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² Nature of the deliverable: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

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List of acronyms and abbreviations

AMBR	Aerobic membrane bioreactor	TET	Terrestrial Ecotoxicity
AnMBR	Anaerobic membrane bioreactor	UASB	Up-flow Anaerobic Sludge Blanket
BES	Bioelectrochemical system	UV-LED	Ultraviolet light-emitting diode
BW	Black water	WC	Water consumption
CC	Climate Change	WWT	Wastewater treatment
FE	Freshwater Eutrophication	WWTP	Wastewater treatment plant
FET	Freshwater Ecotoxicity		
FRS	Fossil Resource Scarcity		
FW	Food Waste		
GW	Grey water/ Global warming		
HTAD	Hyperthermophilic Anaerobic digestion		
HTc	Human Carcinogenic Toxicity		
HTnc	Human non-carcinogenic Toxicity		
IR	Ionizing radiation		
LCA	Life Cycle Assessment		
LU	Land Use		
ME	Marine Eutrophication		
MEC	Microbial Electrolysis Cell		
MET	Marine Ecotoxicity		
MFC	Microbial Fuel Cell		
MRS	Mineral Resource Scarcity		
OFH	Ozone Formation Human Health		
OFH	Ozone Formation Terrestrial Ecosystems		
PMF	Fine Particulate Matter Formation		
SBR	Sequencing Batch Reactor		
SOD	Stratospheric Ozone Depletion		
TAD	Thermophilic anaerobic digester		
TA	Terrestrial Acidification		



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1. Introduction

Life Cycle Assessment (LCA) is a methodology that quantifies the impacts on the environment and supports the decision-making procedure for sustainable development. It is a tool that, due to its ability to operate along various value chains, high data collection and increased awareness of the population regarding the protection of the environment, has undergone a high development since its conception in the 1970s (Guinée et al., 2011)(Sevigné-Itoiz et al., 2021). The application of the LCA in the wastewater treatment sector began in 1990 and ever since this tool has been used to determine the environmental impacts of different wastewater treatment processes, compare them with each other, analyze the impacts of each of the stages of a process, the comparison between the implementation of various technologies and many other comparisons including the comparison between aerobic or anaerobic systems and centralized or decentralized processes (Corominas et al., 2013).

The set of studies incorporated in this document are part of subtask 5.2.1 or “Life Cycle Assessment” framed within the Run4Life project (Recovery and Utilization of Nutrients 4 Low Impact Fertilizer). The development of the environmental analysis, carried out with the LCA methodology, is characterized by the four stages indicated in ISO 14040: 2006 and 14044: 2006 standards: objectives and scope, analysis of the life cycle inventory, evaluation of the life cycle impact and interpretation of results. The first stage aims to determine the objective of the study, the functional unit, the function of the system and the boundaries of the system (Farjana et al., 2021). Typical functional units of wastewater treatment were used, such as the flow of treated water or person equivalent. However, and due to the multifunctionality of the different demo-sites (wastewater treatment, energy recovery and nutrient recovery), other functional units have been used. For one of the configurations of the Run4Life project, different limits of the system have been evaluated trying to cover this multifunctionality and demonstrating how considering the recovery of resources, in addition to wastewater treatment, improves the environmental impact.

In the second stage or analysis of the life cycle inventory, data has been collected for the creation of an environmental inventory. Mass and energy flows describing the system has been quantified. This is the stage that takes the longest in the analysis. The collection of information has been carried out through a spreadsheet to be completed by the different demo-sites. All the documents were sent to the partners involved, who provided design and operational data. This information has been updated throughout the project, since, in some cases, such as for the Ghent and Helsingborg facilities, the collection of operational data has not been carried out until the last years of the project. As demonstrated by the LCA study conducted for Helsingborg, operational data is vitally important as it defines most of the environmental impact of wastewater treatment facilities. In some cases, when the inventory could not be completed with the data provided by the project partners, bibliography has been used. This is the case, for example, of data related to direct emissions into the atmosphere (for example, possible diffuse emissions of biogas). The third stage of the life cycle analysis transforms the physical flows collected from the inventory data into indicators of environmental impact and in the last stage these results were analyzed with the intention of pointing out the strengths and weaknesses of the systems. The SimaPro 9.0.0.29 software has been used as support for these last stages and the ReciPe 2016 v1.04 characterization method was used to select the different impact categories (both midpoint and endpoint).

2. Environmental assessment for each demo-site

2.1 Sneek demo-site

The decentralized wastewater treatment facility located in Sneek (Netherlands) treats the black water (BW) from 32 houses using ultra-vacuum toilets for its collection and a thermophilic anaerobic digester (TAD). Thermal energy from biogas and two different types of fertilizers from the solid and liquid digestate effluents are obtained. The results obtained for this demo-site were constructed based on modeling with data provided by the Run4Life partners. Figures 1 and 2 show the work done in this regard.

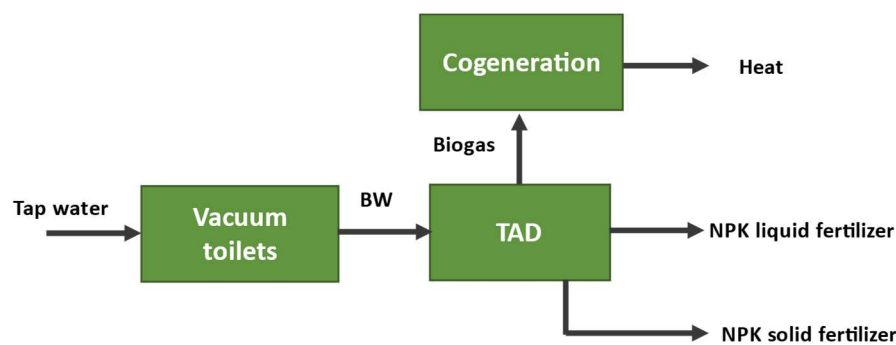


Figure 1. Model scheme for Sneek configuration. TAD: Thermophilic Anaerobic Digestion.

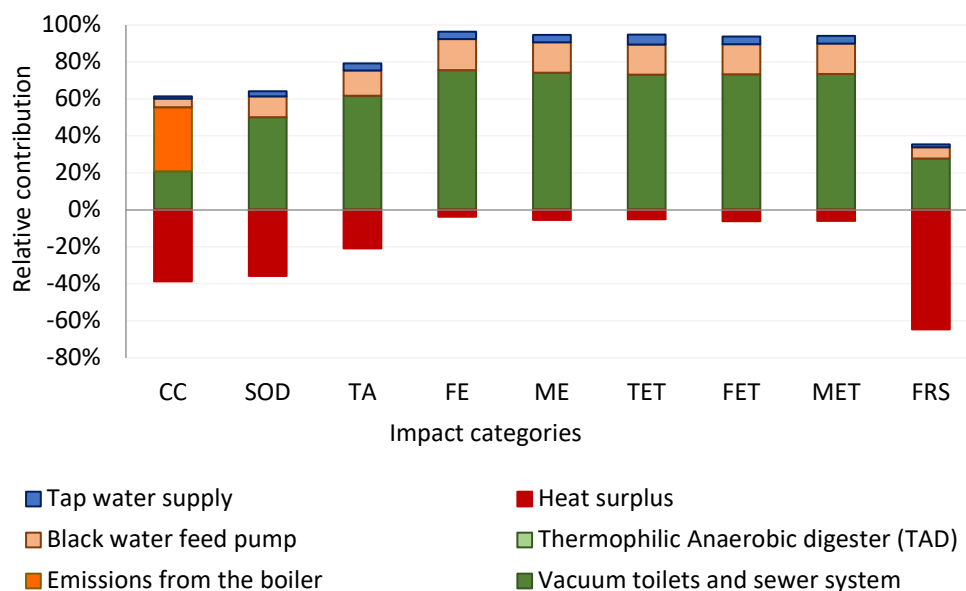


Figure 2. Environmental profile for modelling results. CC: Climate change; TAD: Thermophilic Anaerobic Digestion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; FRS: Fossil Resource Scarcity.

As illustrated in Figure 2, the ultra-vacuum toilets and sewer system for black water transportation have the greatest impact because the energy needed in the TAD was supplied recycling part of the thermal energy produced in the valorization of the biogas. The heat surplus was externalized to the houses and offsets considerably in some impact categories the environmental impact. Global warming, stratospheric ozone

depletion, terrestrial acidification and fossil resource scarcity are some of the most affected impact categories.

To benchmark this decentralized treatment with a centralized one, the greywater treatment has also to be included within the system boundaries. Thus, a partially decentralized system (treating grey water in a centralized water treatment system and black water in the Sneek facility) has been compared to another centralized. Figure 3 shows the different stages of the conventional wastewater treatment system. The stages of extraction and treatment of drinking water, the pumping of drinking water to households, the pumping of the wastewater produced to the treatment plant and the treatment of the wastewater have been included in the analysis. The subsequent stages of waste treatment have not been considered, as well as the construction stages of the facility.

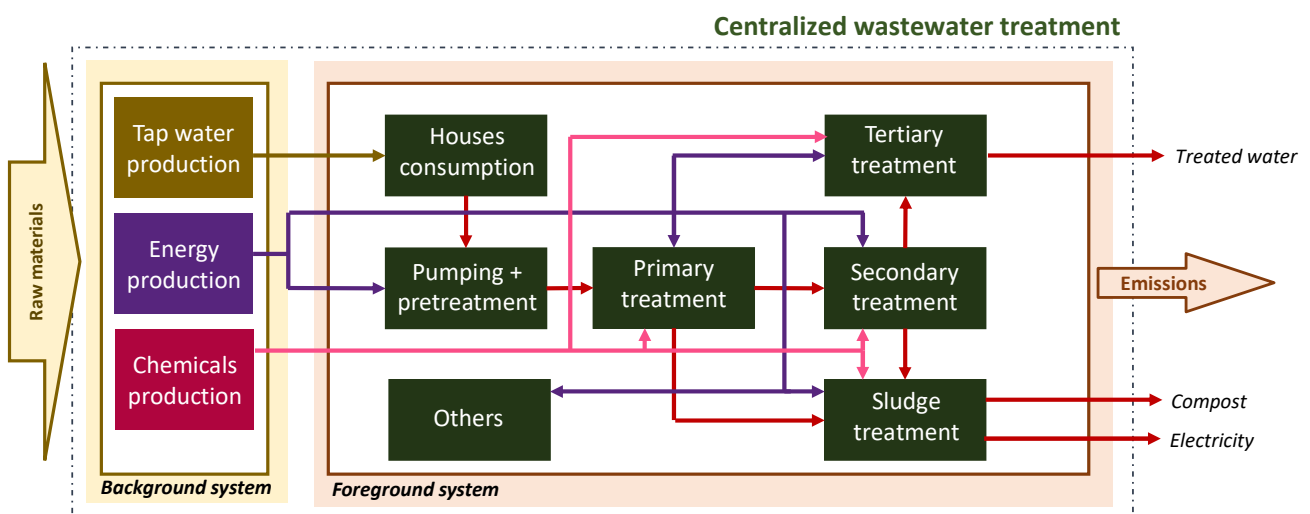


Figure 3. System boundaries and general centralized wastewater treatment scheme.

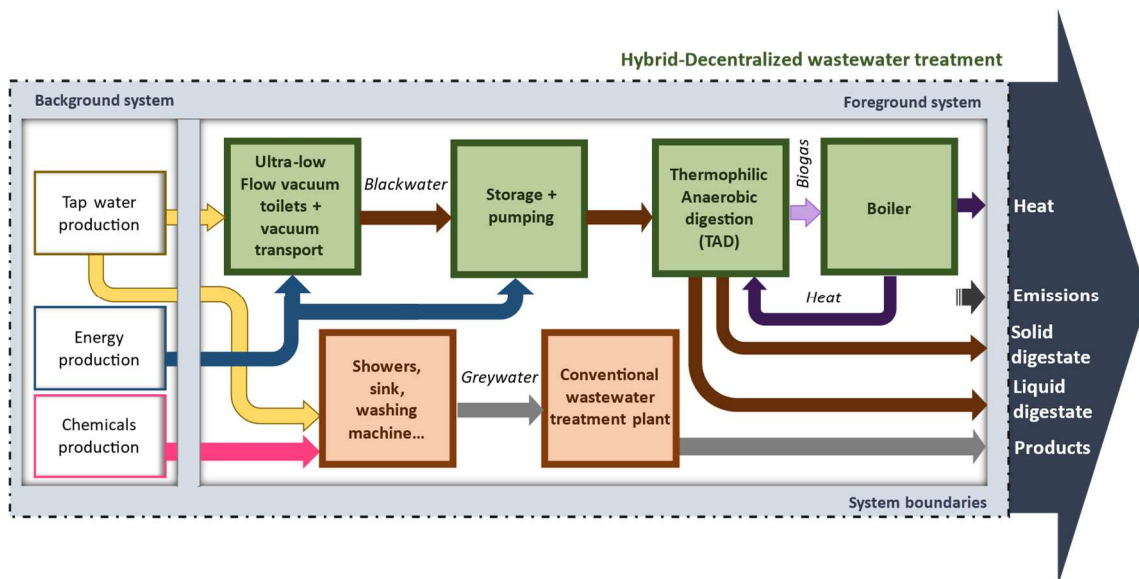


Figure 4. System boundaries and scheme of the hybrid-decentralized wastewater treatment.

On the other hand, Figure 4 illustrates the configuration adopted for the hybrid system and Figure 5 shows the distribution of the environmental impacts. The worst impacts of the hybrid system were due to indirect emissions related to greywater treatment in the centralized plant and tap water consumed in the households rather than

the blackwater treatment in the scheme of Sneek. The main hotspot is the aerobic treatment for greywater rather than the energy demand in the vacuum toilets. The environmental impact of the vacuum toilets is proportionally energy related. The energy consumption of the vacuum toilets (3.53 L/d-person) was compared then with the well-known conventional toilets (49.06 L/person-d). Table 1 shows the energy consumption necessary for the extraction and production of tap water, for its transportation to the households and for the pumping of the wastewater to the treatment plant.

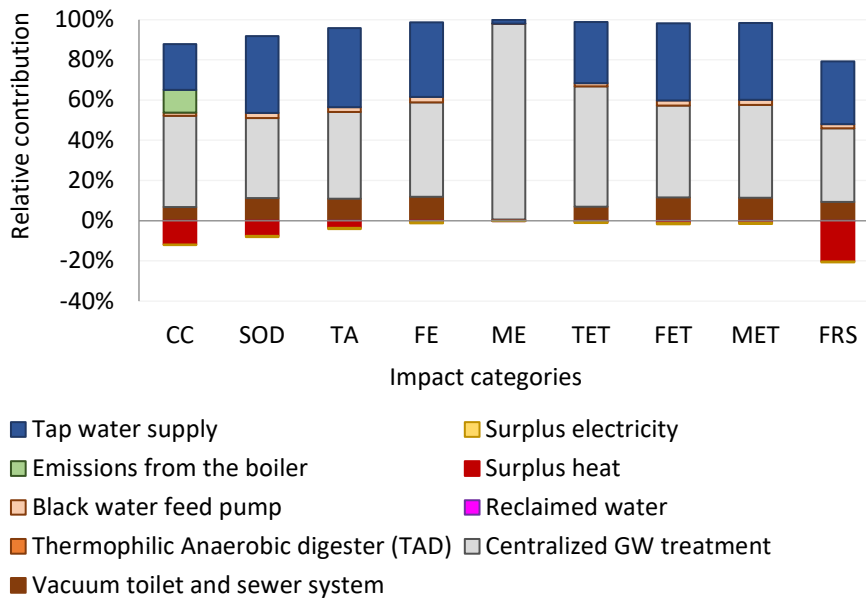


Figure 5. Relative environmental contribution of the different stages of the hybrid wastewater treatment scheme. CC: Climate change; TAD: Thermophilic Anaerobic Digestion; SOD: Stratospheric Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; FRS: Fossil Resource Scarcity.

Table 1. Comparison of the energy consumption in conventional toilets and vacuum toilets (expressed in kWh/person-year)

Stage	Conventional toilets	Vacuum toilets
Extraction and treatment of water	7.05	0.51
Pumping of tap water	3.58	0.26
Wastewater transport	3.58	17.18
Global energy consumption	14.21	17.94

From estimates (Table 1), the energy consumption of vacuum systems has been recorded as slightly higher than that of conventional ones for a 40 km sewer infrastructure and the water consumption was considerably lower in vacuum toilets (around a 93% reduction). Despite its larger energy consumption, the black water collected is more concentrated and thus biogas can be recovered from the organic matter of the wastewater and less tap water is required for flushing.

For a water pumping energy of 0.20 kWh/m³ (Figure 6), the water treatment and wastewater treatment facilities would have to be at distances longer than 60 km to be comparable to the sewer system of a centralized facility

(Gu et al., 2017). The centralized installation in Xinzo de Limia (Spain) has a sewer system of 87.99 km, which results in a total energy consumption of 18.5 kWh/person-year (higher than the demand of the vacuum system). For this reason, the use of vacuum toilets reduces the global energy demand for areas located far away from the centralized wastewater treatment facility.

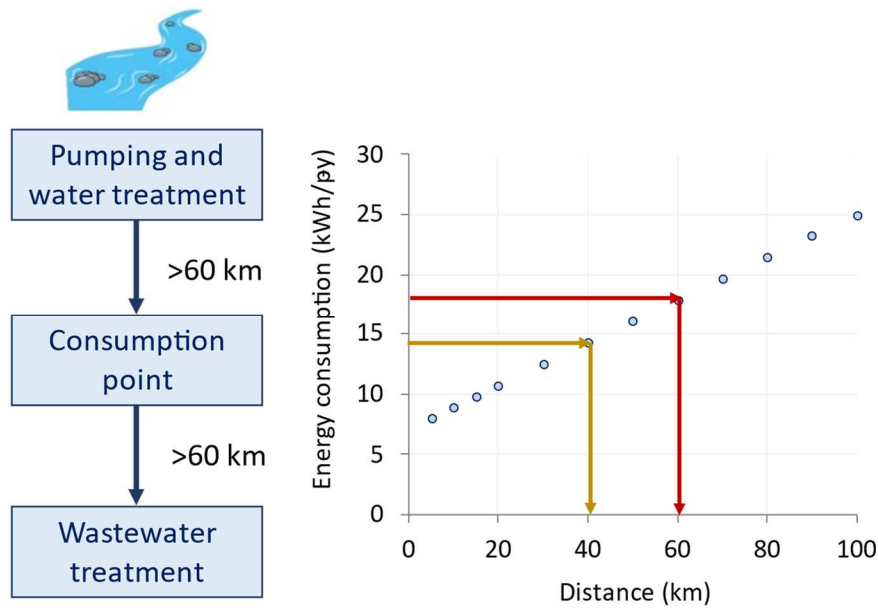


Figure 6. Relationship between the energy consumption from water extraction to wastewater treatment and the distance between the extraction and consumption points and consumption and wastewater treatment points.

In addition to the comparison between the centralized and hybrid systems considering their water treatment function (functional unit of m^3/d), the limits have been expanded to consider the application of fertilizers in agricultural crops using a different functional unit (m^2 of fertilized land). With defined boundaries from cradle to gate, two subsystems were defined. The first includes the wastewater treatment and the production of mineral fertilizers to supplement the exact requirements of nutrient to the crops while the second comprises of emissions and activities related to the agricultural production of carrots, peppers, cabbage, and bush beans. Due to the low rate of fertilizer production in decentralized facilities, its application has been considered for the concept of urban farming seeking to provide the population with local products from renewable fertilizers. Figure 7 summarizes the results of the study conducted as a relative contribution. For both systems, the impact due to the treatment of the wastewater-production of biofertilizer, the production of the mineral nitrogen fertilizer and the emissions derived from the application of the fertilizers are disaggregated.

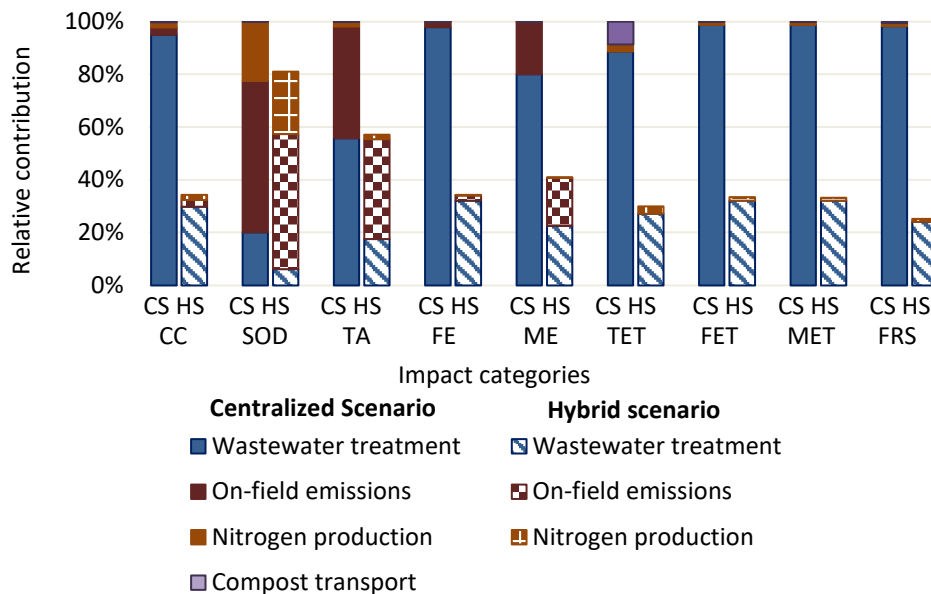


Figure 7. Relative environmental contribution of the different stages of the hybrid wastewater treatment scheme. CC: Climate change; SOD: Stratospheric Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; FRS: Fossil Resource Scarcity; CS: Centralized scenario; HS: Hybrid scenario.

2.2 Vigo demo-site

The decentralized wastewater treatment facility of Vigo treats wastewater (both black and grey water) from an office building that houses 40 small and medium-sized companies. Within the Run4Life project, black water from conventional toilets is treated using an anaerobic membrane reactor (AnMBR). The effluent can be used directly both as a fertilization and irrigation system or can be fed to a Bioelectrochemical system (BES) for nitrogen removal and recovery. Both systems were evaluated. The grey water is treated in an aerobic membrane reactor (AMBR) and the recovered water is used to flush the toilets.

This demo-site presents a compact system that can be used for the wastewater treatment of an office building (with a low flow rate) but also, and due to the scalability of the main equipment included in the system (AnMBR and AMBR), it can be used in other sectors where the treatment flow rate is higher. The treatment of the wastewater of a residential area could be carried out (within the same context established for the Sneek, Ghent and Helsingborg facilities), although it can also be implemented in the tourism sector for hotels and amusement parks. The installation of a decentralized system with this configuration reduces the pressure on the centralized facilities already constructed when intense movements of the population entail a higher flow rate and the plant operates at the limit of its capacity. For these reasons, the modeling of a hotel has been proposed and the wastewater treatment has been performed with a facility similar to that of Vigo. Figure 8 shows the scheme considered.

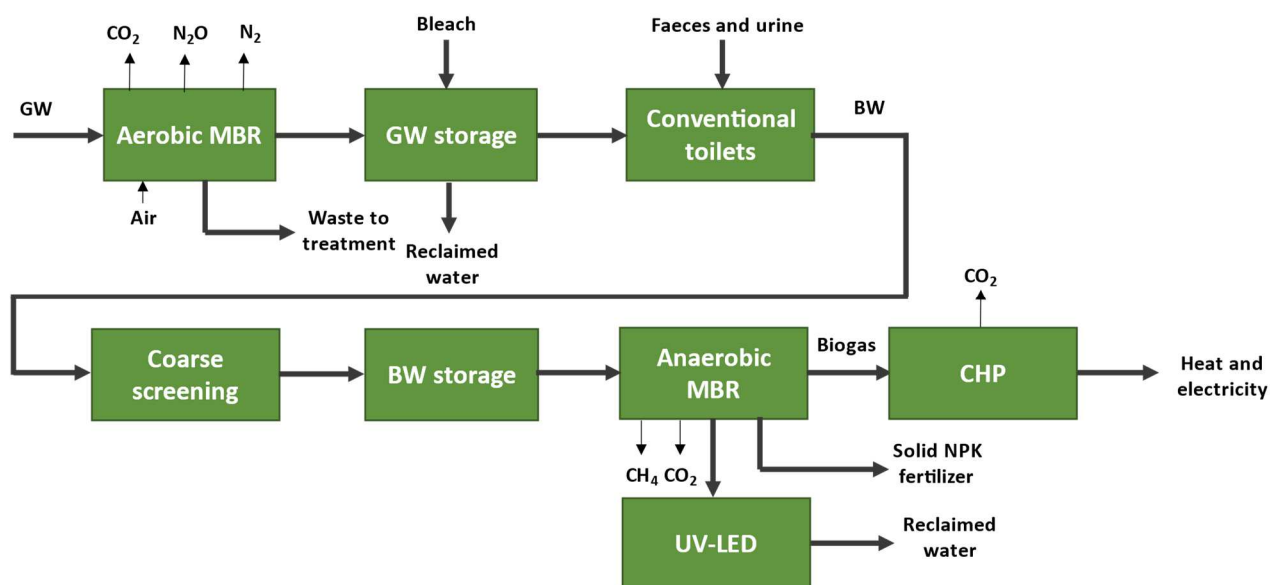


Figure 8. Scheme of the decentralized wastewater treatment of a hotel with the Vigo demo-site configuration.

The environmental analysis compares a centralized and a decentralized system, although an innovative hybrid system (BW decentralization and GW centralization) has also been considered. Using an attributional perspective and an input-based functional unit (cubic meter of wastewater to be treated), the system has been studied using different boundaries. Each boundary of the selected system has included different functions of the system (wastewater treatment and resource recovery). Four possible case studies have been considered:

- 1) The comparative analysis of the facilities considering their wastewater treatment function using gate-to-gate system boundaries (only direct and indirect emissions related to the operation of the facility such as energy and chemicals demand were taken into account).
- 2) Comparison of the systems studied considering, in addition to the wastewater treatment, the supply of the same total mass of fertilizers to the market. The system was expanded to include the effect of the products.
- 3) For the decentralized configuration, the possibility of recovering the treated water and use it in the toilets or in the garden areas of the hotel has been included broadening the limits up to a cradle-to-gate perspective.
- 4) Integration of all the environmental improvements obtained in the three previous case studies and sensitivity analysis of energy variables.

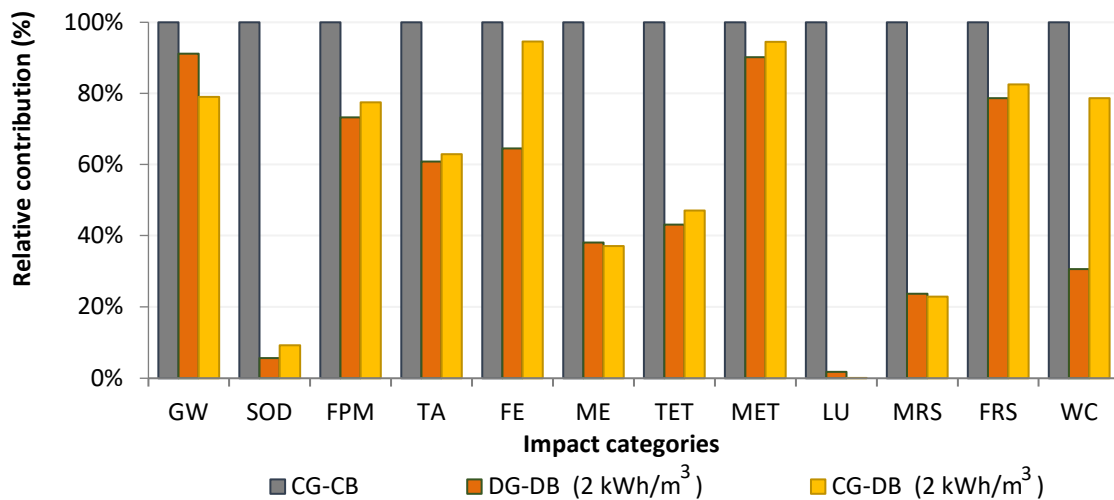


Figure 9. Relative environmental contribution of the comparative profile of a centralized GW and BW treatment (CG-CB), a decentralized treatment for BW and GW (DG-DB) and hybrid treatment for the centralized GW treatment and decentralized BW treatment. GW: Global Warming; SOD: Stratospheric Ozone Depletion; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; LU: Land Use; MRS: Mineral Resource Scarcity; FRS: Fossil Resource Scarcity; WC: Water consumption

Figure 9 summarizes the relative results corresponding to the fourth case study. The figure shows the comparison between a centralized system (CG-CB), the decentralized system with the analogous configuration to that of Vigo demo-site (DG-DB) and a hybrid system in which grey water is pumped to a centralized facility and the black water is treated in a decentralized system (CG-DB). A boundary of the system from cradle-to-gate have been considered and the possible recovery of grey water to flush the toilets has also been taken into account. As can be seen in Figure 9, when the energy consumption in the decentralized treatment of black water is 2 kWh/m³, the environmental profile shows how the implementation of this type of decentralized system improves the environmental impact.

Apart from the direct recovery of nutrients from irrigation, another modeling including the BES has been carried out. The environmental results are shown in Figure 10. The UV unit contributes most to the impact, followed by the AnMBR unit. Irrigation and production of electricity from the biogas revalorization have environmental benefits.

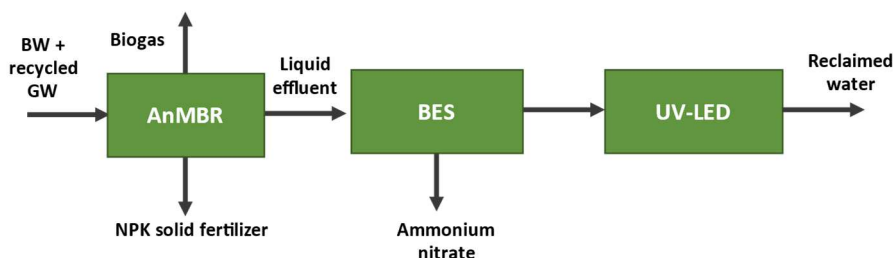


Figure 10. Model scheme of Vigo configuration. AnMBR: Anaerobic Membrane Bioreactor; BES: Bioelectrochemical System; UV -LED: Ultraviolet light-emitting diode.

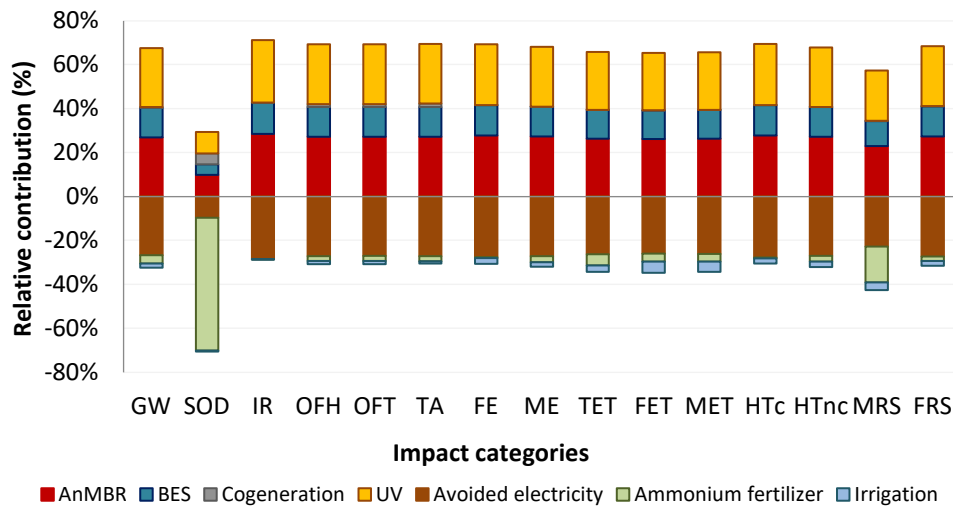


Figure 11. Environmental profile for modelling results. anMBR: Anaerobic Membrane Bioreactor; BES: Bioelectrochemical System; UV: Ultraviolet; GW: Global Warming; IR: Ionizing radiation; OFH: Ozone Formation Human Health; PMF: Fine Particulate Matter Formation; OFH: Ozone Formation Terrestrial Ecosystems; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; HTc: Human Carcinogenic Toxicity; HTnc: Human non-carcinogenic Toxicity; MRS: Mineral Resource Scarcity; FRS: Fossil Resource Scarcity.

Based on the results provided in Figure 11 and to support the development of a novel technology named as bioelectrochemical system (BES), LEITAT has conducted an environmental analysis of this technology. The main objective was to evaluate the environmental performance of the BES system as a reactor to recover nitrogen nutrients that can be used in agriculture. BES can operate in MFC mode or MEC mode. The study allowed the detection of critical operating points of the system and the comparison of both procedures (MFC versus MEC), in order to determine which is the most environmentally friendly in terms of nitrogen recovery.

The functional unit chosen was to obtain 1 kg of ammonium nitrate fertilizer per cubic meter of BW treated by the reactor (MFC or MEC), while reducing the nitrogen content of the treated water. The scope and limits of the system considered in the analysis are depicted in Figure 12. The system considers electricity, water, air and chemicals and their background processes necessary to operate the reactor. As outputs of the system, ammonium nitrate fertilizer and electricity obtained (only for CBM operation) have been considered.

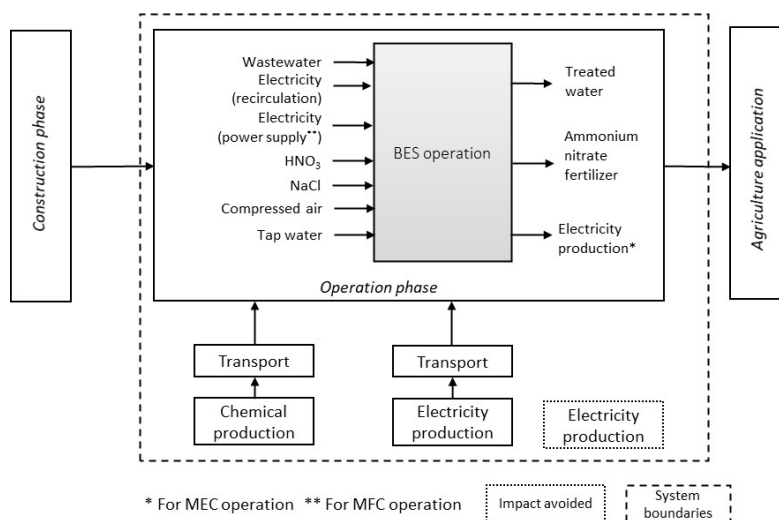


Figure 12. System boundaries of the LCA of BES (Bioelectrochemical System). MEC: Microbial Electrolysis Cell and MFC: Microbial Fuel Cell.

Figure 13 shows the configuration of the BES reactor. The system is composed of an anode and a cathode electrode connected to an external electrical circuit and an ion exchange chamber. Microorganisms oxidise organic matter in the anaerobic chamber, and the reduction takes place in the cathode chamber. Electrons flow through the external circuit and cations migrate across the cationic exchange membrane to balance the electric charge. NH_4^+ is recovered from the cathodic chamber by a stripping system, based on air bubbling over an air-diffusion cathode. Due to the basification of the catholyte, NH_4^+ is converted to NH_3 and the gas is stripped and recovered in the acid trap as ammonium nitrate fertilizer.

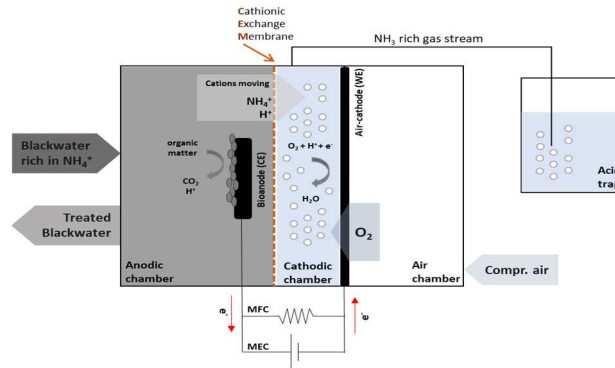


Figure 13. BES reactor of the Run4life project. BES: Bioelectrochemical system.

Data have been obtained from LEITAT and previous experimental and research work conducted at laboratory scale at WP2. The data have been normalized to the ammonium nitrate fertilizer produced, which is the functional unit of the study.

Figure 14 shows that the MEC system has less environmental impact in all categories compared with the MFC system. MFC has more potential environmental impact than MEC system in all categories ranging from 6 to 43%, depending on the impact considered. It should be noted, that despite energy and chemical consumption is higher in MEC than MFC, the environmental profile is favourable for MEC. The consumption impacts are offset by the production of ammonium nitrate fertilizer. The MEC system produces more ammonium nitrate fertilizer than MFC under the same operating conditions.

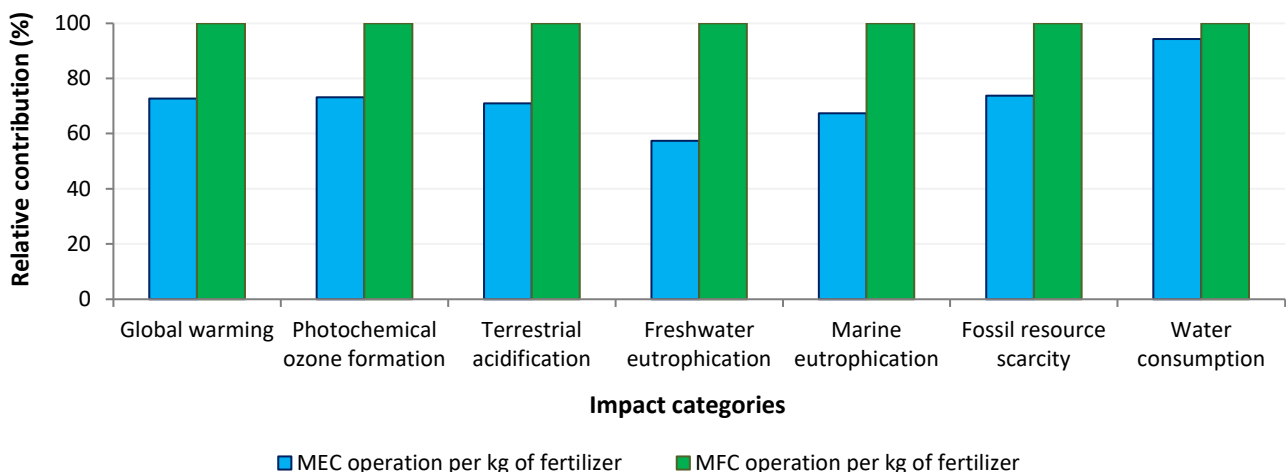


Figure 14. Comparative analysis of source separation system with conventional system.

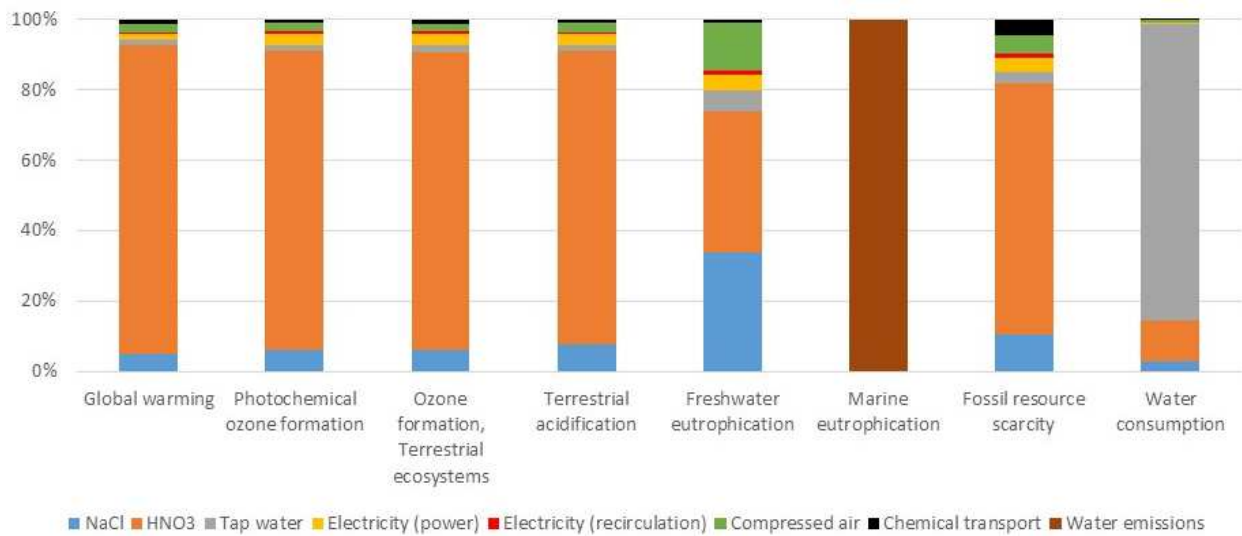


Figure 15. Comparative analysis of MEC system

Figure 15 shows that nitric acid contributes significantly (> 50%) to six out of eight impact categories (73% on average). Ammonium content in treated water contributes 99% to marine eutrophication category. And the main contributor in water consumption is tap water (84%). MFC has approximately the same profile as MEC (Figure 16). Except that there is no impact due electricity consumption, and the contribution of compressed air to freshwater eutrophication is higher than in MEC.

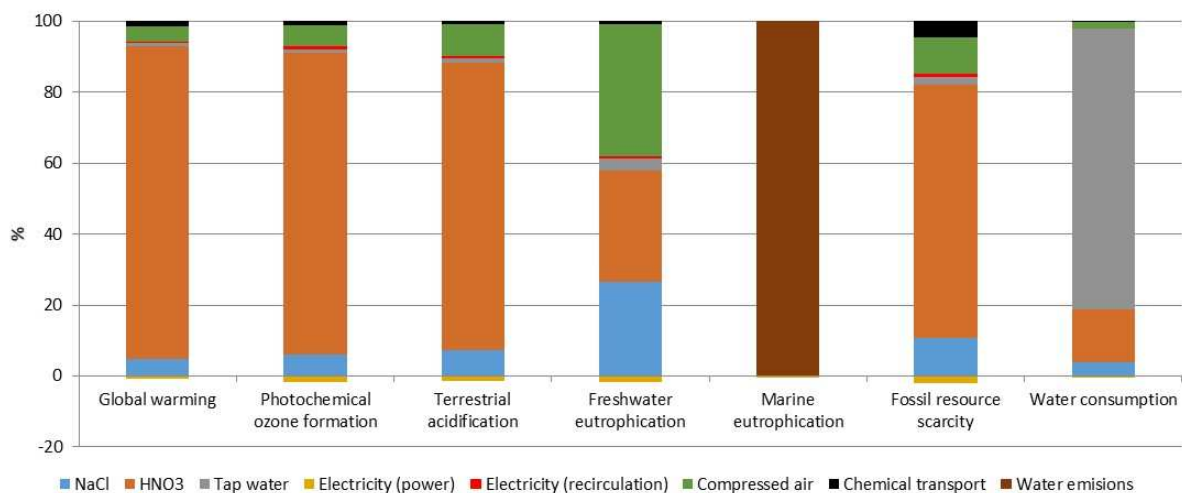


Figure 16. Comparative analysis of MFC system. MFC: Microbial Fuel Cell.

The analysis of the environmental profile of BES shows that HNO₃ has a significant contribution. HNO₃ consumption is strongly linked to fertiliser production. Due to its significant contribution and its link to fertiliser production, a sensitive analysis on HNO₃ extraction has been carried out to look in more detail at the contribution of the other items.

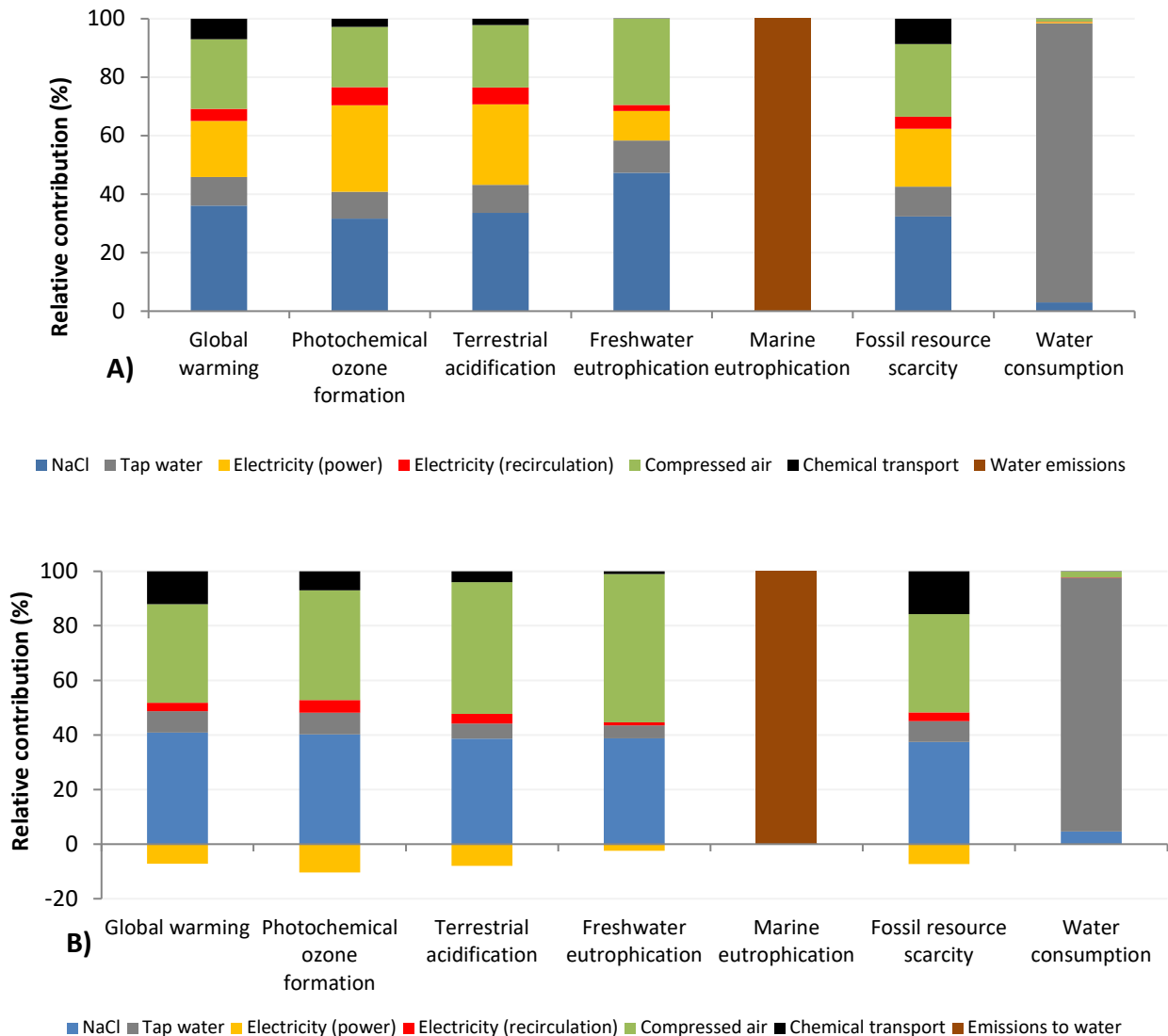


Figure 17. Environmental profile of MEC and MFC (excluding HNO₃). A) MEC: Microbial Electrolysis Cell and B) MFC: Microbial Fuel Cell.

Figure 17 shows that the use of sustainable energy sources and the optimization of NaCl consumption will help to improve the environmental performance of the technology for further developments.

2.3 Ghent demo-site

In Ghent, Belgium, a residential area called Nieuwe Dokken was built which include a source separation wastewater system for black water, grey water and food waste. The objective of using a separative network is to achieve greater efficiency in the treatment of wastewater and increase the capacity to obtain energy and biofertilizers. The demo-site located in Ghent has two distinct areas depending on the research project developed. The Run4Life project is in charge of the treatment of BW and KW which is collected with a vacuum sewage system from around 430 houses with 1250 person equivalents (PE) while worked performed within the

Nereus project was related to the systems for greywater treatment. Figure 18 shows the complete scheme of the demo-site and distinguishes the boundaries between both research projects.

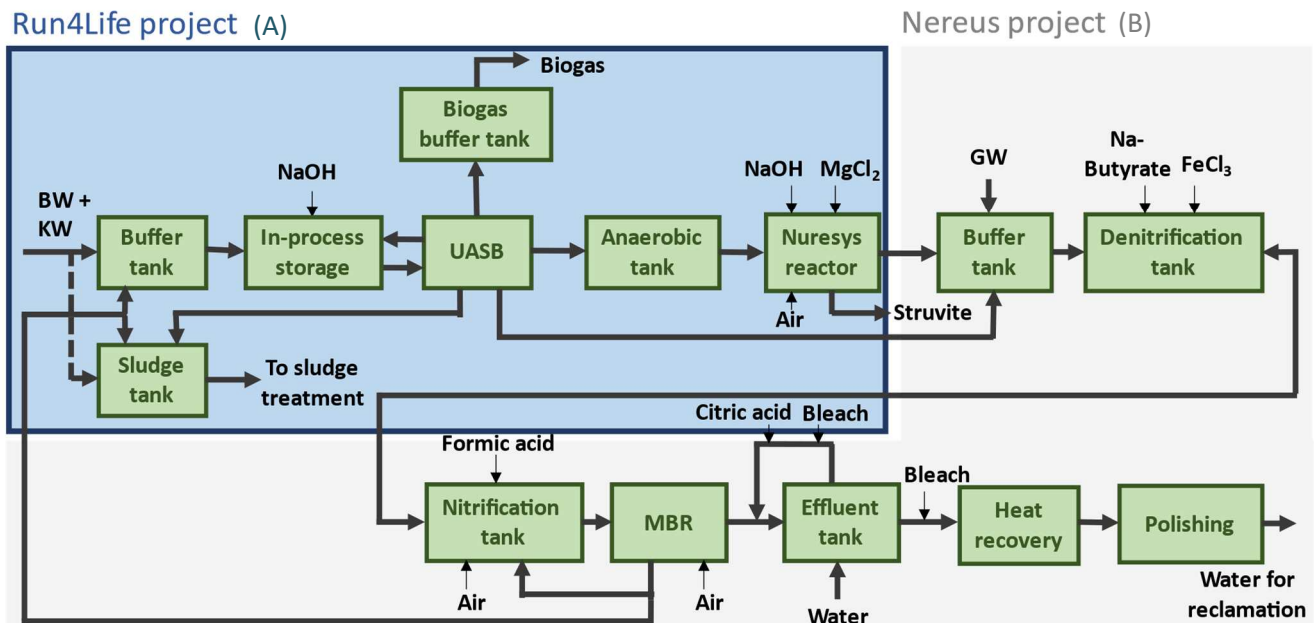


Figure 18. Detailed scheme of Ghent configuration. (A) BW and KW treatment; (B) GW treatment. KW: Kitchen waste; BW: Black water; GW: Grey water; UASB: Up-flow Anaerobic Sludge Blanket; MBR: Membrane bioreactor.

The BW and KW are treated by anaerobic digestion in a UASB reactor. The biogas can be valorized for the production of electrical and thermal energy while the effluent is fed to a struvite precipitator. The sludge, after appropriate treatment, can be used as solid fertilizer. The grey water, although not included in this project, is treated together with the effluent from the treatment of the other two types of waste using an AO-MBR reactor to obtain high quality reclaimed water. Figure 19 shows the results of the detailed LCA with boundaries restricted to the Run4Life project units and systems. The functional unit chosen for this analysis was cubic meter of wastewater treated and the system boundaries were defined as a gate-to-gate which considers only the impacts related to the facility itself. The main environmental impacts of the Run4Life scheme are related to the vacuum system for the collection of the concentrated segregated streams and to the heat required for anaerobic digestion.

Broader system boundaries (cradle-to-gate) were also analyzed in an attempt to identify hot spots in the overall wastewater treatment process (Run4Life and Nereus project). GW treatment and avoided impacts related to the biofertilizers, bioenergy and water reclamation and tap water consumption in the houses were included in the study. A relative contribution profile of the configuration is reported in Figure 20 and reflects the environmental impact of the different stages of the process for an operation at around 10% of its capacity. For the selected system boundaries, the greatest impact on the environment does not longer come from BW or KW treatment but is related to GW treatment. In this sense, the impact of vacuum toilets and anaerobic digestion is much lower than that of the AO-MBR system, which is directly proportional to the electricity demand for aeration and mixing.

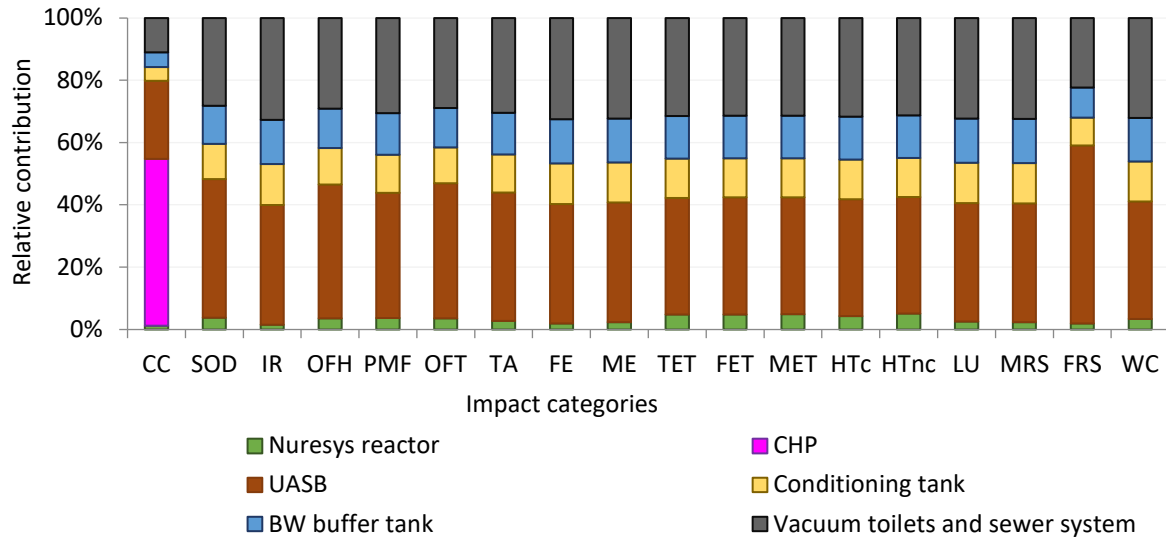


Figure 19. Relative environmental profile of the LCA study of the BW and KW of the Ghent demo-site (disaggregated in stages). CC: Global Warming; SOD: Stratospheric Ozone Depletion; IR: Ionizing radiation; OFH: Ozone Formation Human Health; PMF: Fine Particulate Matter Formation; OFH: Ozone Formation Terrestrial Ecosystems; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; HTc: Human Carcinogenic Toxicity; HTnc: Human non-carcinogenic Toxicity; MRS: Mineral Resource Scarcity; FRS: Fossil Resource Scarcity; WC: Water consumption.

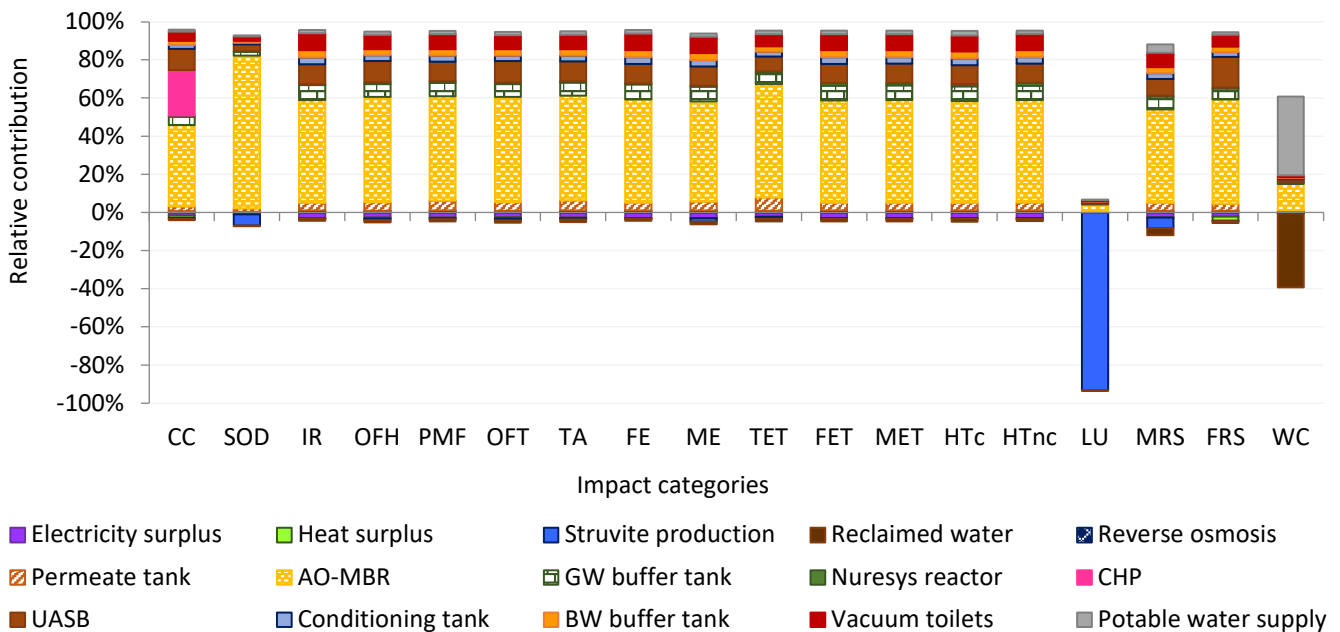


Figure 20. Relative environmental profile of the detailed LCA study of the Ghent demo-site (disaggregated in stages). CC: Global Warming; SOD: Stratospheric Ozone Depletion; IR: Ionizing radiation; OFH: Ozone Formation Human Health; PMF: Fine Particulate Matter Formation; OFH: Ozone Formation Terrestrial Ecosystems; TA: Terrestrial Acidification; FE: Freshwater Eutrophication; ME: Marine Eutrophication; TET: Terrestrial Ecotoxicity; FET: Freshwater Ecotoxicity; MET: Marine Ecotoxicity; HTc: Human Carcinogenic Toxicity; HTnc: Human non-carcinogenic Toxicity; MRS: Mineral Resource Scarcity; FRS: Fossil Resource Scarcity; WC: Water consumption.

The typical centralized-decentralized comparison of facilities with a characteristic functional unit for the wastewater treatment function should be performed for the Ghent facility in 2026, when the plant is already expected to operate under normal flow conditions. However, a study has been performed to describe how the Ghent facility can contribute (according to data from 2021) to reduce the environmental impact of the area in which it is located since the wastewater is no longer treated in a centralized facility. The comparison is not between two wastewater treatment facilities but between the current wastewater treatment situation and a traditional context where a centralized facility was installed. In this case, the function of the facility is the recovery of phosphorus (a limited resource) rather than wastewater treatment. A multifunctional system, which treats wastewater and recovers resources, has been analyzed from another approach with another functional unit (1 kg P₂O₅). Figure 21 shows a comparison between the conventional wastewater treatment scenario and the decentralized scenario with the Ghent demo-site. For the decentralized system there are two possible cases: the recovery of phosphorus only in the form of struvite or the recovery of the nutrient through precipitation and valorization of the sludge through a composting process. It can be seen how the decentralized scenario has better impacts on the environment than a centralized one when the sludge is treated. Although it is true that the sludge can be revalorized through a multitude of processes, it has been shown that improving the efficiency of nutrient recovery and the waste stream segregation contributes to reducing the environmental impact. In that sense, the Ghent facility shows promising environmental impact results due to the potential for resource recovery from wastewater.

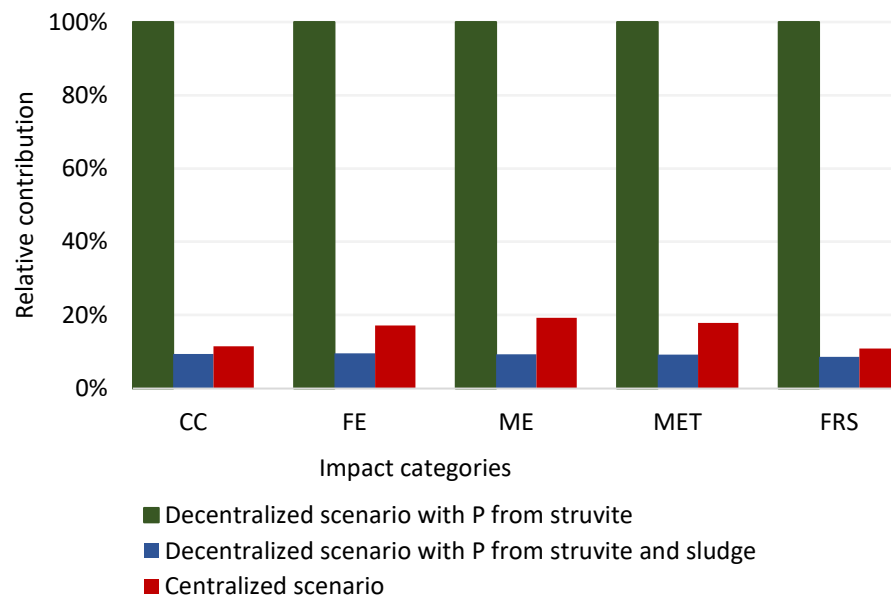


Figure 21. Relative environmental profile of the LCA comparative study of the decentralized scenario of Ghent and a centralized scenario with 1kg P₂O₅ functional unit. GW: Global Warming; FE: Freshwater Eutrophication; ME: Marine Eutrophication; FRS: Fossil Resource Scarcity.

2.4 Helsingborg demonstration site

This demonstration site is located in the city of Helsingborg in Sweden. It is called the Oceanhamnen and is part of the H⁺ project, which renews the old harbour and an industrial area to bring it closer to the city by providing green areas and modern facilities. The site includes an innovative waste and wastewater management system from residential and office buildings.



Figure 22. Pictures of demonstration site, Helsingborg.

Goal and scope

The **goals** of the environmental analysis of this site, based on the LCA methodology, are the following:

- To assess the potential environmental impacts of the system under study: “the demonstration site of Helsingborg” in the framework of RUN4LIFE project.
- To identify the potential environmental hotspots of the system, from the collection of the different flows, the treatment, to the disposal of the different fractions.
- To compare the Helsingborg case study as a decentralized system to recover nutrients and energy from different WW flows, with a conventional system in Sweden.

The **scope and the system** under analysis are the following (see Figure 23 23):

The analysis considers the stages of collection inside the building, transport in the sewer network, treatment, and application of the bio-fertilizers in agriculture and the use of biogas in city buses. Oceanhamnen accommodates 320 apartments with 2.4 persons per apartment and 3 office buildings with a total number of 1600 workers. The total number of person equivalents considered in the system is 1568.

- Collection inside the building. BW is collected inside the building by vacuum toilets, and then transported by vacuum sewers from inside the property to outside. FW is sorted in the building by a food waste disposer, and then transported by another pipe from inside to outside the property. The same applies for GW, which is transported through another pipeline.
- Wastewater transport in the sewer network. BW is transported by a vacuum sewer network divided into five stems, from the buildings to the pump station. BW is then transported in one pipe from there to the treatment plant. Regarding FW, there is one pipe per building (from each building to the pump station) and then from there to the treatment plant. The same as for GW line.

- Wastewater treatment plant.** In the treatment plant, the flows are treated separately by UASB reactors for anaerobic digestion. The biogas produced is used as a fuel for city buses. The liquid effluents from UASB reactors are mixed to recover struvite and ammonium sulphate. Then dewatered sludge from the UASB reactor of FW, previously hygienized, is mixed with recovered struvite and ammonium sulphate to produce NPK pellets. The BW sludge is dewatered and used as BW-biofertilizer. The effluent after the ammonium stripping is mixed with the GW line (not included in the Run4life project), and then is treated and sent to the ocean after treatment. In the next steps of project development (near future), the reuse of this water will be considered after refining treatments.
- Biogas used in city buses.** As mentioned before, the biogas is used in city buses substituting diesel as fuel after previously being upgraded by water scrubber technology. The energy requirement to upgrade the biogas, the air emissions and the diesel consumption avoided have been considered in the analysis.
- Agriculture applications of bio-fertilizer products.** The two biofertilizers produced, NPK pellets and BW fertilizer, are transported from the treatment plant to farmers located in the local area. Then the biofertilizers are applied to soil to grow crops. The analysis considers the avoided impacts of using mineral fertilizers.

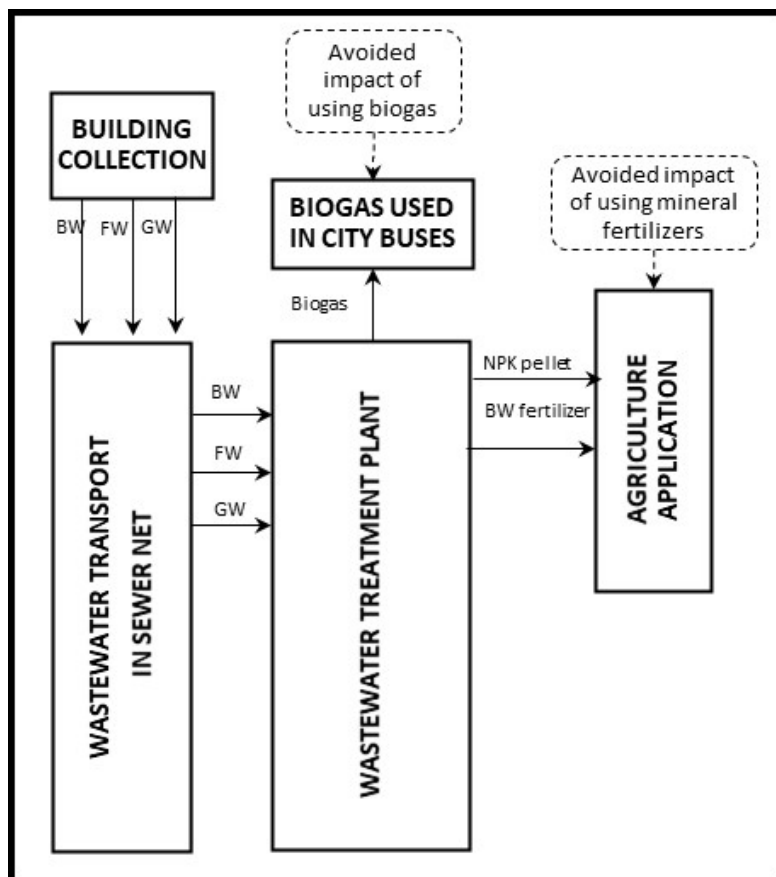


Figure 23. Source separation system. BW: Blackwater; GW: Greywater; FW: Food waste.

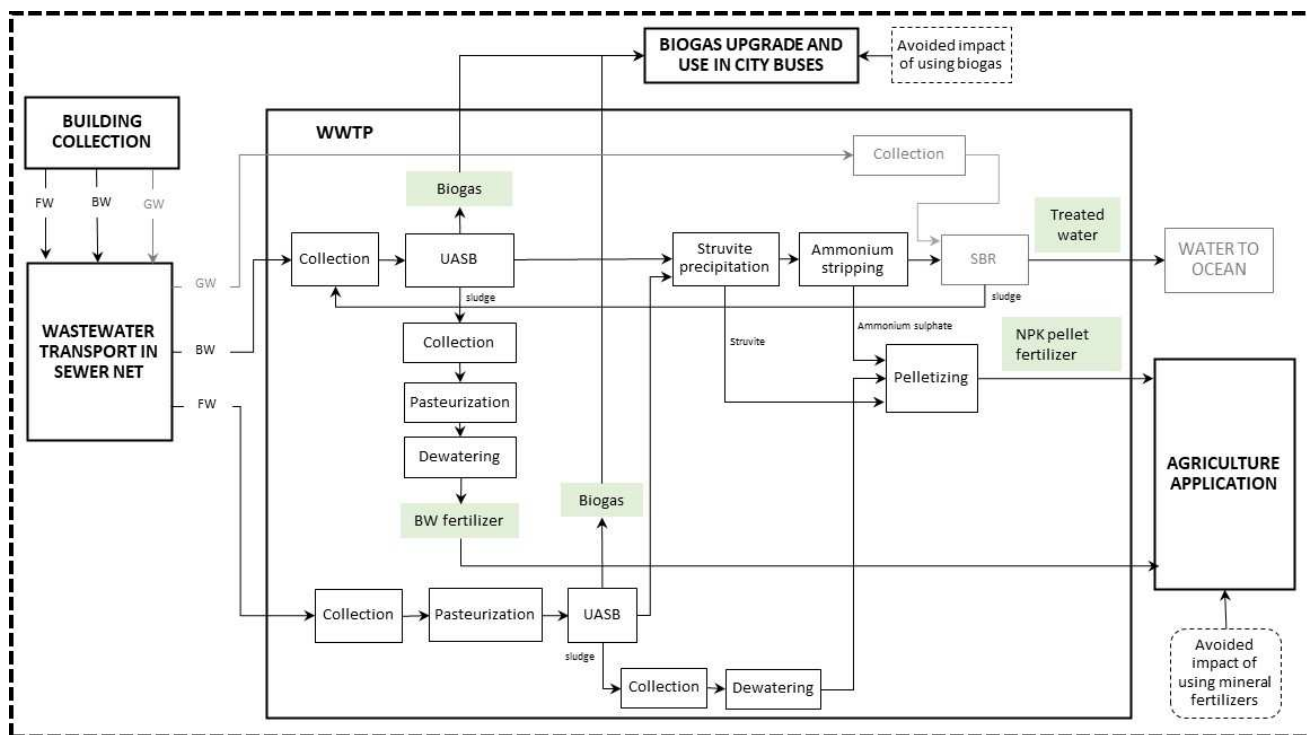


Figure 24. System boundaries of Helsingborg LCA. BW: Blackwater; GW: Greywater; FW: Food waste; UASB: Up-flow Anaerobic Sludge Blanket

- **Description of the conventional system:**

The conventional scenario to compare with the demonstration site is defined by the phases depicted in Figure 26 and based on (Kjerstadius et al., 2015):

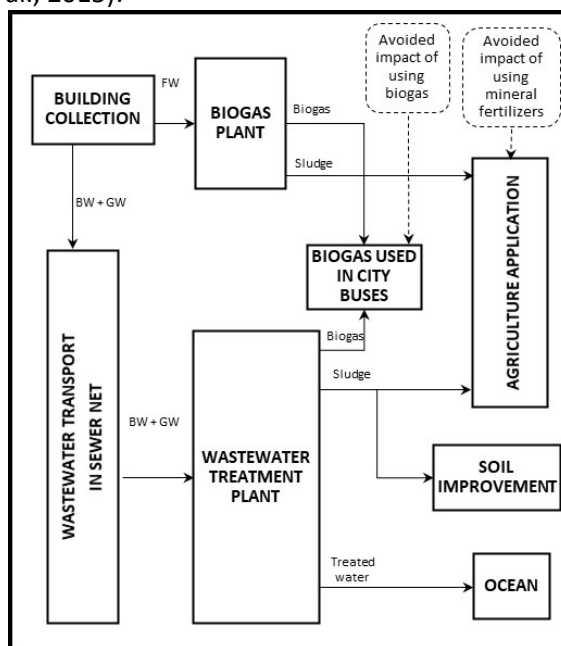


Figure 25. System boundaries of conventional system. BW: Blackwater; GW: Greywater; FW: Food waste

The FW is collected in paper bags in each building, and it has been assumed that the bag is changed every fifth day. The paper bags are placed inside plastic vessels to collect the FW. After the FW collection, it is placed outside in containers and transported by a bi-compartment truck, that collects this waste fraction with other residual waste at the same time. After collection, the FW is transported to the biogas plant, and a pre-treatment is done. It has been assumed that the rejected waste from the pre-treatment is incinerated and the other fraction sent to biogas reactor. The biogas produced is used in city buses and the sludge is applied in agriculture.

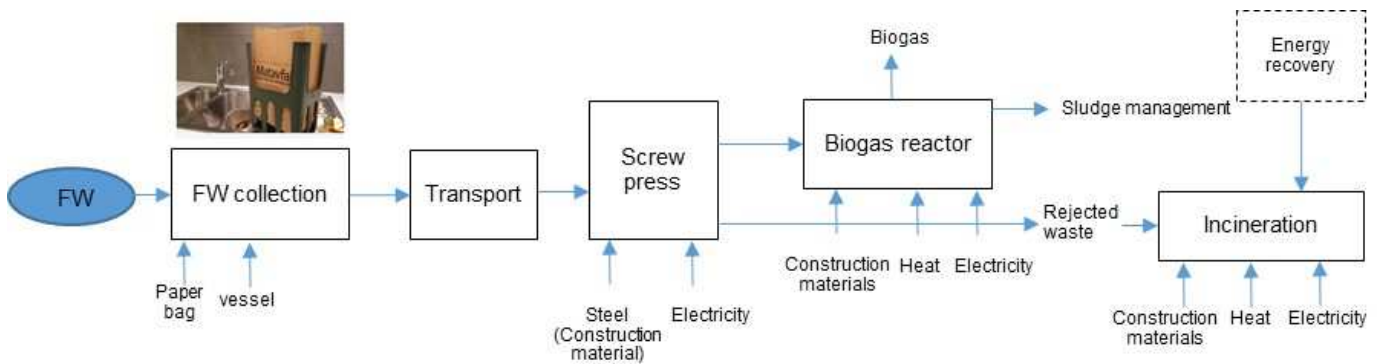


Figure 26. FW management in the conventional system. FW: Food waste.

BW and GW in the conventional system is collected in the same pipeline, and transported by a gravity sewer network, to the wastewater treatment plant where it is treated. The conventional treatment plant was based on Kjerstadius et al. (2015). The biogas obtained is used in city buses, one third of the sludge produced is applied in agriculture and two thirds in soil improvement.

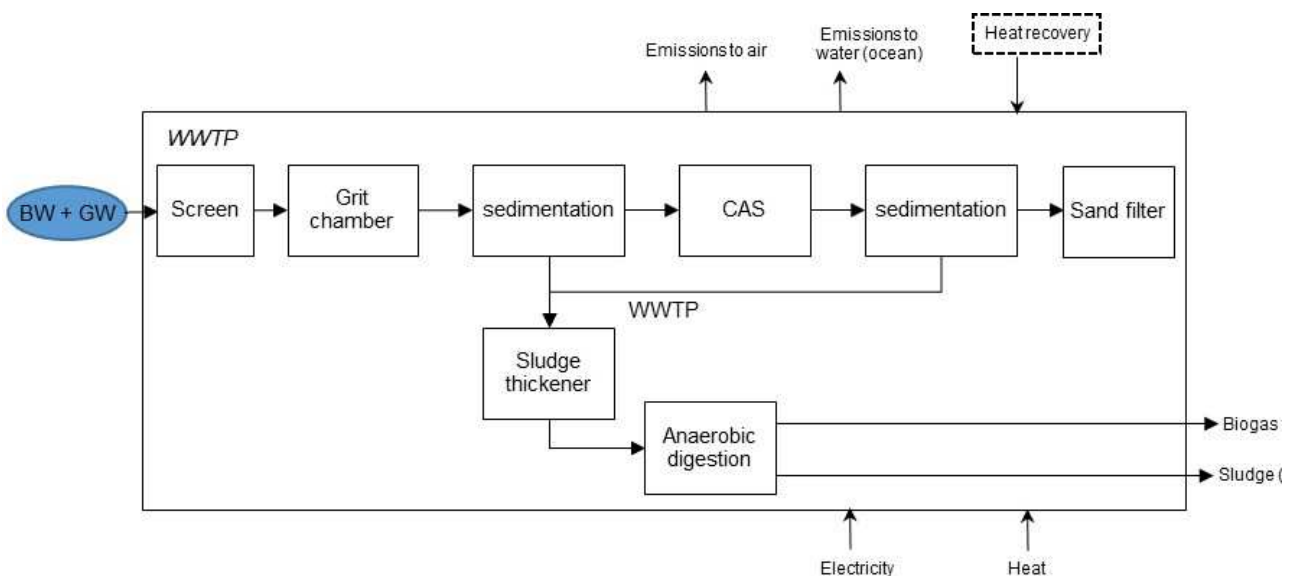


Figure 27. BW and GW management in the conventional system. BW: Blackwater; CAS: Conventional Activated Sludge; GW: Greywater; WWTP: wastewater treatment plant

Functional unit of the study

The functional unit chosen to assess the potential environmental impact of the source separation system is the following: "The management of 1 capita yearly load of food waste (FW), blackwater (BW) and grey water (GW). The management includes collection, treatment, and disposal. As mentioned before, to compare the site with the conventional scenarios the GW line has been included despite this line not being included in the Run4life project. As introduced above, 320 apartments (2.4 p.e) and 1600 workers have been considered and the BW and FW production have been estimated: 11 m³/d (BW) and 3m³/d (FW) and 157 m³/d (GW).

Limitations and assumptions

The main limitation of the study is that the data have been obtained mainly from literature and from the knowledge of the NSVA partner, who is responsible for this demonstration site. Real data about the operation have not been considered because they were not available when the calculations were performed. On the other hand, it is worth noting that the partner has quite robust data due to its experience in the sector.

The following are the assumptions of the study:

- Different life spans of components have been assumed: 50 years for structural elements (tanks, pipes, vacuum toilets), 30 years for equipment (FW disposers, pumps).
- For the comparison analysis, it has been assumed that the GW line and the effluent from the ammonium stripping is treated at the Helsingborg treatment plant and then the treated water is sent to the ocean.
- Means of transport have been assumed for the construction materials of the system and for the biofertilizers.
- Assumptions about biofertilizer emissions have been based on literature.

Life cycle inventory of the system

As previously mentioned, the inventory data have been obtained in close collaboration with the NSVA partner, who is responsible for the demonstration site. Excel files have been created to make data collection easier.

Data on the construction phase of the source separation system were mainly actual data although some estimations were made (i.e., the length of the pipeline). In this life cycle stage, mainly the materials and the transport process, from the provider to site, have been included. A manufacturing standard process has been considered for piping only. Also, an excavation process for piping and backfilling material for trenches are assumed. Literature like (Morera et al., 2016)(Morera et al., 2020) has been consulted to create the construction inventory.

Data concerning the operation phase have been gathered with the partner and calculations and estimations have been done to create the inventory. Also data from literature (Kjerstadius, 2016) have been included. In regards to the operation phase, the summary of the inputs and the outputs considered are: electricity from the national grid, heat from the district heating system, and chemicals (MgCl₂, H₂SO₄, NaOH, KCl, FeCl₃). The outputs of the system are biogas, NPK pellets, BW fertilizer, heat recovery and treated water.

The inventory data of conventional system has been obtained from literature (Kjerstadius, 2016)(Kjerstadius et al., 2015)(För & Ab, 2021)(Remy & Jekel, 2010)(Brogaard, 2013)(Bauer et al., 2014); and also from the project partner who has a broad knowledge of the management of these flows in the city of Helsingborg.

The LCI database Ecoinvent¹ was used for this study, as one of the most comprehensive datasets available in the field. Some data have been adjusted according to Swedish conditions. For example, the heat produced by district heating has been adjusted in line with the energy mix of Helsingborg city (ÖRESUNDSKRAFT, 2019); the production of sodium hydroxide has been adjusted in accordance to the Swedish electricity mix.

Environmental impact assessments results

The impact categories considered to express the results are: Global warming, Stratospheric ozone depletion, Ozone formation (terrestrial ecosystems), Terrestrial acidification, Freshwater eutrophication, Marine eutrophication, Mineral resource scarcity and Water consumption. The impact assessment method used is Recipe2016.

As seen in Figure 28, in 4 out of 8 impact categories the environmental benefits are higher than the environmental impacts. These relevant environmental benefits are due to the NPK pellet application in agriculture and the use of biogas in city buses.

The impacts of the system are mainly caused by the operation of the WWT and the ammonium stripping process is the major contributor in most of these impact categories. Focusing on the terrestrial acidification category, the contribution of the BW fertilizer is remarkable (44%); this is mainly due to the NH₃ emissions. In regard to the construction phase, its contribution to mineral resource scarcity (28%) and 7% to the Global Warming potential both stand out.

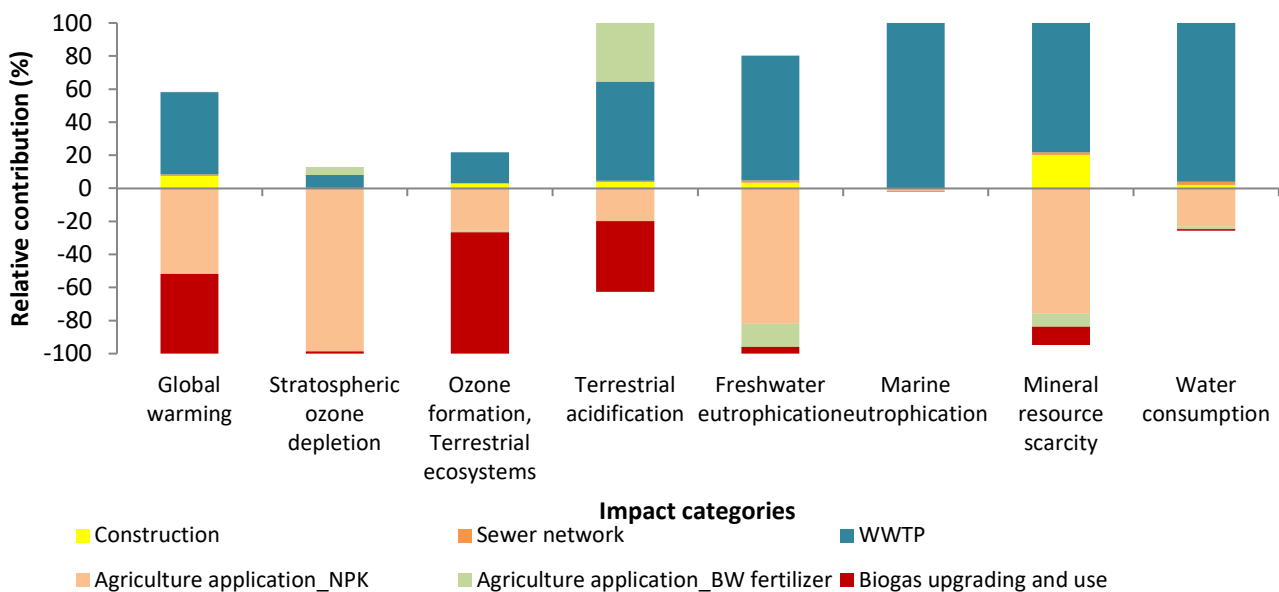


Figure 28. Environmental profile of the source separation system. WWTP: Wastewater treatment plant.

In reference to the environmental profile of the treatment plant operation, the main contributor in 7 out of 8 impact categories is the ammonium stripping process, ranging from 53% to 80%. The major contributor in these impact categories is NaOH, except in the terrestrial acidification category where H₂SO₄ has a major contribution (51% versus 23%). Regarding Figure 29, in the water consumption impact category, the main contributor is ammonium stripping (80%), and this is due mainly to NaOH consumption (64%) and electricity (21%). With regards to marine eutrophication, N discharged to the ocean is the main contributor.

¹ <https://www.ecoinvent.org/>

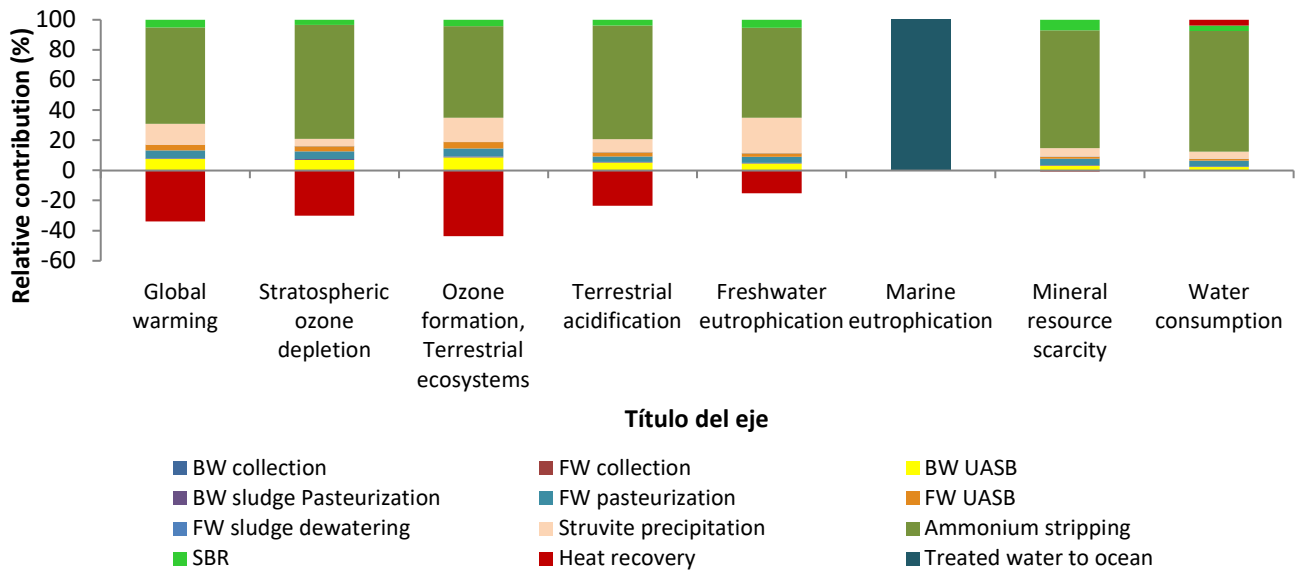


Figure 29. Environmental profile of the WWTP operation. BW: Blackwater; GW: Greywater; FW: Food waste; UASB: Up-flow Anaerobic Sludge Blanket; SBR: Sequencing Batch Reactor

Comparing the environmental profile of the source separation system and the conventional system, the first one has lower environmental impacts in all the impact categories, except for the water consumption category (Figure 30).

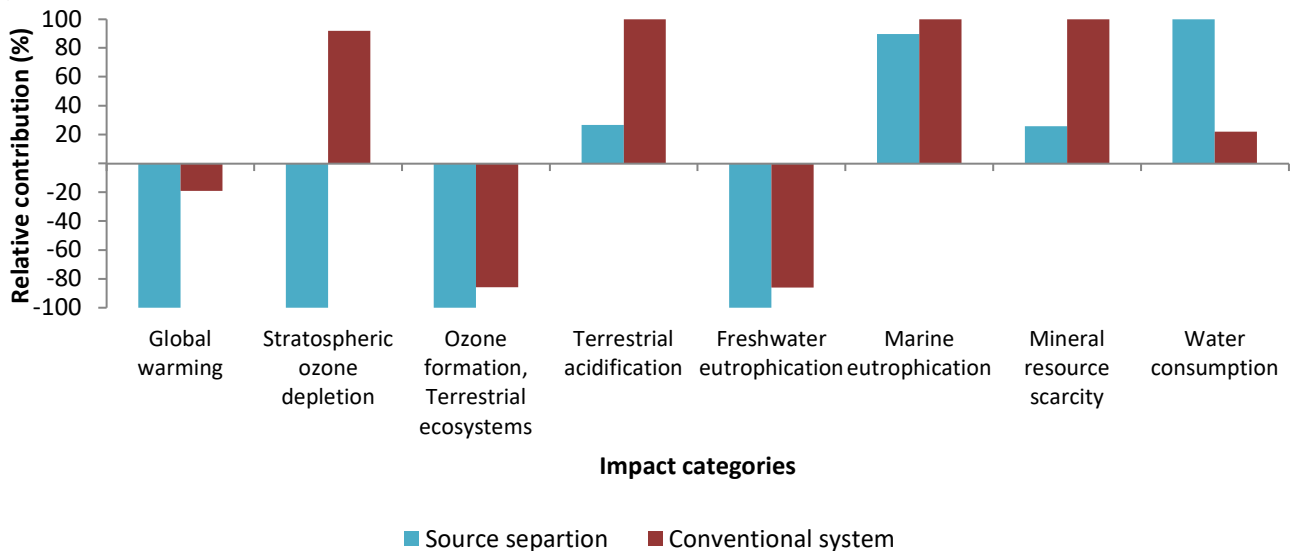


Figure 30. Comparative analysis of source separation system with conventional system.

In the following figures, each potential environmental impact is analyzed in detail to see which are the contributors to each system and to identify differences from one system to each other.

- **Climate change impact category:** GWP in the source separation system is 81% lower compared to the conventional system. Utilizing NPK pellets in agriculture provides relevant benefits and reduces the GWP impact of the whole system, despite the impact of the WWTP operation being higher than in the

conventional system. In reference to the conventional system, there are no environmental benefits due to the sludge and nutrient recovery management because only one third of the sludge from the WWTP is applied in agriculture.

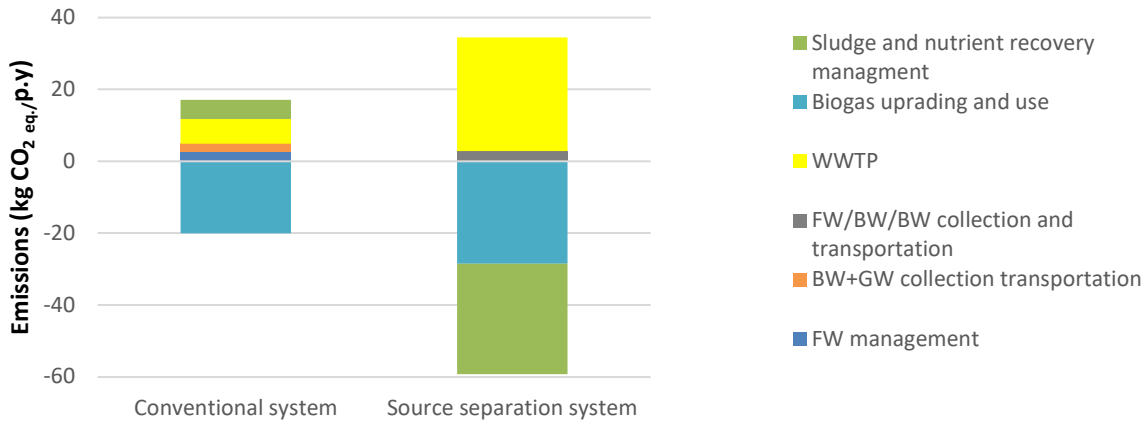


Figure 31. Results for Climate change (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; WWTP: Wastewater treatment plant.

- Stratospheric ozone depletion:** The major contributor in the conventional system is the WWTP operation (74%) and this is mainly due to the air emissions and electricity consumption. Regarding the source separation system, NPK pellet use in agriculture provides relevant benefits and reduces the environmental impact of the whole system.

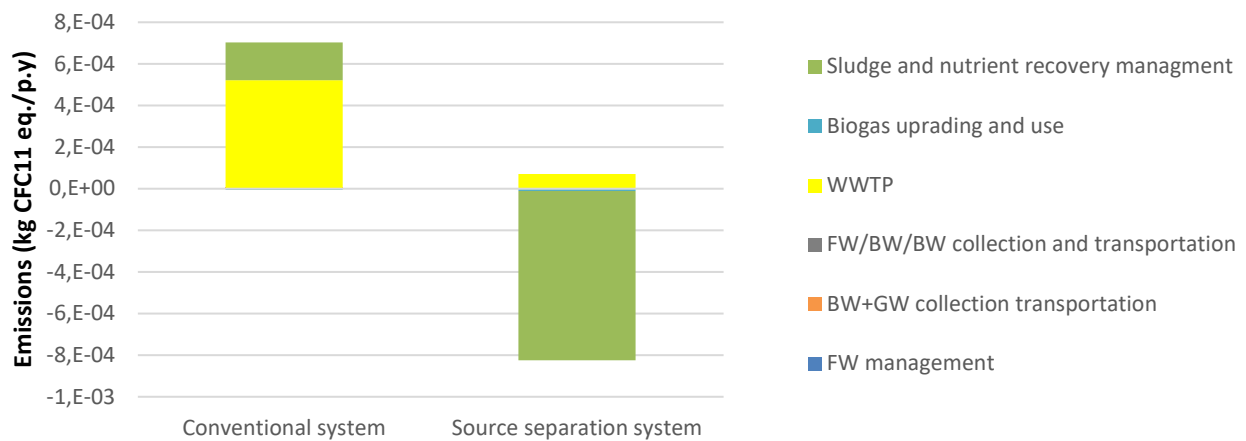


Figure 32. Results for stratospheric ozone depletion (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Ozone formation:** similar net results are obtained in both systems (-0.38 versus -0.31 kg NO_x eq./p.y.). The source separation system is 19% lower in comparison to the conventional system. In the conventional system, environmental benefits are significant if heat recovery is considered.

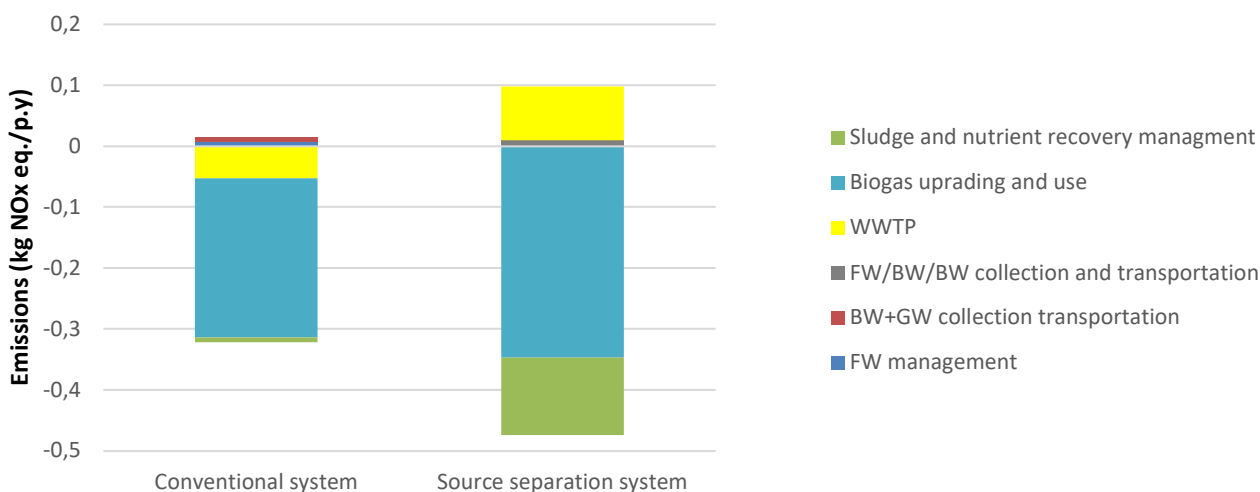


Figure 33. Results for ozone formation impact (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Terrestrial acidification:** The impact of the source separation system is 73% lower than in the conventional system. The main contributor in the conventional system is sludge and nutrient management (67% due to sludge from WWTP to soil improvement and 32% due to sludge from WWTP to agriculture). These contributions are due to the NH_3 emissions to air. The main contributor from the source separation system is the WWTP operation: 40% H_2SO_4 , 34% NaOH and 26% the energy consumed.

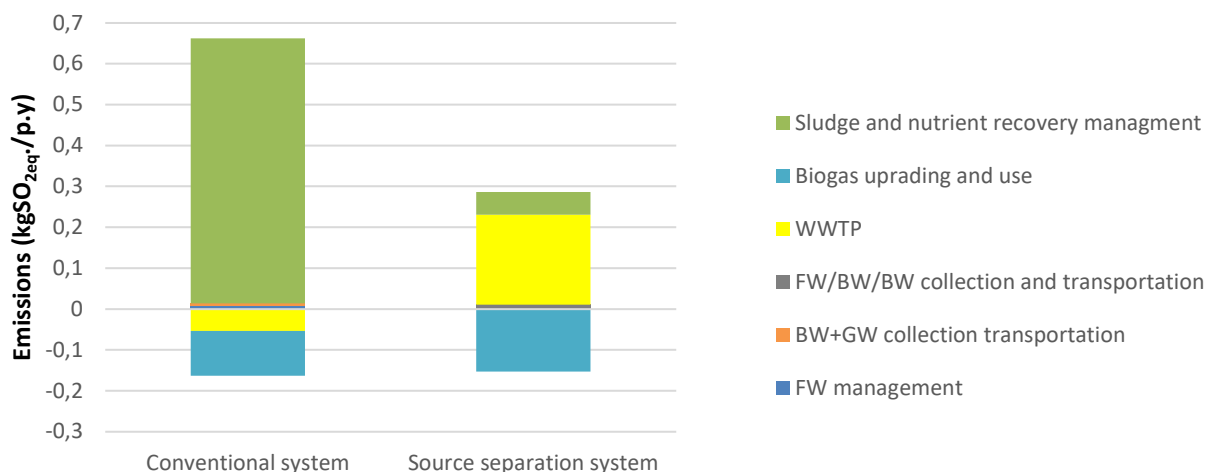


Figure 34. Results for terrestrial acidification (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Freshwater eutrophication:** This impact category is 14% lower in the source separation system compared to the conventional one (Figure 30). The benefits reached in the conventional system are due to the application of the sludge from WWTP to agriculture, and mainly due to the phosphate fertilizer avoided. The quantity of phosphate fertilizer avoided is higher in the source separation system, and that is why the benefits are higher in this system compared with the conventional one.

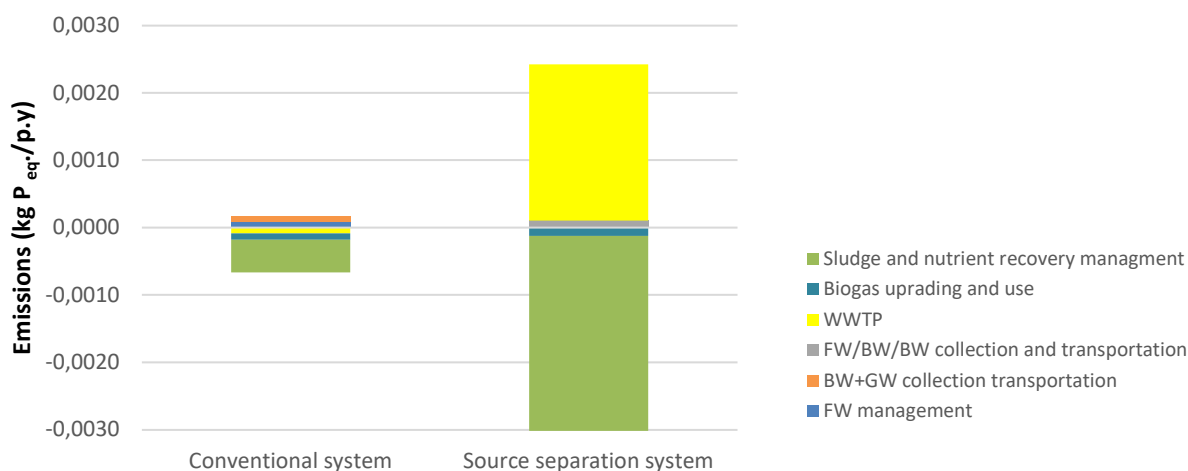


Figure 35. Results for freshwater eutrophication (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Marine eutrophication:** In both cases, most of the impact stems from the WWTP operation, and this is due to the release of nitrogen in the effluent from WWTP to the ocean. As can be seen in Figure 30, the contribution of the source separation system is 10% lower when compared to the conventional system.

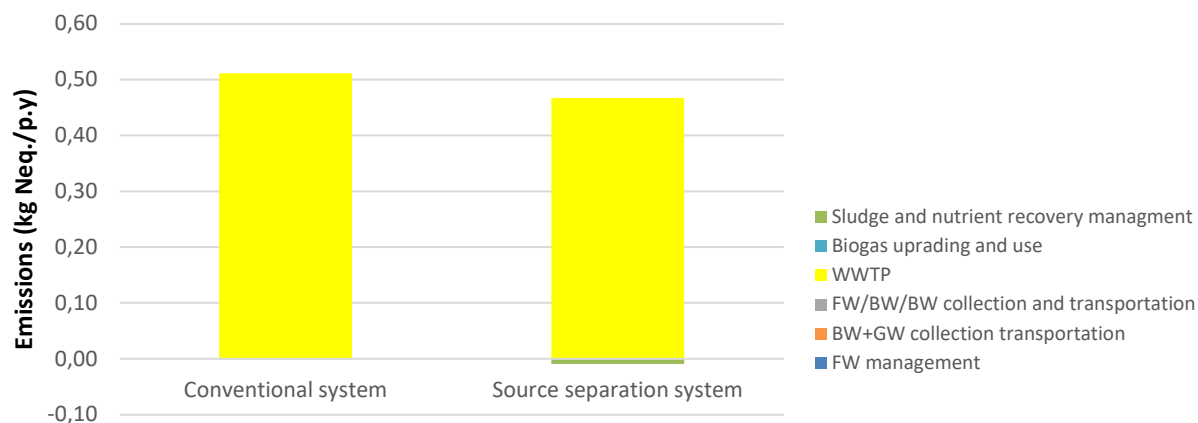


Figure 36. Results for marine eutrophication (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Mineral resource scarcity:** The net result of the source separation system is negative (-0.41 kg Cu eq./p.ye) in contrast to the conventional system (0.112 kg Cu eq./p.ye). The benefits obtained in the source separation system are due to the avoided impacts of mineral fertilizers from the NPK pellet use in agriculture. The main contributor in the source separation system is the WWTP operation and the NaOH consumed in the stripping process.

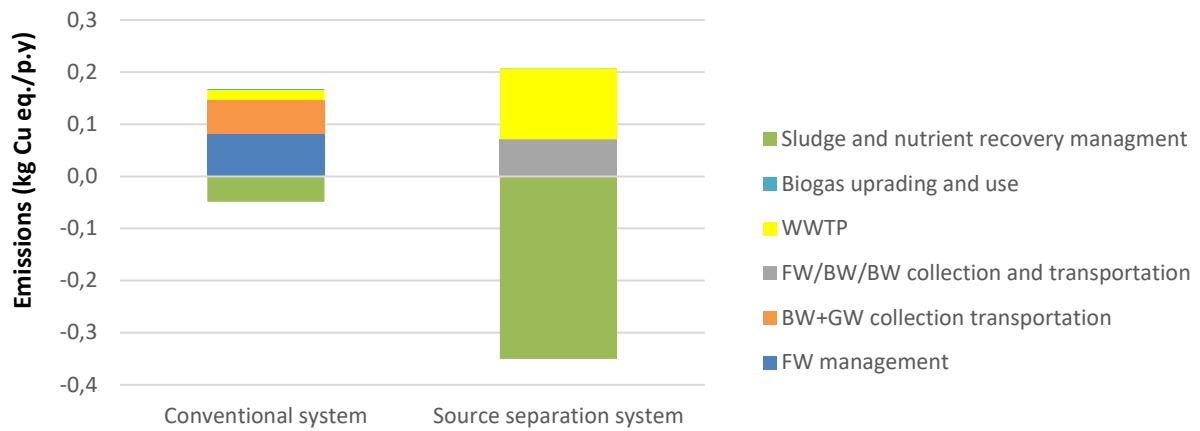


Figure 37. Results for mineral resource scarcity (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

- Water consumption:** The source separation system has 78% more impact than the conventional system due to the WWTP operation. The main contributor in this phase is the ammonium stripping process, due to the consumption of NaOH (64%) and the electricity (21%). This contribution is due to the water consumed in the background processes of NaOH and energy production.

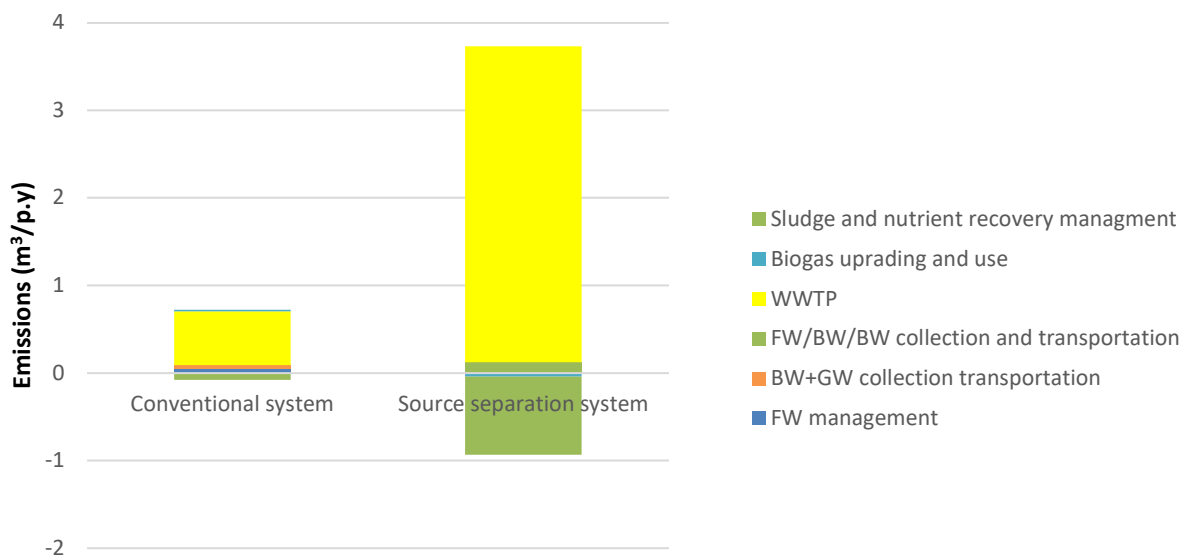


Figure 38. Results for water consumption (per functional unit). BW: Blackwater; GW: Greywater; FW: Food waste; Wastewater treatment plant.

Conclusions and next steps

The environmental analysis of the Helsingborg demo-site has allowed the detection of the hot spots of the system developed under the framework of the Run4life project and to identify the benefits reached by the innovative system compared to a conventional scenario. The source separation system provides environmental benefits (negative impacts) in 5 out of 8 impact categories. In the categories where impacts are higher than benefits, the hot spots are chemicals consumed and nitrogen released to the ocean. But it is important to note that, when comparing the sourced system with the conventional system, the former reduces environmental impact in all categories (except water consumption). In some categories, the difference from one system to the other is very significant (e.g., global warming, stratospheric ozone depletion, terrestrial acidification, freshwater eutrophication, mineral resource scarcity).

The source separation system allows the recovery of more nutrients (P, N) from the waste streams compared to the conventional system, while increasing the amount of biogas produced for the whole system. As a result, the use of biofertilizers in agriculture and the use of biogas in city buses produced relevant benefits in the proposed innovative system in Helsingborg. As future work to be considered, and as the demonstration site is already under implementation, it would be interesting to update the results and compare the updated results with existing studies where other decentralized systems are analyzed in terms of nutrient and energy recovery from waste streams.

3. References

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