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Rockdrain for maintenance of tunnel drainage systems

An application at the Lundby Tunnel in Gothenburg, Sweden

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In cooperation with Trafikverket

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Preface

Rockdrain is a new type of tunnel drainage that has been developed as an alternative to the traditional underground drainage systems with drainage mats of foamed polyethylene used today. This study is part of the Swedish Transport Administration's efforts to investigate Rockdrain as an alternative drainage method. So far, the Rockdrain technology has been evaluated and compared to traditional underground drainage systems. The research has, so far, mainly been focused on new construction of tunnels and large-scale renovation, during which a tunnel can be closed for a long time. Reference objects have been the tunnel at Kattleberg outside Gothenburg and the Hallandsås tunnel on the border between the provinces of Halland and Skåne, both located in Sweden.

In Sweden, the present type of underground drainage was first used in the 1990s and its life expectancy has been calculated to be about 40-60 years. Already in the 1960s, plastics covered mineral wool drainage was tested, however with poor technical results. Narrow (0.5 m) and thin (10-20 mm) polyethylene foam drainage mats were first used in 1980s. This indicates that in the near future and even today, there is a great need for maintenance of these drainages in the Swedish tunnels. In this research study, we have investigated the possibilities and consequences of using Rockdrain for maintenance of old and worn out underground drainage systems. In this limited study, a maintenance operation of the drainage in the Lundby tunnel in Gothenburg has been assessed using Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCC). Methods and models from previous studies have been used in this project. The maintenance installation work in the Lundby tunnel was made at the turn of the year 2014/2015.

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A project and reference group consisting of the following individuals has assisted the project:

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Gothenburg, Sweden, September 2016

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Summary

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In Sweden, the present type of underground drainage was first used in the 1990s and its life expectancy has been calculated to be about 40-60 years. Already in the 1960s, plastics covered mineral wool drainage was tested however with poor technical results. Narrow (0.5 m) and thin (10-20 mm) polyethylene foam drainage mats were first used in 1980s. This means that in the near future and even today there is a great need for maintenance of these drainages in the Swedish tunnels. In this research study, we have tried to investigate the possibilities and consequences of using Rockdrain for maintenance of old and worn out underground drainage systems. In this limited study, a maintenance operation (100 m^2) of the drainage in the Lundby tunnel in Gothenburg has been assessed using Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCC). Methods and models from previous studies have been used in this project.

Many tunnels cannot be closed for a long time. Thus, the maintenance has to be carried out during operation of the tunnel in short time slots (e.g. during night) but during a long time period of may be weeks or months (small-scale maintenance). In this study, Rockdrain has been investigated as a possible way to simplify small-scale maintenance. Only Rockdrain has been tested and no evaluation of small-scale installation of conventional drainage has been carried out.

The test results have shown that Rockdrain very well can be used for small-scale maintenance of tunnel drainage. The technical processes used for the small-scale maintenance does not differ much from the techniques used for large-scale maintenance. The primary energy resource use and the emissions per m^2 drainage are therefore not very different. However, the amount of labour work needed is very different. Much more labour work is needed for the small-scale maintenance due to an increased amount of establishment and unprovisioning. The life cycle cost (LCC) is therefore higher for the small-scale maintenance compared to large-scale maintenance of Rockdrain. However, compared to large-scale maintenance of and with conventional drainage, Rockdrain shows significantly lower values.

The long term effect of Rockdrain for maintenance has not been investigated. Future evaluations are needed to show these effects.

Sammanfattning

Den långsiktiga effekten av Rockdrain är en ny typ av tunneldränering som har utvecklats som ett alternativ till den traditionella tunneldräneringen med dräneringsmattor av skummad polyeten som används idag. Denna forskningsstudie utgör en del av Trafikverkets arbete med att utreda Rockdrain som alternativ dräneringsmetod. Hittills har själva tekniken med Rockdrain utvärderats och jämförts med traditionell tunneldränering. Forskningsarbetet har då framför allt fokuserats på nybyggnation av tunnlar och storskalig renovering där en tunnel kan vara avstängd under en längre tid.

Den nuvarande typen av tunneldränering började användas i Sverige på 1990-talet och livslängden har beräknats till ca 40-60 år. Redan på 1960-talet testades plasttäckt mineralull som dränering dock med dåligt tekniskt resultat. Smala (0,5 m) och tunna (10-20 mm) dräneringsmattor av skummad polyeten användes först på 1980-talet. Detta innebär att det inom en snar framtid och även redan idag finns ett stort behov av underhåll av dessa dräneringar i de svenska tunnlarna. I denna forskningsstudie har vi därför försökt att undersöka möjligheter och konsekvenser med att använda Rockdrain som underhållsåtgärd för gamla och uttjänta tunneldräneringar. I denna mycket begränsade studie har en underhållsåtgärd av dräneringen i Lundbytunneln i Göteborg utvärderats med hjälp av Livscykelanalys (LCA) och Livscykelkostnadsanalys (LCC). Metoder från tidigare studier har använts i detta projekt.

Många tunnlar kan inte vara avstängda under en lång tid för underhåll. Därför måste underhållet utföras under normaldrift av tunneln i korta tidsperioder (t.ex. nattetid) men under en lång tid (småskaligt underhåll). Denna studie har utvärderat Rockdrain som en möjlig metod för att förenkla småskaligt underhåll under drift. Endast Rockdrain har testats och ingen småskalig installation av konventionell dränering har utförts.

Resultaten visar att Rockdrain mycket väl kan användas för småskaligt underhåll av tunneldränering. Den teknik som används för småskaligt underhåll skiljer sig inte mycket från den teknik som används för storskaligt underhåll med en avstängd tunnel under en längre tid. Användningen av primära energiresurser och emissioner per m^2 dränering skiljer sig därför inte heller så mycket. Emellertid är mängden arbete i man-timmar som krävs mycket olika. Mycket mera arbetstid (man-timmar) behövs för det småskaliga underhållet på grund av ökad mängd etableringar och avetableringar (omställningstid). Livscykelkostnaden (LCC) är därför högre för småskaligt underhåll jämfört med storskaligt underhåll av Rockdrain. Jämfört med storskaligt underhåll av och med konventionell dränering, visar Rockdrain dock betydligt lägre värden.

Den långsiktiga effekten av Rockdrain som underhållsåtgärd har inte undersökts. Framtida utvärderingar och uppföljningar av Rockdrain måste påvisa dessa effekter.

1 Introduction

Draining of tunnels and other underground structures are important especially for transport (e.g. road and rail tunnels) but also, for example, for subway system, caverns, mines, etc. This type of drainage prevents leakage of water into the tunnel area from the walls and roof, and thus protects sensitive equipment in the tunnels. Normally today, drainage mats of foamed polyethylene covered with shotcrete are used. This is a relatively complicated and labour intensive method. It has therefore been reasons to improve the drainage method by developing alternative technologies and systems.

Rockdrain is a new type of tunnel drainage that has been developed as an alternative to the traditional underground drainage systems with drainage mats of foamed polyethylene used today. This research study is part of the Swedish Transport Administration's efforts to investigate Rockdrain as an alternative drainage method. So far, the Rockdrain technology has been evaluated and compared to traditional underground drainage systems in a research study [3, 4, 5]. This research has, so far, mainly been focused on new construction of tunnels and large-scale renovation, where a tunnel can be closed for a long time. Reference objects have been the tunnel at Kattleberg outside Gothenburg and the Hallandsås tunnel on the border between the provinces of Halland and Skåne, both located in Sweden.

In Sweden, the present type of underground drainage was first used in the 1990s and life expectancy has been calculated at about 40-60 years. Already in the 1960s, plastics covered mineral wool drainage was tested however with poor technical results. Narrow (0.5 m) and thin (10-20 mm) polyethylene foam drainage mats were first used in 1980s. This means that in the near future and even today there is a great need for maintenance of these drainages in the Swedish tunnels. In this research study, we have tried to investigate the possibilities and consequences of using Rockdrain for maintenance of old and worn out underground drainage systems. In this very small study, a maintenance operation of the drainage in the Lundby Tunnel in Gothenburg has been assessed using Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCC). Methods and models from previous studies have been used in this project. The maintenance installation work in the Lundby Tunnel was made at the turn of the year 2014/2015.

2 Analytical methods and methodological reports

2.1 General methodology

Production of different products, materials, and services is often very complex and may involve many different activities in the society such as extraction of raw materials, construction of buildings, power generation and transports etc. Due to this complexity, it can be difficult to calculate emissions and energy consumption in a relevant way for an entire production system. The complexity may increase when various production systems are compared, or when different process changes have to be evaluated and assessed.

A system is a unit that consists of different parts working together. By applying a system perspective, i.e. taking the entire system into account, one can get a better and more accurate picture of the production system and one can for example avoid sub-optimization. For example, when evaluating materials in terms of energy and environmental aspects it is important not to evaluate only the production process of the material but also ensure that the environmental load does not increase due to e.g. increased maintenance and operation activities. Analysing production systems rather than individual production processes make higher demands on the methodology and the implementation. A logical and structured methodology and a well thought-out analysis are required. Computer based calculations and models are also required.

For this type of system analysis, the most common method is Life Cycle Assessment (LCA). The LCA method offers a fully developed and standardized method with available computer software platforms. This method is also the base for certified Environmental Product Declarations (EPD). In the next chapter, a short presentation of the LCA method is shown. LCA is a comprehensive tool comprising many different environmental aspects. Even if an analysis has a focus on just a few of these aspects (such as CO_2, carbon footprint), an LCA analysis can and should be used to keep track of e.g. eventual side effects of different CO_2 reduction measures.

An economic evaluation can be performed in many different ways and can include many different aspects of the economy. In general, an economic calculation and evaluation of a product or process include the same type of methodological aspects as for the system analysis. Also for the economic analysis, it is important to have a system perspective i.e. to include all costs during the lifetime (or calculation period where the lifetime is difficult to define) of the product or process. For this type of analyses, the Life Cycle Cost (LCC) methodology has been developed.

In this study, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methodology has been chosen for the analysis of the drainage systems. An overview of the methodology is given in chapter 2.2 and 2.3 below.

A useful principle for infrastructure analyses has been to divide the activities in three groups: Construction, Maintenance and Operation. This method has been used also for this study. A calculation period is set to 60 years. All activities from construction start to the following 60 years are included in the calculations. The potential uptake of CO_2 during lifetime of the product is also shown. The full CO_2 uptake potential (~20 % of maximum uptake) is shown in all figures for all concrete use even if the uptake period can cover a longer period than 60 years but the uptake shown in the figures will not include CO_2 uptake during the concrete waste phase. The maintenance and operation calculations are calculated per year for each activity. A yearly share of maintenance/operation is added to the result even if the actual activity does not occur until after a certain number of years. This means that the results are comparable independent of the lifetime for the different products or processes.

It can of course be difficult to estimate technical data (e.g. transport work, electric power production) for such a long time but the aim of the calculation period is not to give a clear picture of the development over the next 60 years. The aim of the calculation period is instead to create a balance between construction, maintenance and operation of the product. The calculation period is set to a time-period close to the lifetime of the product (or an economic calculation period). In this way, one can receive a balanced picture for the influence of construction, maintenance and operation. This also implies that technical data of today can be used in the calculations in absence of technical data during the next 60 years.

2.2 Life Cycle Assessment (LCA)

A system analysis is a tool that allows a product to be analysed through its entire life cycle, from raw material extraction and production, via the material's use to waste handling and recycling. The most common tool for system analysis is the Life Cycle Assessment (LCA) methodology. The LCA methodology is described in, for example, the standards EN ISO 14040:2006 and 14044:2006 [1, 2]. In a life cycle assessment, a mathematical model of the system is designed. This model is of course a representation of the real system, including various approximations and assumptions. The results from the model are then of course, also dependent on the values and assumptions in the model and the model results are valid for these values and assumptions. The LCA methodology allows us to study complex systems, where interactions between different parts of the system exist, to provide as complete a picture as possible of the environmental impacts of, for example, a product.

An LCA is usually made in three steps with an additional interpretation step, see ISO standard. In the goal and scope definition, the model and process layout are defined. The functional unit is also specified. The functional unit is the measure of performance that the system delivers. In the Life Cycle Inventory analysis (LCI), the material and energy flows are quantified. Each sub-process has its own performance unit and several in- and out-flows. The processes are then linked together to form the mathematical system being analysed. The final result of the model is the sum of all in- and out-flows calculated per functional unit for the entire system. The life cycle impact assessment (LCIA) is defined as the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. The impact assessment is performed in consecutive steps including classification, characterization, normalization and weighting. The LCIA phase also provides information for the life cycle interpretation phase, where the final environmental interpretation is made. In this study, only classification and characterization have been included in the impact assessment part. Here, the same classification and characterization scheme as proposed in the EPD system[1] have been used.

2.3 Life Cycle Cost (LCC)

An economic evaluation can be performed in many different ways and can include many different aspects of the economy. The aim of Life Cycle Cost (LCC) is to include all costs during the entire life cycle of the product. This will result in a more accurate description of the entire cost for a product or process than just an analysis of the purchase price. In general, an economic calculation and evaluation of a product or process include the same type of methodological issues as for the system analysis. Also for the economic analysis, it is important to have a system perspective i.e. to include all costs during the lifetime (or calculation period where the lifetime is difficult to define) of the product or process. Thus, the entire system must be taken into account and the analysis must include the entire life cycle of the product or process. In many cases, the underlying background data is the same for LCA and LCC. It can therefore be convenient to include the LCC calculations in the LCA model. In this project, we have combined the two models into one common model.

A difference for example between costs and emissions or energy use is that a cost in a given position in the process flowchart includes all upstream cost. All parts in the upstream flowchart have been paid so the cost in a given position is thus the sum of all upstream costs. A consequence is thus that the economic details of the upstream costs are lost because upstream detailed costs are not included in the model. This also implies that it is very important for the resolution of the cost, how the cost is calculated in the model.

It is also important to define the types of costs that are included and how they are presented. In this case, we have chosen to include only internal costs. External costs (also called externalities) are not included in the model. Internal costs are ordinary costs, which are paid by the different parts in a business transaction. Examples of such costs are material costs, labour costs, energy costs etc. External costs are costs that are not normally paid by the parties in a business deal, but by external parties. Examples of such costs are costs for pollution damage and health costs. The bearers of external costs can be either particular individuals or society at large. External costs are in many cases difficult to

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[1] Environmental Product Declaration is a system designed for presentation of environmental performance and comparison of different products. For further information: www.environdec.com and www.msr.se.

quantify both physically and in monetary terms. Sometimes, the external costs can be of a non-monetary type. This makes it difficult to work with external costs and uncertainties can be substantial. However, external costs can be of great importance.

In the model calculations, the market price for the different activities has been used. This includes normal tax levels paid by the different parties on the market. VAT has not been included in the price. All prices are given at the price level of today. No inflation has been assumed. To achieve a better overview of the different costs, the costs have been divided into the following groups: material costs(/product costs), machine cost, labour cost, transport cost and total costs.

The estimation of the different costs in the model is an important work. Different methods can be used and in this case, we have tried to use actual costs for purchase of materials and rental of machines. Labour cost has been measured on site based on time studies for the different processes. Transport cost has been calculated based on standard prices for used transports. Cost calculation is always a sensitive issue and it is therefore important that the data used are of high quality. To provide cost data for a process or product is therefore relatively time consuming especially if the data collection shall include detailed time studies.

The purpose of the LCC analysis, in this case, is to show the total economic burden for the society of a product or a process during its entire lifetime, which for infrastructure products can be many years in the future. To estimate parameters like discount rate for such a long period of time is practically impossible and infrastructure costs are usually not financed like a business investment but with taxes at the time of payment. For this reason, the actual costs at the time of payment have been used in the LCC calculations. This means that future costs are weighted equally as present costs[2]. It has also been assumed that the society of tomorrow is like today's society. The aim of this LCC analysis is not to estimate the future development of the society but to calculate the pure economic effect of a particular product in a simple and reliable way.

A very uncertain discount rate can often dominate the economic results, which can lead to very unfortunate consequences. There are also other aspects for the future that is more important and that cannot be solved by the choice of discount rate. Example of this is the relative cost of energy, material resources and labour costs in the future. This will, most likely, change significantly in the future but how is difficult to say.

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[2] This can be interpreted as a use of a zero discount rate but the use of pure investment calculus on general society costs are however more complex and needs to be applied carefully.

3 The Lundby Tunnel and the work performed

The Lundby Tunnel is a road tunnel in Gothenburg, Sweden. The tunnel is 2060 m long and consists of two tunnels, each with two lanes in each tunnel. The tunnel was opened in 1998. With regard to underground drainage, this tunnel is relatively unique for Sweden. The Lundby Tunnel is a granite rock tunnel built with traditional tunnelling methods such as drilling and blasting. In this case, an attempt was made to provide a high water resistance (low leakage) in the tunnel from the start by careful blasting and high cement grouting both before and after blasting. Thus, it was hoped to avoid or minimize drainage of the tunnel. No drainage was therefore installed, but the rock wall was covered by a few cm of ordinary shotcrete. However, over the years, the leakage has increased and now constitutes a significant problem such as extensive ice formation in wintertime. For this reason, drainage now needs to be installed in the tunnel and various methods for this has been investigated. In connection with these investigations, Rockdrain has been tested as a maintenance operation in the tunnel on an area of 100 m^2.

Maintenance operations are significantly different from new construction as regards working methods and staffing. Today, there is traffic through the tunnel, so the maintenance operations must be restricted to certain areas and times. In this case, one of the two tunnels could be turned off at night (20:00 - 05:00). The work must then be divided into smaller parts and performed over a long period of time. How this division can be done depends on the type and scope of the work but can, of course, affect the outcome of an analysis. In the previous studies [3, 4, 5] of the Rockdrain system, maintenance of the system was also included as the use of Rockdrain was analysed over a 60 year period. In these studies, it was assumed that maintenance was carried out in the same way as in new production. This means that the drainage has to be replaced at a total renovation of the tunnel, that the tunnel can be closed for a long time, and that the traffic during this time may be diverted. This is not possible in many cases, so the maintenance must be performed during operation of the tunnel and only shorter shutdowns are possible. This study therefore addresses this latter case.

The work processes often differ very little from new construction, but the conditions of work and thus the overall efficiency of the work can vary considerably. Especially, considerably more personnel are needed during maintenance work compared to new construction, which is evident in this study. Table 1 presents the work required for the different tasks in the maintenance work. For the application of Solbruk, dry spraying was used, which works well for this product.

Table 1 Operation specification for the maintenance work at the Lundby tunnel covering 100 m^2.

	Rockdrain work			Establishment and unprovisioning		
Suboperations	Operation time (h)	Number of workers including foreman [1)]	Labour time (man-hours)	Operation time (h)	Number of workers including foreman [1)]	Labour time (man-hours)
Demolition of Rockdrain	15	6	90	6	6	36
Demolition of standard drainage	15	6	90	6	6	36
Mounting of channel net	14	6	84	1	6	6
Shotcrete application, layer 1	3	6	18	4	6	24
Shotcrete application, layer 2	3	6	18	4	6	24
Solbruk application, layer 1	3	6	18	4	6	24
Solbruk application, layer 2	3	6	18	4	6	24
Final unprovisioning				4	5	20
Total			156			122

[1)] One foreman was used at all operations.

The absence of existing drainage in the Lundby Tunnel has also affected this study. A desirable situation would have been if traditional drainage had been installed and could have been replaced with alternatively Rockdrain or traditional drainage. Unfortunately, these options were not available for this study, but only installation of Rockdrain as maintenance measure. Some experience and data are available from installations of traditional drainage during maintenance of other tunnels. Such data were used in this study for comparison. Demolition of traditional drainage or Rockdrain in maintenance has thus not been analysed under real conditions. However, theoretical calculations of this are available from previous studies [4] that can be used to give approximate values for comparison.

To conclude, there are wide variations in conditions and execution of maintenance of underground drainage. In this context, this study should be seen as an example of maintenance operation of drainage in a rock tunnel. More studies are needed to receive a complete picture of the maintenance measure’s different aspects.

4 LCA model structures

The Life Cycle Assessment model includes all the calculations of the different parameters analyzed in the study such as primary energy use, resource use and emissions. The calculations are divided in different modules representing, for example, the different processes included in the study. The flowsheet of the LCA model includes all the different modules and how they are linked to each other. The LCA model used in this study is based on the previous models designed in reference [4] but includes only the maintenance part of the model. The data in the model are also modified according to the specific data for the Lundby tunnel.

5 Results from the LCA model of the Lundby tunnel

In this chapter, the results from the LCA model of the drainage maintenance with Rockdrain are presented. In this case, we assume that the existing drainage is either a conventional drainage or a Rockdrain drainage. The data from the Lundby tunnel installation include only application of Rockdrain in a maintenance situation. No demolition data exist because there was no drainage installed in the Lundby tunnel. However, theoretically and empirically calculated demolition data are available in reference [4] which has been modified to reflect the present maintenance situation. The LCA maintenance model covers thus the demolition of the existing drainage and the application of new Rockdrain. All figures show both demolition alternatives but only one is applicable in a maintenance situation. No specific maintenance LCA data exist for maintenance with conventional drainage so this alternative is thus not covered in this study.

The results from the model are shown per m^2 of maintenance (Rockdrain) area.

The impact categories that are included in the results are:

- Primary energy resource use (MJ/m^2 Rockdrain maintenance).
- Global warming potential, GWP 100 (kg CO_2 eq./m^2 Rockdrain maintenance).
- Acidification potential (kg SO_2 eq./m^2 Rockdrain maintenance).
- Eutrophication potential (kg PO_4 eq./m^2 Rockdrain maintenance).
- Photochemical Ozone Creation Potential, POCP (kg ethene eq./m^2 Rockdrain maintenance).
- Working hours (manh/m^2 Rockdrain maintenance).
- Economy calculated as Life Cycle Cost, LCC (Euro/m^2 Rockdrain maintenance)

The results from each impact category are presented in two different ways, a 60 years perspective and a full lifetime perspective. A full maintenance (replacement) of the drainage occurs after a full lifetime of the drainage. This replacement is divided by the lifetime to get a yearly contribution to the maintenance replacement. In this way, a maintenance impact can be calculated for any number of years independent of the lifetime for the drainage. The lifetime of Rockdrain is estimated to 120 years and the lifetime of the conventional drainage is estimated to 60 years. First, the results are presented in a 60 years perspective. This means that the maintenance impact after 60 years is calculated. This implies that a full lifecycle for the demolition of the conventional drainage is shown but only half (60/120) of the Rockdrain maintenance impact. In the second figure, a full life cycle is shown for both drainage alternatives i.e. a 60 year perspective for demolition of the conventional drainage and a 120 year perspective for the Rockdrain alternative (demolition + maintenance). However, this shows different time periods so these figures are mainly used to show the values for each process separately.

Three significant figures have been used as rounding when uncertainty data is missing. Numerical values in this report represent thus calculated numeric values and do not show the accuracy of the values.

The results in this study are, to some extent and as much as possible, compared to the previous results in reference [4], which can be downloaded from IVL homepage www.IVL.se.

5.1 Primary energy resource use

The primary energy resource use for the maintenance procedure is shown in Figure 1 (60 year perspective) and Figure 2 (a full lifetime period). If a 60 year service life is considered, the total primary energy use has been calculated to 301.5 MJ/m^2 Rockdrain maintenance including Rockdrain demolition and 318.3 MJ/m^2 Rockdrain maintenance including demolition of conventional drainage. Compared to the previous study in [4] which indicates a total primary energy use of 276.2 MJ/m^2, this is somewhat higher. The reason for this is that the data for demolition of Rockdrain have been change to better meet the requirements in the present maintenance situation. However, the corresponding primary energy use for conventional drainage in large scale maintenance has been calculated to 713.8 MJ/m^2 drainage [4].

If the full life cycle process is considered (Figure 2), the total energy use is higher and the demolition process for Rockdrain is higher than for conventional drainage but this also shows different time periods so this figure is mainly used to show the values for each process separately. The crude oil use is the main source of energy. Electric power with Swedish electric power production mix (mainly hydro power and nuclear power) is also used.

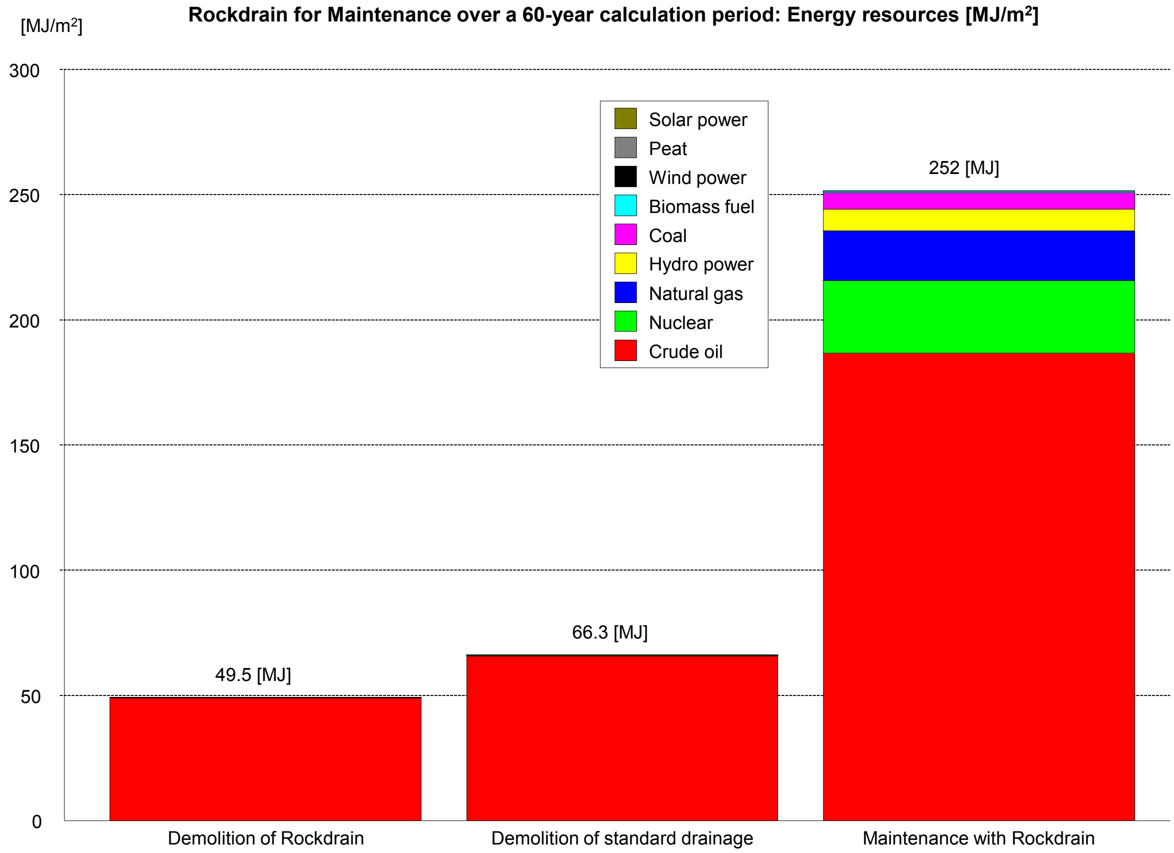

Figure 1 Results from the LCA model of Rockdrain as maintenance measure showing the use of primary energy resources. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.

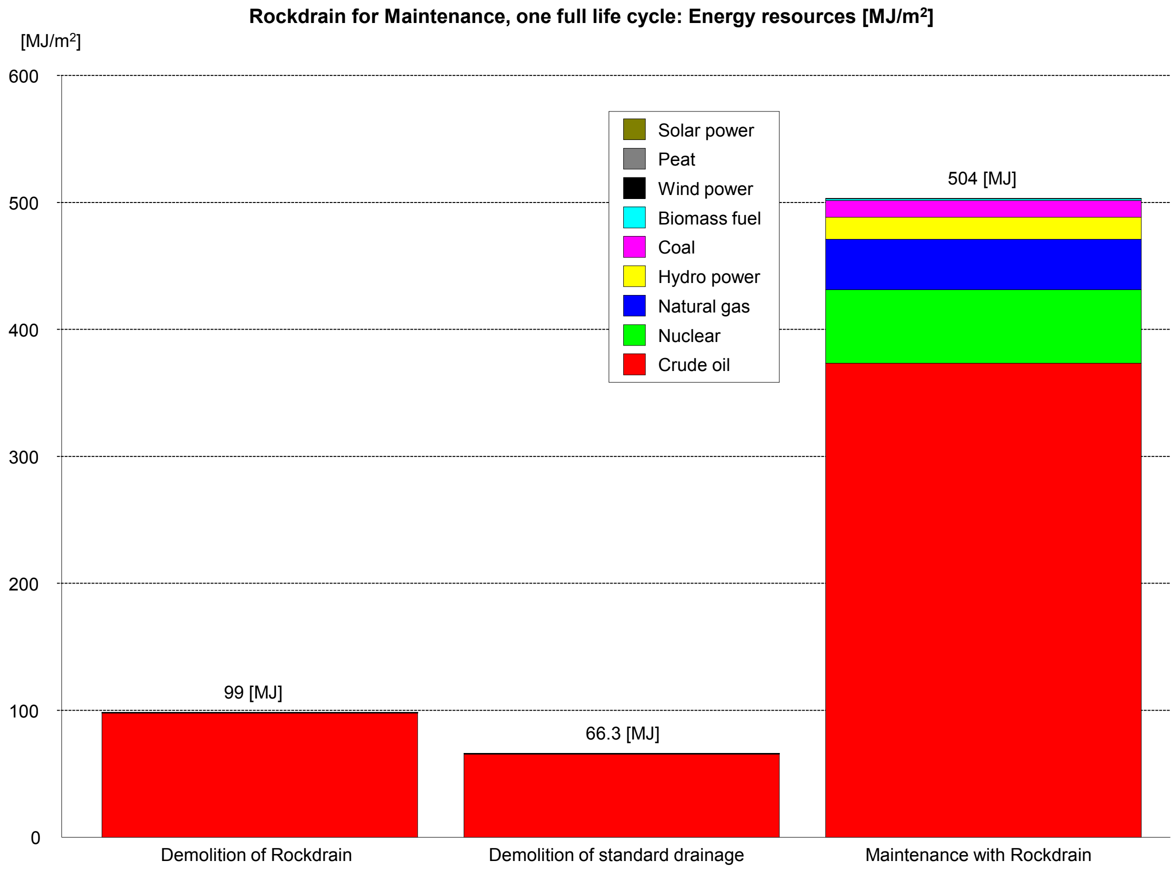

Figure 2 Results from the LCA model of Rockdrain as maintenance measure showing the use of primary energy resources. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.2 Global warming potential (GWP 100)

The global warming potential (GWP 100) is shown in Figure 3 (60 year perspective) and Figure 4 (a full lifetime period). As shown in the figures, the main contributing substances are CO_2 fossil (fossil based carbon dioxide) and CH_4 (methane). Uptake of carbon dioxide (carbonation) in concrete (shotcrete) during the lifespan of the product is also included. Uptake after demolition is thus not included due to difficulties to estimate the uptake. The total net GWP including uptake and demolition has been calculated to 28.6 kg CO_2 eq./m^2 if the demolition is Rockdrain and 29.8 kg CO_2 eq./m^2 if the demolition is conventional drainage. Compared to the previous study in [4] which indicates a GWP of 26.6 kg CO_2 eq./m^2 with Rockdrain demolition, this is somewhat higher due to increased demolition values for Rockdrain demolition. However, the corresponding net GWP for conventional drainage in large scale maintenance has been calculated to 56.8 kg CO_2 eq./m^2 drainage [4]. For the full life cycle, the demolition of conventional drainage (60 year lifespan) show somewhat lower GWP compared to demolition of Rockdrain drainage (120 years lifespan).

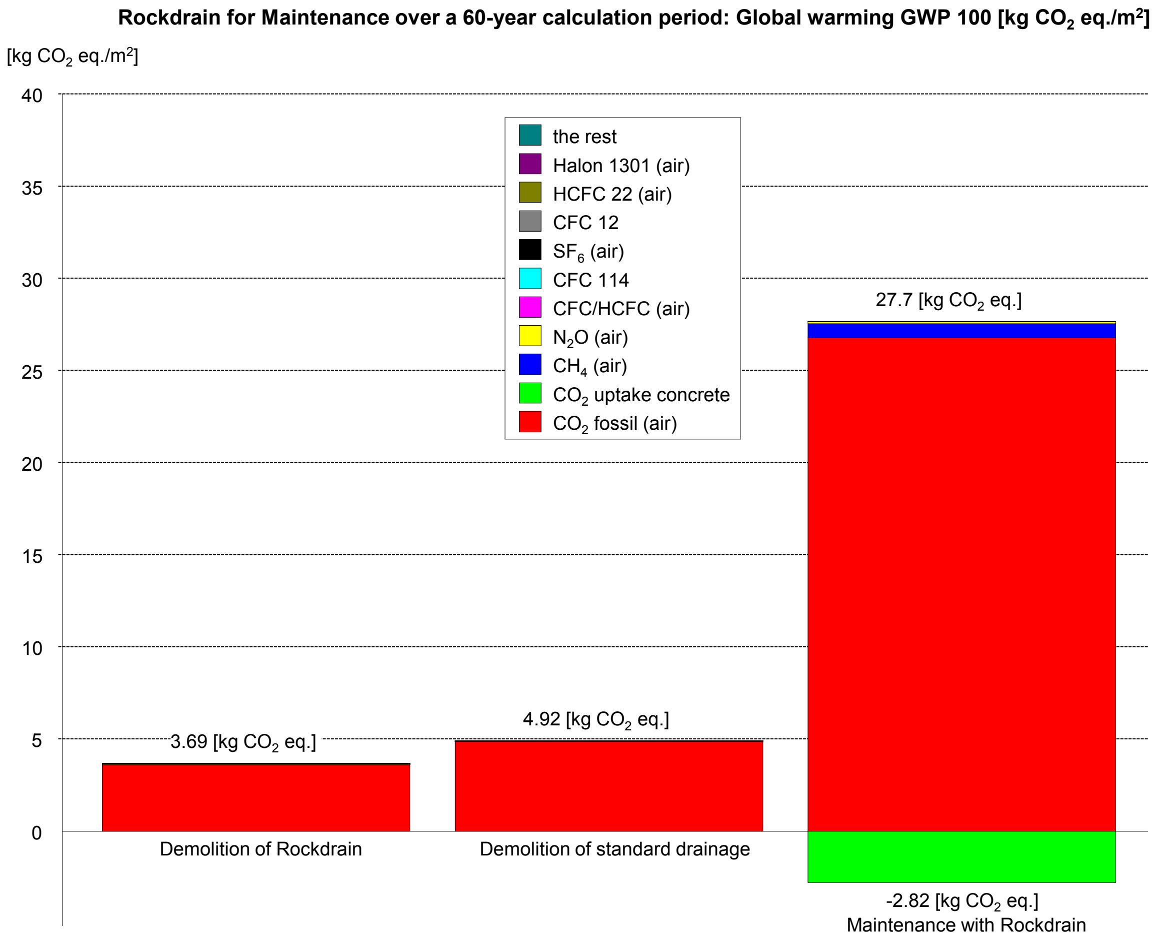

Figure 3 Results from the LCA model of Rockdrain as maintenance measure showing the global warming potential (GWP 100). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.

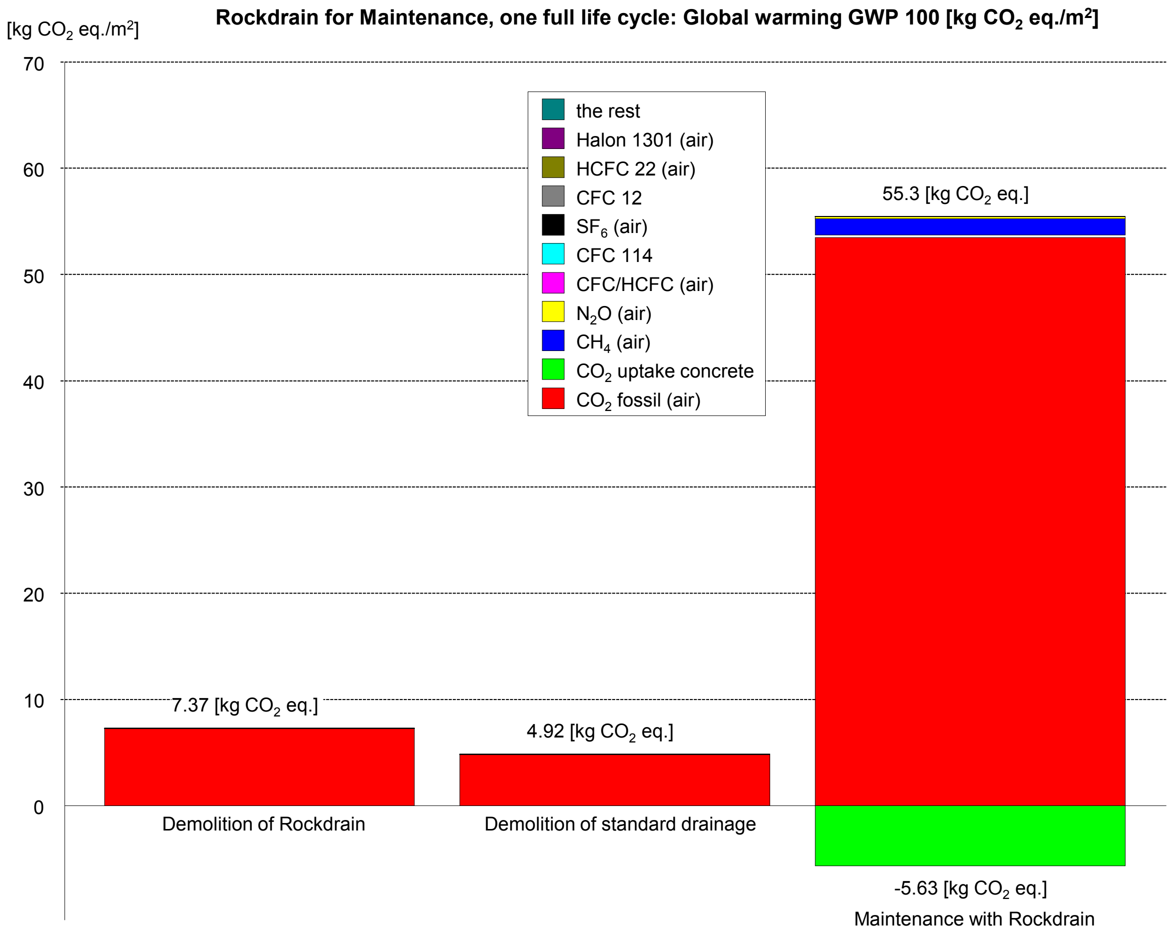

Figure 4 Results from the LCA model of Rockdrain as maintenance measure showing the global warming potential (GWP 100). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.3 Acidification potential (AP)

The acidification potential for the maintenance procedure is shown in Figure 5 (60 year perspective) and Figure 6 (a full lifetime period). The main contributing substances are NO_X and SO_2. The total net acidification potential has been calculated to 0.0983 kg SO_2 eq/m^2 if the demolition is Rockdrain and 0.01044 kg SO_2 eq./m^2 if the demolition is conventional drainage over a 60 years period. The acidification potential shows the same pattern and conclusions as the energy use and GWP. There are thus small changes compared to the production situation shown in the previous study [4], which shows the situation in new production and with large scale maintenance that almost can be compared to new production.

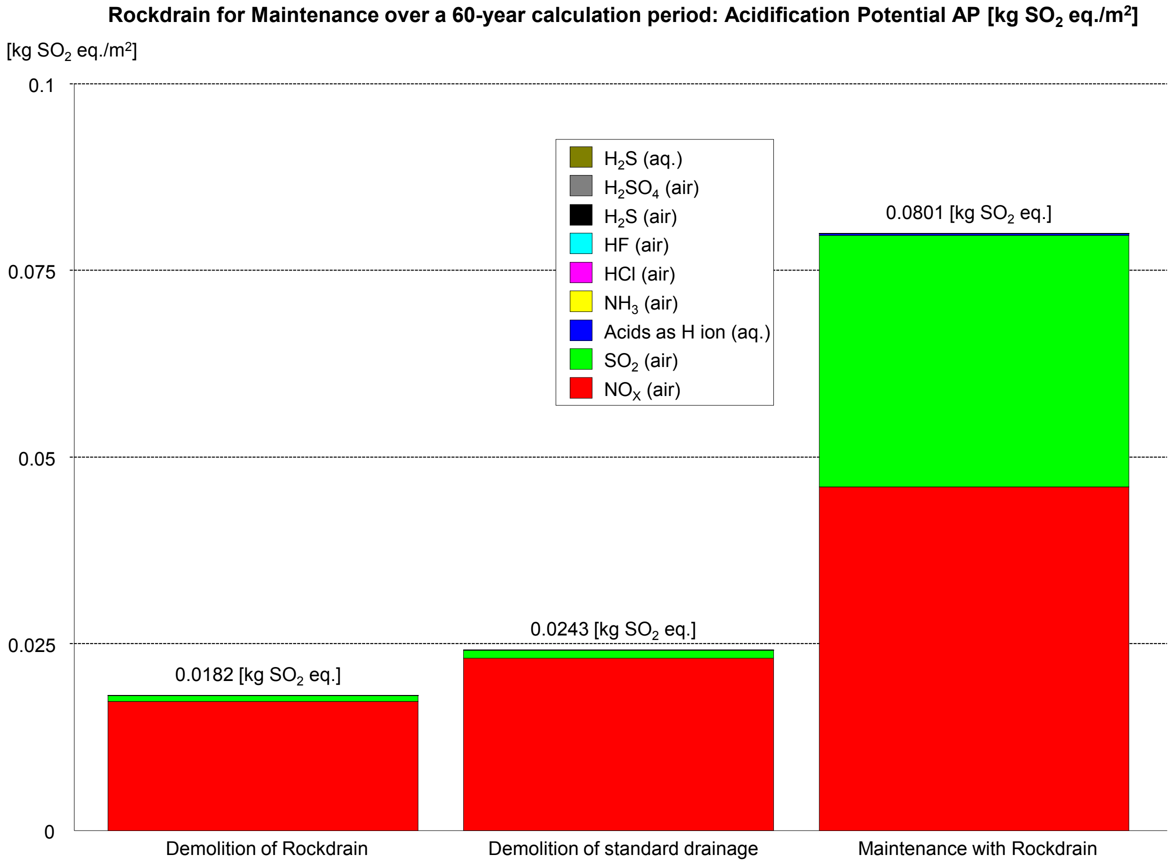

Figure 5 **Results from the LCA model of Rockdrain as maintenance measure showing the acidification potential (AP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.**

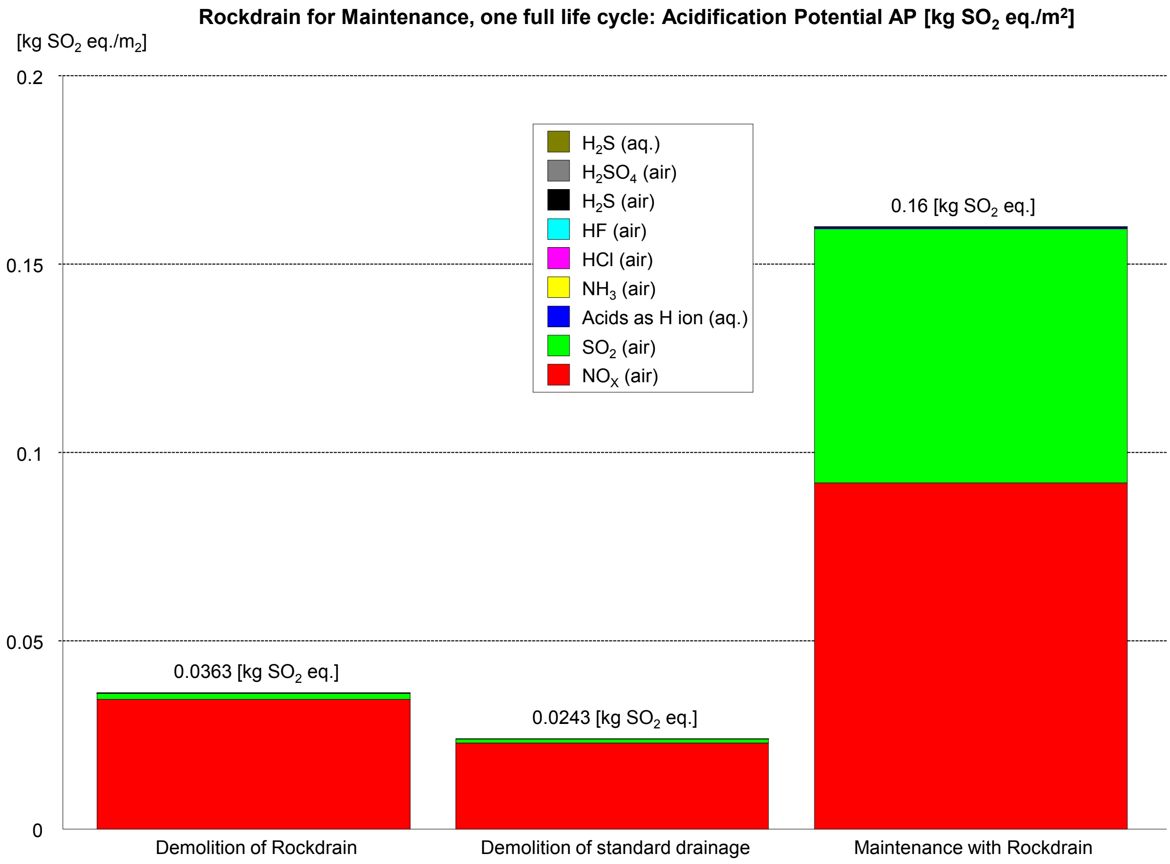

Figure 6 Results from the LCA model of Rockdrain as maintenance measure showing the acidification potential (AP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.4 Eutrophication potential (EP)

The eutrophication potential for the maintenance procedure is shown in Figure 7 (60 year perspective) and Figure 8 (a full lifetime period). The main contributing substance is NO_X. The total net eutrophication potential has been calculated to 0.017 kg PO_4^- eq./m^2 if the demolition is Rockdrain and 0.0185 kg PO_4^- eq./m^2 if the demolition is conventional drainage over a 60 years period. The eutrophication potential shows the same pattern and conclusions as the energy use and GWP. There are thus small changes compared to the production situation shown in the previous study [4], which shows the situation in new production and with large scale maintenance that almost can be compared to new production.

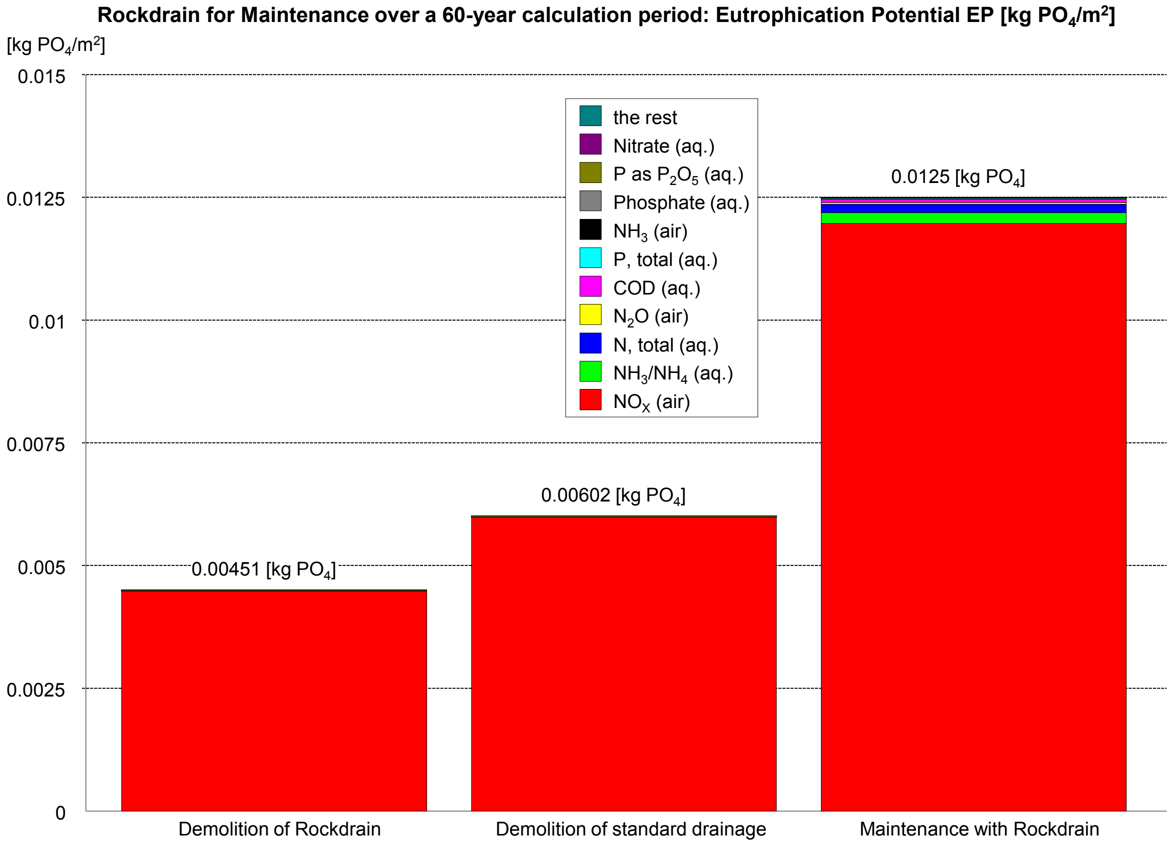

Figure 7 Results from the LCA model of Rockdrain as maintenance measure showing the eutrophication potential (EP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.

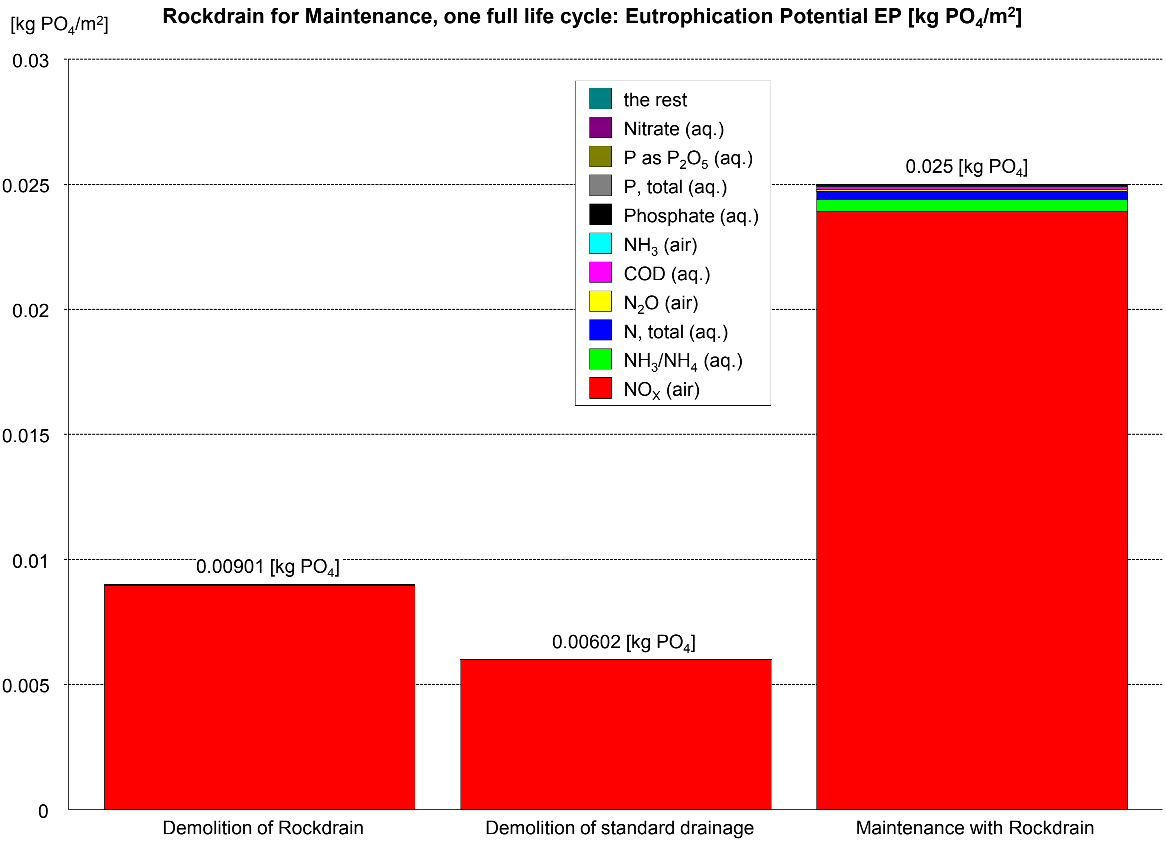

Figure 8 Results from the LCA model of Rockdrain as maintenance measure showing the eutrophication potential (EP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.5 Photochemical ozone creation potential (POCP)

The photochemical ozone creation potential (POCP) for the maintenance procedure is shown in Figure 9 (60 year perspective) and Figure 10 (a full lifetime period). The main contributing substances are hydrocarbons (NMVOC and HC), NO_X and CO. The total net POCP has been calculated to 0.0192 kg ethene/m^2 if the demolition is Rockdrain and 0.02 kg ethene/m^2 if the demolition is conventional drainage over a 60 years period. The POCP shows the same pattern and conclusions as the energy use and GWP. There are thus small changes compared to the production situation shown in the previous study [4], which shows the situation in new production and with large scale maintenance that almost can be compared to new production.

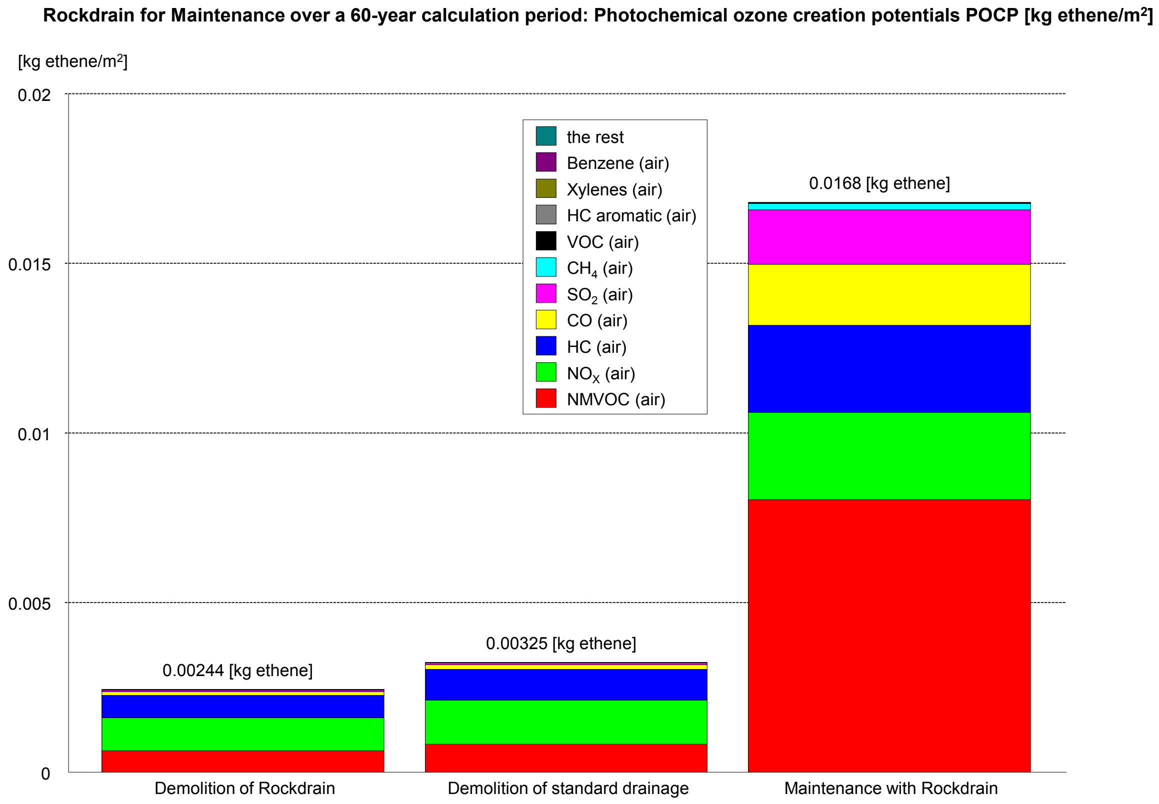

Figure 9 Results from the LCA model of Rockdrain as maintenance measure showing the photochemical ozone creation potentials (POCP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.

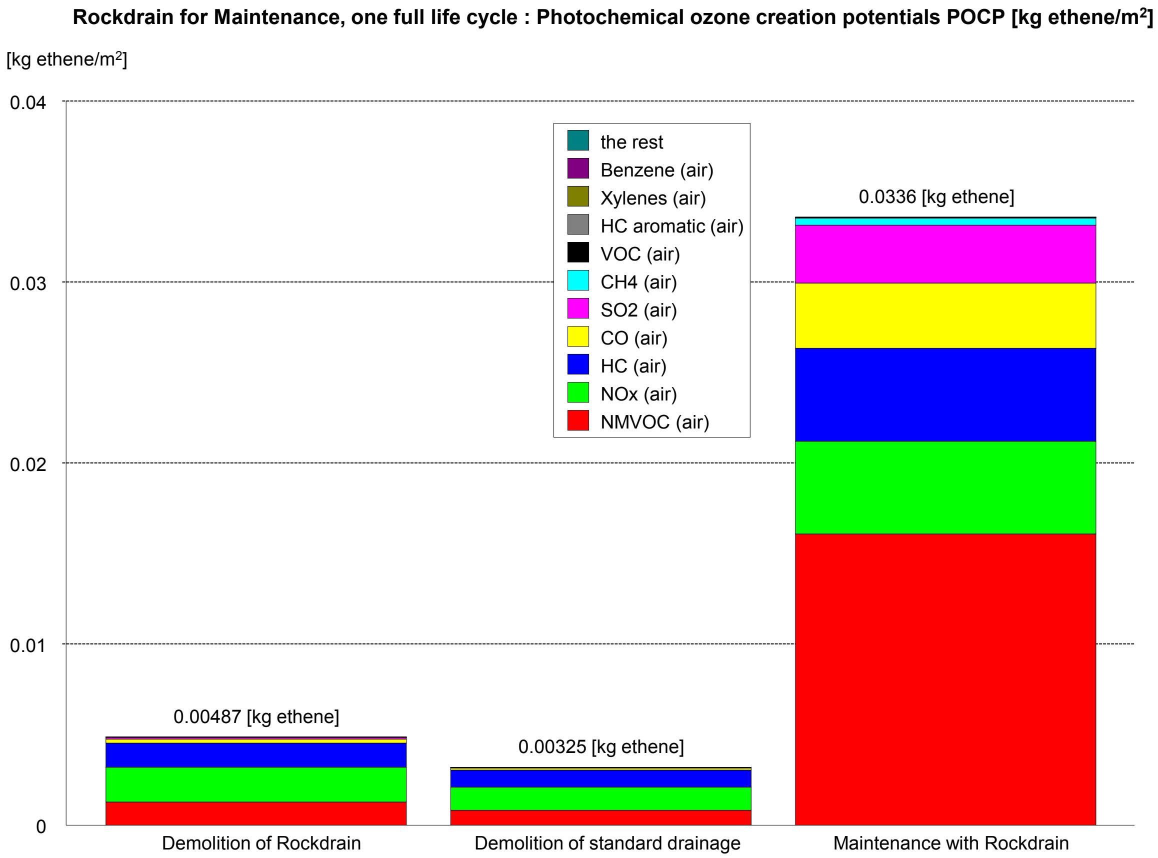

Figure 10 Results from the LCA model of Rockdrain as maintenance measure showing the photochemical ozone creation potentials (POCP). The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.6 Working hours

The data and experimental results from the Lundby tunnel maintenance installation have shown that even if the processes are the same, small scale maintenance requires significantly more staff and working hours compared to new production or large scale replacement installation due to many short working periods and a large share of establishment and unprovisioning. The working hours for the maintenance procedure are shown in Figure 11 (60 year perspective) and Figure 12 (a full lifetime period). These figures includes the working hours for the tunnel work but not working hours for production of purchased material such as cement, plastic lattice net etc. The total number of man hours has been calculated to 1.67 manh/m^2 if the demolition is Rockdrain and 2 manh/m^2 if the demolition is conventional drainage over a 60 years period as shown in Figure 11. The corresponding number with demolition of Rockdrain is 0.132 manh/m^2 from the previous study [4], however not shown in that report.

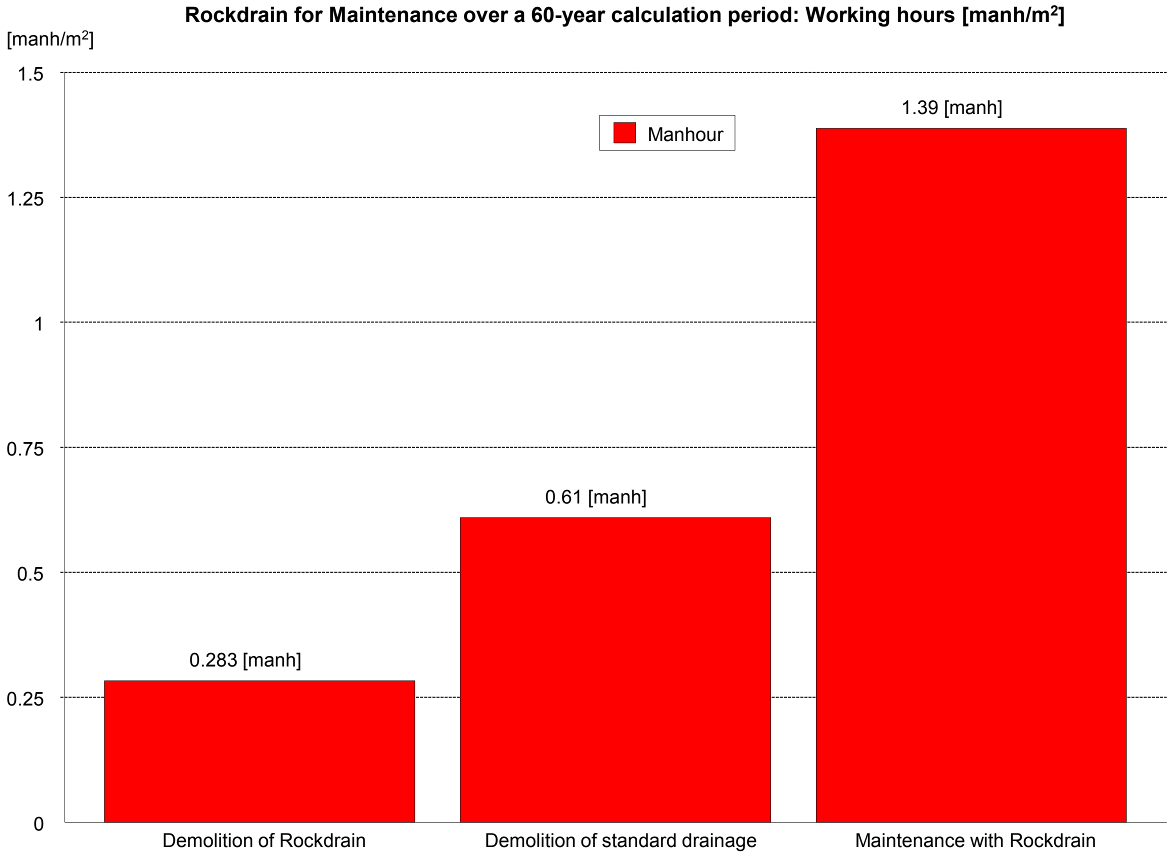

Figure 11 Results from the LCA model of Rockdrain as maintenance measure showing the working hours. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.

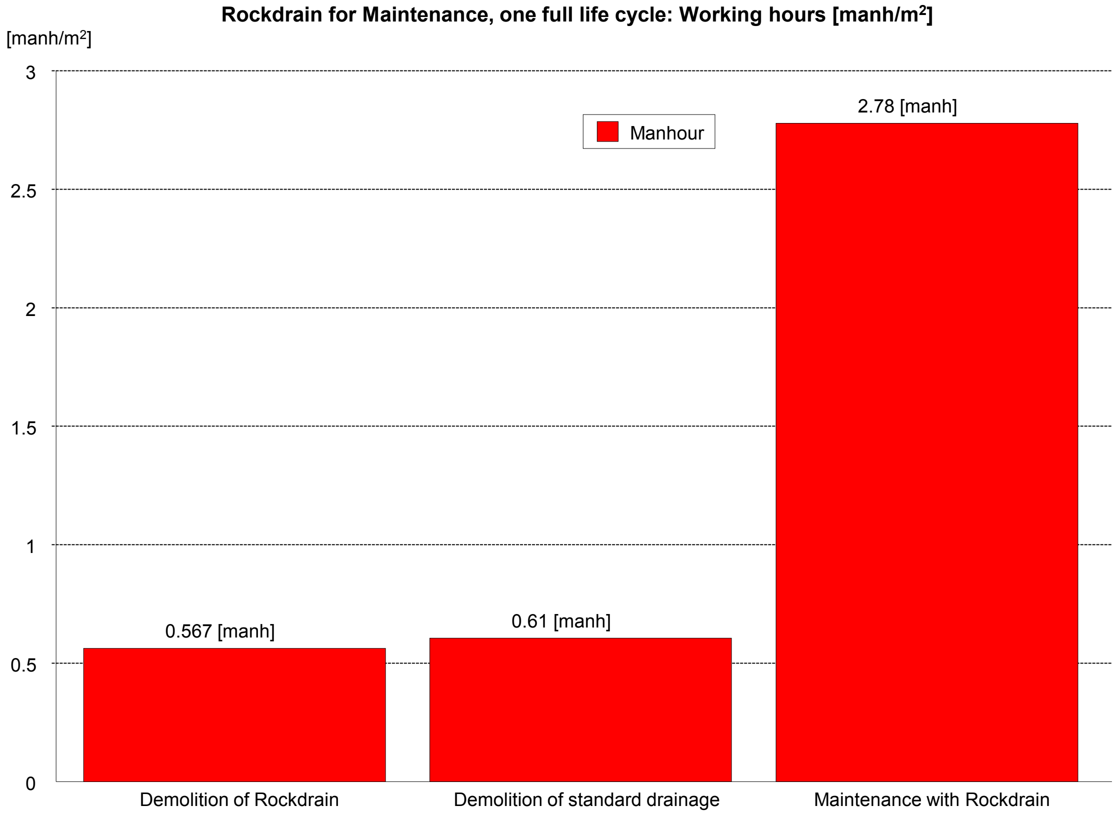

Figure 12 Results from the LCA model of Rockdrain as maintenance measure showing the working hours. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

5.7 Economic analysis – LCA

The number of working hours has of course also a strong effect on the economy of the method. The economic aspects are here shown as Life Cycle Cost (LCC) without inflation and a zero interest rate. The economic results for the maintenance procedure are shown in Figure 13 (60 year perspective) and Figure 14 (a full lifetime period). The total life cycle costs have been calculated to 167.5 euro/m^2 if the demolition is Rockdrain and 191.3 kg euro/m^2 if the demolition is conventional drainage over a 60 years period. Compared to the previous study in [4], which indicates a life cycle cost of 64.4 euro/m^2 with Rockdrain demolition, the small scale maintenance has thus a significantly higher life cycle cost mainly because more labor is needed. However, compared to a large scale maintenance with conventional drainage (215.2 euro/m^2 ref. [4]) it is still lower. For the full life cycle, the small scale installation maintenance of Rockdrain is 287 euro/m^2 (after 120 years), the small scale demolition of Rockdrain is 49 euro/m^2 (after 120 years) and the small scale demolition of conventional drainage is 48.3 euro/m^2 (after 60 years), Figure 14.

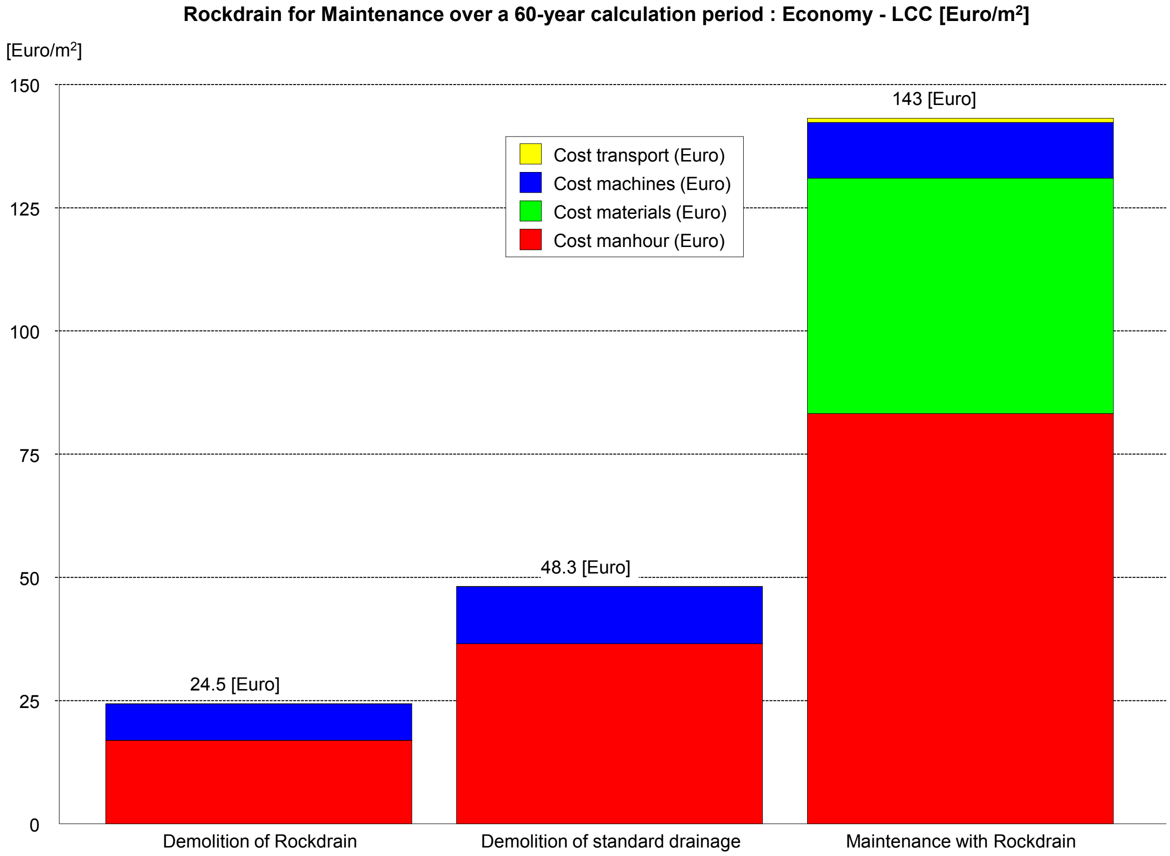

Figure 13 **Results from the LCA model of Rockdrain as maintenance measure showing the economy as LCC. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for a calculation period of 60 years with a lifespan for Rockdrain of 120 years and for conventional drainage of 60 years.**

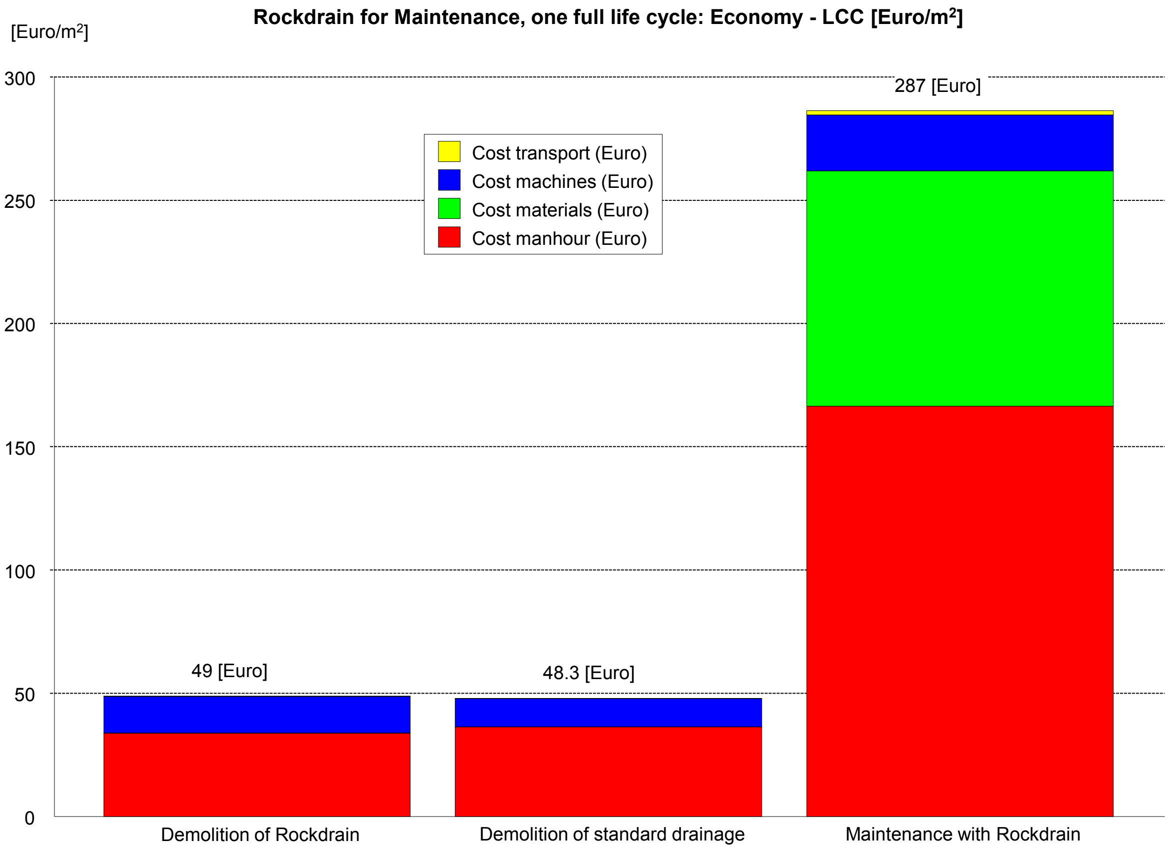

Figure 14 Results from the LCA model of Rockdrain as maintenance measure showing the economy as LCC. The results show the maintenance procedure with Rockdrain and the preceding demolition of either a conventional standard drainage or a Rockdrain drainage. This figure shows the results for the entire life cycle of Rockdrain (120 years) and the entire life cycle of the standard drainage (60 years) respectively. Thus, this figure shows one life cycle of both Rockdrain and standard drainage.

6 Discussion and Conclusions

In a previous study [4], conventional tunnel drainage has been compared to a new drainage system called Rockdrain. This study covers new production and large-scale maintenance production where the entire tunnel is renovated during a long period of time. However, many tunnels cannot be closed for a long time. Thus, the maintenance has to be carried out during operation of the tunnel in short time slots (e.g. during night) but during a long time period (small-scale maintenance). This study has investigated Rockdrain as a possible way to simplify small-scale maintenance. The study is based on a test installation (100 m^2) of Rockdrain in a small scale maintenance situation in the Lundby tunnel. Only Rockdrain has been tested and no evaluation of small-scale installation of conventional drainage systems has been carried out.

The test results have shown that Rockdrain very well can be used for small-scale maintenance of tunnel drainage. The technical processes used for the small-scale maintenance does not differ much from the techniques used for large-scale maintenance. The primary energy resource use and the emissions per m^2 drainage are therefore not very different. However, the amount of labor work needed is very different. Much more labor work is needed for the small-scale maintenance due to an increased amount of establishment and unprovisioning. The life cycle cost (LCC) is therefore higher for the small-scale maintenance compared to large-scale maintenance of Rockdrain. However, compared to large-scale maintenance of and with conventional drainage, Rockdrain shows significantly lower values.

The long term effect of Rockdrain for maintenance has not been investigated. Future evaluations have to show these effects.

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4. Stripple, Håkan, Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) Evaluation of Rockdrain and a Conventional Tunnel Drainage System. Part of the Rockdrain Research Project, IVL report B2067 (2013), www.IVL.se for free download.
5. Stripple Håkan et al., Evaluation of two different drainage systems for rock tunnels, Tunnelling and Underground Space Technology 58 (2016) 40–48.