LCA Case Studies

Life Cycle Assessment of Municipal Waste Water Systems

[1]Anne-Marie Tillman, [2,3]Mikael Svingby [2]Henrik Lundström

[1] Technical Environmental Planning, Centre for Environmental Assessment of Product and Material Systems (CPM), Chalmers University of Technology, S-412 96 Göteborg, Sweden
[2] Chalmers Industriteknik, Chalmers Teknikpark, S-412 88 Göteborg, Sweden
[3] Present address: VBB Viak AB, Box 34044, S-100 26 Stockholm, Sweden

Corresponding author: Anne-Marie Tillman, Associate Professor

Abstract

Life Cycle Assessment was applied to municipal planning in a study of waste water systems in Bergsjön, a Göteborg suburb, and Hamburgsund, a coastal village. Existing waste water treatment consists of mechanical, biological and chemical treatment. The heat in the waste water from Bergsjön is recovered for the district heating system. One alternative studied encompassed pretreatment, anaerobic digestion or drying of the solid fraction and treatment of the liquid fraction in sand filter beds. In another alternative, urine, faeces and grey water would separately be conducted out of the buildings. The urine would be used as fertilizer, whereas faeces would be digested or dried, before used in agriculture. The grey water would be treated in filter beds. Changes in the waste water system would affect surrounding technical systems (drinking water production, district heating and fertilizer production). This was approached through system enlargement. For Hamburgsund, both alternatives showed lower environmental impact than the existing system, and the urine separation system the lowest. Bergsjön results were more difficult to interpret. Energy consumption was lowest for the existing system, whereas air emissions were lower for the alternatives. Water emissions increased for some parameters and decreased for others. Phosphorous recovery was high for all three alternatives, whereas there was virtually no nitrogen recovery until urine separation was introduced.

Keywords: Anaerobic digestion, waste water treatment; biological waste water treatment; case studies; chemical waste water treatment; Life Cycle Assessment (LCA); LCA; mechanical waste water treatment; municipal waste water systems; nutrient recycling; pretreatment, waste water; sewage; sewerage; urine separation; waste water system; waste water treatment

1 Introduction

One of the key issues in shifting societal development in a more sustainable direction is the establishment of recycling plant nutrients, especially phosphorus. Much of the societal flow of plant nutrients passes the waste water treatment systems, the main function of which is to prevent plant nutrients and micro-organisms from reaching the receiving waters.

The environmental consequences of changing the system for municipal waste water treatment were studied using Life Cycle Assessment (LCA) methodology. Selected objects were Bergsjön, a suburb of Göteborg with 12,600 inhabitants, built during the sixties and Hamburgsund, a small village (900 year-round inhabitants) on the Swedish west coast.

Existing waste water systems consist of centralized waste water treatment plants, encompassing mechanical, biological and chemical treatment. The heat of the waste water from Bergsjön is recovered for the district heating system.

Two alternative systems were studied:

1. Existing piping in the areas would be used, but with local treatment consisting of pretreatment, digestion or drying of solid fractions and treatment of liquid fractions in sand filter beds.
2. In the other alternative, it was proposed that urine, faeces and grey water would separately be conducted out of the buildings. The urine would be stored and used as a fertilizer, whereas faeces and solid parts of the grey water would be digested or dried before used in agriculture. The grey water would be treated in filter beds before release.

The Life Cycle Assessment reported in this paper is part of a larger project entitled ECO-GUIDE aimed at developing and applying environmental analysis and planning instruments for municipal planning. In the first part of the project, the alternative scenarios were worked out and described technically (MALMQVIST et al. 1995). In the second part, they were evaluated using Life Cycle Assessment (LCA) (TILLMAN et al. 1996) and environmental impact assessment (EIA) (STENBERG et al. 1996) . The last part of the project consisted of methodological comparisons based on the case studies performed (TILLMAN et al. 1997). Hygienic, economic and user aspects were considered in MALMQVIST et al. (1995).

Life Cycle Assessment (LCA) was focused on the consequences of a change of waste water treatment systems and

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included analysis of the environmental impact of both the investment in the systems (production of components) and their operation. The scope was similar to a study on small-scale sewage treatment processes by EMMERSON et al. (1995) which covered production, operation and demolition phases, as well as comparisons of process alternatives. Other LCAs of waste water treatment systems have focused on the environmental impact from production of the components in the system (SCHUURMANS-STEHMANN et al. 1996). In the ORWARE model which shows similarities to LCA, environmental impact from operation of systems for treating organic waste including sewage are modeled (DALEMO et al. 1996, SONESSON et al. 1996). ROELEVELD et al. (1997) have performed an LCA of municipal waste water treatment on a national Dutch level.

2 Purpose of the Study

The main question the analysis was designed to answer was: Which would be the environmental consequences of changing the waste water treatment systems in Hamburgsund and Bergsjön from existing centralized waste water treatment plants to more local systems, with an increased extent of recycling plant nutrients.

In addition, the choice of objects of the study enabled a comparison between large scale and small scale systems. Another question was to which extent the environmental impact may be ascribed to investing in the systems (production of components) when compared with the impact of operating the systems.

3 Scenarios

One of the objects chosen for the study was Bergsjön, a suburb of Göteborg with 12,600 inhabitants mostly living in rented apartments. There are no large industries in Bergsjön, only one area with a number of small scale industries and offices. Storm water runoff is not connected to the waste water system in this area.

The other area of the study was Hamburgsund, a coastal village with 900 year-round inhabitants. This figure rises to 1,700 inhabitants during the summer. Half of the population live in single family houses, the other half in apartment houses. There is no industry in Hamburgsund.

Detailed technical descriptions of the scenarios studied have been published by MALMQVIST et al. (1995). A summary is given below.

3.1 Existing waste water systems: Alternative 0

The existing waste water systems are described in **Figure 1**. In Bergsjön, the water is pumped to the large waste water treatment plant of Göteborg, Ryaverket which in addition to serving the 554,000 inhabitants also treats industrial waste water and storm water runoff. At Ryaverket, the water is treated mechanically, biologically and chemically. In addition, a denitrification step under construction at the time of the study was included (TILLMAN et al. 1996). The sludge from the biological and chemical treatments is digested, a process that results in the production of biogas. Most of the biogas is used internally. The treated sludge was, at the time of the study, used for compost (8%), agriculture (12%) and urban soil improvement (70%). Ten percent of the sludge went to landfilling. The treated water passes a heat pump which recovers heat to the district heating system before the water is released into the mouth of the Göta Älv River.

In Hamburgsund, there exists a waste water treatment plant for the village. The plant serves 1100 person equivalents, unevenly distributed over the year. The water is treated mechanically, biologically and chemically before being released into the sea. The sludge is transported by truck to a larger waste water treatment plant for dewatering before being deposited on a landfill.

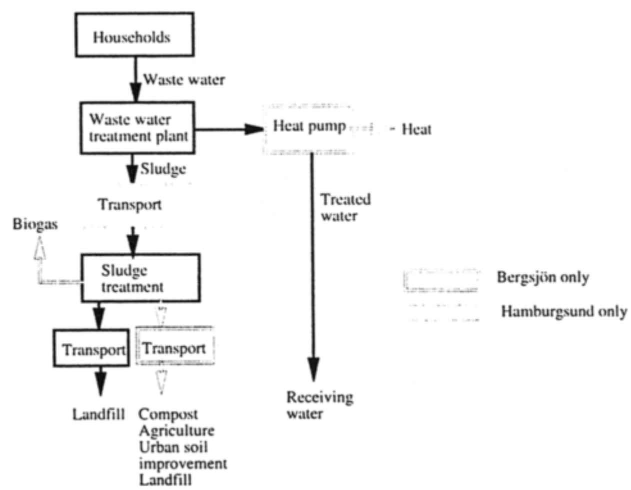

Fig. 1: Schematic flow chart of existing waste water systems – alternative 0. Transport operations performed through pumping are omitted from the figure for the sake of clarity. Dotted lines are used for those activities that take place in only one of the areas studied

3.2 Treatment in sand filter beds: Alternative 1

One of the alternatives studied consisted of pretreatment followed by treatment of the liquid part in sand filter beds. In Bergsjön, this solution would represent a more local system, with the waste water from only Bergsjön locally treated in the area. The existing pipes in the buildings and in the areas would be used, and the different waste water fractions conducted as a mixture out of the buildings. The systems are described in **Figure 2**.

In Bergsjön, the solid fractions of the waste water would be separated from the liquid fraction in pretreatment tanks placed in the street as close as possible to the buildings. The solids would be transported by truck to a biogas production facility placed in the area where it would be digested together with other types of organic waste. The biogas produced would be used for heat production for the district heating system. The solids remaining after the digestion would be transported to agricultural areas. The liquid fraction would be conducted in the existing pipe net supplemented with additional pumps to sand filter beds before being released to local small streams. The streams run out into the Göta Älv River, so that the water would eventually reach the same river mouth as in the existing system. In order to prevent dispersion of micro-organisms, it was suggested that the water would be treated with ultra-violet light before release. Phosphorus retention is high in the filter bed. Denitrification, however, occurs to less extent. The top sand layer of the filter bed becomes saturated with phosphorus after some time and must regularly be changed, approximately every fifth year. It was suggested that the sand would be used for soil improvement.

In Hamburgsund, a similar solution was suggested for the liquid fraction of the waste water but with additional treatment after the filter bed in a ditch and two pools. During the summer, the water would be used for irrigation. The existing waste water treatment plant would be rebuilt into a pretreatment facility where solids are separated from the liquid fraction. The solids would then be transported by truck to sludge drying beds with roofs. The water rejected from the beds would be treated in a separate small filter bed before being released into one of the pools. After six months, the sludge would be considered to be hygienic and could then be used in agriculture.

3.3 Urine separating system: Alternative 2

In this alternative, urine, faeces and grey water would be separated through the introduction of separating toilets and installation of additional piping in the buildings. Treatment would locally be performed in the areas studied. The systems are described in **Figure 3**.

In Bergsjön, the urine would be conducted, together with a small amount of flushing water, to underground tanks close to the buildings where it would be collected by trucks to seasonal storage close to the agricultural areas where it would subsequently be used. Faeces and flushing water would be conducted through a separate piping system to another tank close to the building. In order to reduce the volumes, a vacuum system was suggested for transportation of the faeces out of the buildings. The grey water would pass through a pretreatment tank where solids are separated before treatment in a filter bed followed by release into small local streams. The sludge from the pretreatment tank would be taken, together with the faeces fraction, to a biogas production facility in the area where it would be digested together with other types of organic waste. The biogas produced would be used for heat production for the district heating system. The solids remaining after the digestion would be transported to agricultural areas.

The system suggested for Hamburgsund was similar. Urine would be conducted to underground tanks through thin pipes and taken by trucks to a seasonal storage facility close to agricultural areas. Treatment of the faeces would depend on the type of building. In single family houses with basements it was suggested that the faeces would be composted in the basements. In single family houses without basements it would be flushed to a pretreatment tank from which the

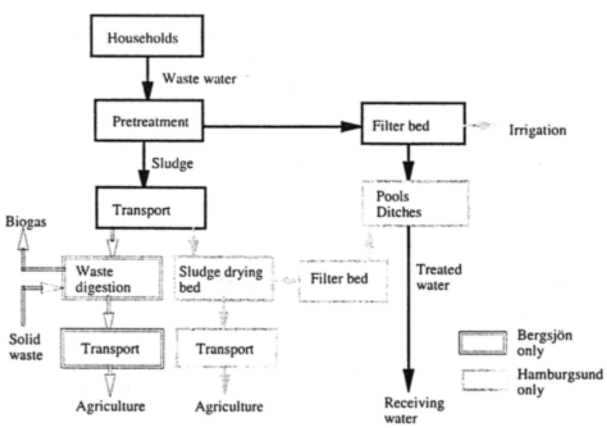

Fig. 2: Schematic flow chart of suggested treatment on filter beds – alternative 1. Transport operations performed through pumping are omitted from the figure. Dotted lines are used for those activities that take place in only one of the areas studied

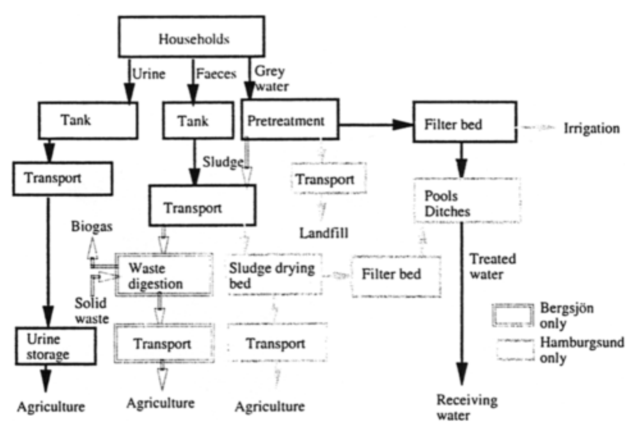

Fig. 3: Schematic flow chart of suggested urine separating system – alternative 2. Transport operations performed through pumping are omitted from the figure. Dotted lines are used for those activities that take place in only one of the areas studied

liquid phase would be led to the grey water system, whereas the solids would be transported by trucks. In the apartment houses, vacuum systems and faeces tanks were proposed, in the same way as in Bergsjön. The faeces would be sanitized in sludge drying beds before use in agriculture. The grey water would be conducted through the existing pipe system. Its content of solids would be removed in the former waste water treatment plant before being treated in sand filter beds, followed by ditches and pools. The solids from the grey water would be deposited on a landfill.

4 Methodology, Delimitations and Assumptions

How is an LCA performed for such systems? The flow charts in **Figures 1-3** essentially describe the waste water treatment systems in the different scenarios. However, a change in waste water treatment systems also affects surrounding technical systems. Separating toilets use less water, and thus the production of drinking water is affected. Recycling of plant nutrients reduces the need for other types of fertilizer if the agricultural production is assumed to be constant. Production of heat energy and biogas reduces the need for other energy sources again provided that the demand for heat does not change. These effects were modeled in the analysis of systems larger than those represented by **Figures 1-3**. The LCA was divided into an assessment of those activities that may be directly affected by a decision based on the study, the *core system*, and an assessment of an *enlarged system* where effects on surrounding technical systems were taken into account as shown in **Figure 4**. For the core system, environmental impact from both investment in and operation of the system was investigated, whereas for the enlarged system only environmental impact from operation was studied.

The *scale* of the change studied resulted in a changed treatment of *all* waste water in the areas originating from homes and other buildings giving rise to similar types of waste water, *e.g.* schools, offices, *etc.* Industrial waste water and storm water runoff were not included in the study. Since the central waste water treatment plant in Göteborg treats all types of waste water, the environmental burdens attributable to waste water from households were calculated based on data on the sewage treatment plant and data on the composition of sewage only from households.

As a *functional unit,* the treatment of the waste water from one person equivalent (p.e.) during one year was used. The chosen functional unit does not express the scale of the change under study, but on the other hand it facilitates comparisons between Hamburgsund and Bergsjön.

This study is prospective rather than retrospective. The *time horizon* is a number of decades since the study deals with components with a long lifetime. The change was assumed to take place at the same rate as components are normally changed, i.e. all components were assumed to be used for their full technical lifetime. Processes in waste deposits were included under a surveyable time, i.e. degradation of organic matter in landfills was included.

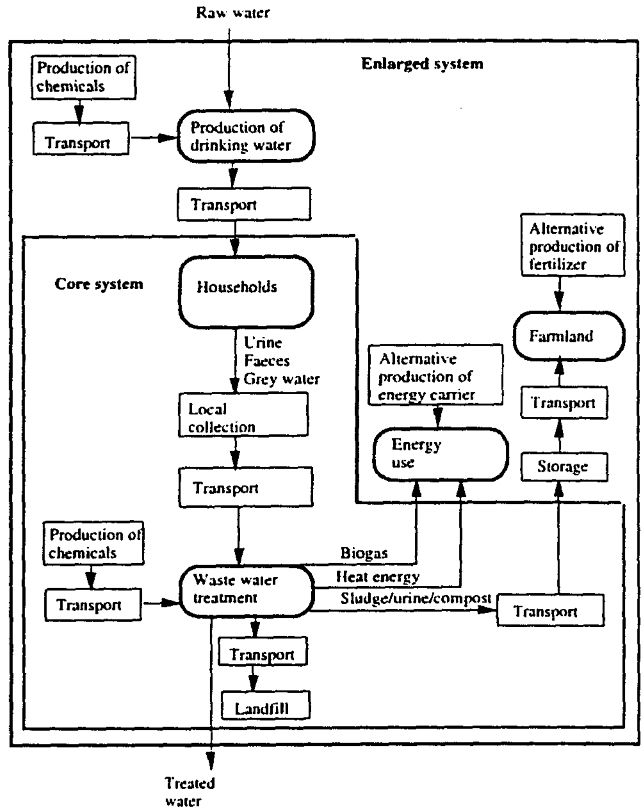

Fig. 4: Principal flowchart for treatment of waste water from households. The core system represents those activities directly involved in the handling of the water, the enlarged system represents all activities affected by a change in the waste water system

Geographically, the operation of the core system is limited to the areas studied, although pollutants from the core system have effects both on a local, regional and global scale. When the investment in the core system is included, the geographical limitation is less clear since production of material and components takes place in many different places. However, most of it takes place in Sweden, presumably. When the system is enlarged to consider effects on surrounding technical systems, its geographical frames are further widened.

The inventory of the operation of the *core system* may be seen as a flow budget over the system quantifying all flows entering or leaving the system, whether to or from nature or to or from other parts of the technical system. Thus, not all flows were traced back to their origin in the natural system or followed until released into the environment. Electricity production was not included in the core system. Instead, electricity as used on the sites was used as an aggregate parameter. Useful flows leaving the system were quantified at the point where they pass the system boundary, and no allocation was made between the multiple functions of the system, i.e. treating sewage and delivering heat and plant nutrients.

In the *enlarged system,* the flows were traced back to the acquisition of natural resources, e.g. for the production of electricity and drinking water. The flows entering the system not affected by a change of waste water treatment system were not modeled, i.e. the inflow of the constituents of the waste water (food, dirt, detergents, *etc.*) and the inflow of energy in the form of hot water. The useful flows that leave the core system were followed up to the point where they could be used. The system was then compensated with an alternative production of an equal utility. The alternative production was traced back to its origin in the natural system. The actual use of the useful flows leaving the core system or their alternatives was not included in the enlarged system since it was considered to be equal between compared alternatives. Specifically, this means that agriculture including the spreading of fertilizers was excluded from the system. Heat pumps and gas furnaces were included as was the combustion of alternative fuels but not the distribution of heat in the district heating system. Through enlarging the system, the model became better adapted to answering the question which would be the environmental consequences of changing the waste water system. The higher relevance of the modeled system in relation to this question was, however, the price of higher uncertainty. More activities are included, which means more data and thus more uncertain data. Another uncertainty concerns the alternative technologies for producing the utilities delivered by the waste water system.

It was assumed that activities outside the core system would be affected on their margin. Peak load margin is, however, not at stake here but rather the average behavior of the marginal technology. Specifically, this means that the production of synthetic fertilizers was assumed to be affected (although the average plant nutrient production is based on a mixture of manure and synthetic fertilizers), and that a reduction of heat from sewage to the district heating system would lead to an increase in natural gas combustion. The electricity production margin was taken as the import and export to Finland and Denmark based on fossil fuels, mostly coal.

The inventory of the operation of the core system was based on site specific data from 1993, supplemented with data for those changes which had already occurred at the time of the study and those that were under construction. Data for the investment in the core system were mostly literature data as recent and as representative as possible for average Swedish production. As many available inventory parameters as possible were collected. Only a selection are presented in this paper.

The inventory of the *core system* was evaluated through dominance analysis of inventory results and sensitivity analysis with respect to specific parameters with a recognized high degree of uncertainty, such as the lifetime of the components. The *enlarged system* was evaluated through dominance analysis and impact assessment using three different methods. The impact assessment results were not used for ranking the alternatives. This was done on the basis of the inventory results supplemented by a verbal, argumentative valuation.

The study involved the collection and use of a large amount of data, which cannot be included in a paper such as this. However, the background data has been published elsewhere (TILLMAN et al. 1996, MALMQVIST et al. 1995)

5 Inventory Results for the Core System

5.1 Investment

The environmental loads resulting from the investment in the core system are summarized in **Table 1** (→ *Annex, p. 155*).

The energy requirement for the investment consists mostly of thermal energy which is based on fossil fuels. Energy is required for the production of the various materials and components.

The energy requirement increases with increasing extents of local treatment and source separation, due to an increased demand for components and materials. The comparison between Bergsjön and Hamburgsund implies that environmental loads attributable to investment are smaller for large scale waste water systems than for small scale systems.

Figures 5 and 6 show that most of the investment energy is required for equipment in or in connection to the buildings. Piping in the buildings required most of the fossil fuel except for the scenario with urine separation in Hamburgsund where a large number of local tanks were suggested, due to the large number of single family houses (→ *Fig. 5*). The requirement of electricity was dominated by the sanitary equipment with the same exception for the urine separation scenario in Hamburgsund with its major utilization of collection tanks (→ *Fig 6*).

Returning back to **Table 1**, iron is used in steel products in the systems and nickel and chromium in stainless steel components. Sand, rock and limestone are used in concrete equipment. Sand is also used in the filter beds, in large quantities. **Table 1** only shows the sand quantities initially used; the top layer that is regularly changed is accounted for under the operation of the core system. Kaolin, feldspar and quartz are used in the production of sanitary equipment, and the use of sodium chloride emanates from the use of components made from polyvinyl chloride.

Air emissions show the same tendencies as the consumption of fossil fuels for most of the parameters. The reader is

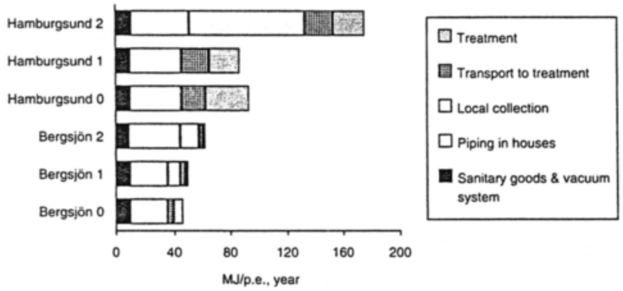

Fig. 5: Fossil fuel required for investment in the core system, separated for different parts of the system. Alternative 0 – existing system, alternative 1 – filter bed system, alternative 2 – urine separating system

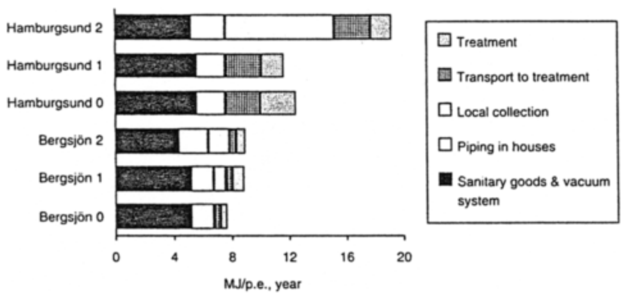

Fig. 6: Electricity required for investment in the core system, separated for different parts of the system. Alternative 0 – existing system, alternative 1 – filter bed system, alternative 2 – urine separating system

reminded that the production of electricity is not included in the core system, and thus air emissions from electricity production are not included either.

Water emissions are minor in comparison with those from the operation of the systems. Waste emanates mainly from production of plastic products and sanitary goods.

5.2 Operation of the core system

The results of the inventory of the operation of the core system are summarized in **Table 2** (→ *Annex, p. 156*).

As shown in **Table 2**, the electricity required for operating the core system is much larger than the amounts of fuels required. The need for electricity decreases with increasing extents of local treatment and source separation. For Bergsjön, the fuel requirement increases in alternatives 1 and 2, whereas the fuel requirement for the existing system in Hamburgsund is higher than in all other scenarios.

Tables 3 and **4** (→ *Annex, p. 156 and 157*) present the dominant activities contributing to the energy requirements from the operation of the systems. As presented in **Table 3** (→ *Annex, p. 156*), the production of chemicals for waste water treatment dominates the fossil fuel requirement of the existing systems, whereas the picture is more diversified for the alternatives. As shown in **Table 4** (→ *Annex, p. 157*), electricity consumption is dominated by operating the waste water treatment plants in the existing systems, whereas electricity is needed for pumping and operating vacuum toilets in the alternatives.

Returning to **Table 2** (→ *Annex, p. 156*), the other resources needed are used for producing chemicals for waste water treatment except sand which is used in large quantities in the filter beds. The comparison with **Table 1** (→ *Annex, p. 155*), however, shows that more sand is used over the lifetime of the beds for the investment than for the regular change of the top layer.

The consumption of drinking water is reduced through the introduction of vacuum toilets. The **emissions to air** show the same tendencies as the consumption of fossil fuels. Methane is an exception since it emanates from the degradation of organic matter in a landfill and not from combustion. The amounts emitted from the landfill where all sludge from the existing system in Hamburgsund is deposited were very roughly estimated from literature data and approximations. However, it should be noted that the methane from the landfill may contribute to a large extent to the global warming potential of the system due to the high global warming potential of methane. Methane from landfilled sludge from Bergsjön is effectively recovered.

The **emissions to water** from operating the waste water treatment plants, of course, far exceed those from investments. The emissions from waste water treatment are measured as biological oxygen demand (BOD), total nitrogen (N_{tot}) and total phosphorus (P_{tot}). The much smaller emissions of chemical oxygen demand (COD) emanate from production processes in the system, mostly production of aluminum chloride for chemical treatment. As shown in **Table 2**, urine separation is a very effective means of separating both BOD and nitrogen when compared with the other alternatives. Urine separation is less effective than the large waste water treatment plant in Göteborg in reducing phosphorus emissions but better than the small plant in Hamburgsund.

Alternatives 1 and 2 produce far less waste of all categories than the existing systems. Red mud is an alkaline sludge, a by-product from the production of aluminum oxide used for the production of treatment chemicals.

The comparison between Bergsjön and Hamburgsund shows that for most parameters there are economies of scale such as environmental loads from the operation of existing systems (alternative 0), whereas no evidence of such economies can be found for the operation of the alternatives 1 and 2 (→ *Table 2*).

The comparison between investment and operation of the core system (→ *Tables 1* and 2) shows that although the environmental burdens from investing in the systems are in no way negligible in comparison with those of their operation, they vary far less between the alternatives from operation.

A number of useful flows leave the core system to other parts of the technical system. The effects are further investigated in the analysis of the enlarged system.

6 Inventory Results for the Enlarged System

The inventory results for the enlarged system are summarized in **Table 5** (→ *Annex, p. 157*).

The existing system in Bergsjön (alternative 0) is a net producer of energy due to the heat recovery from the waste water. Alternative 1, local treatment in sand filter beds, uses the highest amount of energy for Bergsjön, whereas the urine separating alternative (alternative 2) uses less energy. In Hamburgsund, there is no heat recovery, and thus the existing system uses the most energy and the urine separating the least. **Figures** 7 (Bergsjön) and 8 (Hamburgsund) reveal which parts of the systems dominate the energy conversions. The reader is asked to observe the difference in scales, see **Figures** 7 and 8.

For Bergsjön (→ *Fig. 7*), the energy use of the core system is of the same order of magnitude as that needed to produce drinking water. Energy savings from avoided fertilizer production are minor. With the assumption that electricity production is based on condense power, the heat pump uses nearly as much primary energy as is supplied as heat to the district heating system. However, the difference is enough to make the existing system a net supplier of energy.

For Hamburgsund (→ *Fig. 8*), the operation of the core system dominates the energy requirements, especially for the existing system (alternative 0).

As for other resources required by the enlarged system (→ *Table 5*), the use of raw materials for the production of water treatment chemicals (bauxite, limestone, sodium chloride) is increased as compared with the operation of the core system (→ *Table 2*), due to the inclusion of processes to produce drinking water. Raw water consumption is a little less in the urine separating alternatives, due to decreased water consumption for flushing the separating toilets. Consumption figures for raw phosphate are negative. This is explained by the approach used when environmental loads from avoided production of synthetic fertilizers are subtracted from the loads of the core system. Phosphorus recycling is high in all alternatives in Bergsjön, slightly better for the urine separating alternative, whereas there is no phosphorus recycling in the existing system in Hamburgsund.

For Hamburgsund, emissions to air provide the same ranking between alternatives as fossil fuel consumption with the exception of hydrocarbons, carbon monoxide and particulates, for which alternative 1 is preferable to alternative 2. For Bergsjön, the picture is more complex. Although the existing system (alternative 0) consumes the least fossil fuels, it gives rise to the largest emissions not only of carbon dioxide but also of sulfur dioxide, nitrogen oxides, hydrocarbons, carbon monoxide and particulates. This somewhat surprising result emanates from the choice of using marginal technologies to represent the processes added to the core system when enlarging the system. The electricity for operat-

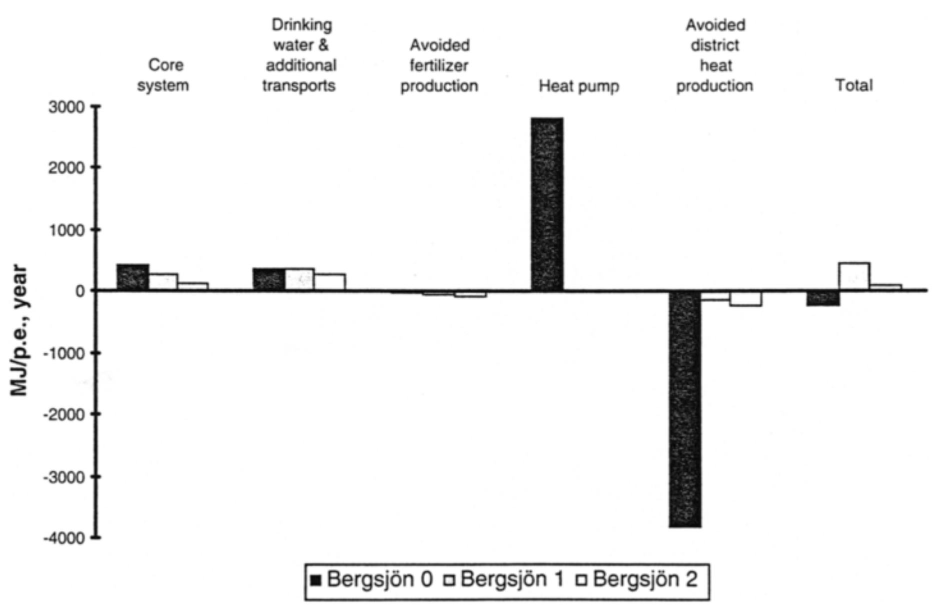

Fig. 7: Use of fossil fuels for the enlarged Bergsjön system, divided into different parts of the life cycle. Alternative 0 – existing system, alternative 1 – filter bed system, alternative 2 – urine separating system

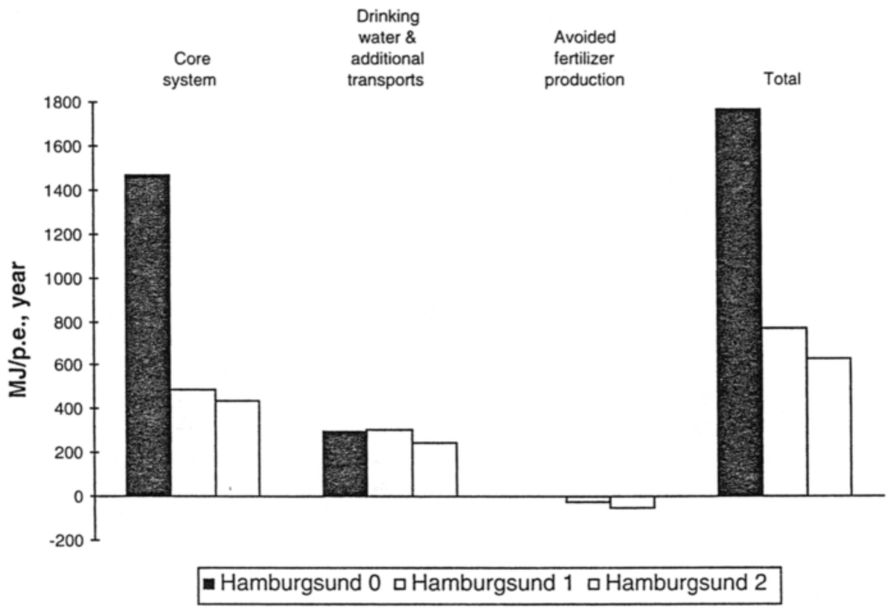

Fig. 8: Use of fossil fuels for the enlarged Hamburgsund system, divided into different parts of the life cycle. Alternative 0 – existing system, alternative 1 – filter bed system, alternative 2 – urine separating system

ing the heat pumps was assumed to be fossil fuel based condense power, mostly based on coal, whereas the avoided heat production was assumed to be combustion of natural gas.

Emissions to water are similar for the enlarged system as for the core system. COD-emissions are added, due to the additional production processes, but these are minor in comparison with the BOD emissions from the waste water treatment. Reductions in nitrogen emission for alternative 2 in Bergsjön and alternatives 1 and 2 in Hamburgsund, as compared with the operation of the core system, are explained by avoiding nitrogen emissions through avoiding the production of N-fertilizers.

The amounts of sludge are the same as for the core system, whereas production of red mud, solid waste and hazardous waste increase, due to more production processes being included in the system. Gypsum waste emanates from the production of phosphorus fertilizers, and thus follows the same trend as the use of raw phosphate.

7 Discussion and Conclusions

7.1 Core system

Environmental impacts from investment in the systems were largely related to fossil fuel consumption. Dominant activities were the production of sanitary goods and piping in or in direct connection with buildings, and in the urine separating alternative, tanks for local collection.

Operation energy for the core system consisted mainly of electricity, mostly for pumping and waste water treatment. Electricity consumption decreased with increasing extents of local treatment and source separation but was in part replaced by the consumption of fossil fuels for transportation.

The comparison between investment and operation showed that for the parameters describing emissions to water and electricity consumption, the impact of operation was larger than that of investment. For the existing alternative in Hamburgsund it may also be concluded that the impact from operation was larger than that of investment. Otherwise, the comparison between investment and operation shows no very clear tendencies. It may, however, be concluded that investment impacts varied far less between alternatives than those of operation.

The differences between Hamburgsund and Bergsjön imply positive economies of scale for waste water treatment from an environmental point of view. This holds true for investment in all three alternatives and for operation of the existing systems.

There were large uncertainties in the study of the investment in the systems. A sensitivity analysis with respect to identified major uncertainties (lifetime of dominant components, contribution from waste water treatment plant) showed that although the results were sensitive to changes in these data, only conclusions concerning the contribution from the waste water treatment plant in Hamburgsund were likely to be affected by the uncertainties.

7.2 Enlarged system

The enlarged system was modeled to enabling the ranking of alternatives. For Hamburgsund, this was relatively easy. All resource parameters except consumption of sand, rank the alternatives in the same manner. Urine separation was found to be preferable to treatment in sand filter beds, which in turn was found to be preferable to the existing system (→ *Table 5*). Most **emissions to air** show the same ranking order, although not all parameters distinguish alternatives 1 and 2. **Emissions to water** depend primarily on the ability of the systems to separate plant nutrients and organic matter. It is obvious that separating the fractions that contain the largest amounts of these substances at their source (alternative 2) was the most efficient means, although alternative 1 (filter bed) would also be an improvement of the present situation. Waste parameters give the same ranking order as the other parameters. Thus, it may be concluded that in most respects the urine separating alternative would be environmentally preferable to the treatment in sand filter beds, which in turn would be better than the existing system. This was supported by all three weighting methods applied. It may also be concluded that there are large improvement potentials in the existing system, i.e. through recovering the sludge to agriculture. Although there were no data on the content of contaminants, such as metals in the Hamburgsund sludge, since there is neither industry nor storm water runoff connected to the system, the sludge quality would probably allow this utilization.

For Bergsjön, the picture is much more complex. Investigating the emissions to water, it is clear that urine separation is an efficient means of reducing discharges of nitrogen to water. A large waste water treatment plant such as Ryaverket, with denitrification is, however, more efficient at reducing both nitrogen and phosphorus than the filter-bed treatment and is also somewhat more efficient at phosphorus reduction than urine separation. As for resource consumption, the existing system is a net supplier of energy, and the filter bed alternative uses the largest amount of energy. Phosphorus recycling is high for all three alternatives, although the urine separating alternative is slightly better than the others. Emissions to air, however, are highest for the existing system. Nevertheless, an attempt was made to rank the alternatives, although such ranking cannot be performed without introducing subjective arguments.

The weighting methods used valued the results very differently. The EPS-method (Steen and Ryding 1993) ranked the existing system as preferable. Dominant parameters in the EPS-valuation were the use of fossil resources, carbon dioxide emissions and raw phosphate, which, however, was quite similar among the alternatives. The other weighting methods used "Weighted Environmental Themes and Ecoscarcity" (Baumann et al. 1993), based on distance to politically set targets, ranked the urine separating alternative as preferable, with reduction of eutrophying substances to receiving waters as the goal dominating the results in this particular study. All three weighting methods ranked the filter bed alternative as least preferable.

The weighting methods were not used for ranking the alternatives. They were, however, used for identifying the most important inventory parameters and for structuring a discussion about them. The discussion below is thus limited to fossil fuel use, carbon dioxide emissions, use of raw phosphate and emissions of nitrogen and phosphorus to receiving waters.

It may be argued that emphasizing both use of fossil fuels and emissions of carbon dioxide is a form of double accounting and that effects of carbon dioxide emissions will probably limit the use of fossil fuels before the coal resources are depleted. Natural gas and petroleum resources are, however, more limited than coal resources. According to the Encyclopædia Britannica world coal resources are difficult to assess, and estimates of how long coal reserves will last range from a few hundred years to more than 1,000 years (Britannica On-Line). According to the BP Statistical Review, economically and technically recoverable coal reserves amount to approximately 1000 Gtons which would last for over another 200 years at the present consumption rate (BP Statistical Review 1996). However, the geological coal resources are much larger, estimated to approximately 10,000 Gtons (Britannica On-Line). Present flow of carbon to the atmosphere originating from fossil fuel consumption and cement production amounts to 5.5 Gtons/year (IPPC 1994). Stabilizing the emissions at that rate would not lead to stabilized carbon dioxide concentration in the atmosphere but to a continued increase to 500 ppm year 2100, which should be compared with the present concentration of 356 ppm and the pre-industrial concentration of 280 ppm. Accepting this line of argument, carbon dioxide emissions may be regarded as the relevant indicator for fossil fuel consumption and fuel consumption as such disregarded.

Carbon dioxide emissions clearly favor alternative 2 (urine separation) over alternative 1 (filter beds) which is favored over the existing system (→ *Table 5*). Use of raw phosphate is slightly lower for the urine separating alternative than the other two. Concerning emissions of nitrogen to water, the urine separating alternative was clearly the preferable one and the sand filter bed alternative the least preferable. Again, the sand filter bed alternative was the least preferable concerning phosphorus releases, but for this parameter the existing system was slightly more efficient at reducing emissions than the urine separating system. In summary, the urine separating alternative shows the least environmental impact for all the parameters highlighted by the impact assessment, except for fossil fuel consumption and release of phosphorus. In this alternative, the waste water would be released to fresh receiving waters, presumably more sensitive to phosphorus than the sea used as receiving water in the other alternatives. On the other hand, the content of phosphorus in the sewage water may be rather easily decreased through the use of low phosphorus or phosphorus free detergents.

A ranking of the alternatives is thus highly sensitive, both to the assumptions concerning surrounding technical systems (i.e. marginal electricity production based mostly on coal, marginal district heat production based on natural gas) and valuations. The alternatives were ranked using these assumptions and the subjective assessments that carbon dioxide emissions were considered more important than depletion of fossil fuels and emissions to water were considered more important than emissions to air for waste water treatment systems.

From these reasons, urine separation was assessed as preferable to the existing alternative which in turn was preferable to local treatment in filter beds. Again, it is stressed that this is not a very robust conclusion.

7.3 Methodological experience from the project

The decision to divide the system studied into a core system and surrounding technical systems was not made from the outset but emerged during the course of the project as a practical means of sorting the data and presenting the results. However, it proved to be a very useful distinction helping the analysts to make consistent methodological choices, *e.g.* what type of data should be used to represent different parts of the system (site specific, annual averages for operation of the core system, and average data on marginal production capacity for surrounding technical systems). The distinction between core system and surrounding technical systems is very similar to the concepts background and foreground systems, as discussed by the SETAC working group on inventory methodology (CLIFT et al. 1997). Since the division involved in this project emerged from practical needs, it is not completely consistent with the SETAC definitions and thus the concepts **core system** and **surrounding technical systems** were presented in this paper.

The decision to enlarge the systems was taken at an early stage of the project. Insofar it was possible to rank the alternatives based on a study that would describe the full effects of the change considered. Uncertainties were introduced into the study concerning the exact effects on the surrounding technical systems. An allocation of the core system's environmental burdens between its multiple functions would also have enabled a ranking of alternatives, although not based on a model of the full effects of the change. Whether or not such a method would have resulted in similar ranking was not investigated. If such a methodological choice had been made, uncertainties would have been introduced when choosing allocation factors and in the data underlying them.

The approach chosen to enlarge the system was highly considered to be relevant in a study as this which is designed to be used in societal decision making. It was shown that the methodology chosen was applicable and feasible, although the results, at least for the part of the study concerned with Bergsjön, were highly sensitive to assumptions regarding which technology in the surrounding technical systems would be affected.

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Annex: Tables 1 to 5

Table 1: Inventory results for investments in the core system (selected parameters), expressed in relation to the functional unit, treatment of waste water from one person equivalent (p.e.) during one year

	Bergsjön			Hamburgsund		
	Alt 0 existing	**Alt 1** filter bed	**Alt 2** urine separation	**Alt 0** existing	**Alt 1** filter bed	**Alt 2** urine separation
Resources						
Energy						
Electricity, MJ	7.6	8.8	8.9	12.4	11.6	19.2
Fossil fuels, MJ	45.7	49.3	62.2	92.4	86.7	174.4
Raw materials						
Fe, kg	0.26	0.098	0.26	1.2	0.9	1.8
Ni, g	1.1	0.7	6.1	9.0	5.1	13.6
Cr, g	3.6	2.2	19.5	28.6	16.2	43.3
Sand, kg	1.9	1800	1400	9.3	2000	2000
Rock, kg	3.3	77.5	64.8	16.4	59.1	85.2
Kaolin/feldspar/quartz, kg	0.54	0.54	0.37	0.58	0.58	0.62
Limestone, kg	1.7	3.6	3.0	8.3	5.3	10.3
NaCl, g	317	320	322	413	418	367
Emissions						
To air						
CO_2, kg	2.6	2.8	3.4	6.7	6.1	11.7
CH_4, g	0.8	0.8	0.9	1.2	1.0	3.7
SO_2, g	11.7	12.6	16.5	28.7	23.7	52.3
NO_x, g	13.6	15.5	18.9	30.8	29.2	57.0
Hydrocarbons, g	10.1	10.5	15.0	14.9	16.8	39.2
CO, g	2.3	2.7	2.9	5.4	5.2	8.2
Particulate, g	2.4	2.6	3.5	4.6	52.5	57.7
To water						
COD, g	0.54	0.54	0.95	0.81	0.78	3.2
N-tot, g	7.1E-3	6.2E-3	17.7E-3	0.03	0.02	0.08
P-tot, g	0.11E-3	0.08E-3	0.31E-3	0.01	0.001	0.001
Waste						
Solid waste, kg	0.15	0.12	0.44	0.67	0.48	1.1
Hazardous waste, g	0.55	0.56	0.57	0.74	0.73	0.67

Table 2: Inventory results for operation of the core system (selected parameters), expressed in relation to the functional unit, treatment of waste water from one person equivalent (p.e.) during one year

	Bergsjön			Hamburgsund		
	Alt 0 existing	**Alt 1** filter bed	**Alt 2** urine separation	**Alt 0** existing	**Alt 1** filter bed	**Alt 2** urine separation
Natural resources						
Fossil fuels, MJ	17.6	39.9	68.0	227.2	9.3	77.5
Bauxite, kg	0.12	0	0	21.1	0	0
Limestone, kg	2.0	0	0	6.2	0	0
Sand, kg	0	590	230	0	249	124
NaCl, kg	0.05	0	0	8.7	0	0
Inflows from other parts of the technical system						
Electricity, MJ	167.0	97.2	24.8	496.8	193.3	150.8
Drinking water, m^3	73.0	73.0	54.8	61	61	50
Hydrogen peroxide, g	0.013	0	0	2.2	0	0
NaClO, g	460	0	0	0	0	0
Emissions						
To air						
CO_2, kg	0.89	3.04	5.36	17.3	0.73	5.07
CH_4, g	0	0	0	1880	0	0
SO_2, g	5.4	6.0	10.5	98.2	1.4	7.8
NO_x, g	16.7	50.5	88.9	139	12.2	74.8
Hydrocarbons, g	1.1	8.1	14.2	20.5	2.0	10.5
CO, g	13.6	11.6	20.5	27.8	2.8	15.1
Particulates, g	1.8	3.9	6.9	125	0.9	5.1
To water						
COD, g	0.94	0.05	0.08	160	0.01	0.06
BOD, kg	2.08	2.3	0.96	1.96	1.42	0.58
N-tot, kg	2.37	3.20	0.31	4.22	2.38	0.76
P-tot, kg	0.11	0.21	0.13	0.18	0.12	0.054
Waste						
Solid waste, kg	2.0	0	0	1.5	0	0
Hazardous waste, g	0.05	0	0	9.1	0	0
Sludge, kg	3.21	0	0	25.6	0	7.6
Red mud, kg	0.09	0	0	14.7	0	0
Outflows to other parts of the technical system						
Heat in waste water, MJ	3078	0	0	0	0	0
Biogas, MJ	19	155	221	0	0	0
Nitrogen to agriculture, kg	0.48	0.47	4.31	0	0.99	3.82
Phosphorous to agriculture, kg	0.96	0.96	1.17	0	0.80	0.85

Table 3: Percentage contribution to fossil fuel requirement from dominant activities in operation of the core system

	Bergsjön			Hamburgsund		
	Alt 0 existing	**Alt 1** filter bed	**Alt 2** urine separation	**Alt 0** existing	**Alt 1** filter bed	**Alt 2** urine separation
Production of treatment chemicals	73	-	-	70	-	35[a]
Transport of treatment chemicals	22	-	-	5	-	-
Acquisition and transport of sand	-	30	14	-	79	5
Digestion facility	-	54	31	-	-	-
Transport of urine to storage	-	-	50	-	-	26
Transport of sludge to treatment	-	16	12	-	21	4
Transport of sludge to landfill	-	-	-	21	-	30

[a] Production of biologically available nitrogen, added to the filter bed when all urine is separated so that it can function properly

Table 4: Percentage contribution to electricity requirement from dominant activities in operation of the core system

	Bergsjön			Hamburgsund		
	Alt 0 existing	**Alt 1** filter bed	**Alt 2** urine separation	**Alt 0** existing	**Alt 1** filter bed	**Alt 2** urine separation
Vacuum toilets	-	-	22	-	-	30
Pumping	9	97	72	19	100	70
Waste water treatment plant	84	-	-	80	-	-

Table 5: Inventory results for the enlarged system (selected parameters), expressed in relation to the functional unit, treatment of waste water from one person equivalent (p.e.) during one year

	Bergsjön			Hamburgsund		
	Alt 0 existing	**Alt 1** filter bed	**Alt 2** urine separation	**Alt 0** existing	**Alt 1** filter bed	**Alt 2** urine separation
Natural resources						
Fossil fuels, MJ	-244	459	107	1771	768	631
Bauxite, kg	1.7	1.6	1.2	22.1	1.0	0.8
Limestone, kg	6.5	4.5	3.4	6.5	0.3	0.2
Sand, kg	0	590	230	0	249	124
NaCl, kg	1.1	1.1	0.8	9.2	0.5	0.4
Water, m^3	73	73	55	61	61	50
Raw phosphate, kg	-5.8	-5.8	-7.1	0	-4.8	-5.1
Emissions						
To air						
CO_2, kg	66.9	43.6	14.7	150	65.9	54.3
CH_4, g	-721	-29.1	-41.8	1880	0	0
SO_2, g	1690	289	160	827	364	293
NO_x, g	858	284	169	775	331	306
Hydrocarbons, g	29.1	20.2	20.3	35.1	10.0	15.8
CO, g	42.1	28.9	33.2	50.5	15.4	23.6
Particulates, g	33.5	20.6	16.8	138	11.1	12.8
To water						
COD, g	12.7	11.8	8.9	167	7.6	6.3
BOD, kg	2.08	2.3	0.96	1.96	1.42	0.58
N-tot, kg	2.37	3.20	0.21	4.22	2.36	0.67
P-tot, kg	0.11	0.21	0.13	0.18	0.12	0.054
Waste						
Solid waste, kg	2.5	0.5	0.4	1.5	0.08	0.06
Sludge, kg	3.2	0.3	0.2	25.6	0	7.6
Red mud, kg	1.2	1.1	0.8	15.4	0.7	0.6
Hazardous waste, g	0.7	0.7	0.5	11.0	1.9	1.5
Gypsum waste, kg	-8.6	-8.6	-10.5	0	-7.2	-7.6