofer-Institute for Interfacial Engineering and Biotechnology IGB	FRAUNHOFER	Germany	RTD
5	Acondicionamiento Tarrasense Associacion	LEITAT	Spain	RTD
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Abstract

This document provides information about the technical, economic and environmental analysis and assessment that have been carried out as additional step that will help bring the MFC4Sludge solution closer to the market.

By conducting a technical analysis main recommendations for further deployment and potential scale-up have been provided. Moreover, different strategies have been proposed in order to increase system performance, allowing this way a cost-effective operation not only in terms of resources but also in economic terms. This recommendations are supposed to be the basis of work for a proposal to design and deploy a full pilot scale commercial plant, which is currently under consideration by the partners within the consortium.

Economic analysis becomes crucial when launching new products to the market since it provide the foundations for further decisions about the design, deployment, access to funding or investments, time and financial planning, etc. The performed financial analysis shows the profitability of the proposed approach considering the typical time horizon for waste management projects (30 years), while it suggests the high sensitivity of the expected incomes to some variables, like the power produced by the microbial fuel cell, the materials used for the cell construction or the final sludge management scenario.

Finally, environmental studies are an important step when assessing the sustainability of a project or a new technical concept. In order to evaluate all the potential impacts that could occur due to the prototype installation and operation, a Life Cycle Assessment has been selected as the best approach for this purpose. As for obtaining consistent information that will allow making decisions and to provide sound information, the MFC4Sludge solution has been compared with two current approaches in sludge management: anaerobic digestion and landfilling. Furthermore, a sensitivity study has been conducted in order to determine the influence of different issues such as materials, energy consumption, etc. in the MFC related environmental impact. All the figures obtained and conclusions drafted provide positive information about the use of the prototype in comparison with current approaches and have allowed to identify the path for future improvement of the MFC so as to decrease its environmental impact.

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1. Introduction

MFC4Sludge project is an effort to find new approaches to valorise wastewater sludge, while reducing its environmental impact. For the last 24 months, a consortium of SMEs and RTDs has worked together to develop a 10L MFC based prototype able to produce electricity and decrease the environmental impact of wastewater sludge handling.

Wastewater sludge (also called sewage sludge or "sludge" hereinafter) is the main by-product of the most-widely employed biological treatment of wastewater with activated sludge. In such a technology, microorganisms metabolise the organic waste and produce the aforementioned sludge as a result. Its production varies between 10 and 30 kg per capita in most European countries being Germany, Spain and Poland the major producing countries with 2.048.500, 1.065.000 and 501.300 tonnes by 2006 and a total production for the EU of around 9.000.000 tons dry solids per year in 2010. The disposing of this sludge easily reach up to 60% of the total operation cost of a treatment plant and consume vast quantities of energy.

In view of the above, it is clear that new strategies for this kind of waste must be addressed. MFC4Sludge proposes a scheme in which waste is partially anaerobically digested to maximise Volatile Fatty Acids (VFA) production. These VFA are the main component to be used by the Microbial Fuel Cell (MFC) in order to produce electricity.

Best conditions and procedures for the anaerobic digestion (AD) were studied in Work Package 1 (WP1); the design and performance maximisation of the MFC was treated in WP2, while WP3 was devoted to development of mathematical models and advanced control solutions. During WP4, the integration of both technologies, partial AD and MFC has been carried out at lab scale. Finally, the prototype has been designed, constructed, deployed and integrated at a real wastewater treatment plant owned by GURAK, end-user and project partner of the project. A battery of tests, which results are presented in corresponding deliverables of the WP5, has been carried out so as to further study the performance of the technologies studied during the project. Along the project lifespan, various dissemination actions have been carried out, including the realization of an explicative video clip for the project. WP6 is fully devoted to dissemination.

Obviously, results dissemination has to be preceded of a set of rational analysis. This document contains techno-financial and environmental studies based on lessons learned from the performance of the prototype and that try to depict the theoretical scenario for introducing in the market the proposed sludge valorisation solution. It also gives a series of design, operation and economic recommendations to ensure the profitability of an up-scaled MFC4Sludge plant.

Through the consecutive stages of the project, from conception to testing, including design and implementation, some technological challenges arose. To surpass these problems, a set of devices, methods and operating protocols had to be included to achieve proposed objectives. A description of all these technological requirements is presented in chapter 3 of this document. Also, some potential sources of inefficiency were identified along with other generic advices regarding the eventual upscale of the plant. Such recommendations for industrial users are documented in chapter 3 as well.

Investment decisions are at the core of any development strategy. Economic growth and welfare depends on productive capital, infrastructure, human capital, knowledge, total factor productivity and the quality of institutions. All of these development ingredients imply - to some extent - taking the hard decision to sink economic resources now, in the hope of future benefits, betting on the distant and uncertain future horizon.

Every time an investment decision has to be taken, one form or another of weighting costs against benefits is involved, and some form of calculation over time is needed to compare the former with the latter when they accrue in different years. Private companies and the public sector at national, regional or local level make these calculations every day. Gradually, a consensus has emerged about the basic principles of how to compare costs and benefits for investment appraisal. Chapter 4 of this document presents a complete financial analysis, based on the discounted cash flow methodology.

From a formal point of view, environmental studies are usually carried out in the form of Environmental Impact Assessment (EIA) or Environmental Assessment (EA). EIA or EA is a systematic process that examines the potential environmental consequences of development actions. The establishment of formal EIA procedures became mandatory in all EU Member States in 1988 after the implementation of Directive 85/337/EEC (CEC, 1985). This was later amended by several directives until today. Currently, Environmental assessment can be undertaken for individual projects, such as a dam, motorway, airport or factory, on the basis of Directive 2011/92/EU (known as 'Environmental Impact Assessment' – EIA Directive) or for public plans or programmes on the basis of Directive 2001/42/EC (known as 'Strategic Environmental Assessment' – SEA Directive). For planning purposes, there are additional tools such as strategic environmental assessment (SEA), life cycle assessment (LCA), positional analysis (PA), cost–benefit analysis (CBA), material intensity per unit service analysis(MIPS), total material requirement analysis (TMR),ecological footprint (EF), exergy analysis, emergy analysis and risk assessment. A major goal of these studies is to present the consequences of designers' choices during the design phase, hence these tools will be studied in order to decide which one fits better this project needs concerning environmental studies.

The use of these tools and procedures aims to provide a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation of projects, plans and programmes with a view to reduce their environmental impact. They ensure public participation in decision-making and thereby strengthen the quality of decisions. Hence they become crucial tools for sustainable development.

2. Overview and General approach

2.1. Technical analysis

Every requirement needed to ensure proper operation of the prototype is defined in the technical analysis. Toward that, electrical consumptions for each auxiliary equipment were measured. Also, a group of procedures has been established to standardize the feeding of the anaerobic digester and its temperature and pH control; and the start-up, inspection and shut-down procedures for the prototype, especially the MFC subsystem.

The second part of the technical analysis contains a set of actions that must be developed with a view to improve the pilot plant so as to make the process more reliable and sustainable. Basically, each action can be classified within one of the following three strategic lines:

- Reduce energetic consumption needed for the MFC4Sludge process to operate.
- Minimise the cost allocated to treated sludge management.
- Improve the design and operating protocols of digestion subunit and MFC subunit to increase its individual efficiencies.

2.2. Economic analysis

The main purpose of the financial analysis is to use the project cash flow forecasts to calculate suitable net return indicators. In this document a particular emphasis is placed on two financial indicators: the Financial Net Present Value (FNPV) and the Financial Internal Rate of Return (FRR), respectively in terms of return on the investment cost, FNPV(C) and FRR(C).

The methodology used here for the determination of the financial return is the Discounted Cash Flow (DCF) approach. This implies some assumptions:

- Only cash inflows and outflows are considered (depreciation, reserves and other accounting items which do not correspond to actual flows are disregarded).
- The determination of the project cash flows should be based on the incremental approach, i.e. on the basis of the differences in the costs and benefits between the scenario with the project (do-something alternative) and the counterfactual scenario without the project (BAU scenario).
- The aggregation of cash flows occurring during different years requires the adoption of an appropriate financial discount rate in order to calculate the present value of the future cash flows.

2.2.1. Time Horizon

The first logical step in the financial analysis is the estimation of how large the total investment cost will be. The investment outlays can be planned for several initial years and some non-routine maintenance or replacement costs in more distant years. Thus a time horizon must be defined.

Time horizon means the maximum number of years for which forecasts are provided. Forecasts regarding the future of the project should be formulated for a period appropriate to its economically useful life and long enough to encompass its likely mid-to-long term impact.

Although the investment horizon is often indefinite, in project analysis it is convenient to assume reaching a point in the future when all the assets and all the liabilities are virtually liquidated simultaneously. Conceptually, it is at that point that one can cost up the accounts and verify whether the investment was a success. This procedure entails choosing a particular time horizon. The choice of time horizon may have an extremely important effect on the results of the appraisal process.

Reference time horizon recommended for the sector of Wastes and environment is 30 years. However, calculations have been extended also to 10 and 15 years-time horizons.

2.2.2. Investment Costs

Having set the horizon, the investment costs are classified by:

- Fixed investments.
- Start-up costs.
- The changes in working capital over the entire time horizon.

Fixed investments are often, but not always, the largest component of total investment costs. The information relating to fixed investments will be taken from the feasibility study data on localisation and technology. The data to consider are the incremental cash disbursements encountered in the single accounting periods to acquire the various types of fixed assets: land, buildings, machinery, etc.

The residual value of the fixed investment must be included within the fixed investment costs account for the end-year with opposite sign (negative if the others are positive), because it is considered as an inflow.

According to a standard definition, all those costs that are incurred in view of the effects that will accrue beyond the financial period in which the relative disbursements were made are of an investment nature. Although the tax rules do not always allow for the capitalization of these costs, they should be included in the total investment costs. These include several start-up costs, such as: preparatory studies (including the feasibility study itself), costs incurred in the implementation phase, contracts for the use of some consulting services, training expenses, research and development, issue of shares and so on.

2.2.3. Operating Costs

The second step in financial analysis is the calculation of the total operating costs and revenues (if any). The operating costs comprise all the data on the disbursements foreseen for the purchase of goods and services, which are not of an investment nature since they are consumed within each accounting period.

The data can be organised in a table that includes:

- The direct production costs (consumption of materials and services, personnel, maintenance, general production costs).
- Administrative and general expenditures.
- Sales and distribution expenditures.

These components together comprise the bulk of the operating costs.

In the calculation of operating costs, all items that do not give rise to an effective monetary expenditure must be excluded, even if they are items normally included in company accounting (Balance Sheet and Net Income Statement). In particular, the following items are to be excluded, as they are not coherent with the discounted cash flow method:

- Depreciation, as it is not effective cash payment.
- Any reserves for future replacement costs; in this case as well, they usually do not correspond to a real consumption of goods or services.
- Any contingency reserves, because the uncertainty of future flows should be taken into consideration in the risk analysis and not through figurative costs.

Interest payments follow a different course according to the type of subsequent analysis: they are not included in the calculation of the performance of the investment FNPV(C), but are included in the table for the analysis of the return on capital FNPV (K).

Moreover, capital, income or other direct taxes are included only in the financial sustainability table (as an outflow) and not considered for the calculation of FNPV(C) and FNPV (K), which should be calculated before deductions. The rationale is to avoid the complexity and variability across time and countries of capital income tax rules.

2.2.4. Revenues

Projects may generate their own revenues from the sale of goods and services; for example water, public works or toll highways. This revenue will be determined by the forecasts of the quantities of services provided and by their prices.

The following items are usually not included in the calculation of future revenues:

- Transfers or subsidies.
- VAT or other indirect taxes charged by the firm to the consumer, because these are normally paid back to the fiscal administration.

The cash outflows of operating costs deducted from the cash flows of revenues determine the net revenues of the projects. These are calculated for each year of the assumed time horizon. This balance is normally quite different from gross or net profit in the conventional accounting sense (as mentioned, the calculation disregards interest, capital and income taxes, depreciation and other items).

2.2.5. Financial Return on Investment

Having collected the data on investment costs, operating costs and revenues, the next logical step in the financial analysis is the evaluation of the financial return on investment.

The indicators needed for testing the project's financial performance are:

- The financial net present value of the project (FNPV).
- The financial internal rate of return (FRR).

The financial net present value is defined as the sum that results when the expected investment and operating costs of the project (suitably discounted) are deducted from the discounted value of the expected revenues:

$$FNPV = \sum_{t=0}^{n} a_t S_t = \frac{S_0}{(1+i)^0} + \frac{S_1}{(1+i)^1} + \cdots + \frac{S_n}{(1+i)^n}$$

Where $S_t$is the balance of cash flow at time t(net cash flow) and a_t is the financial discount factor chosen for discounting at time$t$.

The financial internal rate of return is defined as the discount rate that produces a zero FNPV:

$$FNPV = \sum_{\forall t} \left[\frac{S_t}{(1+FRR)^t} \right] = 0$$

The calculation of the financial return on investment measures the capacity of the net revenues to remunerate the investment cost.

More specifically, the financial net present value, FNPV(C), and the financial rate of return, FRR(C), on the total investment cost, measure the performance of the investment independently of the sources or methods of financing. The FNPV is expressed in money terms (Euro), and depends on the scale of the project. The second indicator is a pure number, and is scale-invariant. The preferred indicator should usually be the net present value because the rate of return may be somewhat misleading and contains no useful information about the 'value' of a project.

Mainly, investors use the FRR(C) in order to judge the future performance of the investment in comparison to other projects, or to a benchmark required rate of return. This calculation also contributes to deciding if the project requires EU financial support: when the FRR(C) is lower than the applied discount rate (or the FNPV(C) is negative), then the revenues generated will not cover the costs and the project might need EU assistance.

2.3. Environmental aspects

In order to environmentally assess the impact of the deployment and operation of the MFC4sludge project solution for sludge valorisation a Life Cycle Assessment (LCA) will be conducted.

LCA is an internationally accepted and standardized technique (subjected to ISO regulations), which is recognized as a strategic and effective tool to evaluate the potential environmental impacts occurring in the whole product's life cycle as well as to identify possible areas for improvement. However, the methodological choices and the hypotheses made by the practitioners as well as the data used can affect the comparability of the results of the assessment. Consequently, the comparability of different LCA studies on the same product or on different products that fulfil the same function is a complex and critical issue, which has been frequently discussed. In fact, the results of studies on the same product carried out by different authors are often characterized by large results variability, due to the different parameters used as well as the technological systems and impact assessment methods considered in the assessment. Some initiatives such as Product Environmental Footprint (PEF) (EC, 2013), Envifood protocol (Food SCP RT, 2013) and Product Category Rule Guidance Development Initiative have been developed in Europe and the U.S. to overcome this critical subject.

With this method the environmental impacts of a product, process or system are systematically assessed from raw material production to waste management. LCA is a useful tool for public decision-makers involved in the evaluation of new projects, and it is also useful for improving the overall environmental performance and boosting eco-efficiency related to production chains. Actual decision-making, on the other hand, is usually based on profitability of the evaluated options and a variety of other socio-political and technical aspects including legislation, regional development and existing infrastructure. These issues can lead to solutions that are not optimal from the viewpoint of the environmental life cycle impacts. There are emerging approaches, such as social life cycle assessment, which aim at widening the scope of LCA studies to also address non-environmental effects of the product life cycle. These methods need to be further developed in order to provide tools for reliable and systematic sustainability assessment.

In the present document, and in order to carry out a sound assessment, the proposed valorisation process will be compared with the traditional process, i.e. anaerobic digestion (which is carried out currently in GURAK and in around 50% of Europe) and landfilling after dewatering (currently in Europe around 25% of WWTP do not apply any treatment for sludge management). Then, in order to have a closer look to MFC environmental impact, the contribution of each component will be assessed and a sensitivity study will be carried out so as to evaluate and identify MFC design aspects to be further improved so as to minimize environmental impact.

2.3.1 Life Cycle Assessment approach and SimaPro software

The software SimaPro (System for Integrated environMental Assessment of PROducts), developed by the Dutch PRé Consultants, has been used as the LCA modelling and analysis tool. SimaPro is a well-known, internationally accepted and validated tool and since its development in 1990 has been used in a large number of LCA studies by consultants, research institutes, and universities. The software allows to model and analyse complex life cycles in a systematic and transparent way, following the recommendations of the ISO 14040 (1997) series of standards.

SimaPro is available in the "Compact", "Analyst" and "Developer" professional versions and in the “Classroom”, “Faculty” and “PhD” educational versions. For this study the “Developer” version has been used as for the SimaPro software.

Included in the software are several inventory databases (libraries) with a range of data on most commonly used materials and processes, such as electricity production, transport and materials such as plastics or metals, which can be used for background data in the study. One of the databases included is the Eco invent database, developed by the Swiss Centre for Life Cycle Inventories (2005) and includes over 2500 up-to-date processes, covering a broad range of materials and processes with uncertainty data. According to an evaluation of several LCA tools report the SimaPro database is one of the more comprehensive ones as all of the embedded data are fully referenced as to their source. Furthermore SimaPro includes several standard impact assessment methods and allows the practitioner to add or edit these methods.

2.3.1.1 Basic concepts

A product system is a collection of unit processes, which are linked to one another by flows of intermediate products and/or waste for treatment (ISO 14041). SimaPro distinguishes five process types (materials, energy, transport, processing, use, waste scenario and waste treatment) each of which can be either a unit process, i.e. describing a single operation or a process system describing a set of unit processes as if it is one process. Nevertheless, all process types have exactly the same purpose, to quantify the flows of resources, products and emissions in and out of the system and the main purpose of process classification is to facilitate model building. As a result, the way flow and other data are imported into any process is rather similar. With the exception of the waste treatment and waste scenario processes, where the input name is used to identify the record, all other processes are referenced by the products that flow out of the process.

Product stages describe the way a product is produced, used and disposed of and they have links to processes, which contain the flow data. SimaPro by default has five product stages:

[1] An assembly, which defines the production stage of the product studied
[2] A disposal scenario, which describes the end of life scenario for the product if disassembled or reused,
[3] A disassembly scenario, which describes what parts of a product are being disassembled and where the disassembled parts and the remaining parts are going,
[4] A reuse stage, which describes the processes needed to reuse a product or a disassembled part and
[5] The life cycle stage, which describes the total life cycle and therefore links to the assembly and disposal stages, as well as any processes during the use of the product.

It should be highlighted that stages [2], [3] and [4] refer to disposal, disassembly and reuse of the product of the study and not to waste from intermediate processes. Therefore, as a “cradle to gate” analysis is performed in this study only the assembly and lifecycle stages are relevant. Demolition (disassembly) of the WWTP is not considered in the analysis. The assembly of the prototype links to the processes, which describe the materials, production, transport and energy processes that are needed to produce the reference flow of sludge treated to be defined in next subsections.

2.3.1.2 LCA using SimaPro: main steps

The following figure summarises main steps to be carried out when conducting a LCA using SimaPro.

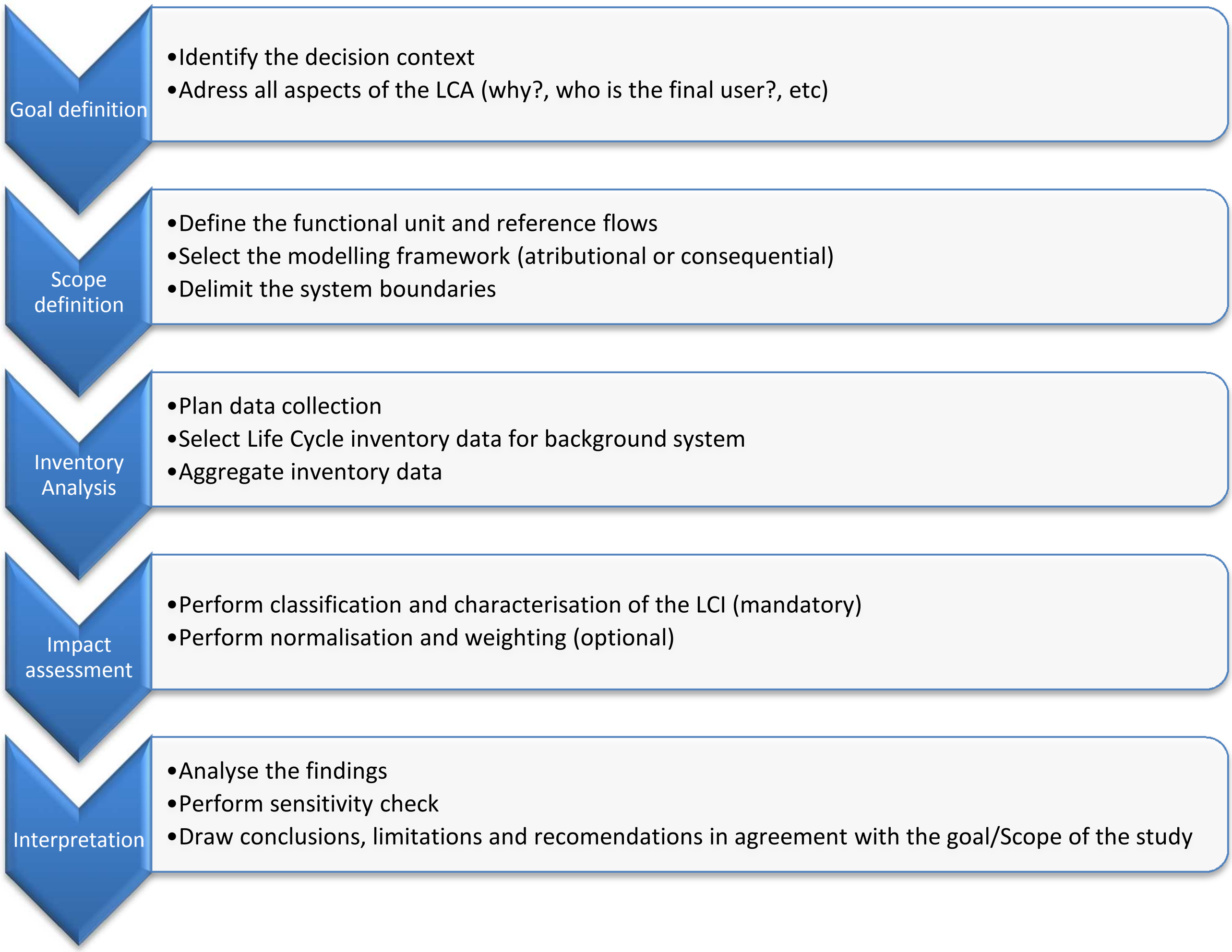

Fig. 1. Main steps in a LCA

As mentioned before, the LCA will be conducted both for the MFC4Sludge solution and the traditional solutions. In such case, when comparing different alternatives, some steps can be done jointly. For example, Goal definition and Impact assessment and interpretation can be done for both alternatives at the same time, while scope definition and inventory analysis must be done for each case by separate.

Further information about these steps can be found in the guidance documents of the International Reference Life Cycle Data System (ILCD) Handbook. The ILCD handbook consists of a set of documents that are in line with the international standards on LCA (ISO 14040/44):

- The General guide for Life Cycle Assessment consists of both a comprehensive, detailed guide as well as a “cook-book”-style guide for experienced LCA practitioners. It covers all aspects of conducting an LCA: defining the objective and target audience, gathering data on resource consumption and emissions that can be attributed to a specific product, calculating the contribution to impacts on the environment, checking the robustness and significance of results and conclusions, and reporting and reviewing to ensure transparency and quality.
- The Specific guide for Life Cycle Inventory (LCI) data sets builds on the general guide. It provides more detail for the generation of specific types of data. For example, it describes how to create LCI data sets that best reflect the average situation regarding emissions and resource consumption.

- The Life Cycle Impact Assessment (LCIA) guides provide requirements for assessing the emissions and resource consumption associated with a product in terms of impacts on the environment, human health, and resources depletion. It outlines criteria against which models and indicators for use in LCIA should be evaluated, covering both scientific aspects and stakeholder acceptability. The guides consist of:
    - Analysis of existing Environmental Impact Assessment methodologies for use in Life Cycle Assessment (LCA)
    - Framework and requirements for Life Cycle Impact Assessment (LCIA) models and indicators
    - Recommendations for Life Cycle Impact Assessment in the European context describes the indicators and models recommended for Life Cycle Impact Assessment.
    - Updated LCIA Characterisation Factors: The recommendation of LCIA models is complemented with associated characterization factors (CFs) also in ILCD format. A technical note supports the correct use of the CFs and points out some known limitations. The CFs dataset, entailing metadata and errata correction, is available as a MS excel® files and as ILCD formatted xml files. The complete dataset, could be download here.
- The guide on Review schemes for Life Cycle Assessment presents the minimum requirements for review for life cycle data or assessments for different applications. The guide on Reviewer qualification specifies the requirements on the experiences and expertise of reviewers.

3. Report on technical aspects

3.1. Technical requirements

As for the installed prototype, an electricity production of 1 W/h has been obtained. For the sake of this energy production, a set of equipment and technical requirements has to be met in order for the whole process to run continuously:

- Introducing the sludge inside the digester tank with a 0.75 KW three-phase pump that use short periods of switching on. The average consumption of the pump is 3.9 W/h.
- In order to introduce water inside the digester tank, it uses a 100 W pump. The average consumption of the pump is 0.37 W/h.
- Periodic gas agitation using a 75 W pump, which has an average consumption of 5 W/h.
- Heating of the sludge inside the digester, by means of heater/cooler equipment, which keeps the temperature around 35 ºC. An estimated average consumption of 100 W/h is considered for this task.
- Removing the solid waste of the sedimentation tank using a 100 W pump working in periods. The average of the consumption is 0.37 W/h.
- The MFC block must be fed with a 75 W pump. The average consumption of this pump is 4.5 W/h.
- 4 recirculation pumps are used in the MFC block with a consumption of 3.5 W/h each one.
- 40W of additional electricity consumption is allocated for the rest of auxiliary equipment (active loads, power source, computer, control boards, etc.)
- In the start-up phase, acetate has to be diluted in a tank to feed the MFC block using a mixer.

Initially, the prototype produces only 1 W/h and consumes about 170 W/h which looks like very inefficient, but the MFC block could be scale up easily with a very low increment of consumption allocated to the rest of devices. Strategies for improving system electrical efficiency are provided in section 3.2.

A techno-economic analysis has been carried out to determine the production costs per kWh of produced electricity. As economies of scale appear when scaling-up the productive capacity of the plant, different scenarios of installed power have been considered within the analysis, namely 250 We, 500 We and 700 We.

Sludge digestion data and MFC consumption and electrical generation data have been linearly interpolated from data obtained from MFC4Sludge prototype. The amount of sludge introduced inside the digester (processed by the prototype) is between 45 and 65 l/day (a mean of 55 L per day) according to the different HRT used in the tests.

Assuming stationary regime of operation has been reached, the use of the following daily amounts of sludge is necessary to generate electrical powers linked to the three proposed scenarios.

Table 1. Daily consumption of sludge processed with the MFC approach for each scenario

	250 We	500 We	700 We
TOTAL Daily Renovation of sludge	13.75 m^3/day	27.5 m^3/day	38.5 m^3/day

- The average amount of wastewater processed at a WWTP is between 10000 and 200000 m^3 per day. GURAK WWTP receives 14540 m^3 of water per day and, after the process, it obtains 38.18 m^3/day of sludge (13935 m^3 yearly, average). The following table shows the portion of yearly processed sludge that would be used for each scenario. Due to system automation, the MFC4Sludge solution can be operated 365 days/year.

Table 2. Relation between sludge yearly consumed within MFC4Sludge and processed during a year for each scenario

	250 We	500 We	700 We
Sludge consumed yearly (% of total processed in GURAK)	5018.75 m^3 (36.02 %)	10037.5 m^3 (72.31 %)	14052.5 m^3 (100.84 %)

- Assuming required digester tank volume is around 7 times the volume of the sludge introduced per day inside the digester and required sedimentation tank volume is around 1 time the volume of the sludge introduced per day inside the digester, the volumes of the tanks are showed in the next table (see Table 3, considering a HRT of 4,5 days).

Table 3. Required volume for the digester and sedimentation tank and land utilization for each scenario

	250 We	500 We	700 We
Digester Volume	95 m^3	190 m^3	266 m^3
Sedimenter Volume	14.3 m^3	28.6 m^3	40 m^3
Land Utilization	20 m^2	40 m^2	56 m^2

- Considering the occupation of the MFC block, about 0.2 m^2, and the possibility of stacking some blocks over others, i.e. 10 MFCs blocks in the same land space, the space used by the whole MFC4Sluge pilot plant could be calculated and is showed in the table 4. Current land utilization is around 45.000 m^2 for GURAK depuration plant. Digesters currently installed at GURAK are 4.000 m^3. Comparing this figure to the volume required for implementing MFC4sludge solution, the solution proposed implies less land occupation and would not require the acquisition of land for its deployment. This has a positive impact in economic terms and also from the environmental point of view.

Fig. 2. Current land utilization associated to GURAK treatment plant in Aduna, Guipuzcoa.

Table 4. Used and saved space due to the implantation of MFC4Sludge disposal approach for each scenario

Land utilization	250 We	500 We	700 We
Traditional AD approach	145 m^2	285 m^2	400 m^2
MFC4Sludge solution	20 m^2	40 m^2	56 m^2
Saved space	125 m^2	245 m^2	344 m^2

3.2. Technological recommendations for further scale-up/industrial users

The main objective of the installation of the MFC4Sludge prototype was to serve both as a proof of the concept and also as a test bench to experiment how different operation set points affect its productivity. At such scale it is difficult to achieve a high energetic efficiency. However, the situation changes when the plant is scaled-up. The bigger the capacity of the equipment, the more important the appearance of economies of scale is over global efficiency.

There are a series of strategic lines and generic objectives that might be optimized to accomplish a suitable level of efficiency to ensure the profitability of the investment, namely, minimize energy consumption of all auxiliary equipment, improve the quality of the digested and sedimented sludge, and optimize the design of the main devices that form each subsystem to maximize its individual efficiencies.

(a) Reduce energy consumption in order to increase global efficiency

- *By using serial or parallel connection to reduce the number of active loads:*
  In the prototype, MFC subsystem has got connected as many active loads as number of cells there are inside it. For this reason, using some kind of scheme of connections for the cells of the subsystem (serial, parallel, different electrodes separation distance, etc.) could reduce the number of active loads and, in this way, the energy consumption.
- *By using renewable sources to supply needed electricity:*
  An option that might be considered to further reduce operating costs is the use of renewable energies to supply the electricity that the process requires, especially for the partial AD since it’s the system section with higher energy consumption. Considering both two previous points, the main remaining consumptions would be the heating system and the auxiliary equipment (MFC subsystem feeding pump, solid waste removing pump, etc.). So, the installation of micro-wind or micro-photovoltaic power stations associated to the global plant could be studied right from the design phase.

(b) Improve properties of the sludge in order to increase its economic return

- *Further final treated sludge characterisation:*
  Through an exhaustive treated sludge characterisation new end-of-life scenarios for this sludge could be identified. For example, its use as digestate could be studied and accordingly, the corresponding revenues to be obtained from its distributions could be included in the economic analysis. In case the treated sludge might not meet the required criteria for further agricultural use, further dewatering strategies aiming to reduce its disposal could be studied.

(c) Increase individual efficiencies

- *Improve the energy production of the MFC:*
  Microbial Fuel Cell technologies are actually in development. It means that further improvements in efficiency can be achieved by finding better material for the construction of the MFC, catalysts for the cathode or through fine adjustment of the optimal dimension and operational conditions of the MFC.
- *Reduce power consumption of subsystem of both HA-AD and MFC:*
  Some of the auxiliary equipment might have been oversized during the design of the prototype, due to the low size of this last one and the lack of commercial solutions for the prototype size. This fact might be taken into account when designing the scaled-up plant, as the relation between produced and consumed electricity within the prototype might be misleading.

4. Report on economic aspects

The rest of the financial analysis has been possible through the evaluation of processes yields or ratios of products. Also, with the aim of assess inversion, sales and operating costs a set of assumptions has been made.

4.1 Main assumptions for the financial analysis

Concerning investment costs:

- For the construction of buildings (digestion and sedimentation tanks, industrial unit where microbial fuel cell will be placed, etc.) and infrastructures (conduits for sludge and water for feeding, conduits for the transportation of the processed sludge between digester and sedimentation tank/s and between the sedimentation tank/s and MFCs block/s), a cost of 300 € per m^3 of digester volume has been considered, adding 20% of the global amount for instrumentation and auxiliary equipment.
- As the pilot plant is considered to be placed in same place of the depuration plant, land costs have negative values, stating that there are terrains owned by the treatment plant that will be disused and might be sold or rented. The value of the land is estimated in 50€/m^2.
- According Leitat research and following EMEFCY recommendations about how to calculate electrodes cost, a cost of 200 € per We has been considered for the MFC units.
- The operating life of MFC units has been considered to be 12 years. Thus, in 13th and 25th years a replacement cost equal to half the initial investment in equipment is considered.
- The cost of the remaining necessary equipment for agitation, heating, pumping and control has been calculated as a 10% of the sum of the costs of digester and MFC units.
- Feasibility study and similar costs have been considered to be 10% of the sum of investment in buildings, infrastructures and equipment.

Concerning operating costs:

- As the plant is planned so as to replace the sludge treatment section, the sludge will be pumped directly inside the digester tank. The rest of the process is totally automated, thus only 0.5 skilled worker (36000 €/year) and 0.2 unskilled workers (21600 €/year) partial time have been considered as necessary.
- The energy production of a MFC considered for the study is 500 W/m^3. A global energy efficiency of 80% has been considered for the whole process, so consumed electricity is equal to 20% of total produced electrical energy. This budget item could be further reduced following some of the indications presented in point 3.2 of this document.
- The cost of raw material is null because the sludge, at the beginning, do not have any value itself. Currently, energy consumption of treatment deployed at GURAK is 0.31 kWe/m^3 of sludge.
- Intermediate services and goods include mainly the costs of inoculums for the MFC, cleaning products, etc.

Concerning sales:

- Sales of the plant are electricity (actually electricity is not sold but saved –self-consumed–).
- Price for saved electricity equals the price of the mean industrial tariffs for electricity, i.e. 0,07 €/kWh.
- The plant yearly operation is 365 days because it can be operated in automatic mode and the inlet of the sludge to the depuration plant can be consider a relatively constant amount.
- Discount rate is set to 3% (given the current low price of capital).
- The real growth rate for other elements of the analysis, considering the evolution of different markets in Spain during past years are:
    - Electricity costs/selling price: 4%.

- Labour costs: 1%.

4.2. Results

The tables below detail net cash flows associated to the 250 W-scenario (Table), 500 W-scenario (Table 7) and 700 W-scenario (Table 9). In addition the Financial Net Present Value on investment –FNPV (C)– and Financial Rate of Return –FRR (C)–, have been calculated for three time horizons, namely, 10 years, 15 years and 30 years for each scenario.

As can be seen at the Tables 5 and 6, the implantation of a full pilot scale plant applying the MFC4Sludge is loss-making for the scenario, in fact the FRR could not be calculated. It is because the cost of fabrication of the MFCs is expensive, although Leitat has reached a cheapest fabrication of the cathode part, and the pilot plant would need many cells to raise the electric power desired.

Table 5. Financial Return on Capital for the 250 W-scenario (values in thousands of €)

	1	2	3	4	5	6	7	8
Electricity	0	0,1533	0,157	0,161061	0,165087	0,169215	0,173445	0,177781
Energy save	0	7,161	7,340	7,524	7,712	7,904	8,102	8,305
SALES		7,3143	7,4971575	7,684586	7,876701	8,073619	8,275459	8,482346
Labour cost	0	18	18,180	18,3618	18,54542	18,73087	18,91818	19,10736
Electrical Energy	0	0,01533	0,016	0,016581	0,017244	0,017934	0,018651	0,019397
Water services	0	0,5	0,510	0,5202	0,530604	0,541216	0,55204	0,563081
Raw Material	0	0	0,000	0	0	0	0	0
Intermediate services and goods	0	0,1	0,102	0,10404	0,106121	0,108243	0,110408	0,112616
TOTAL OPERATING COSTS	0	18,61533	18,808	19,00262	19,19939	19,39827	19,59928	19,80246
Feasibility study, tender cost, etc.	3,9348	0	0,000	0	0	0	0	0
Land acquisition	0	0	0,000	0	0	0	0	0
Buildings & Infrastructures	39,348	0	0,000	0	0	0	0	0
Equipments	63,1	0	0,000	0	0	0	0	0
Investment costs	106,3828	0	0,000	0	0	0	0	0
Replacement costs	0	0	0,000	0	0	0	0	0
Remediation and decontamination costs	0	0	0,000	0	0	0	0	0
Residual value	0	0	0,000	0	0	0	0	0
Other Investment Items	0	0	0,000	0	0	0	0	0
TOTAL INVESTMENT COSTS	106,3828	0	0,000	0	0	0	0	0
TOTAL OUTFLOWS	106,3828	18,61533	18,808	19,00262	19,19939	19,39827	19,59928	19,80246
NET CASH FLOW	-106,3828	-11,30103	-11,311	-11,318	-11,3227	-11,3246	-11,3238	-11,3201

9	10	11	12	13	14	15	16	17	18	19	20	21
0,182226	0,186781	0,191451	0,19623696	0,201143	0,206171	0,211326	0,216609	0,222024	0,227575	0,233264	0,239096	0,245073
8,512	8,725	8,943	9,167	9,396	9,631	9,872	10,118	10,371	10,631	10,896	11,169	11,448
8,694404	8,911764	9,134558	9,36292238	9,596995	9,83692	10,08284	10,33491	10,59329	10,85812	11,12957	11,40781	11,69301

19,29844	19,49142	19,68633	19,8831983	20,08203	20,28285	20,48568	20,69054	20,89744	21,10642	21,31748	21,53065	21,74596
0,020173	0,02098	0,021819	0,02269214	0,0236	0,024544	0,025526	0,026547	0,027608	0,028713	0,029861	0,031056	0,032298
0,574343	0,58583	0,597546	0,60949721	0,621687	0,634121	0,646803	0,659739	0,672934	0,686393	0,700121	0,714123	0,728406
0	0	0	0	0	0	0	0	0	0	0	0	0
0,114869	0,117166	0,119509	0,12189944	0,124337	0,126824	0,129361	0,131948	0,134587	0,137279	0,140024	0,142825	0,145681
20,00782	20,2154	20,42521	20,6372871	20,85165	21,06834	21,28737	21,50877	21,73257	21,9588	22,18749	22,41866	22,65235
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	53,1914	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	53,1914	0	0	0	0	0	0	0	0
0	0	0	0	53,1914	0	0	0	0	0	0	0	0
20,00782	20,2154	20,42521	20,6372871	74,04305	21,06834	21,28737	21,50877	21,73257	21,9588	22,18749	22,41866	22,65235
-11,3134	-11,3036	-11,2907	-11,274365	-64,4461	-11,2314	-11,2045	-11,1739	-11,1393	-11,1007	-11,0579	-11,0108	-10,9593

22	23	24	25	26	27	28	29	30
0,2512	0,25748	0,263917	0,270515	0,277278	0,28421	0,291315	0,298598	0,306063
11,734	12,027	12,328	12,636	12,952	13,276	13,608	13,948	14,297
11,98533	12,28497	12,59209	12,90689	13,22956	13,5603	13,89931	14,24679	14,60296
21,96342	22,18305	22,40489	22,62893	22,85522	23,08378	23,31461	23,54776	23,78324
0,03359	0,034934	0,036331	0,037784	0,039295	0,040867	0,042502	0,044202	0,04597
0,742974	0,757833	0,77299	0,78845	0,804219	0,820303	0,836709	0,853443	0,870512
0	0	0	0	0	0	0	0	0
0,148595	0,151567	0,154598	0,15769	0,160844	0,164061	0,167342	0,170689	0,174102
22,88858	23,12739	23,3688	23,61286	23,85958	24,10901	24,36117	24,61609	24,87382
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	53,1914	0	0	0	0	0
0	0	0	0	0	0	0	0	6,31
0	0	0	0	0	0	0	0	-3,155
0	0	0	53,1914	0	0	0	0	3,155
0	0	0	53,1914	0	0	0	0	3,155

22,88858	23,12739	23,3688	76,80426	23,85958	24,10901	24,36117	24,61609	28,02882
-10,9032	-10,8424	-10,7767	-63,8974	-10,63	-10,5487	-10,4619	-10,3693	-13,4259

Table 6. Financial Indicators for the 250 W-scenario(values in thousands of €)

	10 Years	15 Years	30 Years
Discount Rate (%)	0,03	0,03	0,03
FNPV (C)	-188,82 €	-263,39 €	-373,09 €
FRR (C) (%)	-	-	-
Funding Gap Ratio	1,774910948		

Table 7. Financial Return on Capital for the 500 W-scenario (values in thousands of €)

	1	2	3	4	5	6	7	8
Electricity	0	0,3066	0,314	0,322122	0,330175	0,338429	0,34689	0,355562
Energy save	0	14,322	14,680	15,047	15,423	15,809	16,204	16,609
SALES		14,6286	14,994315	15,36917	15,7534	16,14724	16,55092	16,96469
Labour cost	0	18	18,180	18,3618	18,54542	18,73087	18,91818	19,10736
Electrical Energy	0	0,03066	0,032	0,033162	0,034488	0,035868	0,037303	0,038795
Water services	0	0,5	0,510	0,5202	0,530604	0,541216	0,55204	0,563081
Raw Material	0	0	0,000	0	0	0	0	0
Intermediate services and goods	0	0,1	0,102	0,10404	0,106121	0,108243	0,110408	0,112616
TOTAL OPERATING COSTS	0	18,63066	18,824	19,0192	19,21663	19,4162	19,61793	19,82185
Feasibility study, tender cost, etc.	7,8696	0	0,000	0	0	0	0	0
Land acquisition	0	0	0,000	0	0	0	0	0
Buildings & Infrastructures	78,696	0	0,000	0	0	0	0	0
Equipments	126,2	0	0,000	0	0	0	0	0
Investment costs	212,7656	0	0,000	0	0	0	0	0
Replacement costs	0	0	0,000	0	0	0	0	0
Remediation and decontamination costs	0	0	0,000	0	0	0	0	0
Residual value	0	0	0,000	0	0	0	0	0
Other Investment Items	0	0	0,000	0	0	0	0	0
TOTAL INVESTMENT COSTS	212,7656	0	0,000	0	0	0	0	0
TOTAL OUTFLOWS	212,7656	18,63066	18,824	19,0192	19,21663	19,4162	19,61793	19,82185
NET CASH FLOW	-212,7656	-4,00206	-3,830	-3,65003	-3,46323	-3,26896	-3,06701	-2,85716

9	10	11	12	13	14	15	16	17	18	19	20	21
0,364451	0,373562	0,382901	0,39247392	0,402286	0,412343	0,422651	0,433218	0,444048	0,455149	0,466528	0,478191	0,490146
17,024	17,450	17,886	18,333	18,792	19,261	19,743	20,237	20,743	21,261	21,793	22,337	22,896
17,38881	17,82353	18,26912	18,7258448	19,19399	19,67384	20,16569	20,66983	21,18657	21,71624	22,25914	22,81562	23,38601

19,29844	19,49142	19,68633	19,8831983	20,08203	20,28285	20,48568	20,69054	20,89744	21,10642	21,31748	21,53065	21,74596
0,040346	0,04196	0,043639	0,04538429	0,0472	0,049088	0,051051	0,053093	0,055217	0,057426	0,059723	0,062112	0,064596
0,574343	0,58583	0,597546	0,60949721	0,621687	0,634121	0,646803	0,659739	0,672934	0,686393	0,700121	0,714123	0,728406
0	0	0	0	0	0	0	0	0	0	0	0	0
0,114869	0,117166	0,119509	0,12189944	0,124337	0,126824	0,129361	0,131948	0,134587	0,137279	0,140024	0,142825	0,145681
20,02799	20,23638	20,44703	20,6599792	20,87525	21,09288	21,31289	21,53532	21,76018	21,98751	22,21735	22,44971	22,68464
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	106,3828	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	106,3828	0	0	0	0	0	0	0	0
0	0	0	0	106,3828	0	0	0	0	0	0	0	0
20,02799	20,23638	20,44703	20,6599792	127,2581	21,09288	21,31289	21,53532	21,76018	21,98751	22,21735	22,44971	22,68464
-2,63919	-2,41285	-2,17791	-1,9341344	-108,064	-1,41904	-1,14721	-0,86549	-0,5736	-0,27127	0,041798	0,36591	0,70137

22	23	24	25	26	27	28	29	30
0,5024	0,51496	0,527834	0,54103	0,554555	0,568419	0,58263	0,597195	0,612125
23,468	24,055	24,656	25,273	25,905	26,552	27,216	27,896	28,594
23,97066	24,56993	25,18418	25,81378	26,45913	27,12061	27,79862	28,49359	29,20593
21,96342	22,18305	22,40489	22,62893	22,85522	23,08378	23,31461	23,54776	23,78324
0,06718	0,069867	0,072662	0,075568	0,078591	0,081735	0,085004	0,088404	0,09194
0,742974	0,757833	0,77299	0,78845	0,804219	0,820303	0,836709	0,853443	0,870512
0	0	0	0	0	0	0	0	0
0,148595	0,151567	0,154598	0,15769	0,160844	0,164061	0,167342	0,170689	0,174102
22,92217	23,16232	23,40513	23,65064	23,89888	24,14987	24,40367	24,6603	24,91979
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	106,3828	0	0	0	0	0
0	0	0	0	0	0	0	0	12,62
0	0	0	0	0	0	0	0	-6,31
0	0	0	106,3828	0	0	0	0	6,31
0	0	0	106,3828	0	0	0	0	6,31
22,92217	23,16232	23,40513	130,0334	23,89888	24,14987	24,40367	24,6603	31,22979

1,048495	1,407609	1,779044	-104,22	2,560251	2,970733	3,394953	3,833292	-2,02387

Table 8. Financial Indicators for the 500 W-scenario (values in thousands of €)

	10 Years	15 Years	30 Years
Discount Rate (%)	0,03	0,03	0,03
FNPV (C)	-231,38 €	-309,57 €	-352,85 €
FRR (C) (%)	-	-	-
Funding Gap Ratio	1,087492174		

Table 9. Financial Return on Capital for the 700 W-scenario (values in thousands of €)

	1	2	3	4	5	6	7	8
Electricity	0	0,42924	0,440	0,45097	0,462245	0,473801	0,485646	0,497787
Energy save	0	19,89456	20,392	20,902	21,424	21,960	22,509	23,072
SALES		20,3238	20,831895	21,35269	21,88651	22,43367	22,99451	23,56938
Labour cost	0	18	18,180	18,3618	18,54542	18,73087	18,91818	19,10736
Electrical Energy	0	0,042924	0,045	0,046427	0,048284	0,050215	0,052224	0,054313
Water services	0	0,5	0,510	0,5202	0,530604	0,541216	0,55204	0,563081
Raw Material	0	0	0,000	0	0	0	0	0
Intermediate services and goods	0	0,1	0,102	0,10404	0,106121	0,108243	0,110408	0,112616
TOTAL OPERATING COSTS	0	18,642924	18,837	19,03247	19,23043	19,43055	19,63285	19,83737
Feasibility study, tender cost, etc.	11,016	0	0,000	0	0	0	0	0
Land acquisition	0	0	0,000	0	0	0	0	0
Buildings & Infrastructures	110,16	0	0,000	0	0	0	0	0
Equipments	176,68	0	0,000	0	0	0	0	0
Investment costs	297,856	0	0,000	0	0	0	0	0
Replacement costs	0	0	0,000	0	0	0	0	0
Remediation and decontamination costs	0	0	0,000	0	0	0	0	0
Residual value	0	0	0,000	0	0	0	0	0
Other Investment Items	0	0	0,000	0	0	0	0	0
TOTAL INVESTMENT COSTS	297,856	0	0,000	0	0	0	0	0
TOTAL OUTFLOWS	297,856	18,642924	18,837	19,03247	19,23043	19,43055	19,63285	19,83737
NET CASH FLOW	-297,856	1,680876	1,995	2,320226	2,656083	3,003126	3,361661	3,732004

9	10	11	12	13	14	15	16	17	18	19	20	21
0,510231	0,522987	0,536062	0,54946349	0,5632	0,57728	0,591712	0,606505	0,621668	0,637209	0,653139	0,669468	0,686205
23,648	24,240	24,846	25,467	26,103	26,756	27,425	28,110	28,813	29,534	30,272	31,029	31,804
24,15861	24,76258	25,38164	26,0161823	26,66659	27,33325	28,01658	28,717	29,43492	30,1708	30,92507	31,69819	32,49065
19,29844	19,49142	19,68633	19,8831983	20,08203	20,28285	20,48568	20,69054	20,89744	21,10642	21,31748	21,53065	21,74596
0,056485	0,058744	0,061094	0,06353801	0,06608	0,068723	0,071472	0,07433	0,077304	0,080396	0,083612	0,086956	0,090434

0,574343	0,58583	0,597546	0,60949721	0,621687	0,634121	0,646803	0,659739	0,672934	0,686393	0,700121	0,714123	0,728406
0	0	0	0	0	0	0	0	0	0	0	0	0
0,114869	0,117166	0,119509	0,12189944	0,124337	0,126824	0,129361	0,131948	0,134587	0,137279	0,140024	0,142825	0,145681
20,04413	20,25316	20,46448	20,6781329	20,89413	21,11252	21,33331	21,55655	21,78227	22,01048	22,24124	22,47456	22,71048
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	148,928	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	148,928	0	0	0	0	0	0	0	0
0	0	0	0	148,928	0	0	0	0	0	0	0	0
20,04413	20,25316	20,46448	20,6781329	169,8221	21,11252	21,33331	21,55655	21,78227	22,01048	22,24124	22,47456	22,71048
4,114479	4,509416	4,917157	5,33804934	-143,156	6,220733	6,683268	7,160444	7,652656	8,160312	8,683829	9,223633	9,780164

22	23	24	25	26	27	28	29	30
0,70336	0,720944	0,738967	0,757441	0,776378	0,795787	0,815682	0,836074	0,856976
32,600	33,415	34,250	35,106	35,984	36,883	37,805	38,751	39,719
33,30291	34,13549	34,98887	35,86359	36,76018	37,67919	38,62117	39,5867	40,57637
21,96342	22,18305	22,40489	22,62893	22,85522	23,08378	23,31461	23,54776	23,78324
0,094052	0,097814	0,101726	0,105795	0,110027	0,114428	0,119005	0,123766	0,128716
0,742974	0,757833	0,77299	0,78845	0,804219	0,820303	0,836709	0,853443	0,870512
0	0	0	0	0	0	0	0	0
0,148595	0,151567	0,154598	0,15769	0,160844	0,164061	0,167342	0,170689	0,174102
22,94904	23,19027	23,4342	23,68087	23,93031	24,18257	24,43767	24,69566	24,95657
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	148,928	0	0	0	0	0
0	0	0	0	0	0	0	0	17,668
0	0	0	0	0	0	0	0	-8,834
0	0	0	148,928	0	0	0	0	8,834
0	0	0	148,928	0	0	0	0	8,834
22,94904	23,19027	23,4342	172,6089	23,93031	24,18257	24,43767	24,69566	33,79057
10,35387	10,94522	11,55467	-136,745	12,82987	13,49662	14,1835	14,89104	6,785797

Table 10. Financial Indicators for the 700 W-scenario (values in thousands of €)

	10 Years	15 Years	30 Years
Discount Rate (%)	0,03	0,03	0,03
FNPV (C)	-266,71 €	-348,50 €	-340,63 €
FRR (C) (%)	-30%	-	-
Funding Gap Ratio	0,895447069		

In order to go further with this economic analysis and to be able to identify the conditions that would make this process solution more profitable, an ideal scenario has been depicted for a 700W installation at GURAK facilities. This ideal scenario would require the following modifications:

- Increase the electric power obtained by each MFC unit at 1000 We/m^3. This would allow to reduce the number of MFC to be used to a 30% (decreasing this way MFC related CAPEX)
- Reduce the 'buildings and infrastructures' cost to a 25%.
- Use the raw material (solid waste) like fertilizer, producing revenues from its trade. The following considerations could apply:
  - The production of solid waste is around 13% of the amount of processed sludge.
  - The price of the m^3 of fertilizer used is 2 €, assuming the cost of processing the solid waste in order to obtain fertilizer.

The result for the 700 W-scenario with the modified MFC and the other consideration could be observed in tables 11 and 12.

Table 11. Financial Return on Capital for the 700 W-scenario with modified MFC (values in thousands of €)

	1	2	3	4	5	6	7	8
Electricity	0	0,85848	0,880	0,901941	0,924489	0,947601	0,971291	0,995574
Energy save	0	19,89456	20,392	20,902	21,424	21,960	22,509	23,072
SALES		20,75304	21,271866	21,80366	22,34875	22,90747	23,48016	24,06716
Labour cost	0	18	18,180	18,3618	18,54542	18,73087	18,91818	19,10736
Electrical Energy	0	0,085848	0,089	0,092853	0,096567	0,10043	0,104447	0,108625
Water services	0	0,5	0,510	0,5202	0,530604	0,541216	0,55204	0,563081
Raw Material	0	-3,65365	-3,690	-3,72709	-3,76436	-3,802	-3,84002	-3,87842
Intermediate services and goods	0	0,1	0,102	0,10404	0,106121	0,108243	0,110408	0,112616
TOTAL OPERATING COSTS	0	15,032198	15,191	15,3518	15,51435	15,67876	15,84505	16,01326
Feasibility study, tender cost, etc.	2,754	0	0,000	0	0	0	0	0
Land acquisition	0	0	0,000	0	0	0	0	0
Buildings & Infrastructures	27,54	0	0,000	0	0	0	0	0
Equipments	44,754	0	0,000	0	0	0	0	0
Investment costs	75,048	0	0,000	0	0	0	0	0
Replacement costs	0	0	0,000	0	0	0	0	0
Remediation and decontamination costs	0	0	0,000	0	0	0	0	0
Residual value	0	0	0,000	0	0	0	0	0
Other Investment Items	0	0	0,000	0	0	0	0	0
TOTAL INVESTMENT COSTS	75,048	0	0,000	0	0	0	0	0

TOTAL OUTFLOWS	75,048	15,032198	15,191	15,3518	15,51435	15,67876	15,84505	16,01326
NET CASH FLOW	-75,048	5,720842	6,081	6,451858	6,834403	7,228714	7,635106	8,053902

9	10	11	12	13	14	15	16	17	18	19	20	21
1,020463	1,045975	1,072124	1,09892698	1,1264	1,15456	1,183424	1,21301	1,243335	1,274418	1,306279	1,338936	1,372409
23,648	24,240	24,846	25,467	26,103	26,756	27,425	28,110	28,813	29,534	30,272	31,029	31,804
24,66884	25,28556	25,9177	26,5656457	27,22979	27,91053	28,60829	29,3235	30,05659	30,808	31,5782	32,36766	33,17685
19,29844	19,49142	19,68633	19,8831983	20,08203	20,28285	20,48568	20,69054	20,89744	21,10642	21,31748	21,53065	21,74596
0,11297	0,117489	0,122188	0,12707601	0,132159	0,137445	0,142943	0,148661	0,154607	0,160792	0,167223	0,173912	0,180869
0,574343	0,58583	0,597546	0,60949721	0,621687	0,634121	0,646803	0,659739	0,672934	0,686393	0,700121	0,714123	0,728406
-3,91721	-3,95638	-3,99594	-4,0359026	-4,07626	-4,11702	-4,15819	-4,19978	-4,24177	-4,28419	-4,32703	-4,3703	-4,41401
0,114869	0,117166	0,119509	0,12189944	0,124337	0,126824	0,129361	0,131948	0,134587	0,137279	0,140024	0,142825	0,145681
16,18341	16,35553	16,52964	16,7057683	16,88395	17,06422	17,24659	17,43111	17,6178	17,80669	17,99781	18,19121	18,38691
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	7,5048	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	7,5048	0	0	0	0	0	0	0	0
0	0	0	0	7,5048	0	0	0	0	0	0	0	0
16,18341	16,35553	16,52964	16,7057683	24,38875	17,06422	17,24659	17,43111	17,6178	17,80669	17,99781	18,19121	18,38691
8,485432	8,930038	9,388067	9,85987746	2,841035	10,84631	11,3617	11,89239	12,43879	13,00132	13,58039	14,17645	14,78994

22	23	24	25	26	27	28	29	30
1,406719	1,441887	1,477935	1,514883	1,552755	1,591574	1,631363	1,672147	1,713951
32,600	33,415	34,250	35,106	35,984	36,883	37,805	38,751	39,719
34,00627	34,85643	35,72784	36,62104	37,53656	38,47498	39,43685	40,42277	41,43334
21,96342	22,18305	22,40489	22,62893	22,85522	23,08378	23,31461	23,54776	23,78324
0,188104	0,195628	0,203453	0,211591	0,220055	0,228857	0,238011	0,247531	0,257433
0,742974	0,757833	0,77299	0,78845	0,804219	0,820303	0,836709	0,853443	0,870512
-4,45815	-4,50273	-4,54776	-4,59323	-4,63917	-4,68556	-4,73241	-4,77974	-4,82753
0,148595	0,151567	0,154598	0,15769	0,160844	0,164061	0,167342	0,170689	0,174102
18,58495	18,78535	18,98817	19,19343	19,40117	19,61144	19,82426	20,03969	20,25775
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0

0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	7,5048	0	0	0	0	0
0	0	0	0	0	0	0	0	4,4754
0	0	0	0	0	0	0	0	-2,2377
0	0	0	7,5048	0	0	0	0	2,2377
0	0	0	7,5048	0	0	0	0	2,2377
18,58495	18,78535	18,98817	26,69823	19,40117	19,61144	19,82426	20,03969	22,49545
15,42133	16,07108	16,73967	9,922805	18,13539	18,86354	19,61259	20,38309	18,93789

Table 12. Financial Indicators for the modified 700 W-scenario (values in thousands of €)

	10 Years	15 Years	30 Years
Discount Rate (%)	0,03	0,03	0,03
FNPV (C)	-18,51 €	11,59 €	128,79 €
FRR (C) (%)	-2%	5%	11,093%
Funding Gap Ratio	0,246630893		

As it can be observed, this modified scenario provide better results when analysing solution economics since the prototype is rentable by itself since the year 15th. This fact did not happen in the 250 W, 500W and 700 W with standard cells. Moreover, as for this potential scenario, summing all the investment costs during the lifetime of the project and dividing this value by the installed power, the price per installed We is obtained; if this value is summed to the average of the operating costs during the lifetime, divided by the installed power, the cost per produced We results (see Table 13).

Table 13. Costs per produced and installed We

Cost per m^3 of treated sludge (€)	0,219
Cost per installed We (k€)	0,066
Cost per produced We (k€)	0,078

Both results are quite high when compared to current installation costs within the industry. This is due to the fact that they only take in account the energy produced, not the energy saved. The following table provides information about the different scenarios regarding energy consumption by GURAK plant and the energy that the plant could potentially produce using the prototype (to be use by themselves or fed to the grid).

Table 14. Comparison consumption/production of energy (values in kWe/m^3)

	Energy consumption(kWe/m^3)	Energy production (kWe/m^3)	Balance
GURAK plant – current scenario	0,31	0,05 [1]	-0,26
250 W-scenario	0,036	0,161	0,125
500 W-scenario	0,071	0,321	0,25
700 W-scenario	0,1	0,45	0,35
700 W-scenario modificated	0,03	1	0,97

[1] Gurak plant produces biogas during the sludge treatment process. However, they only use around 35% of the production to heat the digesters. The rest of biogas produced is burn without providing any benefit/revenue.

5. Report on environmental aspects

The previously described LCA and SimaPRO® software have been used for the environmental assessment of the project. Hence, and according to LCA definition, the following steps have been carried out.

5.1 Step 1: Goal definition

5.1.1 Overall considerations

The ISO standards outline the goal definition as the part framing the intended uses and users of the LCA case- study based on its overall context description (ISO, 2006). The ILCD Handbook guidelines divide the goal definition in 6 aspects, viz. the intended applications, the limitations to usability of results, the drivers and motives, the target audience, the potential disclosure to the public, and the commissioner of the study. Although the goal definition of an LCA can be adapted depending on its background, e.g. commissioned ISO-compliant LCA study versus research-support LCA case study, the authors are recommended to provide sufficient information on the context of the study and the usability of the results, including the limitations of the LCA to prevent misinterpretation of its results.

A proper identification of the context situation is important because it determines the type of LCI modelling framework to apply, which has a considerable influence on the results and their interpretation. For example, the use of either allocation or system expansion in an attributional modelling can lead to opposite results.

5.1.2 Goal definition for MFC4Sludge project LCA

Main goal of the LCA is to compare the environmental impact of the proposed solution against traditional approaches. These information can be introduced in the software under the tab “Goal and scope – Description”. In the next section a screen capture will be provided.

5.2 Step 2: Scope definition

5.2.1 Overall considerations

When defining project scope special attention must be paid to the following issues:

FUNCTIONAL UNIT AND REFERENCE FLOWS

The review of the studies led to identifying four major classes of functional unit (f.u.), namely (i) unitary f.u., defined by a unitary measure, e.g. management of 1 tonne of waste, (ii) generation based f.u., defined by the waste generation in a delimited region for a specified period of time, (iii) input-based f.u., defined by the waste amounts entering a given facility, and (iv) output-based f.u., defined by the waste by-products, e.g. amounts of recovered energy or recycled material. The functional unit gives a quantitative description of the primary function fulfilled by the systems under study and is a guarantee of their comparability. The practitioners are encouraged to include local specifications as well as any relevant aspects to guarantee the comparability of the systems.

APPLIED LCI MODELLING FRAMEWORK AND ISSUES OF MULTI-FUNCTIONAL PROCESSES

The LCI modelling framework describes the modelling approach that has been adopted for solving the multi-functionality of some processes, i.e. the point that some processes provide more than one function, e.g. the incineration of mixed waste with energy recovery or the recycling processes are such examples (both providing the service of treating the waste and delivering a commodity as output). Multi-functional processes can be addressed by two fundamentally different approaches – by attributional or consequential modelling. In the first one the practitioners allocate different portions of the impacts to the different outputs of the system according to estimations. In the second one, the allocation of impacts to each output is based in actual references.

SYSTEM BOUNDARIES

The system boundaries define which processes in the life cycle are included or excluded from the assessed system (ISO, 2006). The system delimitation needs to ensure that all relevant processes, and hence their potential environmental impacts, are included in the assessment.

5.2.2 Scope definition for MFC4Sludge project LCA

Functional Unit: As for this study requirements, the functional unit considered will be unitary type. Specifically, the unit to be used is the management of all the sludge produced by GURAK in one year, i.e 13.935 m^3.

Applied LCI modelling framework: attributional

System Boundaries: the analysed process is a cradle to gate approach since main outputs of the proposed solutions are considered not as re-usable flows but as avoided flows. More information about system boundaries and modelling can be found in net section.

The next picture is a print screen of the Goal and scope – Definition tab where all the previous information is loaded in the software.

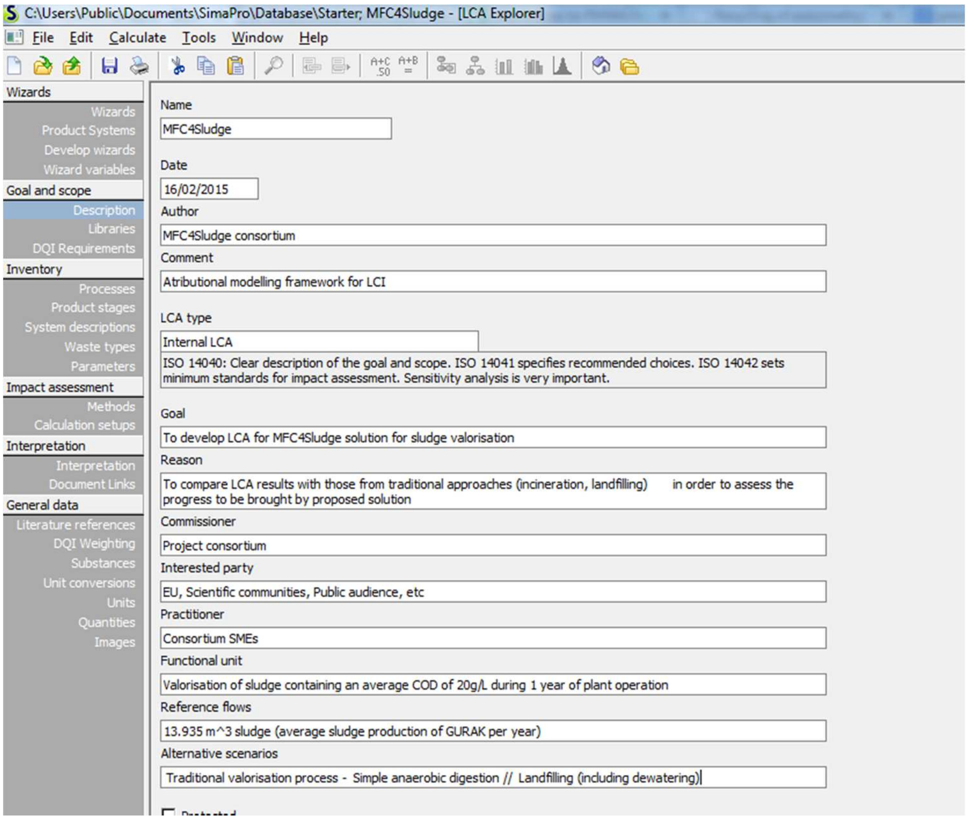

Fig. 3. Goal and scope definition of the MFC4Sludge LCA

5.3 Step 3: Life Cycle Inventory (LCI)

5.3.1 Overall considerations

The life cycle inventory analysis is the phase, which builds on the requirements defined in the goal and scope phases to conduct the collection of data on flows to and from the processes of the waste management system, the further data handling to reach a comprehensive emission and resource consumption inventory, and the modelling of the analysed system. In typical LCA studies, this phase is the most time- and resource-demanding for LCA practitioners.

5.3.2 LCI for MFC4Sludge project LCA

The basic model of the sludge generation in the WWTP cycle is built by creating the unit processes of sludge production, partial AD and MFC (which will be integrated in the prototype LCA), traditional AD and landfilling. It is noted that for such a complex system the classification into SimaPro categories is subjective, however as previously discussed, process categories only serve model building and do not have any impact on the results.

Main hypothesis considered when identifying each process unit are:

- The proposed sludge valorisation approach is treated as two independent unit processes.
- Final sludge disposition for traditional AD and prototype use is considered similar to the landfill option, i.e. dewatering and transportation to landfill.
- Distance to landfill considered is 250 km.
- Sludge production and dewatering process units have been simplified in order to focus all the attention in the valorisation cases.

After modelling each subsystem, and identify all the inputs and outputs, all the information is introduced in the system. Main data have been gathered from feedback from GURAK (sludge production process and landfilling scenario), during the operation of the prototype (valorisation case A) or from literature and partners (materials used for the construction of each subsystem of the prototype). As for the different cases, materials used in the construction of the units have been also considered.

Next figures depict the three possibilities to be compared, providing information of each system boundaries. Then, each process unit is also depicted so inputs and outputs considered can be listed.

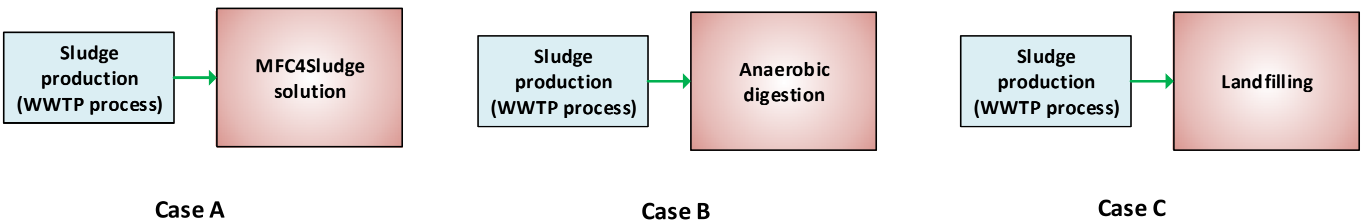

Fig. 4. Systems to be analysed and compared within the present LCA. Case A is the project proposed solution and Case B and C are current approaches in Europe.

Process unit "Sludge production (WWTP process)" is the common starting point for all the cases. For simplification, the WWTP Sludge mixture material has been created. Information about LCI is provided next as well as a screen capture.

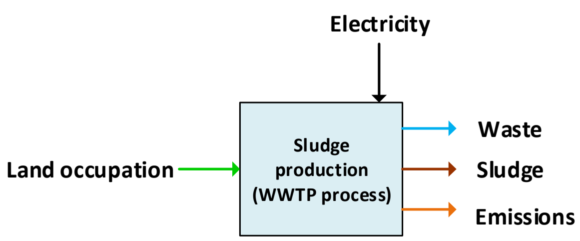

Fig. 5. Sludge production (WWTP process) unit processes

Table 15. LCI for process unit – Sludge production

Sludge production		
Inputs	*Qty.*	*Units*
Electricity	1.803.209	kWh
Land occupation	45.000	M^2

Emissions	*Qty.*	*Units*
Methane	17.528,3	*kg*
Nitrogen oxides	49.192	*kg*
Ammonia	12.326,4	*kg*
COD	366.398,6	*kg*
Phosphate	26.575,2	*kg*
Ammonium	150.404,38	*kg*
Chromium	4.000	*kg*
Mercury	1.374	*kg*
Copper	276,5	*kg*
Cadmium	836,36	*kg*
Nickel	1.509,7	*kg*
Lead	14.362	*kg*
Zinc	151	*kg*
Outputs	*Qty.*	*Units*
WWTP sludge mixture	13.935	m^3
Waste inert to landfill (aside from sludge)	297,3	ton

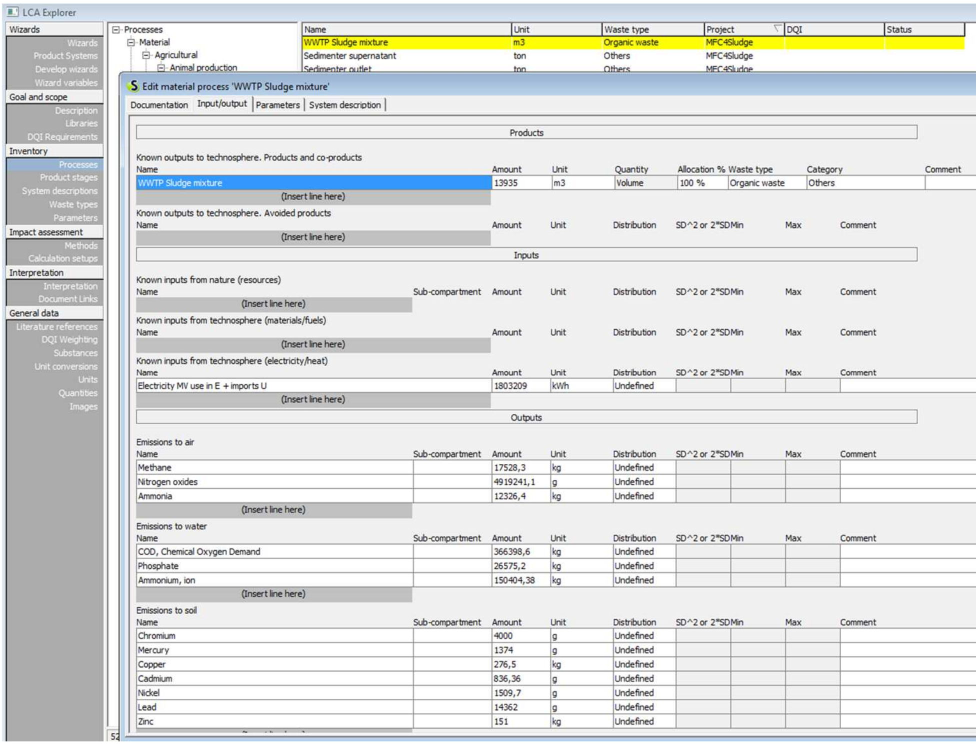

Fig.6. Simapro WWTP Sludge mixture material

Case A is detailed next. For simplicity, the whole prototype has been considered as two process units coupled. As for such unit, partial AD and MFC, both have been considered as black boxes so as to simplify system boundaries and inputs/outputs.

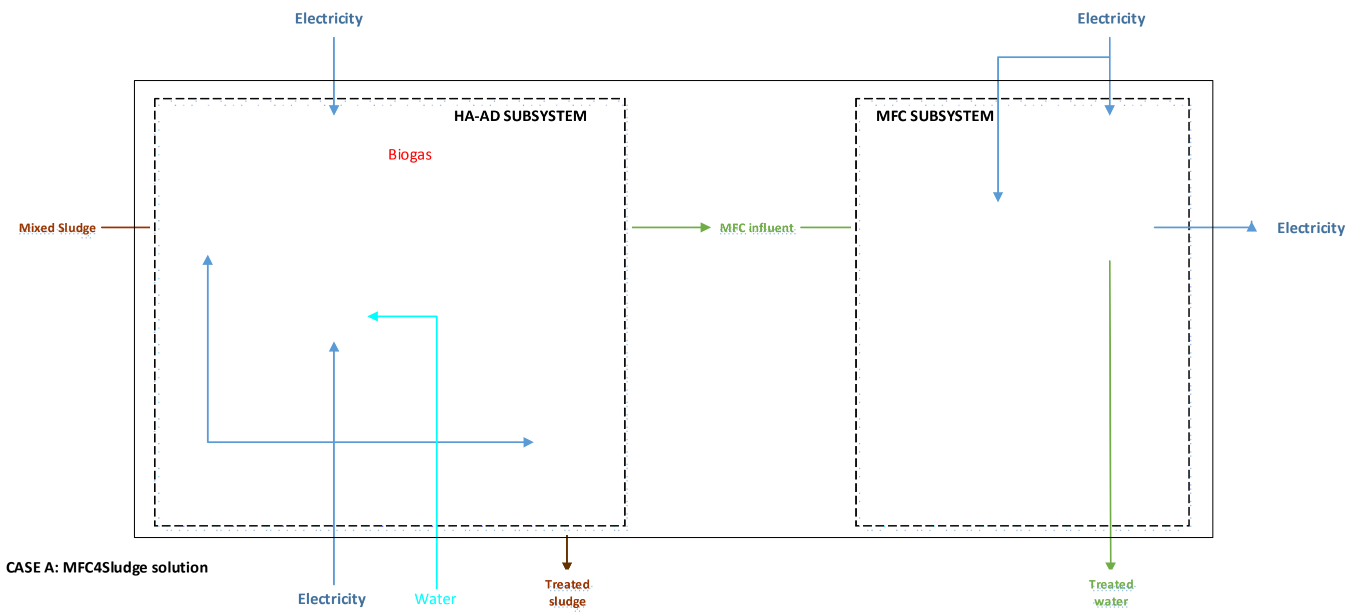

Fig. 2: Valorisation CASE A: MFC4Sludge system as the coupling of two process units

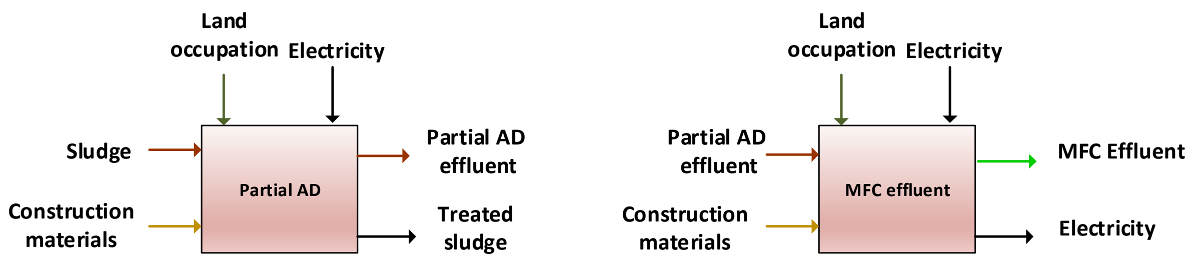

Fig. 3: Details of each sub-unit of CASE A

Table 16 and Table 17. LCI for CASE A – subprocess units

Partial AD		
Inputs	*Qty.*	*Units*
Steel	5,43	ton
Ceramics	2,17	ton
Concrete	302,4	ton
Wood	0,6	ton
Electricity	62000	kWh
Land occupation	48	m^2
Outputs	*Qty.*	*Units*
Partial AD effluent	11.230	m^3
Treated sludge	2.725	m^3

MFC		
Inputs	*Qty.*	*Units*
Rubber	0,86	ton
PMMA	12,272	ton
Steel	18,25	ton
PET	0,26	ton
Electricity	4087	kWh
Land occupation	8	m^2

Outputs	*Qty.*	*Units*
Electricity	70,2	kWh
MFC Effluent	11230	m^3

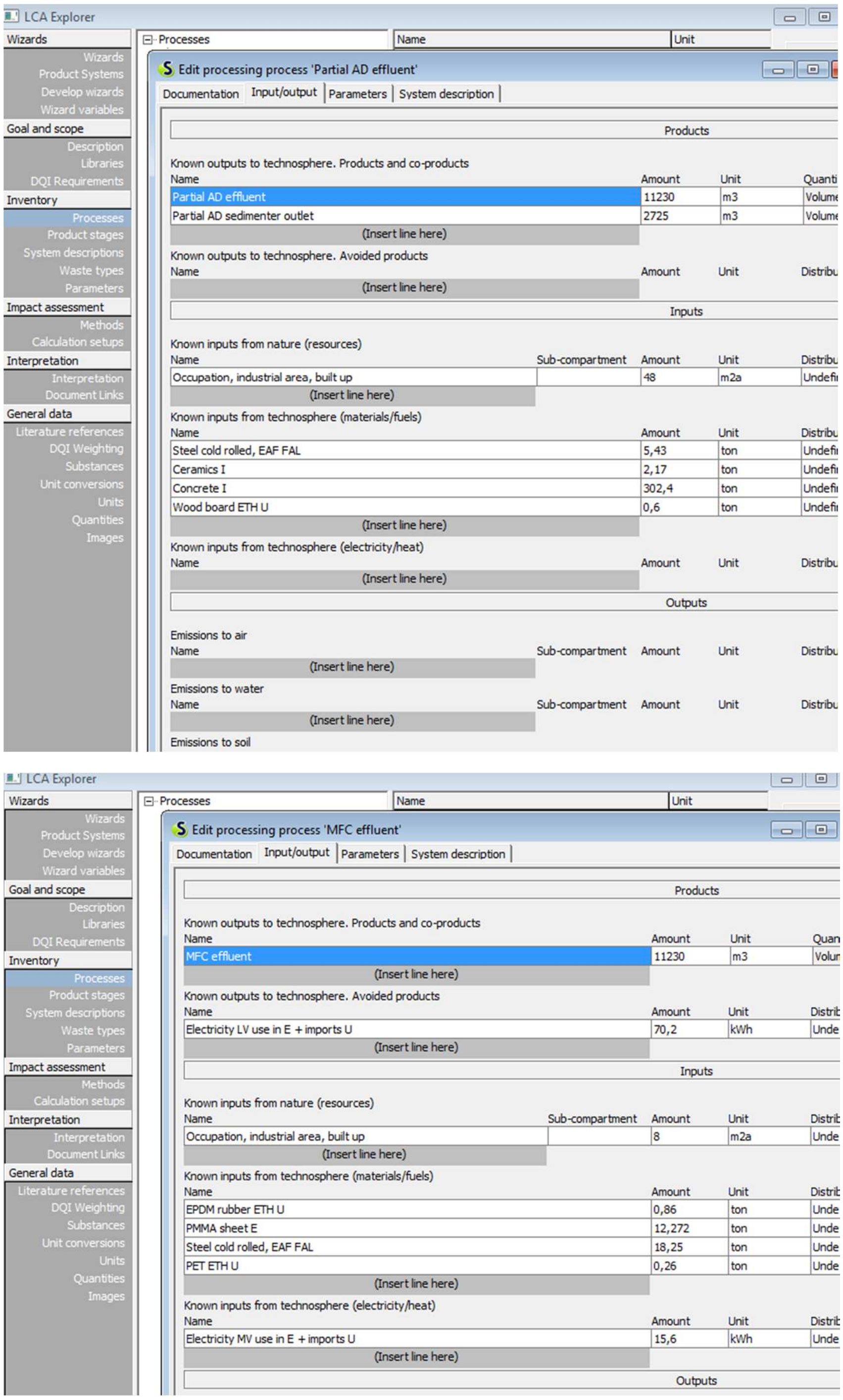

Fig. 4. CASE A sub-unit processes definition

Here it is important to notice that an allocation of outputs to the technosphere has been done using the attributional modelling approach in the case of the partial AD. Specifically, a 75% allocation has been attributed to the treated sludge.

Once materials and processes have been created the life cycle

As for CASE B, the process unit of anaerobic digestion that follows has been considered:

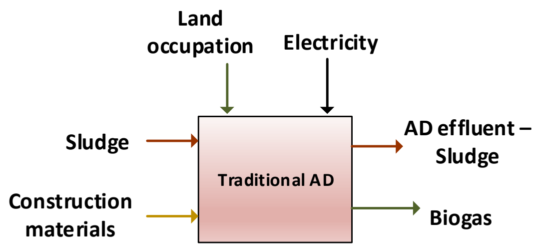

Fig. 10. Details of CASE B process

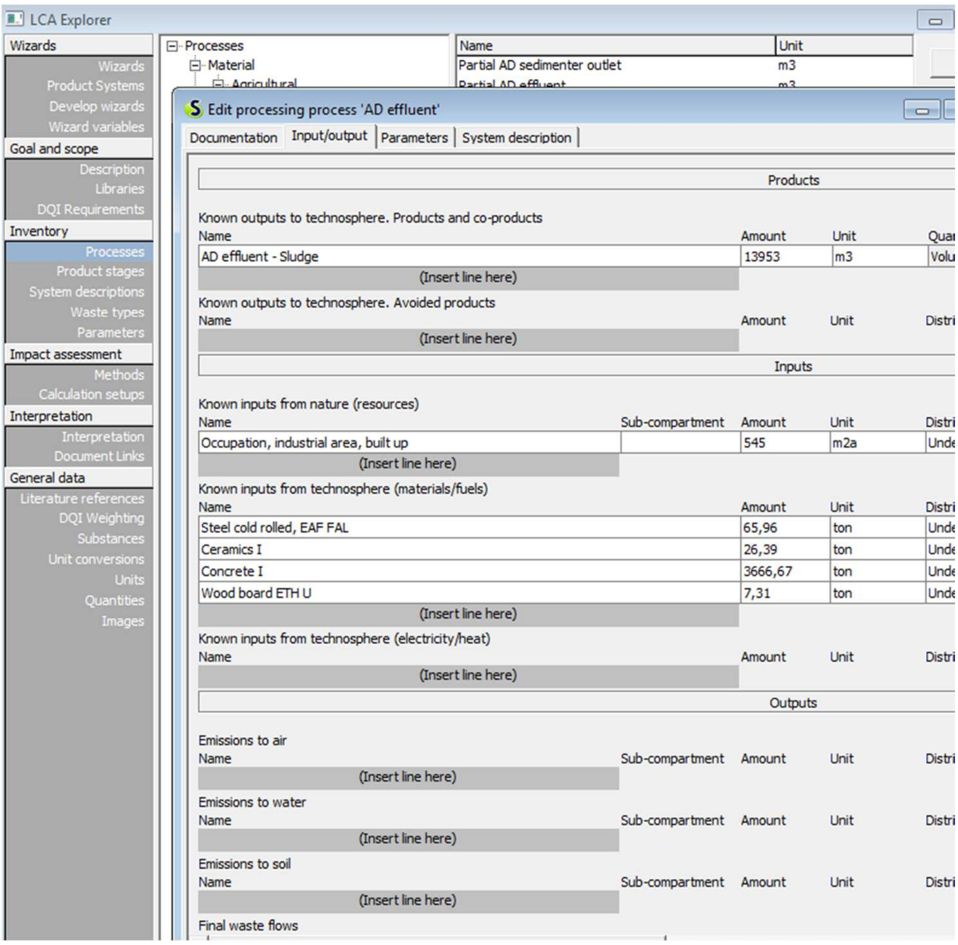

Fig. 11. CASE B process definition

Table 18. LCI for process unit – Partial AD

Traditional AD		
Inputs	*Qty.*	*Units*
Steel	65,96	ton
Ceramics	26,39	ton
Concrete	3666,67	ton
Wood	7,31	ton
Electricity	889.062,70	kWh
Land occupation	545	m^2
Outputs	*Qty.*	*Units*
AD effluent - Sludge	13.935	m^3

As for CASE C, no process unit has been considered since the sludge is not treated and just dewatered and landfilled.

Regarding the end of life scenario of the treated sludge, dewatering and landfilling scenario similar in the three cases has been defined. Hence, three waste scenarios have been created for case A and case B considering the energy consumption for dewatering of each amount of sludge and the transport by truck to the landfill (250km distance).

Table 19. LCI for waste scenarios from CASE A, B and C

Waste Scenario	CASE A – Prototype sludge landfilling	CASE B - WWTP Sludge landfilling after AD	CASE C – WWTP Sludge landfilling
Dewatering energy (kWh)	4.087	11.655	20.902
Truck 40t transport (tkm)	70.000	350.000	627.500

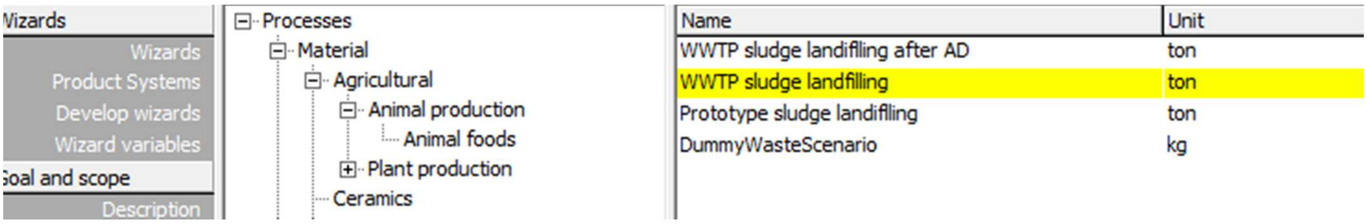

Fig. 12. Example of waste scenario definition.

ASSEMBLY

One main assembly has been defined, the sludge production.

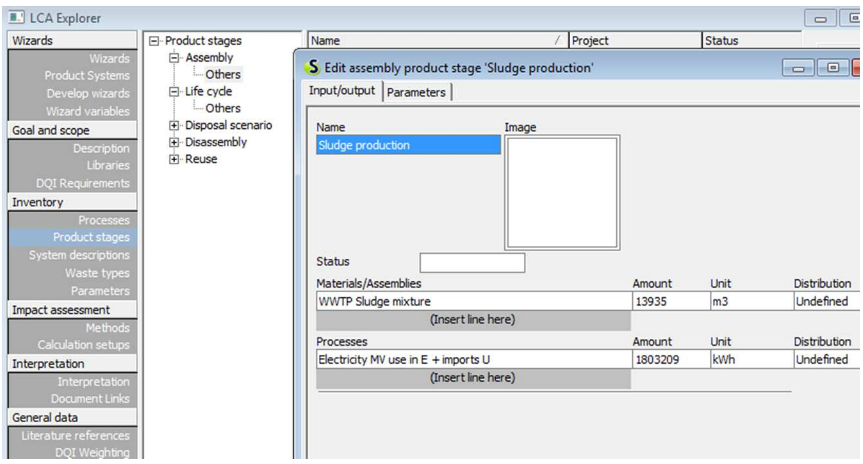

Fig. 53: Assemblies definition

LIFE CYCLE

For the life cycle, the valorisation cases have been defined, using the materials and transformation unit processes as well as the assembly and waste scenarios produced before. As example, the LCA of the Case A is provided next.

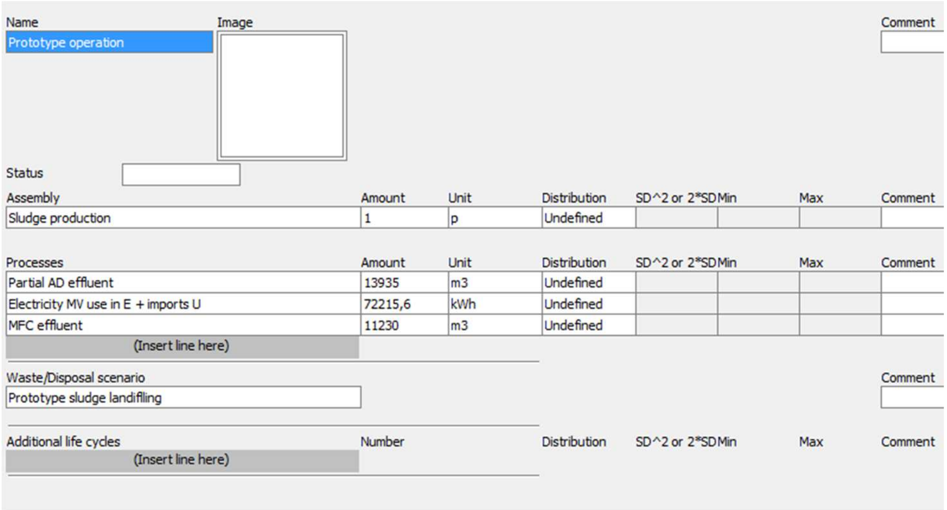

Fig. 64: LCA definition for CASE A

5.4 Step 4: Impact assessment

5.4.1 Overall considerations

As for the impact assessment, several methodologies can be used. CML (31%), EDIP (21%) and Eco indicator 95 or 99 (EI95/99; 14%) are the most widely used LCIA methodologies.

Selection of the assessment methodology becomes crucial. One of the parameters to be taken into account is the coverage of more impact categories as well as if they include the optional steps of normalisation or weighting which provide information using the same reference and, hence, it is easier to draft conclusions.

In regards to the approach followed by each method, the majority of the methods use the problem-oriented (mid-point) approach as opposed to the damage-oriented (end-point) approach. It is often argued that the mid-point approach provides more reliable results, while the results from end-point methods are easier to understand and use for decision making. Thus the application of two fundamentally different approaches will obviously provide a greater certainty in the assessment. The impact chain describes the environmental mechanism from “exchanges” to “endpoints”. An “endpoint” is something that needs to be protected (a value item) such as trees, crops, rivers and human health. A “midpoint” in the other hand, refers to all elements in an environmental mechanism of an impact category that fall between environmental exchanges and endpoints. An example of an exchange is the emission of CFC gases, which causes a depletion of the ozone layer in the stratosphere (mid-point), which results in increased levels of radiation (mid-point) that eventually cause a certain number of people to die from skin cancer (end-point) depending on exposure and sensitivity on receiving environment (dark versus light skin colour, amount of sun block etc.). This is the second parameter taken into account in the selection.

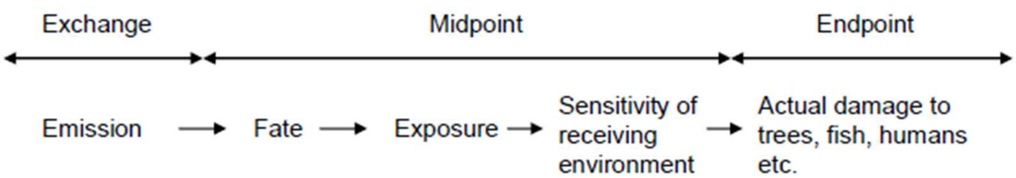

Fig. 75: Midpoint and Endpoint scenarios

A third issue that must be taken into account when selecting an impact assessment method is how long ago the method was developed. The assessment of environmental impacts is a dynamic field where new information is made available every day. Thus, a method which is developed based on the best information available ten years ago might be not too applicable today. Therefore, the third parameter taken into account in the selection is the "age" of each method.

5.4.2 LCI for MFC4Sludge project LCA

From all the methodologies available in SimaPro two of them have been selected in order to compare results and also to cover different impact indicators.

- CML as a Mid-point method, where main impacts assessed are abiotic depletion, global warming, ozone layer depletion, human toxicity, water ecotoxicity, acidification and eutrophication
- Eco-Indicator 99 – Europe as an End-point method, which has proven to be applicable to analyse the environmental impact of agricultural systems as it gives a comparative analysis of the systems under investigation related to global warming, acidification, eutrophication and summer smog.

Therefore, the impacts to be considered in this study are: abiotic resource exhaustion, global warming, ecotoxicological and human toxicological impacts, ozone layer depletion, photochemical oxidant formation, acidification, eutrophication and land use.

Methodology: CML baseline 2000

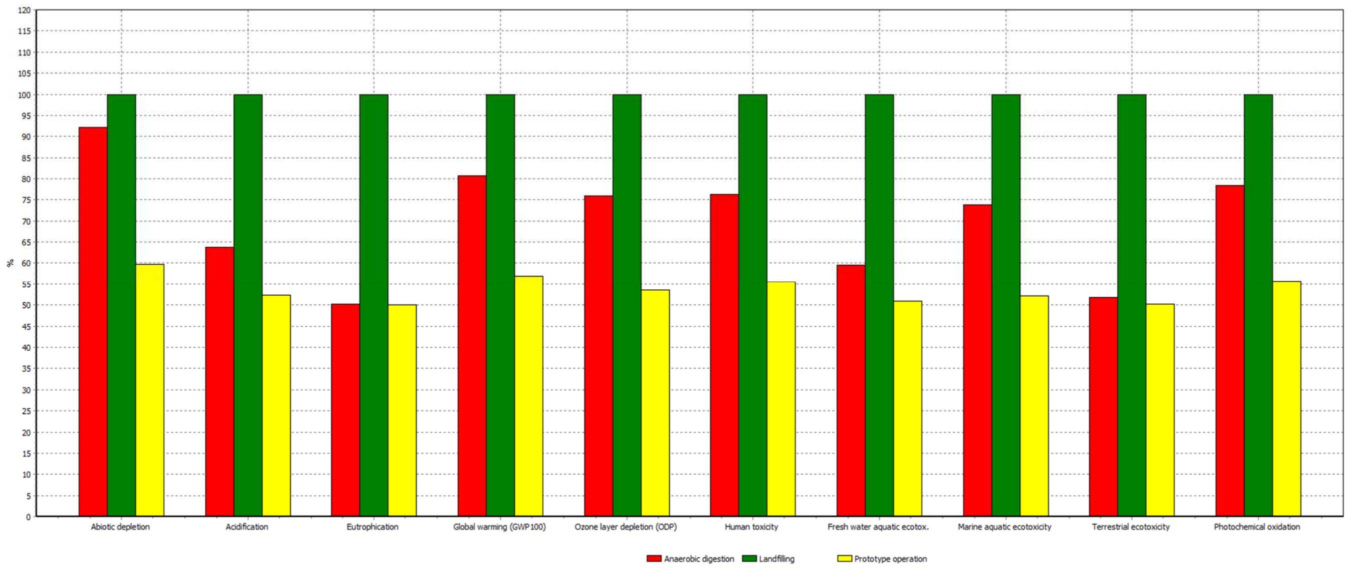

Fig. 16: Midpoint comparative LCA – characterisation

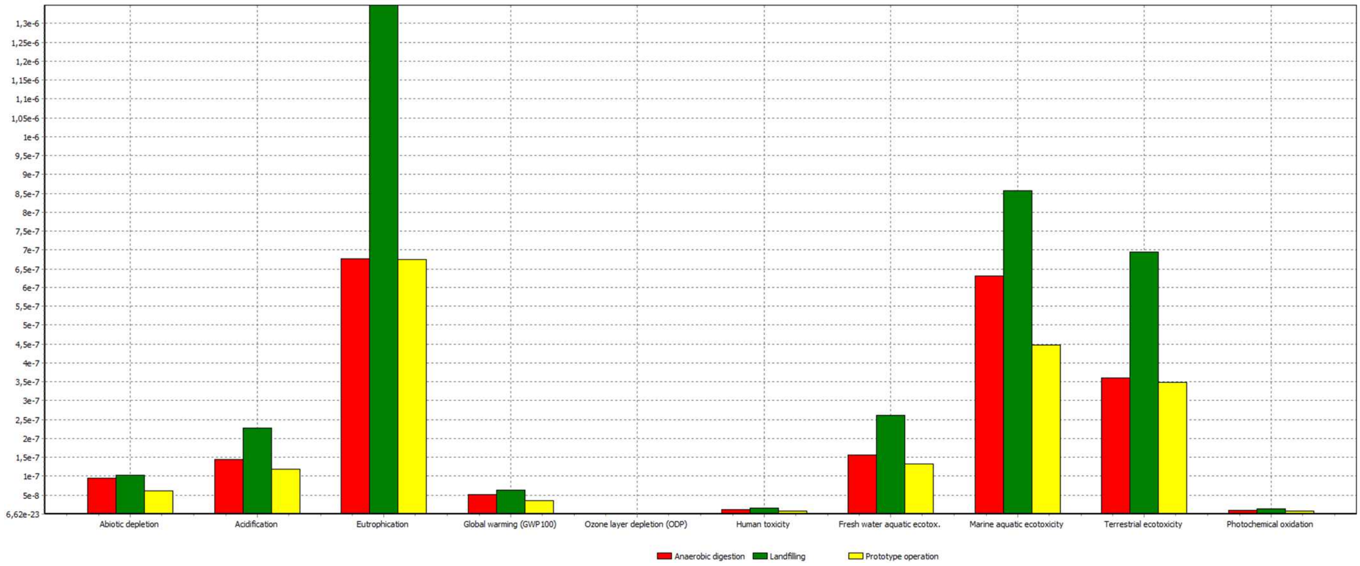

Fig. 17. Midpoint comparative LCA – normalisation

Methodology: Eco-Indicator'99 – Europe

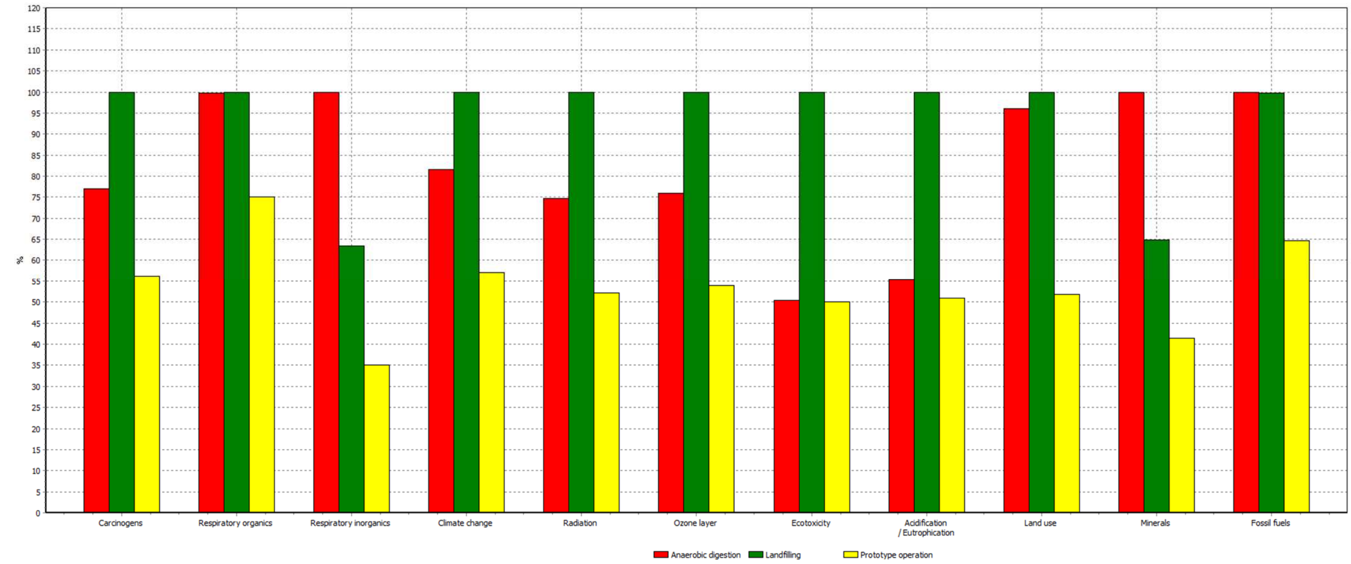

Fig.18: Endpoint comparative LCA - characterisation

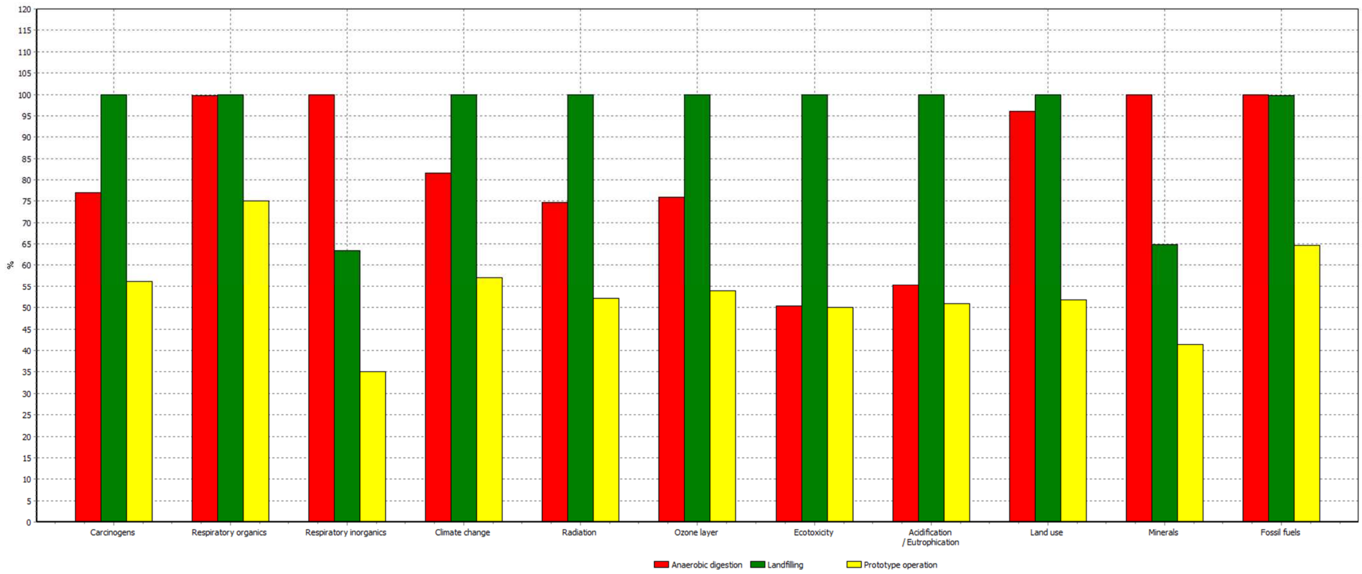

Fig.19: Endpoint comparative LCA - damage assessment

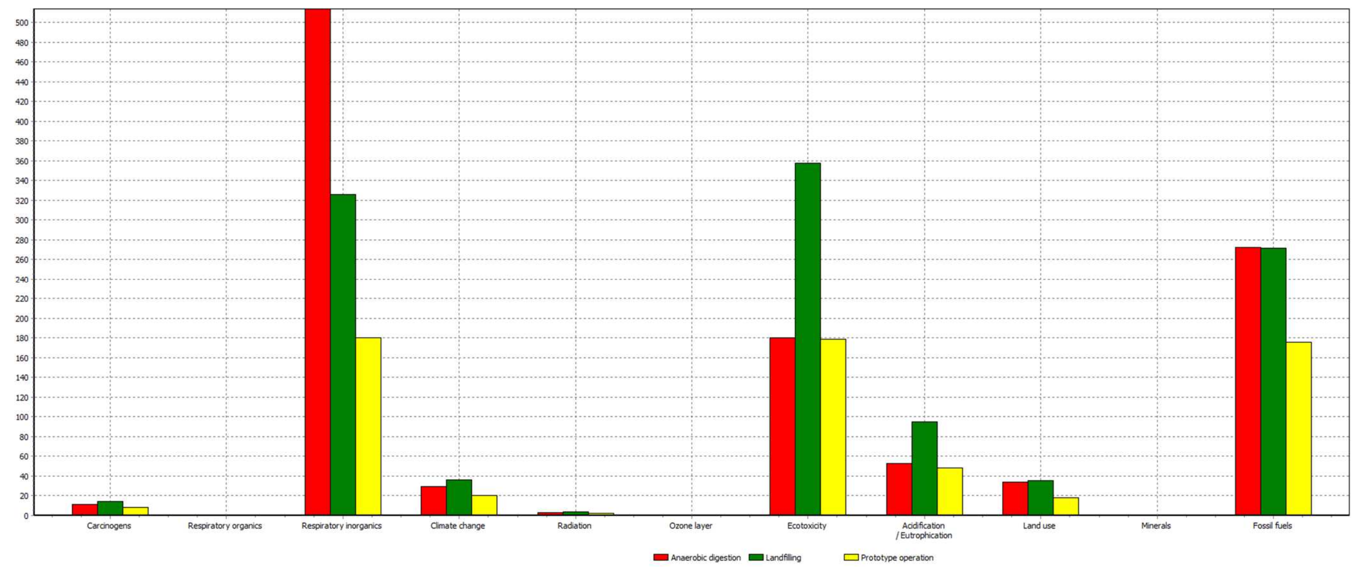

Fig. 80: Endpoint comparative LCA - normalisation

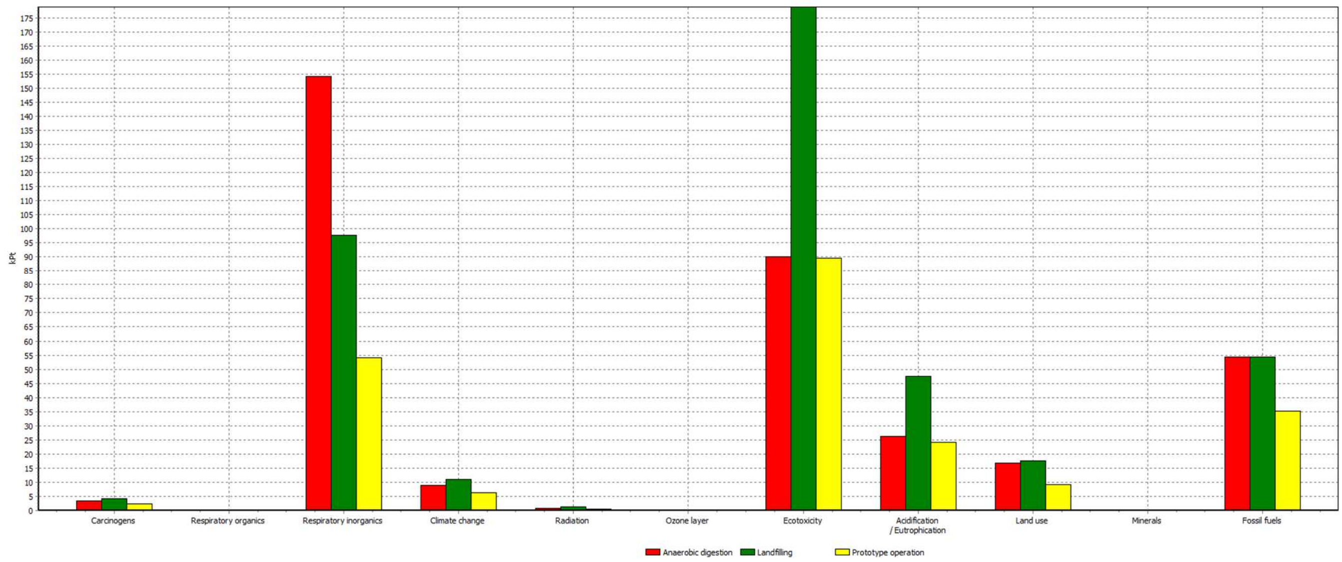

Fig. 91: Endpoint comparative LCA - weighting

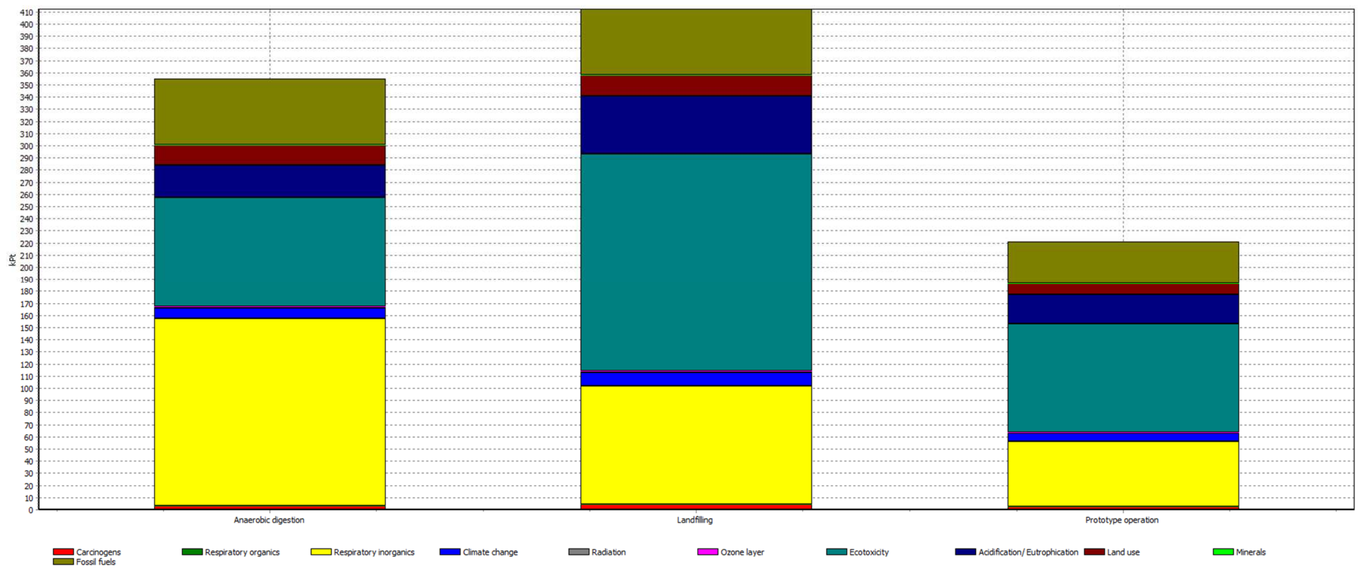

Fig. 102: Endpoint comparative LCA - single score

5.5 Step 5: Interpretation

5.5.1 Interpretation for MFC4Sludge project LCA – Cases comparison

From a Mid-point of view (using CML baseline 2000) the following conclusions can be drafted:

- Main impact of sludge treatment processes is related to ecotoxicity effects and eutrophication of the media. Biggest impact is allocated to landfill since the lack of treatment produces a higher amount of sludge disposal, i.e. emissions from landfilling and impact of transportation are bigger than in the other cases. Regarding anaerobic digestion and prototype use, the majority of negative environmental impact are caused by electricity consumption and transportation/disposal of treated sludge. This is a common issue for wastewater treatment processes, with energy consumption (e.g., for pumping and aeration) accounting the most for environmental impact.
- Both AD and prototype use have normalized benefits mainly accounted in the “respiratory inorganics”, “global warming”, and “non-renewable energy” categories.
- In general terms, it can be drafted that the case with lower environmental impact is the use of the prototype. This is mostly due to the lower use of materials for its construction (when compared with the traditional AD), lower land occupation and lower energy consumption as well as by the positive contribution of supplying electricity. Currently, this contribution is small and therefore there is a need to improve the MFC performance so as to increase this positive environmental impact, but it can be used as evidence of the lower environmental impact of the proposed sludge management solution.
- The life cycle global warming emissions from MFC-generated electricity are calculated to be around 0.6 kg CO_2-e per kWh. Which is not so far from 0.56 kg CO2-e per kWh for UK grid electricity for example. Considering the wide room for technology improvement, this allows to draft that the process solution could achieve a lower CO2 emission for electricity production than current fossil-fuels based production.

From and End-point of view (using Eco-Indicator’99) the following conclusions can be drafted:

- Weighting step of the analysis provides accurate information about the most important categories to be considered. Fossil fuels consumption is a important impact category due to the use of electricity and materials. Although both AD and the prototype produce energy, which has a positive impact in fossil fuels, the energy required for the operation of AD is higher than the required for the prototype operation. Hence, prototype impact in fossil fuels is lower.
- Another important factor is land-use, which can be seen that in long term will be lower for the prototype.
- Again, also in the long term, ecotoxicity and acidification/eutrophication are the most important impacts affected by sludge treatment. Moreover, respiratory inorganics must be considered in the long term, especially for the AD.
- Single score comparison provides crucial information since it can be drafted that prototype operation has the lowest environmental impact. Taking a closer look and considering the single score impact for human health, ecosystem quality and resources, it can be seen from the picture below that the lower environmental impact of the prototype operation is mainly due to a decreased human health and resources used when compared with anaerobic digestion. This is due to the positive contribution of the energy produced by the MFC.

5.6 Sensitivity study

In order to low the environmental impact of the proposed solution, strategies aimed to introduce changes must be applied. As for AD, a lot of strategies can be found in literature, while the MFC field is still unexplored.

Hence, a sensitivity study has been carried out so as to identify the aspects that contribute in a higher extent to the MFC environmental impact. This will set the base for future decision and also will identify future topics for further R&D activities.

A closer look to the MFC impact in the long term (using the Eco-Indicator 99 (E) method) provides the following information (for simplicity only the single score is presented).

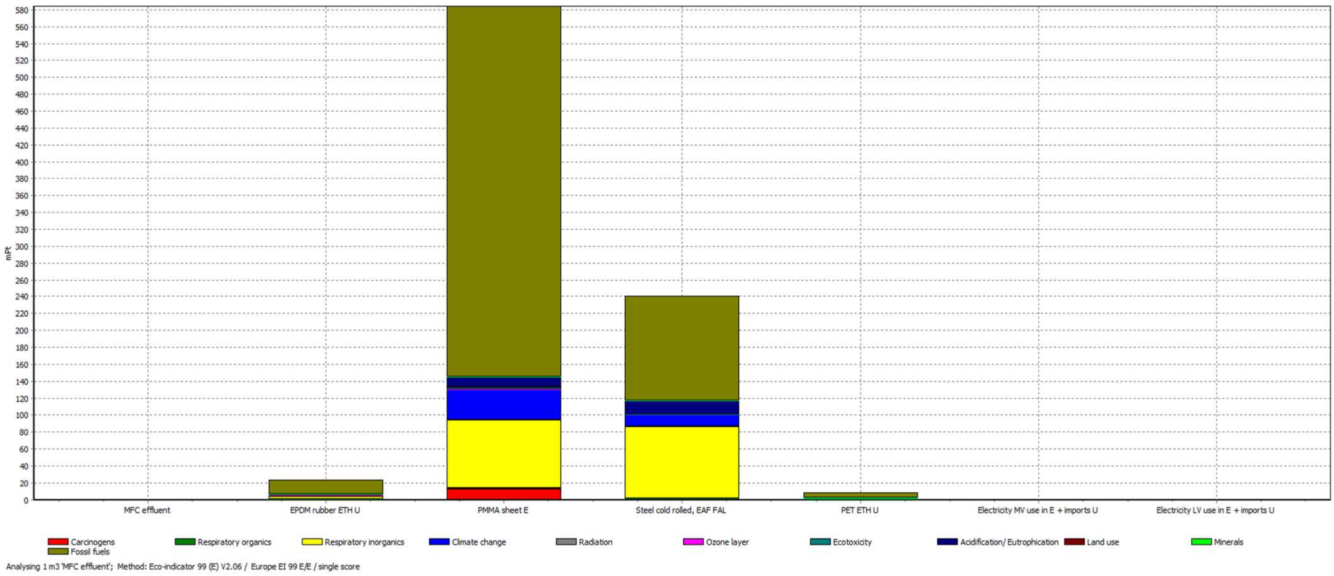

Fig. 23. Analysis of the different aspects contributing to MFC environmental impact.

It can be seen that the aspects that most contribute to the MFC impact are the materials used in its construction. In fact, positive environmental impact of energy produced is eclipsed by the contribution of PMMA and steel to the whole system LCA.

As for the sensitivity study is therefore decided to study two potential alternatives, i.e. the replace of PMMA by other polymers/plastics in order to study its contribution in the whole MFC impact. Current commercial alternatives to PMMA that can be found in the market are PC (polycarbonate) and PVC (Polyvinyl chloride). The analysis of the three options provides the following information:

- Mid term (use of mid-point method CML 2000): the most noticeable impact is the one from PVC use in fresh water aquatic ecotoxicity and this could suggest that replacing PMMA by PVC would not have a positive impact. However, a closer look helps drafting that use of PMMA has a higher impact in Global warming (CO2 emissions go from 12,6 kg CO_{2eq} for PMMA to 7,03 kg CO_{2eq} for PVC). As for the rest of important parameters such as the ones related to abiotic depletion, acidification and marine aquatoxicity is also the PMMA the most dangerous.

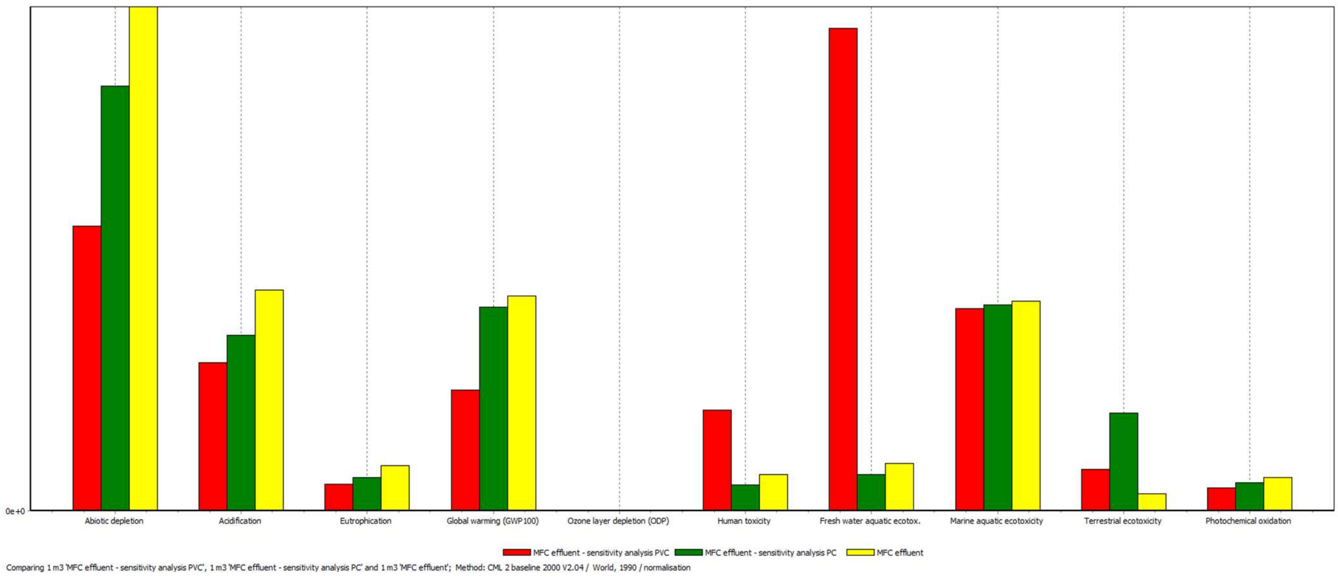

Fig. 24. Mid-term sensitivity study of MFC construction material

- Long term (use of end-point method Eco-Indicator 99): it can be drafted that the most important impact to consider when selecting the material for building the MFC is the use of fossil fuels. In this case, use of PMMA provide by far the highest impact in fossil fuels consumption (it almost duplicate the impact of PVC). However, carcinogens impact is extremely high for PVC. In order to have an objective view of the three materials, single score must be analysed.

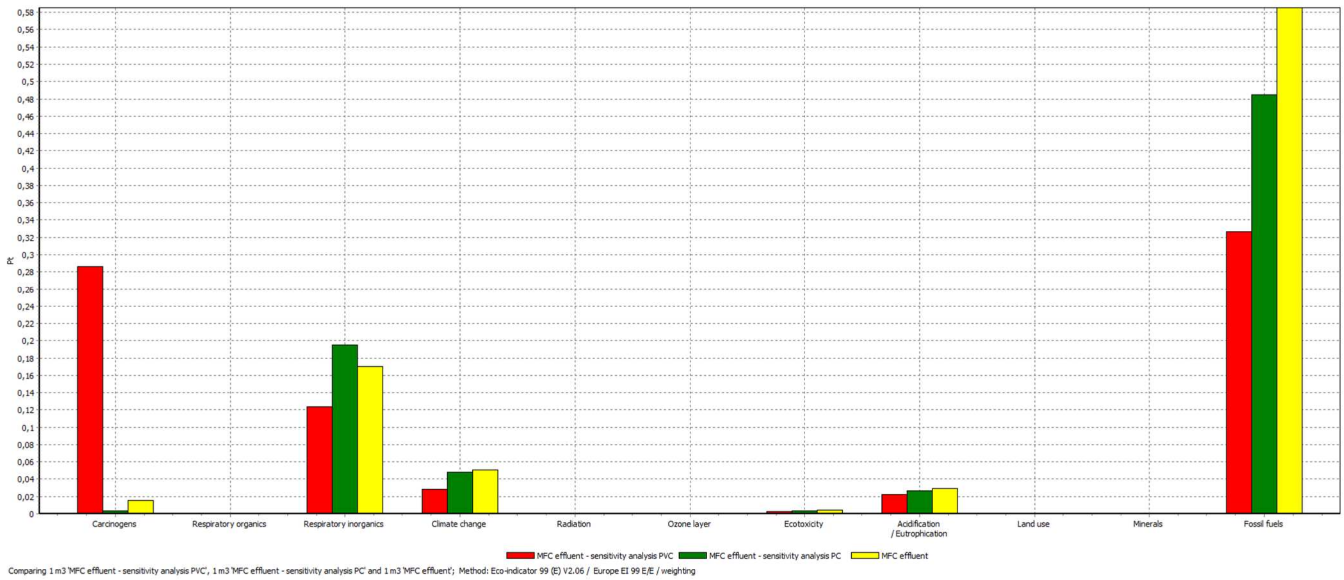

Fig. 25. Long-term sensitivity study of MFC construction material

From single score point of view it can be concluded that environmental impact is as follows: PMMA >> PVC >> PC. By taking a closer look it can be noticed that ecosystem quality impact is similar for the three materials and that the real difference is the human health impact, which is higher in PVC. Alternatively, as it was shown previously resources impact is higher for PMMA mostly due to PMMA use of fossil fuels for its production.

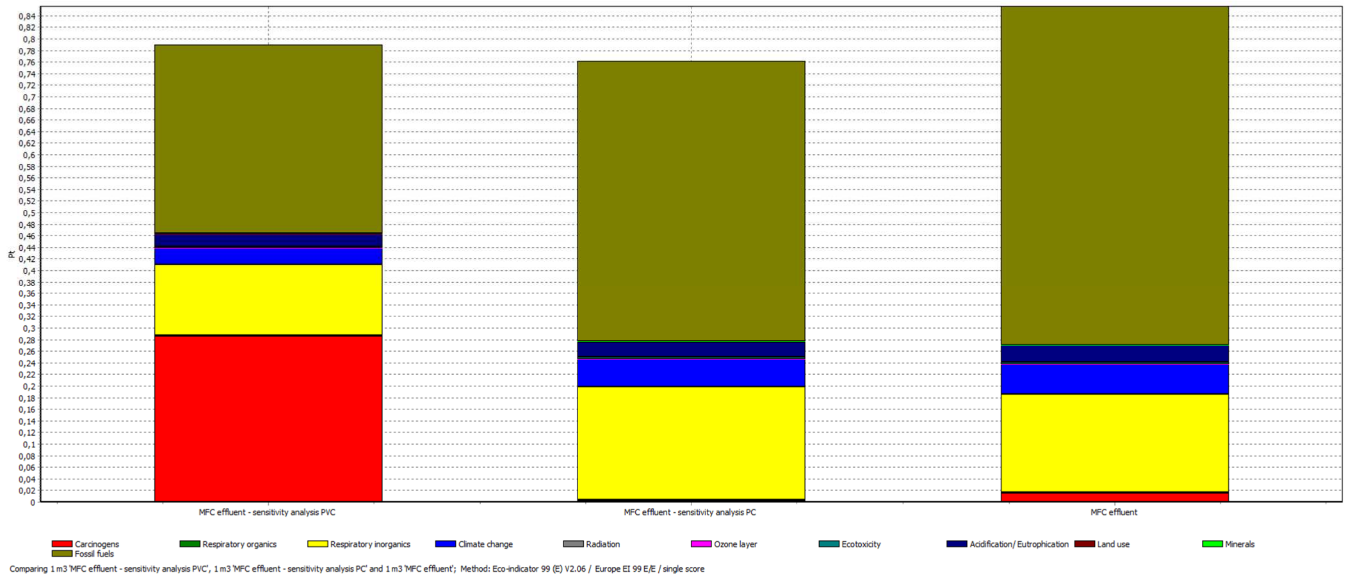

Fig. 26. Long-term sensitivity study of MFC construction material (single score)

Fig. 27. Long-term sensitivity study of MFC construction material (single score-overall impact categories)

6. Conclusions

A techno-economic analysis has been performed to evaluate MFC4Sludge project performance. Technical requirements for the operation of the deployed 10L MFC pilot scale prototype are given. Technical recommendations for industrial users were also provided to ensure energetic profitability of a future up scaled version of the prototype deployed.

Regarding economic profitability of the proposed approach, a financial analysis has been carried out, being the following the main findings:

- Financial Net Present Value on investment is negative for power installations of 250, 500 and 700 We. However, they result positive for 15 and 30 years-long time horizons of the 700We with modified MFC scenario. This leads to the need to plan plants with a relatively long expected lifespan and, where maintenance and replacement costs have to be curbed. Main improvements/modifications of the scenario are:
    - Reduce the cost of fabrication of the cells.
    - Increment the energy production.
    - To valorise remaining sludge, i.e. to sell it as fertiliser.
- Models show a high sensitivity to some variables, such as electricity price and seasonal variation (WWTP and prototype performance is affected by incoming wastewater conditions). The effect of these variables must be completely characterized in order for the rest of the Cost Benefit Analysis to be realistic.

Regarding environmental impact of the proposed solution for sludge waste valorisation, it has been compared to the traditional procedures and the following conclusions can be drafted:

- In the midpoint, the deployment of the proposed solution would have a positive impact in global warming (since it produces energy, decreasing this way the energy consumption of the wastewater treatment plant since it could use its own produced energy). Regarding anaerobic digestion and prototype use, negative environmental impact is mostly due to electricity consumption and transportation/disposal of treated sludge.
- From and endpoint approach, the main positive impact is climate change, respiratory inorganics, minerals and fossil fuels. This is due to the long-term effect of the decrease of energy production, i.e. the use of renewable energies. This is fully aligned with the European targets related to the use of renewable energy, helping this way to address planned scenarios. Land occupation impact ofr MFC4Sludge solution is the lowest of the evaluated cases.
- Moreover, after a closer look to MFC environmental impact, it can be drafted that the main drawback in MFC use is the resource and emissions-intensive materials required for its construction (i.e., stainless steel, membrane materials such as PMMA, etc.). This represents a substantial opportunity for future improvements by appropriate materials selection and development. Hence, a sensitivity study has been conducted in order to study the replacement of PMMA by other polymers and plastics such as PVC or PC. The one with lower environmental impact is PC. However, further improvements in net contributions could be expected if a bioplastic is used for membranes or electrodes construction.

In brief, the use of the prototype as alternative to traditional approaches when valorising WWTP waste might have a positive impact in the environment, especially concerning the use of fossil fuels and global warming. These conclusions must be viewed only within the tightly framed context of this analysis and the conditions used in prototype operation. Different construction materials, operating performance parameters, background inventories (e.g., different countries energy mix), and different LCIA methodologies may alter the outcomes, particularly in comparing cases A and B.

Finally, as a summary, the potential of the proposed solution has been confirmed from economic and environmental point of view and the aspects to be improved for a full market commercialisation have been pointed out. These results provide evidence that the performance of an MFC needs to exceed at least 500 W/m^3 reactor to be competitive with existing anaerobic treatment technology. Although there is a considerable scale-up challenge, these results suggest that there is sufficient cause from the analysed perspectives to continue the development and commercialization of MFC4sludge proposed technology.