REPORT

Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) evaluation of Rockdrain and a conventional tunnel drainage system

Part of the Rockdrain research project

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Report Summary

Project title

Full-scale test of Rockdrain

Project sponsor

Trafikverket, Sweden. (the Swedish Transport Administration).

Author

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Title and subtitle of the report

Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) evaluation of Rockdrain and standard drainage system. - Part of the Rockdrain research project.

Summary

Water leakage into rock tunnels can often cause problems. The water pressure in combination with cracks in the rock allow water to leak into the tunnels and causing problems such as icicles, water in the tunnels, significant power consumption for pumping of water, etc. When injection is not sufficient to fulfill the function requirements of the tunnel, additional external drainage systems have to be used to drain the water from the roof and walls. This drainage is usually carried out by mounting sheets of extruded polyethylene foam, which is affixed with rock bolts onto the rock surface and finally covered with shotcrete. This drainage method is relatively labor-intensive, material and space consuming.

Rockdrain is a new drainage system based on a new drainage principle. Drainage channels are formed in a water permeable shotcrete layer. The permeable shotcrete layer is then covered with a less permeable shotcrete layer (Solbruk T) which is specially designed for the Rockdrain application. The formed piping lattice in the permeable shotcrete traps the water inside the shotcrete layer and lead the water away from the tunnel. The Rockdrain system is intended to simplify construction and improve performance through a more solid construction with fewer and less sensitive technical components. The main application for the Rockdrain system is in different tunnels and especially road and train tunnels.

Many different aspects of the drainage system have to be explored in a research project. The main research project was thus divided in three sub-projects; Material and function tests, Fire tests and “Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of the Rockdrain system”. This report covers the later LCA and LCC analysis. In this part, which is performed by IVL Swedish Environmental Research Institute, the energy, resource, and environmental aspects are analyzed along with the economic aspects. To be able to evaluate the results, the new Rockdrain system is compared with a conventional drainage system of today. The results look very promising for the Rockdrain system. A cost reduction of 55 % and an energy reduction of 43 % when switching from a conventional drainage system to Rockdrain are some of the results.

Keyword

Tunnel, drainage, shotcrete, cement, concrete, Rockdrain, Solbruk, carbon dioxide, LCA, LCC, cost, economy

Bibliographic data

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Preface

The environmental issue is today one of the most important questions from a society perspective. Most likely, our society is facing considerably changes in the energy situation and in the climate/environmental situation in the future. It is therefore very important to develop new products, processes and technics that are more efficient for example in terms of energy resource use, material resource use and emissions. The economic aspects of new and alternative products are also very important. The price or cost of a product or a process is of course highly interesting in itself but it also reflects an overall effort for the society to perform a certain activity.

In this project, a new drainage method for drainage of rock tunnels has been tested and evaluated in a full-scale test. The test has been performed at the tunnel of Kattleberg where parts of the tunnel have been drained with the new method called Rockdrain. Conventional drainage has been used for most of the tunnel at Kattleberg.

The main research project, Full-scale test of Rockdrain, has been performed as a co-operation project between different research organizations in Sweden. The research organizations involved has been IVL Swedish Environmental Research Institute, SP Technical Research Institute of Sweden and CBI Swedish Cement and Concrete Research Institute. The main research project has been divided in three different sub-projects (Material and function tests, Fire tests and LCA & LCC) shown below. In addition, technical support and material delivery have been provided from Solbruk (Rockdrain) and BESAB.

Sub-projects and technical support	**Main performing organization**	**Project leaders**
LCA & LCC	IVL	Håkan Stripple
Material and function tests	CBI	Robert Melander
Fire tests	SP	Lars Boström
Rockdrain material delivery and specifications	Solbruk	Andre Solberg
Shotcrete technical support	BESAB	Tommy Ellison

The present sub-project covered in this report is "Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of the Rockdrain system". In this project, the environmental performance and life cycle costs of the Rockdrain system has been studied and compared with a conventional drainage system of today. The project work has been performed by IVL Swedish Environmental Research Institute. The project is co-financed by IVL research foundation (50 %) and the Swedish Transport Administration, Trafikverket (50 %).

The main research project has been managed by a project group. In connection to the projects, a reference/technical advisory group was formed. The entire project and reference groups include the following persons and organizations.

Project group
Lars Boström, SP
Tommy Ellison, BESAB
Cathrine Ewertsson, CBI
Olof Kallin, Trafikverket
Peter Lund, Trafikverket
Robert Melander, CBI
Andre Solberg, Solbruk (Rockdrain)
Håkan Stripple, IVL

Reference/technical advisory group
Anna Andrén, Trafikverket
Lars Boström, SP Brandteknik
Lars-Olof Dahlström, NCC Teknik
Tommy Ellison, BESAB
Patrik Hult, Faveo
Peter Lund, Trafikverket
Behnam Shahriari, Trafikverket
Per Vedin, Trafikverket
Lasse Wilson, Veidekke
Kjell Windelhed, Trafikverket

Uncertainties and accuracy of the various calculations are always an important but difficult issue to handle. In the calculations in this project, it has not been possible to calculate uncertainties and accuracies in detail for every value, but these may be estimated and judged at a later stage when more information is available. Some indicative estimates for some parameters have however been included. The reader can also form their own view on these issues based on their own experiences. Numeric values in the results and other numerical values are therefore not adjusted for the accuracy of the measurement. Numerical values in the report are to be considered as pure numeric values unrelated to the accuracy of the measurement. For this reason, a slightly higher numerical precision of numerical values consistently have been used to certainly not lose precision due to rounding errors. The accuracy of the analysis can also vary depending on whether one analyzes the absolute values or differences between values. Since the same calculation principles have been used for the different models (drainage methods), should the differential analyzes and thus the conclusions have higher accuracy compared to the absolute values.

Gothenburg, December 2013

Håkan Stripple

Summary

Water leakage into rock tunnels can often cause problems. The water pressure in combination with cracks in the rock allow water to leak into the tunnels and causing problems such as icicles, water in the tunnels, significant power consumption for pumping of water, etc. In order to prevent ingress of water in the tunnel, the rock is pre-injected with cement slurry, which seals the rock prior to blasting. After blasting, the rock can be post-injected in those locations where leaks are detected to further seal the rock against water intrusion. When injection is not sufficient to fulfill the function requirements of the tunnel, additional external drainage systems have to be used to drain the water from the roof and walls. This drainage is usually carried out by mounting sheets of extruded polyethylene foam, which is affixed with rock bolts onto the rock surface and finally covered with shotcrete. This drainage method is relatively labor-intensive, material consuming and space consuming.

Rockdrain is a new drainage system based on a new drainage principle. Drainage channels are formed in a water permeable shotcrete layer. This is achieved by a plastic lattice of half tubes which are attached to an underlying shotcrete layer sprayed directly on the bare rock surface. The half-pipe lattice is covered with a permeable shotcrete and in this way, the drainage channel lattice is formed. The permeable shotcrete layer is then covered with a less permeable shotcrete layer (Solbruk T) which is specially designed for the Rockdrain application. The formed piping lattice in the permeable shotcrete, traps the water inside the shotcrete layer and lead the water away from the tunnel. The Rockdrain system is intended to simplify construction and improve performance through a more solid construction with fewer and less sensitive technical components. The main application for the Rockdrain system is in different tunnels and especially road and train tunnels.

Many different aspects of the drainage system have to be explored in a research project. The main research project was thus divided in three sub-projects; Material and function tests, Fire tests and “Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of the Rockdrain system”. This report covers the later LCA and LCC analysis. In this part, which is performed by IVL Swedish Environmental Research Institute, the energy, resource, and environmental aspects are analyzed along with the economic aspects. To be able to evaluate the results, the new Rockdrain system is compared with a conventional drainage system of today.

The energy use is essential for all type of processes and a comparison between the two drainage systems can be found in Figure A. As shown in the figure, the total use of primary energy is 1421 MJ/m^2 drainage during 60 years for the conventional drainage compared to 814 MJ/m^2 for the Rockdrain system. This is an energy reduction of 43 %. A part of this reduction (~291 MJ/m^2) can be referred to the expected longer lifetime for the Rockdrain system.

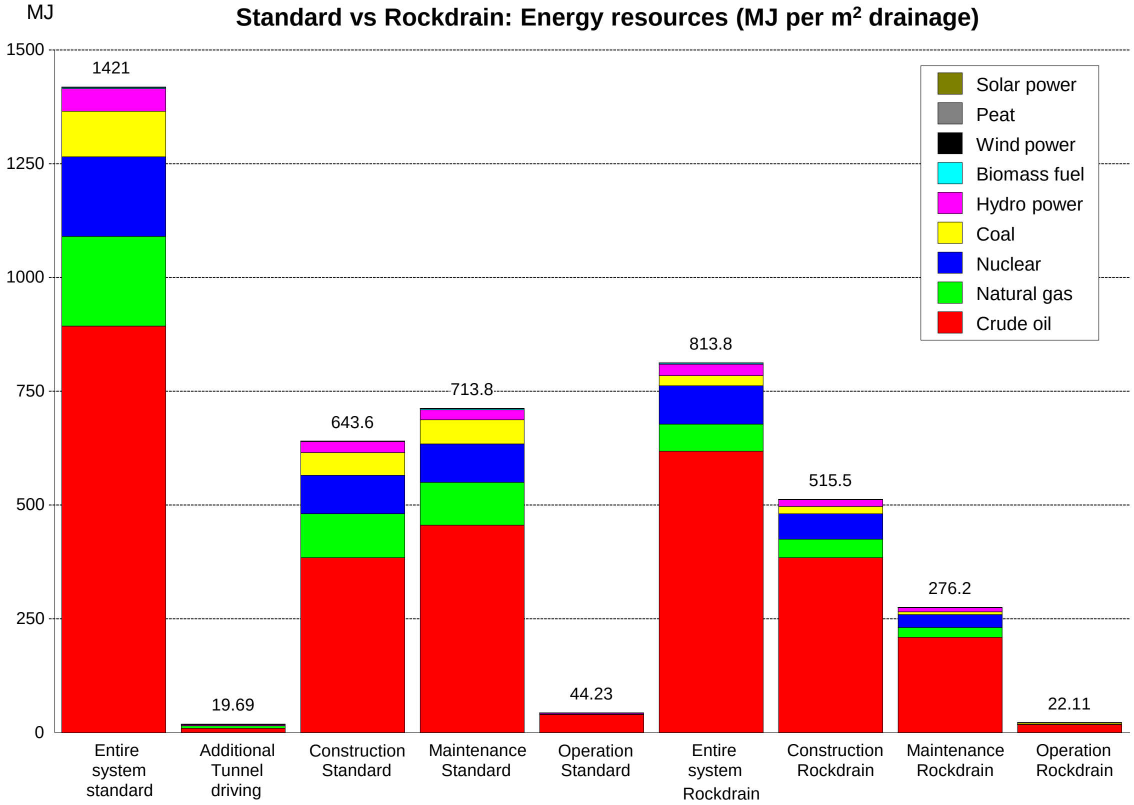

Figure A The figure shows a comparative energy analysis between the Rockdrain system and a conventional drainage system. The analysis is based on primary energy resource use in MJ/m^2 installed drainage during 60 years in the same way as the previous energy analyses. The figure shows the energy use for the entire system and divided into construction, maintenance and operation for both the drainage systems. Both non-renewable and renewable energy resources are included. The additional tunnel driving for the conventional system is also included.

The difference in global warming potential (GWP) for the two systems is shown in Figure B. If the CO_2 uptake is taken into account, the net GWP for the entire systems will be 114 kg CO_2 eq./m^2 drainage during 60 years for the conventional drainage and 79 kg CO_2 eq./m^2 for the Rockdrain system. This is a reduction of 31 %. The reduction effect due to the increased lifetime for the Rockdrain system is ~32 kg CO_2 eq./m^{2}. Note that the potential CO_2 uptake is included also for the maintenance even if that uptake mainly will occur after the 60 years.

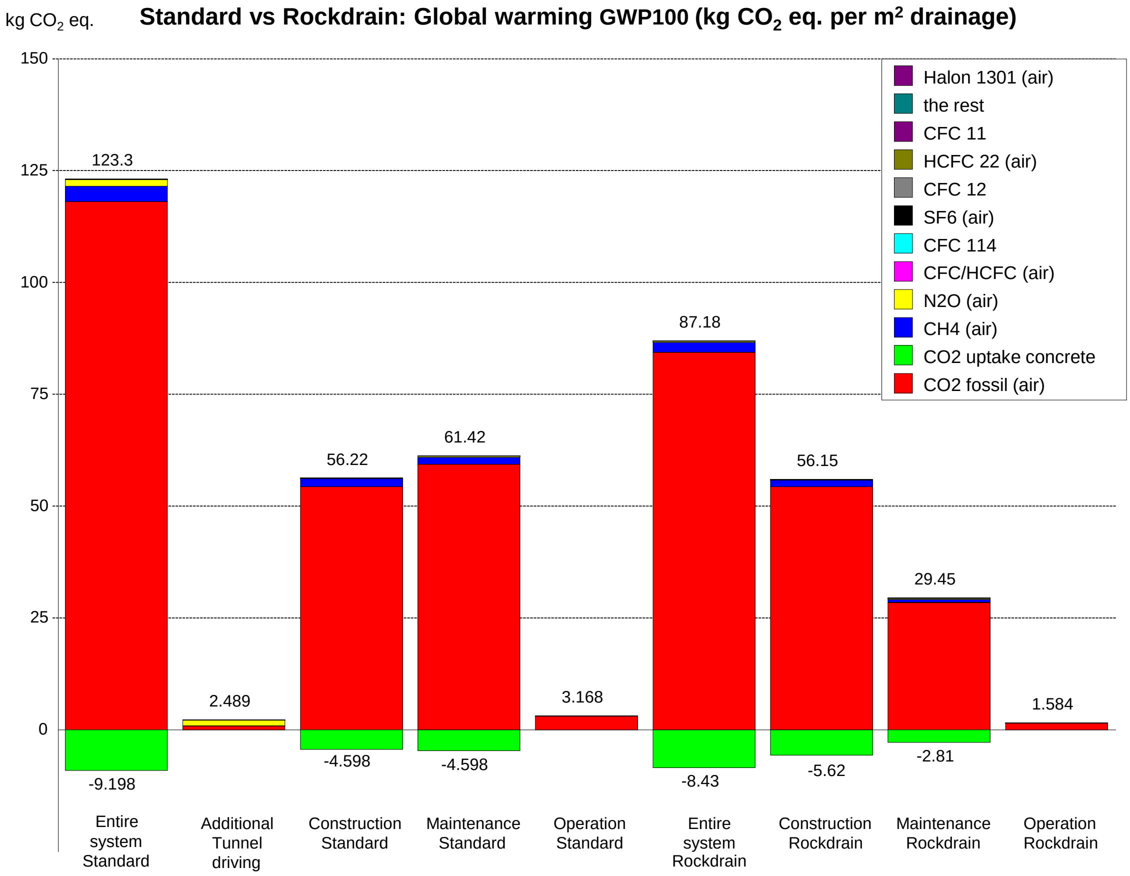

Figure B The figure shows a comparative analysis of global warming potential (GWP) between the Rockdrain system and a conventional drainage system. The figure shows GWP (kg CO_2 eq. per m^2 drainage during 60 years) for the entire system and divided into construction, maintenance and operation for both the drainage systems. The additional tunnel driving for the conventional system is also included.

The difference in costs between the two systems is obviously of great interest. It should be noted that the reliability and the technical quality of the systems also play a big role when it often can be very costly and cause huge problems to repair the system during operation or to renew the systems before the expected lifetime. These aspects have been difficult to judge in this project and have therefore been omitted. Likewise, the effect of preventive installation of tunnel drainage has neither been taken into account. If larger areas can be treated as a preventive measure by a simpler and less costly system, this could mean that costly additional measures can be avoided.

Figure C shows the combined LCC results for the two systems. The entire cost for the conventional system (450 Euro/m^2 drainage and 60 years) is significantly higher compared to the Rockdrain system (201 Euro/m^2 drainage and 60 years). This is an overall cost reduction of 55 %. The construction cost has been calculated to 198 Euro/m^2 (construction+additional tunnel excavation) for the conventional system and 119 Euro/m^2 for Rockdrain. This is a cost reduction of 40 %.

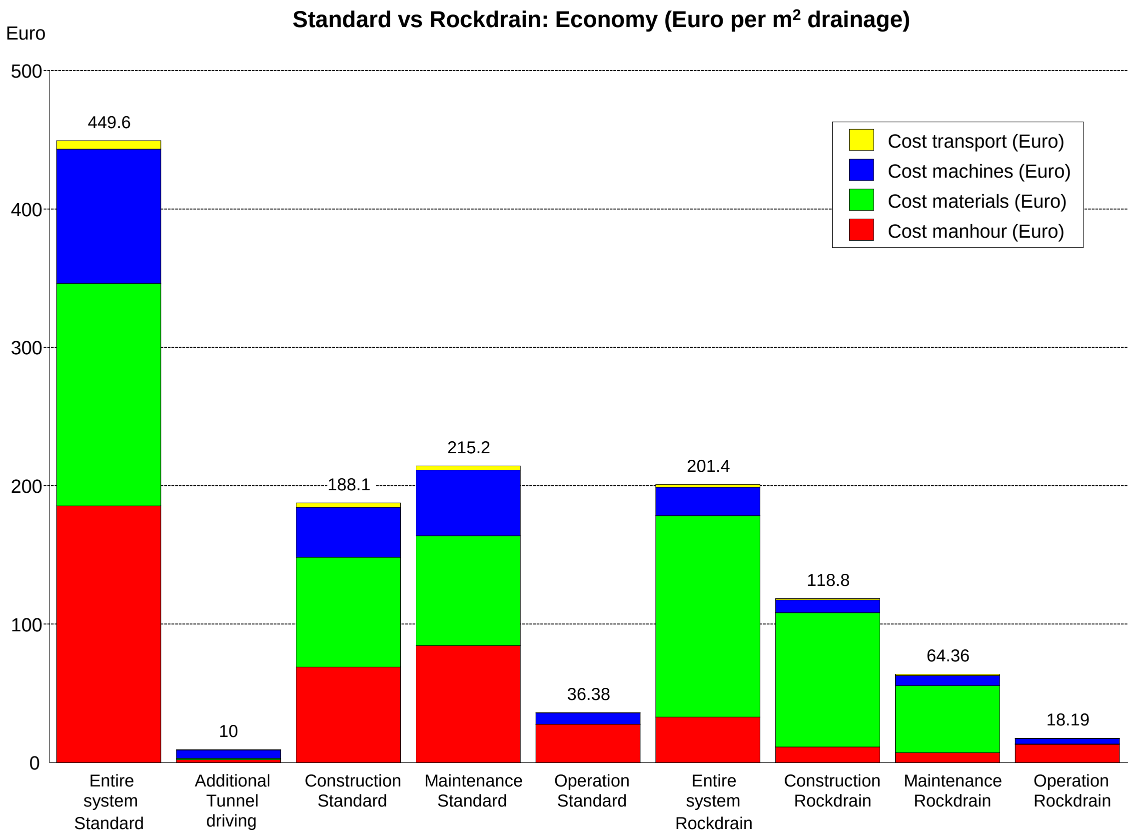

Figure C The figure shows a comparative analysis of the life cycle costs (LCC) between the Rockdrain system and a conventional drainage system. The figure shows LCC in Euro per m^2 drainage during 60 years for the entire system and divided into construction, maintenance and operation for both the drainage systems. The additional tunnel driving for the conventional system is also included.

Finally remains the crucial question which is to assess whether Rockdrain may be a better option to drain the tunnels than today's standard systems. In this report, the two drainage options are analyzed from several aspects such as the use of primary energy, different emissions and costs. The analysis was done in a 60 year perspective with an assumed lifetime of 60 years for today's standard system and 120 years for the Rockdrain system. No ongoing maintenance is assumed. The maintenance is performed by installing new drainage at the end of the lifetime of the old drainage. However, this maintenance has been allocated annually. In addition, some inspection work has been assumed for the two systems.

In the project, the Rockdrain system has partly been used in a tunnel near Gothenburg (the Kattleberg tunnel) which thus includes both today's standard drainage system and the new Rockdrain system. One can use the test tunnel in Kattleberg as an example of implementation of the Rockdrain system in a tunnel. This tunnel is a 1.8 km long double track train tunnel. The total amount of installed drainage is estimated to 20 895 m^2 of which 18 745 m^2 is conventional drainage and 2 150 m^2 is Rockdrain. The maximum possible drainage area in the tunnel (total area of walls and roof) is 52 490 m^2 which means that 39.8 % of the maximum possible drainage area is covered with drainage in this tunnel.

In Table A below, a summary comparison of the two systems are shown including different parameters. The table shows the results for both the systems, if they were to be implemented on the total drainage area (20 895 m^2) of the tunnel. The table also shows the effect of switching from a conventional system to Rockdrain both in absolute values and in percent. As shown in the table, there are significant reductions in all parameters. A cost reduction of more than 5 million euros or 55 % can be expected. An energy reduction of more than 12 million MJ or 42 % representing an energy content of 349.5 m^3 crude oil. This is indeed very promising results. One should however keep in mind that this is calculated model values and the real industrial implementation will show the accuracy of the model results. The assumed lifetime of the systems of course influence the results to some extent and both 60 years and 120 years are very long time for technical products. The biggest question marks, however, has been for the conventional system. There are no such old systems today as 60 years, but significant age problems have been detected at much newer installations.

The technical long term properties of the Rockdrain system are still relatively untested, but so far, technical tests show very promising results. Provided that the Rockdrain system also meets the technical requirements, the Rockdrain system must be regarded as a very good alternative to the current tunnel drainage system. Future industrial applications of the Rockdrain system will show its true potential.

Table A The table uses the tunnel in Kattleberg as an example and shows the effect of a change from conventional drainage to Rockdrain. A drainage area of 20 895 m^2 has been used in the model. The table shows the entire model results for a calculation period of 60 years. Please note that one can not deduce any relative importance between the different parameters, only compare the two drainage systems for each parameter.

Parameter	Unit	Conventional drainage	Rockdrain	Difference when switching to Rockdrain	Percent change
Cost	Euro	9 394 000	4 208 000	-5 186 000	-55.2%
Energy	MJ	29 692 000	17 004 000	-12 688 000	-42.7%
GWP	kg CO_2 eq.	2 384 000	1 645 000	-739 000	-31.0%
Acidification	kg SO_2 eq.	8 500	5 500	-3 000	-35.3%
Eutrofication	kg PO_4 eq.	1 900	880	-1 020	-53.7%
POCP	kg ethene eq.	1 500	1 100	-400	-26.7%
Waste	kg	5 439 000	1 624 000	-3 815 000	-70.1%

Contents

List of abbreviations and explanations

Abbreviation/term	Explanation
IVL	IVL Swedish Environmental Research Institute/IVL Svenska Miljöinstitutet
Trafikverket	Swedish Transport Administration
CBI	CBI Swedish Cement and Concrete Research Institute/CBI Betonginstitutet
SP	SP Technical Research Institute of Sweden/Fire protection
BESAB	Swedish company specialized in shotcreting processes.
Veidekke	Large construction company
NCC Teknik	Large construction company
Faveo	Project management firm
GHG	Greenhouse gases (in this case mostly CO_2, CH_4 and N_2O)
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Dinitrogen oxide, Nitrous oxide, Laughing gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
Carbonation	Uptake of CO_2 in concrete.
EIA	Environmental Impact Assessment

1 Introduction

Water leakage into rock tunnels can often cause problems. The water pressure in combination with cracks in the rock allow water to leak into the tunnels and causing problems such as icicles, water in the tunnels, significant power consumption for pumping of water, etc. In order to prevent ingress of water in the tunnel, the rock is pre-injected with cement slurry, which seals the rock prior to blasting. After blasting, the rock can be post-injected in those locations where leaks are detected to further seal the rock against water intrusion. When injection is not sufficient to fulfill the function requirements of the tunnel, additional external drainage systems have to be used to drain the water from ceilings and walls. This drainage is usually carried out by mounting sheets of extruded polyethylene foam, which is affixed with rock bolts onto the rock surface. The bare rock surface is first covered with a layer of shotcrete. The conventional drainage system is then applied and finally covered with a layer of shotcrete. This drainage method is relatively labor-intensive, material consuming and space consuming. In many tunnel projects, water leakage occurs in many places in the tunnel why large areas of drainage must be used. Spots of water leakage can also show up in different locations in a tunnel from time to time. It can therefore be of interest to install drainage in larger areas of a tunnel as a preventive measure. However, this requires simple and cost effective drainage techniques.

Rockdrain is a new drainage system based on a new drainage principle. Drainage channels are formed in a water permeable shotcrete layer. This is achieved by a plastic lattice of half tubes which are attached to an underlying shotcrete layer sprayed directly on the bare rock surface. The half-pipe lattice is covered with a permeable shotcrete and in this way, the drainage channel lattice is formed. The permeable shotcrete layer is then covered with a less permeable shotcrete layer (Solbruk T) which is specially designed for the Rockdrain application. The formed piping lattice in the permeable shotcrete, traps the water inside the shotcrete layer and lead the water away from the tunnel. The Rockdrain system is intended to simplify construction and improve performance through a more solid construction with fewer and less sensitive technical components.

The main application for the Rockdrain system is in different tunnels and especially road and train tunnels. New techniques need to be tested and evaluated in order to use them in normal operation. For that reason, The Swedish Transport Administration (Trafikverket) wanted to test and evaluate the method in a research project. A full-scale test of the Rockdrain system[1] was launched including several analytical investigation methods. In that project, approximately 100 m test sections was built in a newly constructed, 1.8 km long, train tunnel at Kattleberg, 40 km north east of Gothenburg, Sweden. In this way, it was possible to follow the construction work and evaluate not only the final result but also the construction process.

Many different aspects of the drainage system have to be explored in a research project. The main research project was thus divided in three sub-projects; Material and function tests, Fire tests and "Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) analysis of the Rockdrain system". This report covers the later LCA and LCC analysis. In this part, which is performed by IVL Swedish Environmental Research Institute, the energy, resource, and environmental aspects are analyzed along with the economic aspects. The energy, resource, and environmental aspects are analyzed with LCA methodology and the economic aspects are analyzed with LCC methodology. Mathematical models of the systems have been developed in the project where the LCA and LCC models have been integrated.

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[1] See more information in Preface.

To be able to evaluate the results, the new Rockdrain system is compared with a conventional drainage system that is used elsewhere in the same tunnel. The conventional system is selected to have an equal function and technical application as the Rockdrain system.

2 Technical description of the tunnel drainage systems

In this study, two different drainage systems for rock tunnels have been studied and compared both from an environmental and an economic point of view. The drainage systems are Rockdrain which is a new drainage system that aims at reducing installation work and provide a more solid system with fewer components and a longer lifetime. The other system is a conventional/standard drainage system that is frequently used today in Swedish rock tunnels. In this chapter, a technical description of the two systems is presented. The presentation includes a description of the system and of the installation process.

An important factor for the analysis is the expected lifetime of the different systems. The lifetime has been estimated in the project and the estimated values are clearly shown and in the results one can easily see the effect of the estimated lifetime. The conventional drainage system has been in service for more than 30 years. Many old installations show already aging problems. However, the materials used at that time have been improved and the installations of today can be expected to have a somewhat longer lifetime. The design of the conventional drainage systems is made in such a way that the polyethene mats are hanging on supporting threaded rods mounted on the rock wall. Even if the drainage mats are covered with shotcrete, the construction can be sensitive for corrosion, fatigue and physical stress such as pressure fluctuation due to passing vehicles. The lifetime has therefore been set to 60 years which can be considered as a long lifetime for such a system. The Rockdrain system is constructed of a polyethene half pipe lattice mounted directly on a prepared shotcrete layer. The polyethene lattice is only used to form the drainage channels in the shotcrete during construction. After that, the lattice has no function in the system, but is left in the system. The channel lattice is then sprayed with ordinary shotcrete and Solbruk T shotcrete. The drainage system consists thus of a shotcrete layer with drainage channels. This is not much different from ordinary shotcrete layers in a tunnel. The lifetime of the Rockdrain system has thus been set to the same lifetime requirements as any other shotcrete in a tunnel which is 120 years.

2.1 The Rockdrain tunnel drainage system

The Rockdrain drainage system consists mainly of three parts; a half pipe polyethene lattice which form the drainage channels inside the permeable conventional shotcrete layer, a 25 mm thick permeable shotcrete layer and a 60 mm thick less permeable shotcrete layer called Solbruk T. The Rockdrain system is mounted on a conventional shotcrete layer which is applied on the bare rock surface to provide a smooth surface with good adhesion for the drainage channel lattice. The function is relatively simple. When leakage water from the rock tunnel walls penetrates the conventional water permeable shotcrete layer, the water will be trapped between the rock wall and the less permeable Solbruk T layer. The leakage water is then forced into the drainage channels and drained off to a larger drainage channel on the bottom of the tunnel. The Solbruk T layer is also isolating to prevent ice formation in the drainage system during winter time.

The half pipe lattice is mounted directly on the prepared shotcrete layer. The lattice is delivered in sheets with size 1.2 m x 0.8 m=0.96 m^2. The weight of such a lattice sheet is 450 gram giving 0.45 kg/0.96 m^2 = 0.469 kg/m^2 Rockdrain drainage lattice. The lattice is made of polyethene plastics. The lattice is attached to the shotcrete surface with nails. A manual nailer is usually used. In Figure 1, a mounted lattice is shown. Small overlaps and gaps can exist between the lattice sheets due to the shape of the underlying surface. The lattice is mounted with 2 persons using a boom lift as shown in Figure 2.

The channel lattice is then covered with 25 mm of ordinary shotcrete. The shotcrete was delivered with a concrete truck from a concrete station nearby. The transport distance was 25 km one way. The ordinary shotcrete was applied by a large spraying robot on a heavy truck. The spraying robot can run on both diesel and electricity. Electricity is mainly used in the tunnel but diesel is also used for example to move the spraying robot truck. The spraying operation is very much a standard operation. It is however important to apply the shotcrete perpendicular to the lattice to prevent clogging the channels. The filling of shotcrete into the spraying robot is shown in Figure 3.

After the shotcrete has cured, 60 mm Solbruk T shotcrete is applied. This shotcrete is applied in two stages (30 mm + 30 mm). Solbruk T is a specially designed cement based shotcrete. It is delivered in dry form in large container bags (big bags, 800 kg/bag). Solbruk T is delivered with ordinary trucks from the production site (80 km one way). The dry Solbruk T is mixed with water to form the Solbruk T shotcrete. A small amount of Superplasticizer is also used. In the spraying process, an accelerator is used (water glass, sodium silicate Na_2SiO_3). A typical mixing recipe can be as follows:

Solbruk T (dry powder in 800 kg big bags): 800 kg
Water: 180 litre
Superplasticizers 1.5 litre (Polycarboxylatepolymer 40-60 % and water 40-60 %)
Accelerator (water glass, sodium silicate Na_2SiO_3): 4-8 % of cement weight.

The Solbruk T shotcrete is mixed on-site using a shotcrete mixing equipment. The mixer is mounted on a truck which also drives the mixer. The mixer needs one person for the operation. This person also loads the big bags of Solbruk T into the mixer using a medium/small size wheel loader. In this case, the mixed shotcrete is transported with a wheel loader to the shotcrete robot using a specially designed bucket. The filling of the spraying robot is shown in Figure 4. This transport requires one person. The mixing process is not really optimal and can probably be improved for better function and lower costs. Mixing at a concrete mixing station can also be an alternative for a future application.

For the shotcrete spraying operation, a standard spraying robot can be used. Two persons are needed for the operation of the spraying robot (may be that can be reduced to just one person in the future). The spraying of Solbruk T shotcrete is shown in Figure 5. However, the spraying process requires special equipment, knowledge and training. A screw pump[2] for the shotcrete is required for a smooth operation due to the special properties of Solbruk T shotcrete. This process has been used in the LCA models of the Rockdrain drainage method. This process represents a wet spraying method. However, Solbruk T can also be used with a dry spraying technique. In this process, water is added in the spraying nozzle and no mixing process is needed. This simplifies the entire application process. Less equipment and fewer persons are required. This technique has also

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[2] Test applications in the project have shown that piston pumps does not work well with Solbruk T shotcrete.

been included in the LCA model as an alternative. The spraying robot requires two persons for the operation with both the wet and dry technique today.

As shown in the technical description above, the Rockdrain system is directly attached to the rock surface in the tunnel and thereby becomes a solid integral part of the tunnel structure. This results in less movement in the structure and thus a longer life expectancy. An estimated lifetime of 120 years has been used for the Rockdrain system compared to 60 years for the conventional drainage system.

Figure 1 Mounted polyethene plastic lattice forming the drainage channels in the Rockdrain system.

Figure 2 Mounting of the channel lattice using a boom lift.

Figure 3 **Filling of ordinary premixed shotcrete in the spraying robot.**

Figure 4 Filling of Solbruk T shotcrete in the spraying robot.

Figure 5 Shotcreting with Solbruk T shotcrete.

2.2 Conventional/standard tunnel drainage system

Compared to the Rockdrain system, conventional drainage systems work in a complete different way. Conventional drainage is built of large foamed polyethene mats mounted on steel rods with a distance of a few centimeters to a few decimeters from the tunnel rock surface. Leaking water from the tunnel walls will drip on the polythene mat and run down along the drain to the bottom of the tunnel. The polyethene mat is sensitive to mechanical damage and also flammable which can be a problem, especially in a tunnel. The drain mat is therefore covered with shotcrete.

The conventional drainage system is mounted on a shotcreted tunnel wall like the Rockdrain system. The installation of the conventional system can be divided into several process steps. These process steps are described below in chronological order as the installation take place.

1. Drilling hole in the rock wall. The diameter of the hole is approximately 60 mm and the depth of the hole 1 m. The distance between the holes is 0.7-1 m. For the drilling work, a single-boom drilling rig is used. The drilling rig is powered by electricity. One person is operating the drilling rig. The drilling capacity is estimated to 20 holes per hour.
2. Installation of threaded rods. Threaded rods with a length of 1.5 m and a diameter of 16 mm are mounted in the holes with a cement paste consisting of Portland cement and water. The cement paste is injected in the holes with a tube and the threaded rods are pressed into the hole. The

operation is performed with a boom lift and a cement mixer. Two persons are needed for the operation. One stands on the lift and injects cement paste into the holes and attaches the threaded rods. The other person is handling the cement mixer. The mounting speed is estimated to 20 rods per hour. The mounting of threaded rods is shown in Figure 6, the cement paste mixing is shown in Figure 7 and the final result of mounted rods is shown in Figure 8.

3. The next step in the working process is the assembly and fixing of the drainage mats on the threaded rods. The drainage mats are fixed with different steel materials. This work is done by two persons on a lift platform. It is a manual work and the pace of work has been estimated to 1 m^2 drainage per man-hour. The lift platform is shown in Figure 9 and the assembled drainage mats are shown in Figure 10.
4. For mechanical protection of the drainage and for fire protection, the drainage is covered with two layers of ordinary shotcrete. The first layer is 60 mm thick and consists of standard shotcrete reinforces with steel fibers for mechanical strength and polypropene fibers for fire resistance. The second layer is 20 mm thick and is only mixed with polypropene fibers for fire resistance.

In the list below, all materials used for conventional drainage are presented.

<u>Materials and specifications for a conventional tunnel drainage system:</u>
1 piece of nut to the threaded rod: 34 g
2 pieces of large round steel washer: 360 g
Steel stripe: 122 g/0.58 m=210 g/m (holder along the longitudinal edge)
Holder of steel stripe: 98 g (screw with square washer)
Large concrete reinforcing washer/nut: 0.639 kg (diagonal length 0.63 m)
Longitudinal holder, rebar ladder tapes: 1.378 kg/0.97 m=1.421 kg/m holder
Threaded rod for drill hole in the rock: 1880 g/1.5 m=1.253 kg/m threaded rod
Drill holes in the rock: 60 mm diameter and 1 m depth
Length of threaded rod: 1.5 m with a diameter of 16 mm
Portland cement and water for fixing of the threaded rod in the rock drill hole.
Foamed polyethene drainage mat (thickness 50 mm): 192 g per 0.43 m × 0.29 m=1.54 kg/m^2 drainage mat

As shown in the technical description above, the conventional drainage system is a technical system that is attached to the rock surface by steel rods with a distance of 0.7 – 1 m between the rods. For the rest, the structure is hanging lose from the tunnel wall. This can create movements in the structure for example when trains or trucks are passing. The construction material is polyethene plastics which are more responsive to mechanical wear and aging than pure concrete. This means that one can expect a shorter lifetime for the conventional drainage compared to the Rockdrain system. An estimated lifetime of 60 years has been used for the conventional drainage system compared to 120 years for the Rockdrain system. Another aspect that affects the positions is that the design requirements concerning lifetime is different for the main construction and technical products used in addition to the construction. In this case, the Rockdrain system can be classified as a part of the main construction while conventional drainage can be classified as additional technical products. This can probably also affect the expected lifetime in a more formal way. However, this is of course all estimations and speculations. Future evaluations will show the real potential and lifetime of both the systems.

Figure 6 Mounting of threaded rods.

Figure 7 Mixing of cement paste for fixing of the threaded rods.

Figure 8 Mounted threaded rods ready for assembly of the standard drainage.

Figure 9 Lift for the assembly process of the standard drainage.

Figure 10 Mounted standard drainage ready to be covered with ordinary shotcrete.

2.3 Repair of tunnel drainage systems

The possibility for repair of different types of tunnel drainage systems is an important aspect in the choice of a drainage system. Experiences of such repairs exist to some extent for the standard drainage system which was introduced on the market approximately 30-40 years ago. For the Rockdrain system, no such experience exists. Maintenance in the LCA models is based on the replacement of the drainage systems at end of life. No repairs of this type have been included in the LCA model calculations.

Several different types of damages can occur on drainage systems in tunnels. One type is damage due to external influences such as collision damage from vehicles. In such a case would damages on standard drainage systems become larger compared to the Rockdrain system which has a physically more stable construction. A collision can destroy large parts of a system with drainage mats hanging loose on steel bars. In the Rockdrain system, the drainage lattice can easily be replaced and the damage can be refilled with shotcrete/Solbruk T while for the standard drain, the construction need to be rebuilt. Internal damages to the drainage system due to material problems or to disintegration of the rock wall with new leakage is another type of problem. In this case, it is more a question of building a new drainage to replace the damaged drain. The difference between the drainage systems in this case is approximately equal to the difference in new construction or maintenance, as used in the LCA models where also the demolition of the old drainage system is included.

For leakage problems, the Rockdrain system can offer another possible method where a new Rockdrain system is placed on top of the old Rockdrain system without removing the old system. The Rockdrain system has thus good opportunities for effective repairs. However, there is still much research to be performed and experiences to be gained before one can say anything for certain about the repair of the new systems.

3 Analytical methods and methodological aspects

3.1 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. Analyzing 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 3.2 and 3.3 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.

3.2 Life Cycle Assessment (LCA)

A system analysis is a tool that allows a product to be analyzed 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[3]. 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 analyzed. 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

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[3] ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework.
ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines.

(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[4] have been used.

3.3 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, labor 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 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

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[4] 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.

better overview of the different costs, the costs have been divided into the following groups: material costs(/product costs), machine cost, labor 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. Labor 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[5]. 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 labor costs in the future. This will, most likely, change significantly in the future but how is difficult to say.

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[5] 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.

4 The LCA models of the Rockdrain and the conventional drainage system

The overall aim of this study is to compare two different tunnel drainage methods in terms of environmental and economic performance. To be able to do this, a system perspective has to be applied. The system models need to cover the entire life cycle of the two drainage methods from extraction of raw materials to waste handling. For that purpose, two different LCA models have been developed representing the two different drainage methods. The models also need to be detailed and accurate so that small differences can be evaluated and changes in many different parameters can be studied.

The models have been developed in the LCA software KCL-ECO[6]. The model structure for the Rockdrain system is shown in Figure 11 and the model structure for the conventional system is shown in Figure 12. Due to the size of the model, it is difficult to show the entire model in the report in a readable form. However, it is important to show the entire model for the understanding of the study and the different analyses. The solution to this problem is to show the model as it is in the report and then use the zoom function in the computer to look at the figure on the screen. In this way, both the details and the overview will be available.

The models are built-up of different process modules and transports representing different processes in the technical system. All materials are calculated back to its material resource in the earth crust. The wastes from the system is presented as outgoing flows and no further waste treatment processes are included.

In the models, the processes (production methods) described in chapter 2 are converted into a mathematical form. In the construction part of the models, the used process/method is followed in detail and upstream processes are calculated. The maintenance procedure includes demolition of the old drainage structure and a reconstruction of the drainage in the same way as for the new construction. No other maintenance has been included. This can of course be an underestimation of the environmental bourdon but the expected maintenance for both the systems is small so the estimation can be considered as acceptable. The operation activities are also expected to be limited. Two items have been considered; inspection of the drainage systems and uptake of CO_2 in the shotcrete. The inspection requirements are assumed to be twice as high for the conventional system compared to Rockdrain. For the Rockdrain system, only a yearly overview inspection is assumed to be required compared to the conventional system where both an overview and a detailed inspection are assumed to be required.

Overview inspection: One inspection per year with an inspection rate of 500 m^2/h.
Detailed inspection: One inspection each 10 years with an inspection rate of 50 m^2/h. This inspection includes inspection behind the drainage.

For the uptake of CO_2 in the shotcrete, the uptake is presented as the potential uptake during 60 years including both construction and maintenance even if this uptake level is not fully reached during the 60 years. The CO_2 uptake in shotcrete during product lifetime is estimated to 20 % of the theoretical maximum possible CO_2 uptake. This maximum uptake is set equal to the amount of CO_2 driven off in the cement production. In the shotcrete, this represents a carbonation depth of

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[6] A LCA software developed in Finland by KCL (Finish pulp and paper research laboratory) which today is a part of VTT Technical Research Centre of Finland.

~16-17 mm of 80-85 mm. Of practical reasons, the uptake is shown in construction and maintenance even if the uptake occur over a longer time and could have been shown under operation. Also in the waste handling phase, the concrete will continue to take up CO_2 from the atmosphere but this phase is not included in this study. However, the remaining uptake potential is 80 % of the theoretical maximum possible CO_2 uptake.

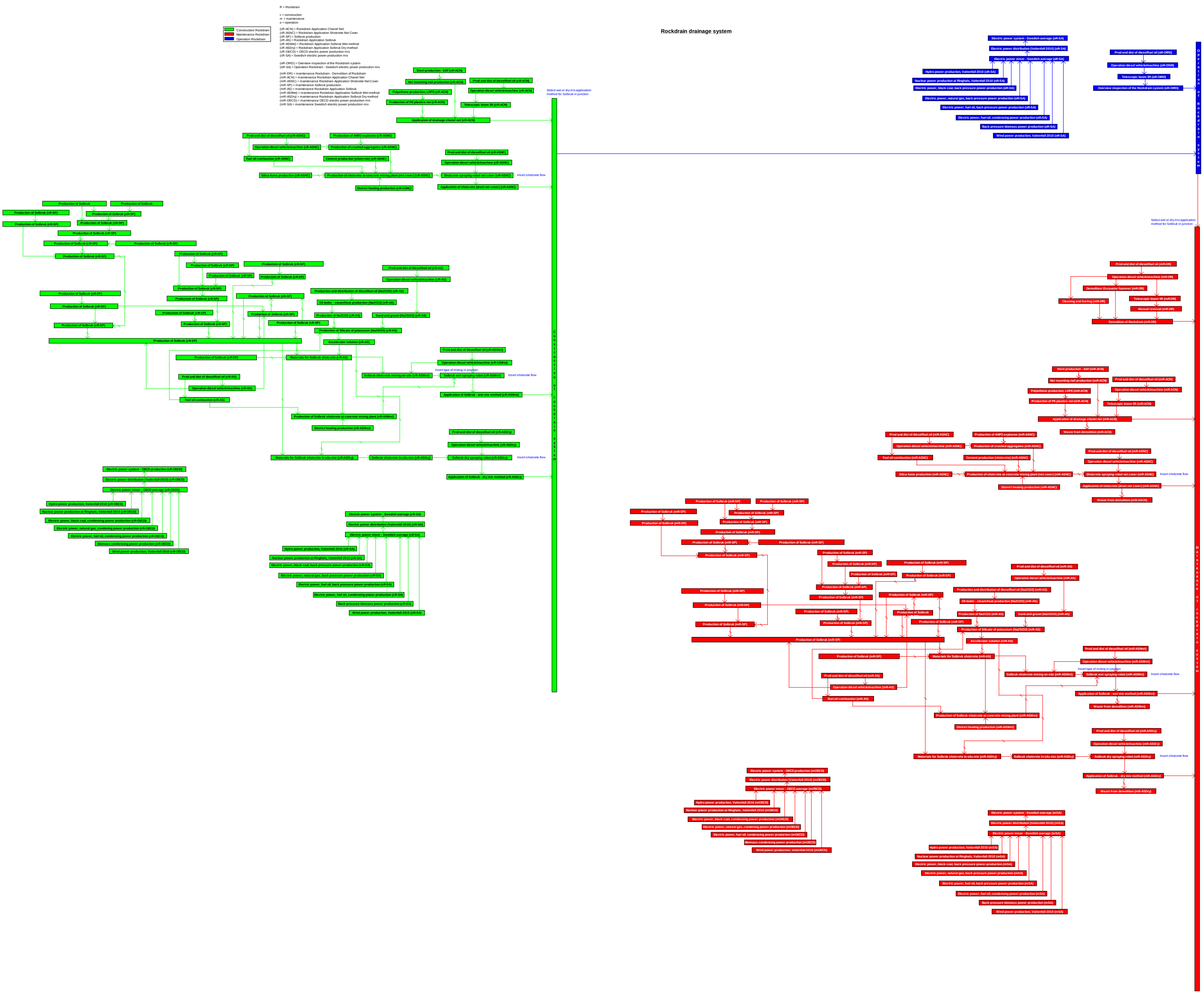

Figure 11 The LCA model flow chart showing the life cycle system of the Rockdrain tunnel drainage system. (Use pdf file/zoom and read figure from screen for improved readability).

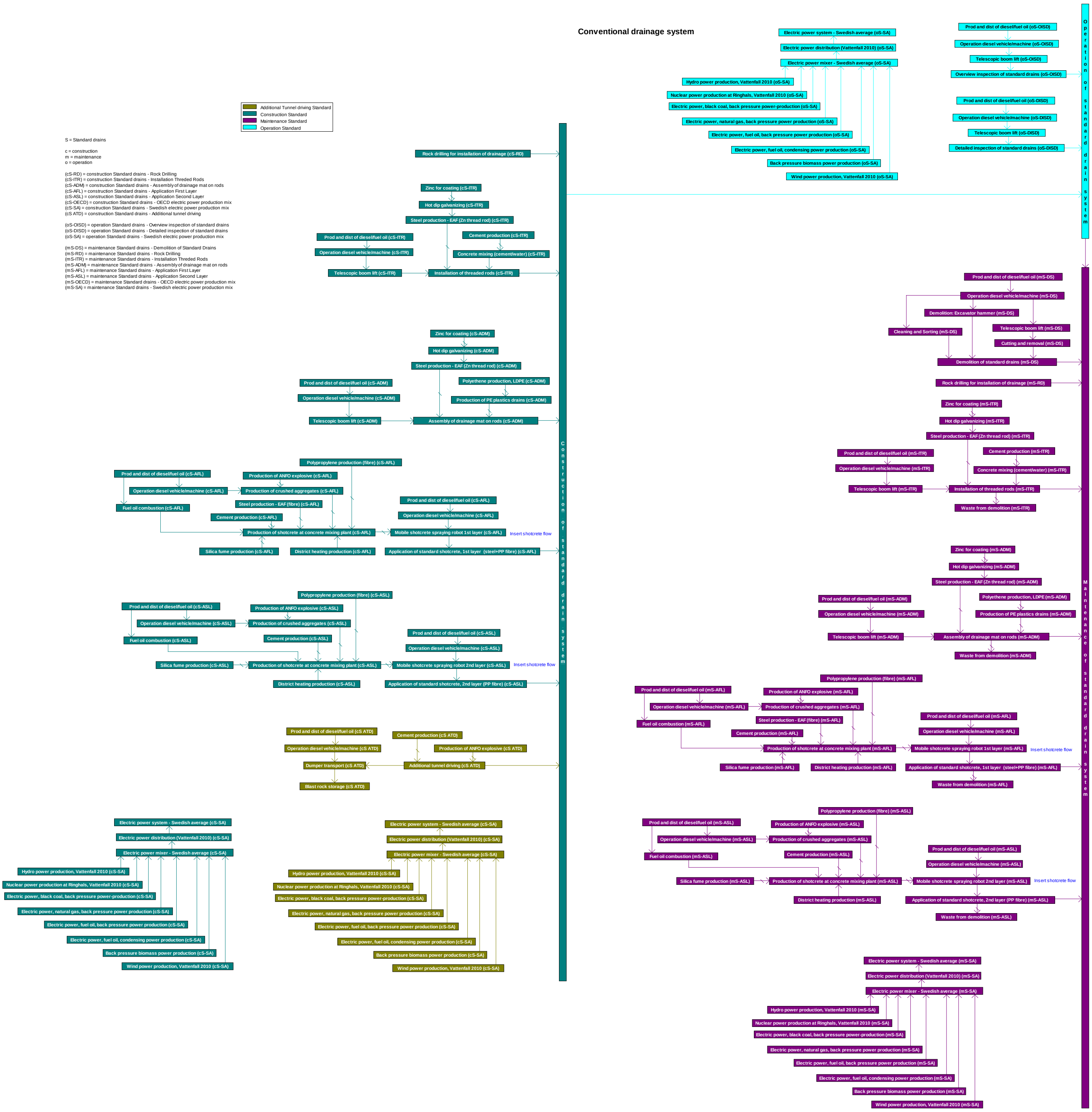

Figure 12 The LCA model flow chart showing the life cycle system of the conventional tunnel drainage system. (Use pdf file/zoom and read figure from screen for improved readability).

5 Life cycle inventory calculations

Data for the LCA models have been collected from various sources. Actual production figures have been used for the production at the tunnel in Kattleberg. For materials and other more general activities, data representing international/European data have been used. Site specific data for the tunnel in Kattleberg have also been used (e.g. transport distances, Swedish electric power production). Production data representing the entire production chain from raw material extraction to the finished product has been analyzed. Thus, primary energy resource use, primary material resource use, emissions and generated wastes has been collected from the entire production chain.

The **functional unit** of the system is set to 1 m^2 drainage area during 60 years of drainage lifetime.

For the economic calculations, four different types of costs have been used as shown below. All costs are calculated in euro. All costs are calculated at current prices (year 2012) and with zero cost of capital.

Machines costs in Euro: Hourly rental costs for construction machines × Machine hours
Man-hour costs in Euro: Hourly labor cost (60 Euro/h) × Man-hours
Materials costs in Euro: Specific material cost × Material amounts
Transport costs in Euro: Calculated cost in Euro/(tonne*km) for Swedish transports.

The wastes are calculated as an outgoing product from the system and no further treatment of the wastes is included. For concrete products, an uptake of CO_2 (carbonation) is included during the use phase of the product. The uptake is shown as the potential uptake during the use phase and has been estimated to 20 % of the CO_2 that was driven off in the cement production. The uptake is shown as the potential uptake in the installed amount of concrete even if some of this uptake can occur after the 60 years of lifetime (especially for the uptake in maintenance). However, the waste concrete will continue to take up CO_2 after the lifetime also in the waste phase. This is not included in the model results but has a theoretic potential of 80 % of the CO_2 driven off in cement production. However, waste processes optimized for this uptake is not developed and the uptake rate depends very much on the handling and storage/use of the crushed waste. In a very long term perspective, the concrete will be almost completely carbonated and thus all CO_2 driven off from the raw meal in the cement kiln will be taken up by the concrete.

The accuracy of the data is always an important aspect in an LCI analysis. The accuracy of the model results is always dependent on the precision of the data input. An input value can vary due to many different circumstances such as measurement variations, variability in the parameter e.g. high variability in the emission of CO and HC, variations in the data population e.g. emission variations between different plants, different production conditions etc. Generally for this model, the accuracy is relatively high for the energy resource use, for the material resource use and for the emissions of CO_2. The accuracy is lower for the emission of CH_4 and N_2O. Generally, the precision is higher for the most common and best mapped emittants such as CO_2, SO_2 and NO_X compared to the other emittants.

Transport data (per tonne-km) for different transports has been obtained from NTM[7], Sweden. All data sets have been described carefully in the models with references.

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[7] The Network for Transport and Environment (Nätverket för Transporter och Miljön), Sweden.

The use and calculation of the electric power supply is always an important part in an LCA. In general, specific electric power for the different processes has been used if possible. For general use in Sweden, a Swedish average electric power production mix (5 years average) has been used. For global commodities and processes, an OECD electric power production mix has been used (year 2005). All electric power supply calculations include production of the electric power, the distribution grid and distribution losses in the electric power grid. The distribution losses have been estimated to 4 % in the electric power grid to industrial applications. All energy use is calculated back to primary energy resource use. This means for example that a specific quantity of diesel oil use is calculated as the corresponding use of crude oil resource including e.g. crude oil extraction, transport, refining and distribution. The resource use for hydropower is calculated as the produced amount of electric power with addition of production energy and distribution losses. The resource use for nuclear power is calculated as the total amount of heat formed in the nuclear reactor with addition of production energy (nuclear power station) and distribution losses. The energy in the cooling water from the reactor is thus calculated as an energy use.

Based on the requirements in the ISO standard the following general information can be given concerning the data quality, see Table 1 below.

Table 1 General specification of inventory data.

Data quality subject	Coverage and strategies for inventory data
Time-related coverage	Generally, the most recent data available has been used in the study. Most of the production data for both systems are collected at the construction work for the tunnel in Kattleberg (during 2011-2012) where both methods were used. Electric power production is mainly from year 2010. Data for polyethene plastics, cement and steel will reflect international data and the data are from 2003-2010.
Geographic coverage	The production site is located to a tunnel in Kattleberg 40 km northeast of Gothenburg, Sweden. Data in the model e.g. transports are adapted to that production site. For production of materials, international average data have been used to reflect an international use of the product.
Technology coverage	The conventional drainage method is a well established method which has been used in approximately 40 years. The Rockdrain method is completely new and has only been used in smaller areas in different tests. This can indicate that the Rockdrain method is not as optimized as the conventional method and that further development can improve the product.
Precision, completeness and representativeness of the data	Most of the base data in the model is based on actual studies of the production process such as shotcreting, mounting, rock drilling etc. Variations exist in the processes due to work skill of the staff, physical conditions at work site (winter/summer) etc. This can mean lower efficiency for new methods like Rockdrain compared to well-established methods like conventional drainage. Some technical problems occurred for the Rockdrain system during the installation mainly due to use of piston pump. When using screw pumps for the shotcrete the work proceed as normal. Data for "normal" operation has been used for Rockdrain. However, further optimization of the process can improve the production efficiency. All major production activities have been included in the model. However, activities for maintenance and operation of both the systems are difficult to estimate but the same strategy has been used for both the systems so the comparison between the systems should be correct. The data in the model represent an international/European typical use of the product but site specific data have been used for the application in the tunnel at Kattleberg.
Consistency and reproducibility of the methods used throughout the LCI	The model calculates the overall results from the analysis based on the input data used in the model. Each production chain is unique to some extent due to type of plant, used material and energy, process conditions, transport distances etc. Generally, one can say that materials and the production method are relatively consistent while local parameters such as transport distances can vary significantly.
Sources of the data and their representativeness	Production data for construction of the drainage in the tunnel are obtained from the construction site in Kattleberg. The tunnel is an ordinary double track train tunnel. The rock is granite which is a hard stone. Low to medium water leakage in the tunnel. For material data such as polyethene plastics, cement and steel, general LCA data have been used representing an international or European average/typical production. For some more unusual products used in small quantities (mainly chemical), LCA data have been calculated based on theoretical and literature data.
Uncertainty of the information	Exact figures of the uncertainty of the data are not possible to achieve.

6 Results from the LCA/LCC model analyses

In the inventory analysis of the study, different types of data (such as technical data, environmental data, economic data etc.) were collected. These data were then transferred to the LCA model, which is a mathematical model of the technical system. In this chapter, the models have been used to analyze the properties of the two drainage systems. Model analyses have been made of both the systems and the results are presented in this chapter along with a technical analysis and comments.

The results are presented per m^2 drained tunnel area which also is the functional unit of the LCA models. This also means that effects including coverage of different tunnel areas for example as a preventive measure will not be taken into account. A simpler and less expensive system could be used on larger areas for preventive drainage purposes and thus provide a better long-term result and save costly future additional drainage installations. This study considers such an effect as another functional unit and has thus not taken that effect into account. It is also very difficult to evaluate such an effect in an accurately and neutral way even if the technical effect will exist.

The results are evaluated based on the following parameters:

- Energy resource use
- Material resource use
- Greenhouse gases
- Acidification
- Eutrophication
- Photochemical Ozone Creation Potential
- Waste
- Economy

In the result bar charts showing individual processes these processes refers to a module in the process flow sheets. A code is also used for each individual module which makes it possible to find the process in the flow charts (Figure 11 and Figure 12). The codes are also defined in the flow charts. An example of such a code is “Production of Solbruk (cR-SP)”. In this specific example “Production of Solbruk” refers to several modules due to confidentiality.

6.1 The Rockdrain drainage system

6.1.1 Energy resource use analysis

Energy resources or primary energy resources are energy resources in the original form in the earth crust. A use of, for example, diesel oil in a construction machine also gives rise to a consumption of primary energy in the form of crude oil. This crude oil is the real energy resource use for the process and includes also extraction of the crude oil and refining of the crude oil into diesel oil as well as different types of transports. For that reason, the primary energy resource use has been used for the energy evaluations in this study.

The results from the energy analysis of the Rockdrain system are shown in two bar charts. The first bar chart, presented in Figure 13, shows the primary energy resource use for the entire system and divided into construction, maintenance and operation. The second bar chart, presented in Figure 14, shows the different energy resources divided into the individual processes that build up the Rockdrain system.

As shown in Figure 13, the total use of primary energy during a 60 years calculation period is 813.8 MJ/m^2 drainage and of that, the construction phase is 515.5 MJ/m^2. The maintenance is calculated mainly as a demolition and new construction after the lifetime of the drainage but the activity is calculated as a yearly contribution which is 100 % at the end of the lifetime. One can also see this as a yearly wear and tear. This means that, at the end of the lifetime, the energy use should be slightly larger than the construction phase. In this case, the lifetime of the Rockdrain system is estimated to 120 years and the calculation period is 60 years so the maintenance is slightly more than half of the construction phase. The primary energy use for operation of the Rockdrain system (inspection activity) is relatively small, only 22.11 MJ/m^2 and related to diesel use for a boom lift.

As a comparative example, one can also consider the Rockdrain system assuming a lifetime of 60 years instead of the projected 120 years used in the study. For a calculation period of 60 years, the construction and operation phases would remain unchanged while the energy use for maintenance would double. This would give a total energy use of 1090 MJ/m^2 and 60 years instead of 813.8 MJ/m^2 and 60 years.

As shown in Figure 14, the main energy resource for the Rockdrain system is crude oil. The oil is mainly used for production of Solbruk T and other cement and for operation of diesel engines. Electric power is also used in the system and that is mainly shown as a use of nuclear and hydro power due to the Swedish electric power production mix. Natural gas is mainly used for production of polyethene plastics.

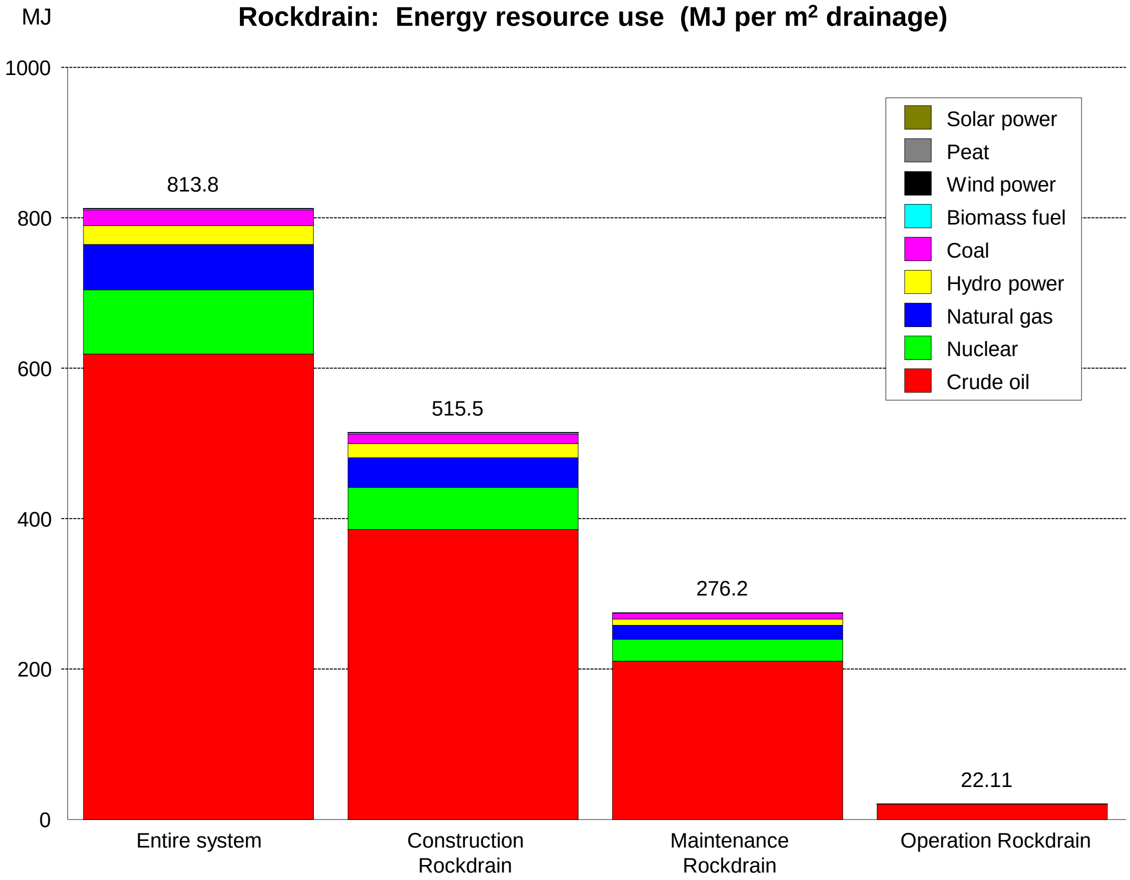


Figure 13 **The figure shows primary energy resource use in MJ/m^2 installed drainage for the Rockdrain system during 60 years. The figure shows the energy use for the entire system and divided into construction, maintenance and operation. Both non-renewable and renewable energy resources are included in the figure.**

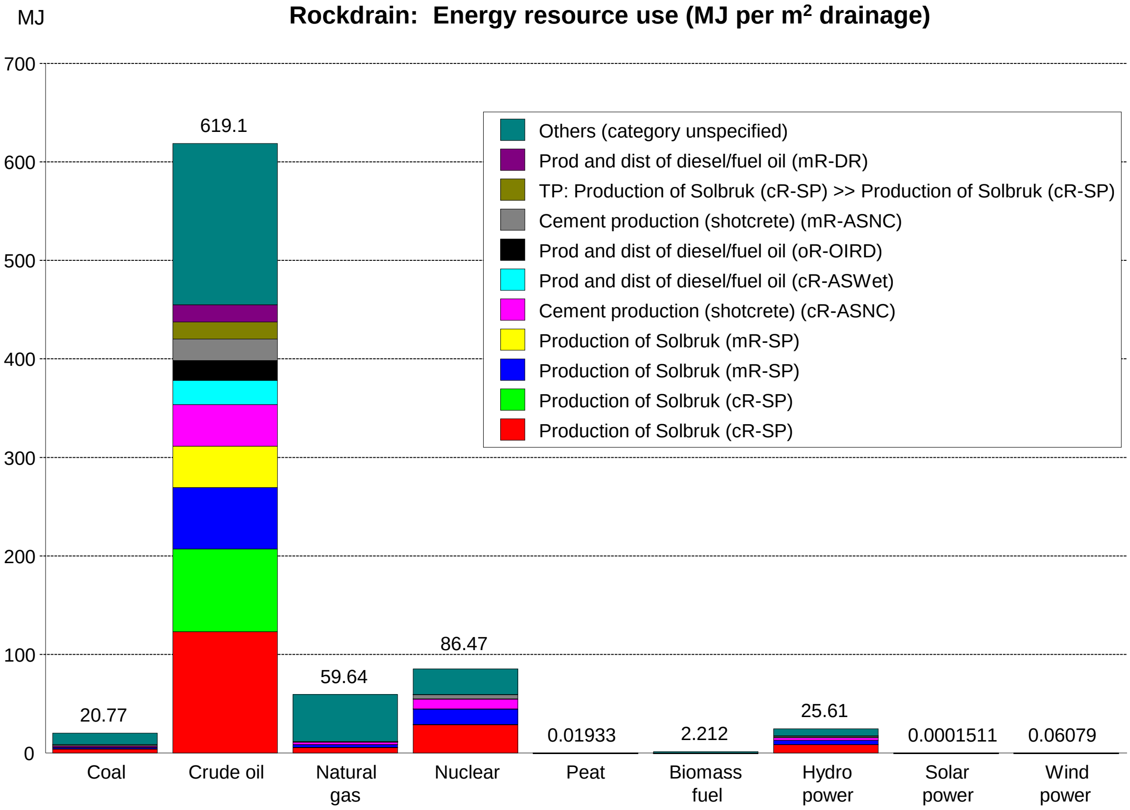


Figure 14 The figure shows the main use for the different energy resources used in the Rockdrain system. The energy use is shown in MJ/m^2 installed drainage. Both non-renewable and renewable energy resources are included in the figure.

6.1.2 Material resource use analysis

The material resource use is calculated in the same way as the energy resource use. This means that the primary material resources have been used as a measure for the use of material resources. The material resource use has thus been calculated back to its origin in the earth crust/nature.

For reasons of confidentiality, it is not possible to present a complete picture of the material resources used in the Rockdrain system. Therefore, only an overview of the system's material resources is presented. No remarkable environmentally harmful substance was found in the analysis. The total amount of non-renewable material resources is calculated to 254.4 kg/m^2 installed drainage. The largest uses of non-renewable material resources are: limestone, solid rock, sand & gravel and other resources used for Solbruk T.

6.1.3 Emission and impact assessment

In this chapter, the emissions of different substances are shown both as direct emissions (in kg) and as impact potentials. In the impact potentials the different substances are weighted according to their effect contribution to a specific impact category. For example, in the Global Warming

Potential the impact is calculated in CO_2 equivalents which means that the CO_2 is measured in kg, the CH_4 emission is multiplied by 23 and the N_2O emission is multiplied by 296 due to their effect as greenhouse gases compared to CO_2.

6.1.3.1 Greenhouse gases

In Figure 15, the Global Warming Potential (GWP) for the entire system and divided in construction, maintenance and operation is shown per m^2 drainage for the Rockdrain system during a calculation period of 60 years. As shown in the figure, the emission of fossil based carbon dioxide CO_2 (e.g. CO_2 from crude oil, coal and natural gas) is the most important source for GWP. Methane (CH_4) emissions give only a small contribution. The other emissions in the figure are so small that they cannot be quantified in the figure.

CO_2 is also taken up in concrete by a process called carbonation. This is a relatively slow (compared to the emission) but significant process caused by the fact that concrete is not a chemically stable form. The CO_2 uptake during product use has been estimated for the calculation period (60 years) to 20 % of the CO_2 that was driven of the stone material (mainly lime stone) in the cement production (cement kiln). This represents a carbonation depth in the shotcrete of ~16-17 mm of 85 mm. In addition, the shotcrete will continue to take up CO_2 as long as it is used in the tunnel and it will also continue to take up more CO_2 when the shotcrete is demolished and stored (e.g. crushed and used as aggregates). In fact, the CO_2 uptake rate will increase when the concrete is crushed due to the formation of many more concrete surfaces provided that CO_2 is available. In a very long time perspective one can expect that most of the CO_2 will be taken up. However, in this study, only the CO_2 uptake during the calculation period of 60 years has been taken into account. The CO_2 uptake is shown as negative emissions in the figure.

In Figure 16, the process contribution to the GWP is shown. As expected, only fossil based CO_2 emissions will make a significant contribution. Of that emission, approximately 80 % emanates from production of Solbruk T or cement production. The emissions come both from construction and maintenance.

A comparative example for the Rockdrain system assuming a lifetime of 60 years instead of the projected 120 years and a calculation period of 60 years would result in unchanged construction and operation phases while the GWP for maintenance would double. This would give a total GWP of 116.6 kg/m^2 and 60 years instead of 87.18 kg/m^2 and 60 years. The CO_2 uptake in the shotcrete will also increase but it is more difficult to estimate the exact uptake rate. An increased amount of fresh concrete will both increase the uptake rate and the uptake capacity.

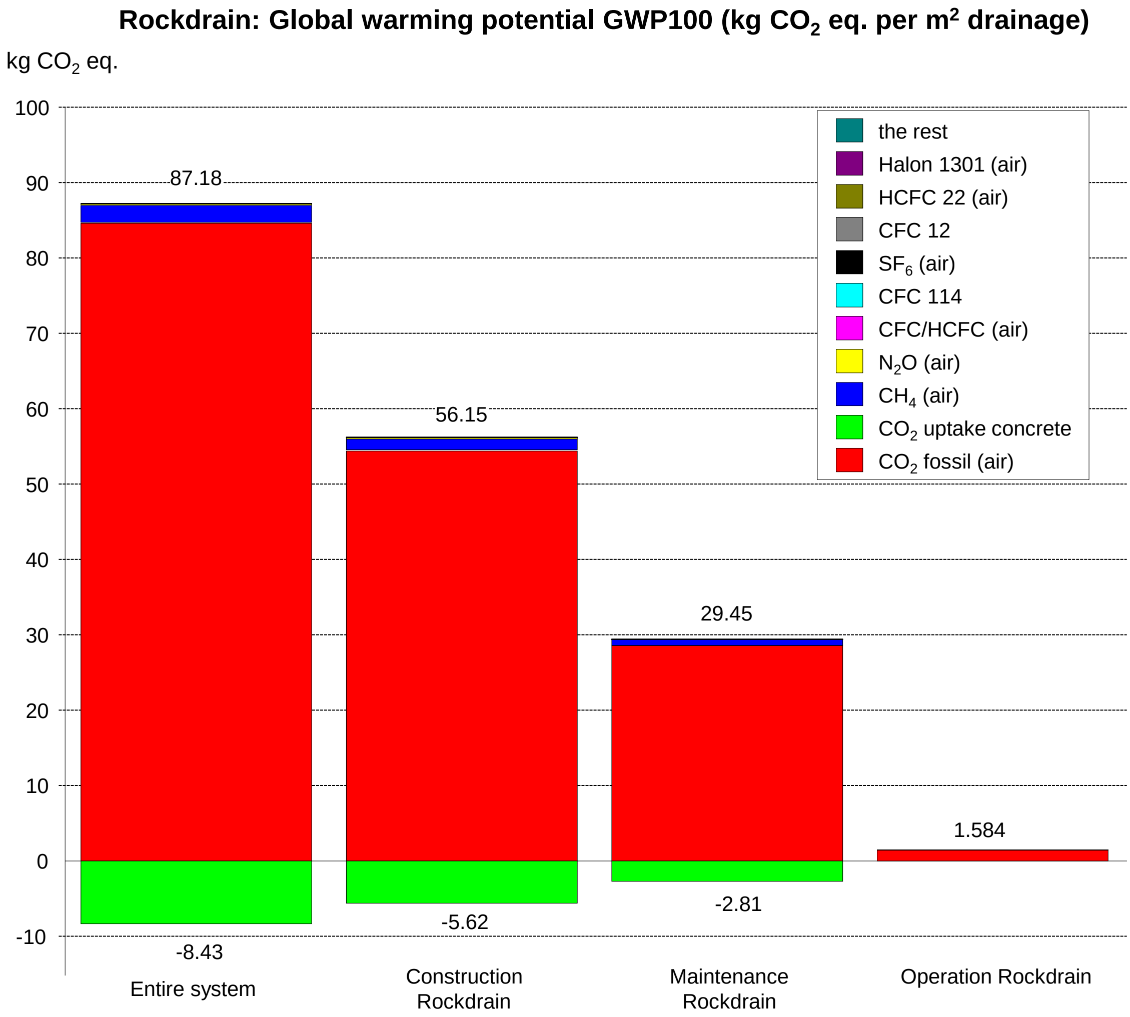


Figure 15 The figure shows the Global Warming Potential (GWP) in kg CO_2 eq./m^2 installed drainage for the Rockdrain drainage system. The figure shows the GWP for the entire system and divided into construction, maintenance and operation during 60 years. The figure also shows the expected CO_2 uptake in the concrete due to carbonation during the calculation period of the product. CO_2 uptake during the waste phase is thus not included.

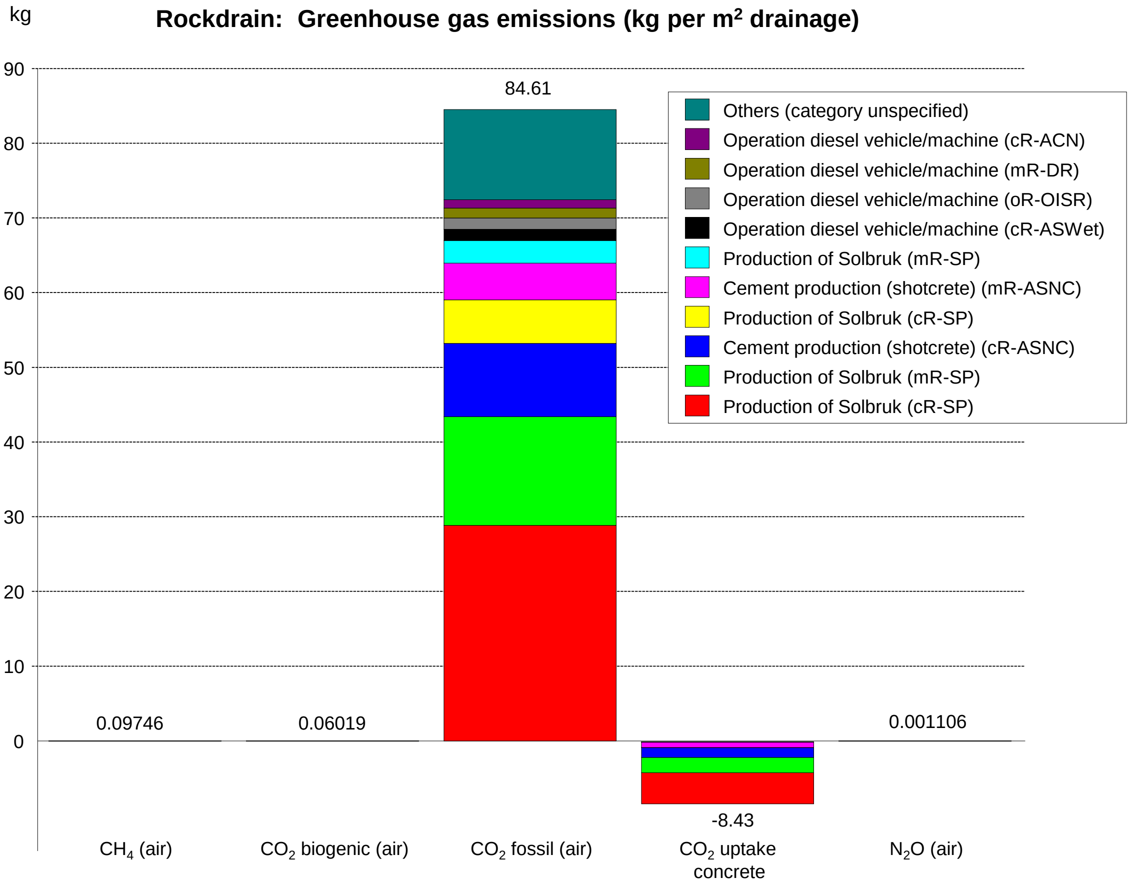


Figure 16 The figure shows the main emissions of greenhouse gases from different parts of the Rockdrain drainage system. The emissions are shown in kg/m^2 installed drainage. The uptake of CO_2 in concrete due to carbonation is also shown in the figure.

6.1.3.2 *Acidification potential*

In this chapter, the acidification potential has been calculated and is presented as kg SO_2 equivalents per m^2 drainage. As shown in Figure 17, the acidification potential is almost entirely caused by the emissions of SO_2 and NO_X. The contribution of NO_X is approximately 60 % in the entire system. Figure 18 shows the origin of the NO_X and the SO_2 emissions. For the NO_X emissions, the production of Solbruk T and cement account for approximately 50 % of the emissions and for the SO_2 emissions the corresponding figure is 61 %. Note the difference in acidification potential and the actual emission. The difference is caused by a stronger acidification potential for SO_2 compared to NO_X.

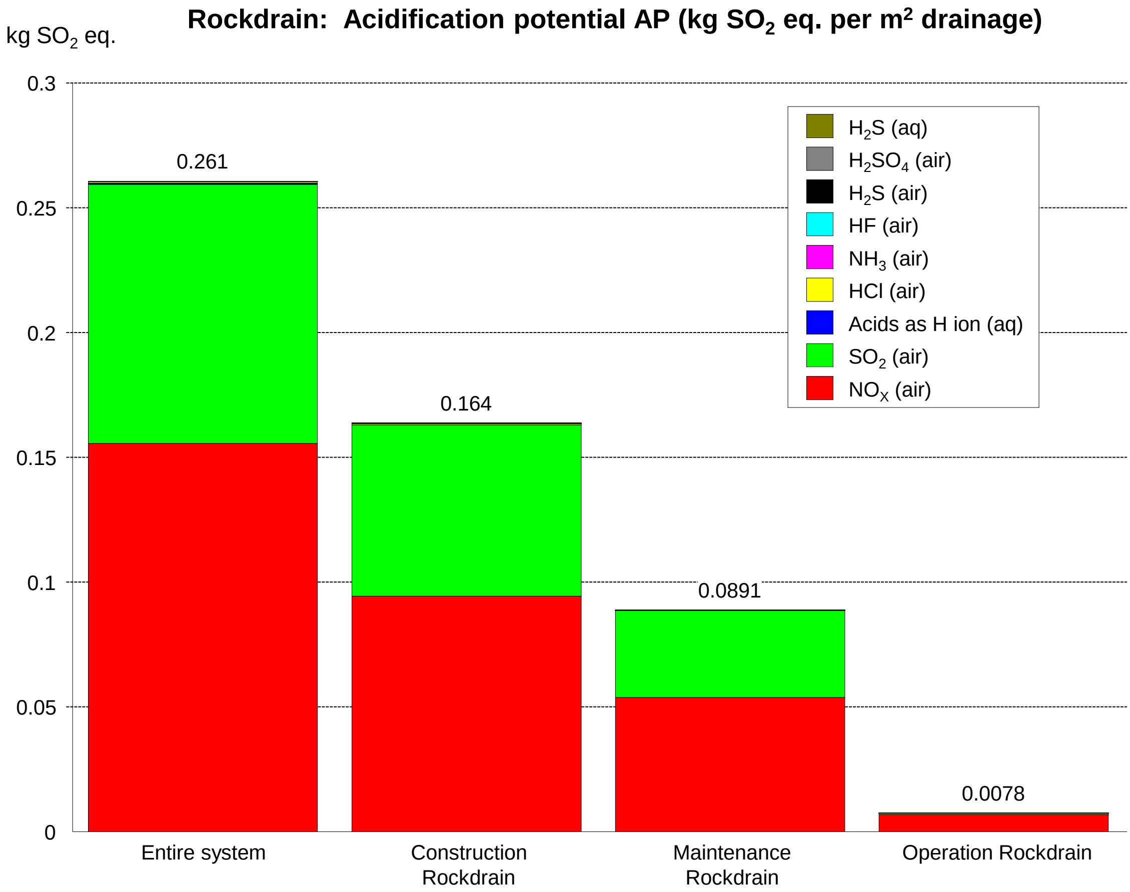


Figure 17 The figure shows the acidification potential (AP) in kg SO_2 eq./m^2 installed drainage for the Rockdrain drainage system. The figure shows AP for the entire system and divided into construction, maintenance and operation.

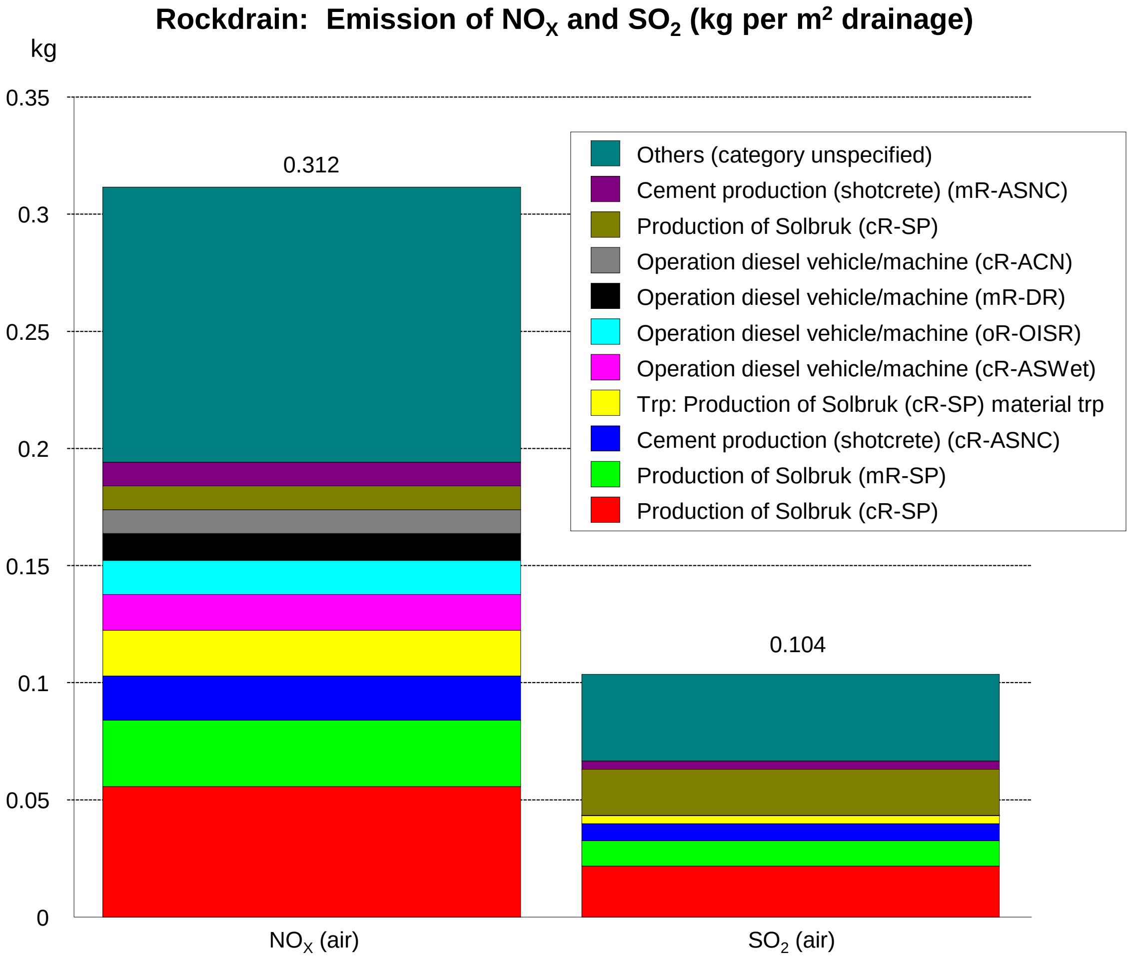


Figure 18 The figure shows the main emissions (NO_X and SO_2) of the acidification potential from different parts of the Rockdrain drainage system. The emissions are shown in kg/m^2 installed drainage.

6.1.3.3 Eutrophication potential

The eutrophication potential (EP) is calculated in kg PO_4 equivalents/m^2 installed drainage. The EP results are shown in Figure 19 and of those results one can see that the emission of NO_X is definitely the most important factor. The origin of the NO_X emissions is of course the same as for the acidification potential and is thus shown in Figure 18.

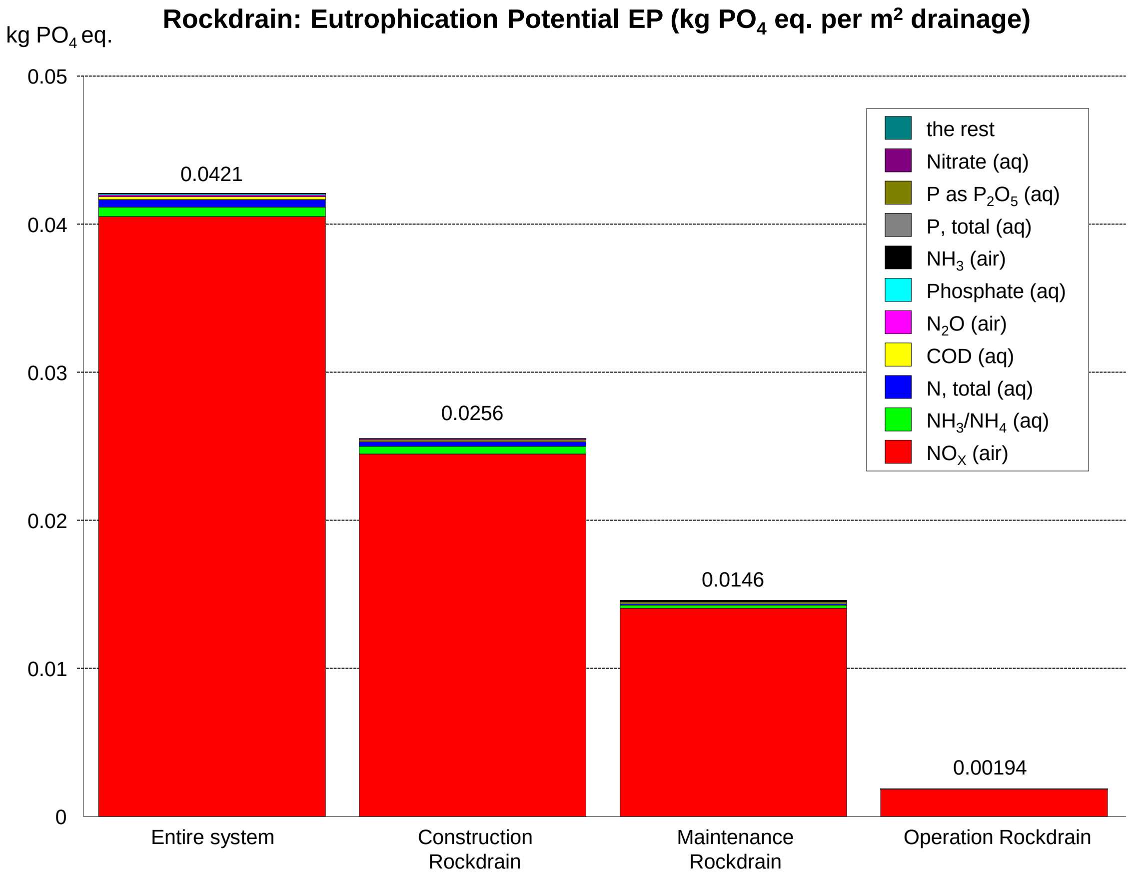


Figure 19 The figure shows the eutrophication potential (EP) in kg PO_4 eq./m^2 installed drainage for the Rockdrain drainage system. The figure shows EP for the entire system and divided into construction, maintenance and operation.

6.1.3.4 Photochemical Ozone Creation Potential

The formation of photochemical oxidants (mainly ozone) is the result of reactions between nitrogen oxides (NO_X) and volatile organic compounds (VOC) exposed to UV radiation. The potentials for these reactions are usually estimated by calculating the Photochemical Ozone Creation Potential (POCP) for different VOC's. The POCP value is related to a reference substance, in this case, ethene ($H_2C=CH_2$). The Photochemical Ozone Creation Potential (POCP) is thus calculated in kg ethene equivalents per m^2 installed drainage. It is here worth to notice that we are dealing with ground level ozone (and not the ozone layer depletion). Ozone at ground level can have both ecological effects and health effects. Different materials such as polymers can also react with ozone.

The results from the POCP calculations are shown in Figure 20 and as shown in the figure, the emissions are relatively small but significant. The main sources for emissions taken place in the POCP reactions are production of Solbruk T and cement (contribution 75-80 %).

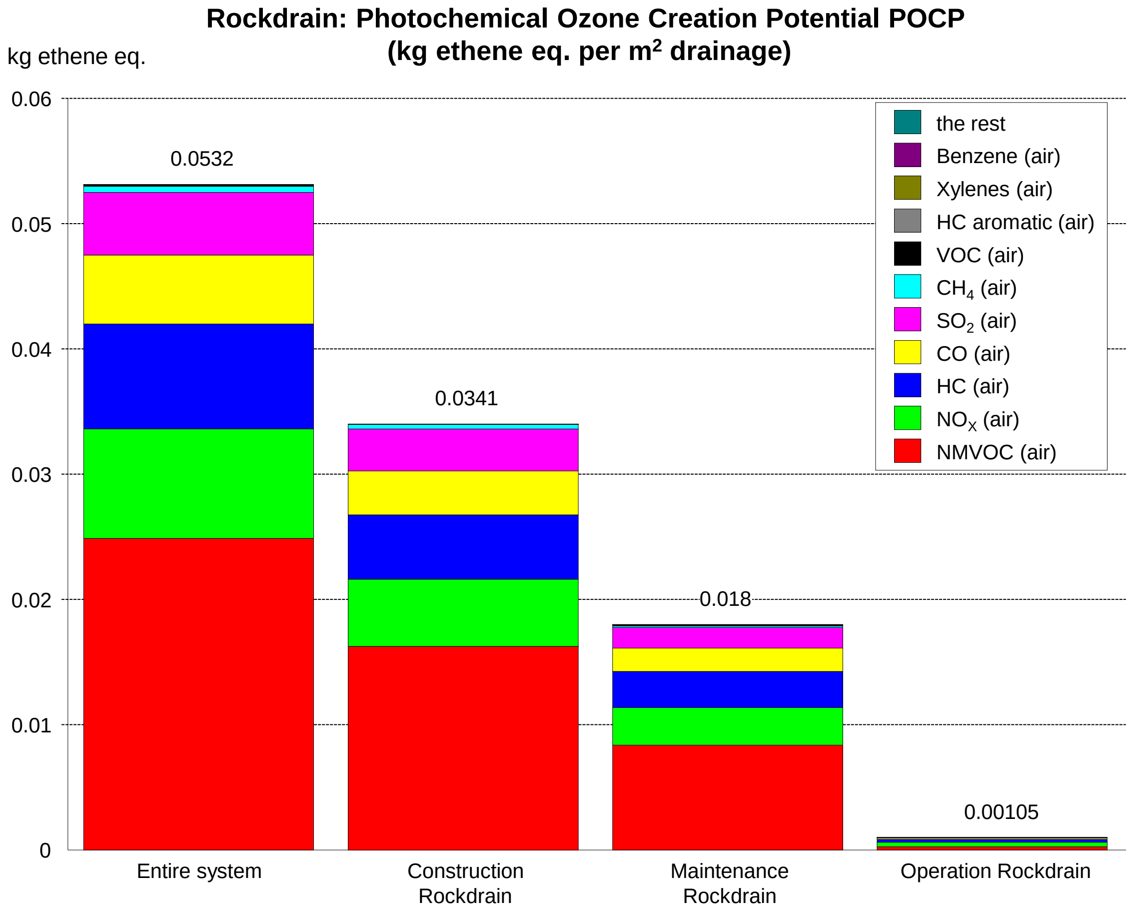


Figure 20 The figure shows the Photochemical Ozone Creation Potential POCP in kg ethene eq. per m^2 drainage for the Rockdrain drainage system. The figure shows POCP for the entire system and divided into construction, maintenance and operation.

6.1.4 Waste analysis

The waste from the Rockdrain system during 60 years is shown in Figure 21. As shown in the figure, the main waste is generated as demolition waste when the drainage system is replaced after the lifetime. The main waste material is concrete. In the model, the replacement is distributed during the lifetime of the product which in this case means that only half of the waste from the drainage system is shown in the figure because the lifetime of the Rockdrain system is estimated to 120 years but the calculation period in the model is only 60 years. Packaging from building materials has not been included in the model due to lack of information. However, the amount of packaging materials are relatively small and sometimes also recyclable containers and packagings are used. It is also worth noting that what we here call waste can be new products, for example, the concrete can be crushed and used as aggregates in different constructions.

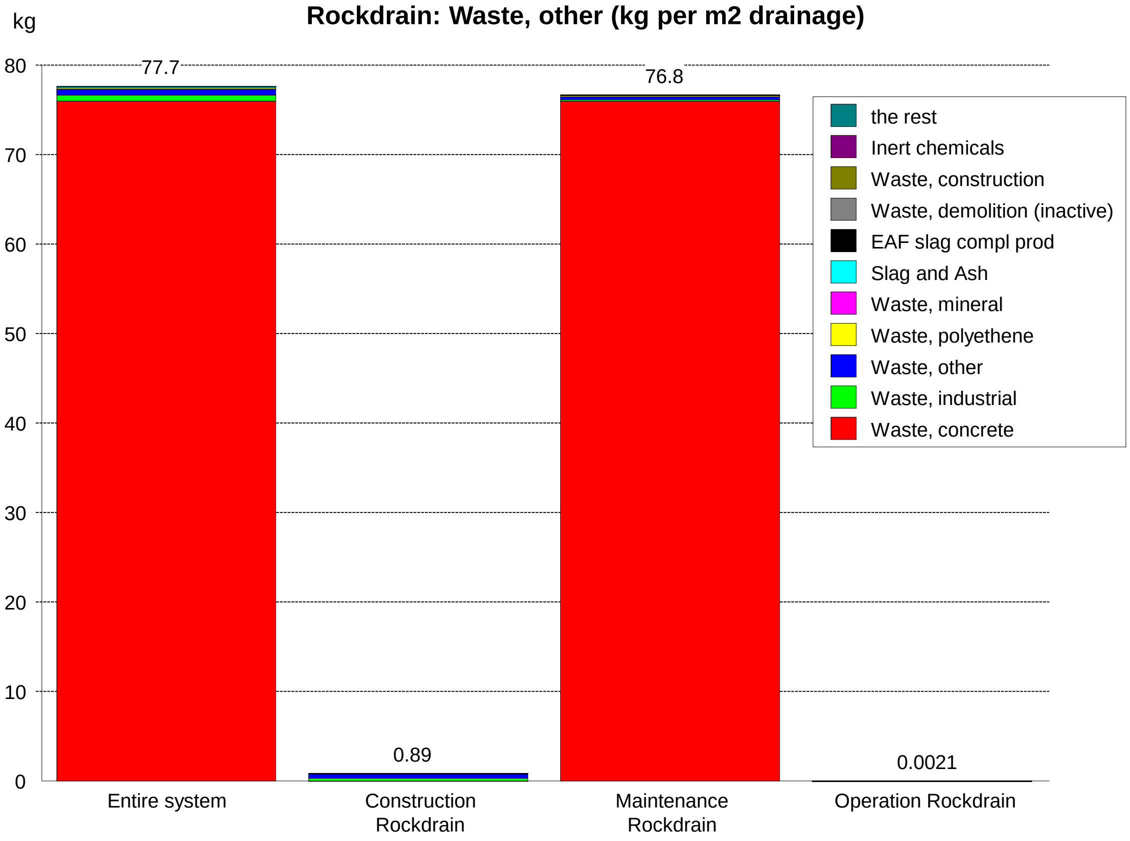


Figure 21 The figure shows generated waste in kg per m² drainage for the Rockdrain drainage system. The figure shows waste for the entire system and divided into construction, maintenance and operation.

6.1.5 Economic analysis

In the economic analysis, the Life Cycle Cost (LCC) has been calculated for the entire system as well as for construction, maintenance and operation. An LCC analysis is describing the costs for the entire life cycle of the product from raw material extraction via product production and use to waste handling. In this case, economic data has been collected from the entire system and the different production processes have been studied in order to calculate the labor cost based on man-hours.

In Figure 22, the costs in Euro per m^2 drainage during 60 years are shown for the Rockdrain system. The total cost is calculated to 201.4 Euro per m^2. Of the total cost, 145.2 Euro is costs for materials, 33.9 Euro is costs for man-hours, 20.2 Euro is machine costs and 2.1 Euro is transport costs. The construction cost is calculated to 118.8 Euro per m^2 and the maintenance cost is calculated to 64.4 Euro per m^2 due to the lifetime of the Rockdrain system which is set to 120 years (see the discussion in Chapter 6.1.1). The cost for operation (inspections) is calculated to 18.2 Euro per m^2. As shown in the figure, the costs for materials are the most dominating cost for the Rockdrain system. However, one can also express it as the other costs are low. The aim of the Rockdrain system is to create a more efficient drainage system with respect to installation work, maintenance and lifetime. Thus, the figure shows that the cost for man-hours and machines are relatively low for the system.

In Figure 23, the costs are shown in a more detailed way. The figure shows were the different costs arise both for the entire system and for the different cost items. Of the total costs, the costs for Solbruk T and for the plastic channel lattice are the most significant and account for 64 % of the total costs. In the figure we can also see that the application of the plastics lattice and the inspection of the drainage in the operation also play a significant role. Of the costs for man-hour, these costs account for 42.5 % each, thus in total 85 % of the labor costs. Of the machine costs, the cost for mobile mixing plant accounts for 34 %, cost for shotcrete spraying robots accounts for 15.3 % and cost for boom lifts accounts for 37.8 %.

A comparative example for the Rockdrain system assuming a lifetime of 60 years instead of the projected 120 years and a calculation period of 60 years would result in unchanged construction and operation phases while the cost for maintenance would double. This would give a total cost of 265.7 Euro/m^2 and 60 years instead of 201.4 Euro/m^2 and 60 years.

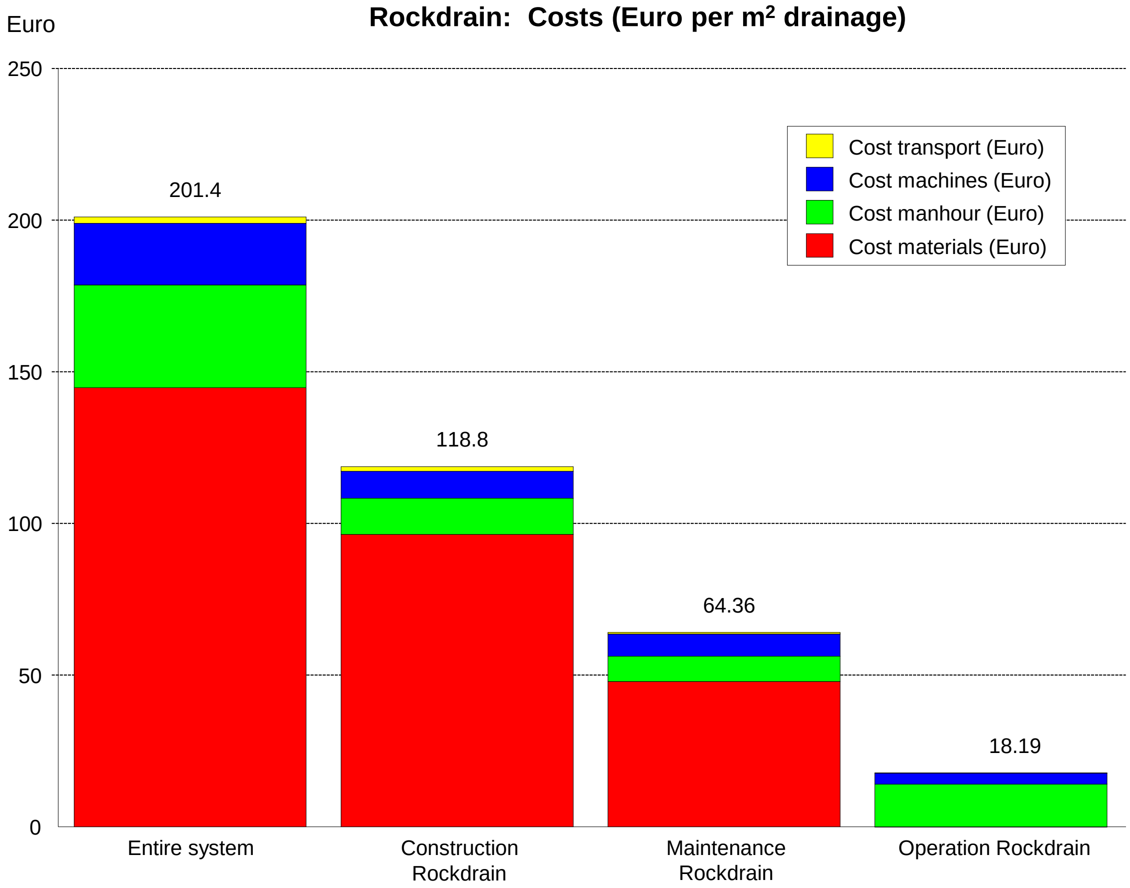


Figure 22 Cost analysis for the Rockdrain method divided into construction, maintenance and operation during 60 years. The figure shows type of cost in Euro. The costs are shown per m^2 of installed drainage.

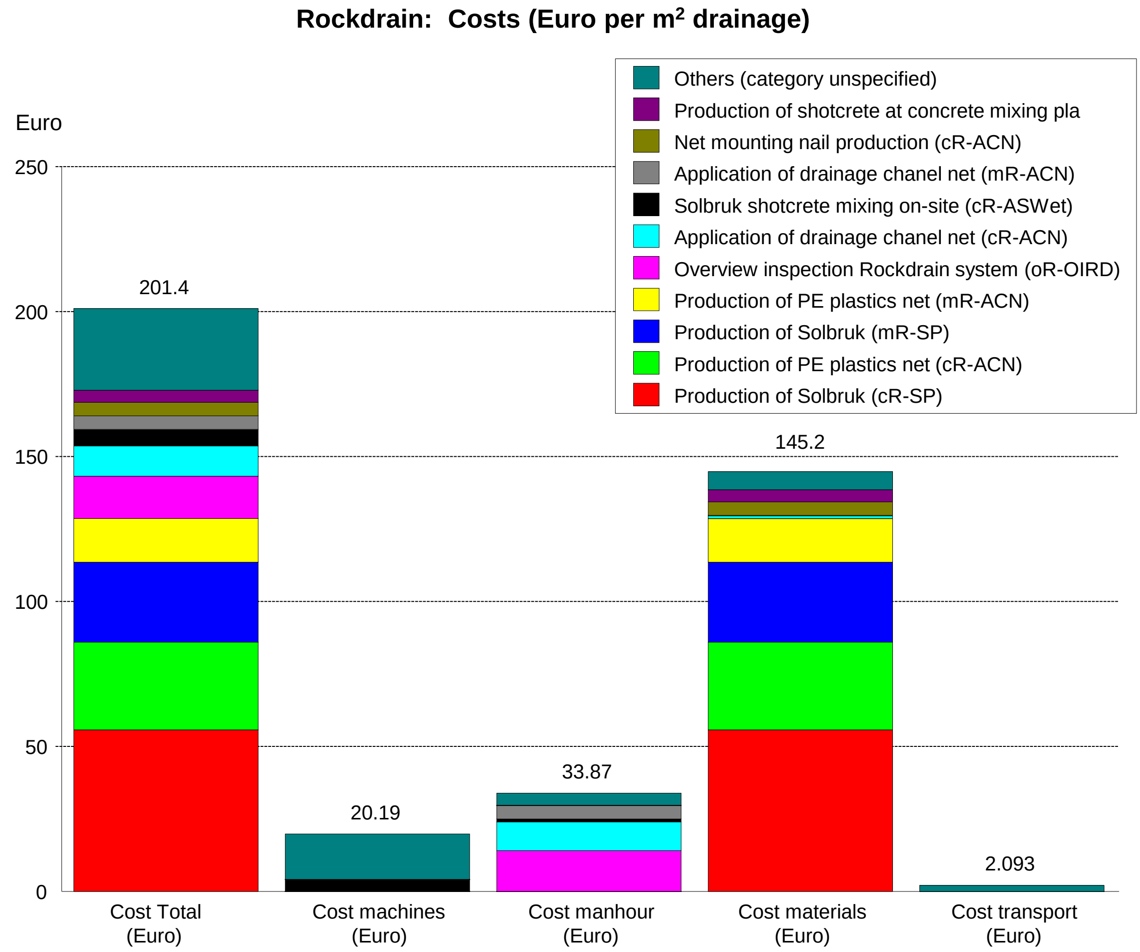


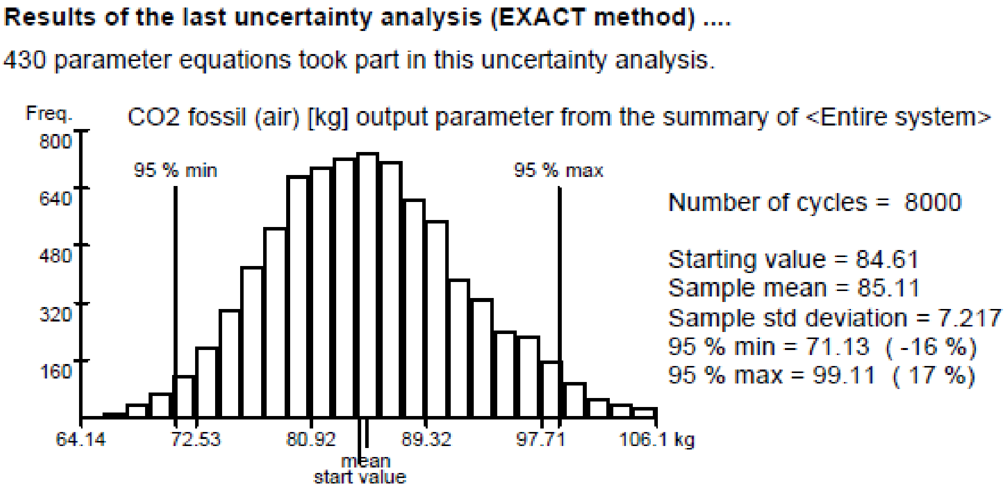
Figure 23 Cost analysis for the Rockdrain method showing cost items for different types of costs. The costs are shown per m^2 of installed drainage.

6.1.6 Sensitivity analysis

Sometimes it might be interesting to know how the performance of a certain parameter such as CO_2 emission changes upon a change in the input data for the model. You may also want to know which parameters are most important for the result and how a change in these parameters affects the result. In a sensitivity analysis, one analyses a model based on a relationship between output and input in the model.

The different result figures in this report show relatively well which aspects are most important for a particular result. You can use these figures to get an idea of how variations in the input data affect the final result by studying the different parts that build up the final result. The figures give a good overview of a particular aspect (e.g. total cost or energy use).

In addition to such analyses, direct sensitivity analyses have been made of two model results (CO_2 fossil fuel emissions and total cost). For each of these results, the computer model has selected all of the equations that have an impact on the results and added a variation of ±10 % to the input data and run the model 8000 times with different randomly selected values within the variation range of ±10 %. The results from the simulation calculations are then presented in a frequency diagram. These diagrams can be found in Figure 24 and Figure 25. As shown by the calculations, there is a fairly good agreement between the input and output variation and deviations are moderate. This indicates a relatively robust mathematical model. However, this says nothing about whether a variation of ±10 % reflects a real variation.



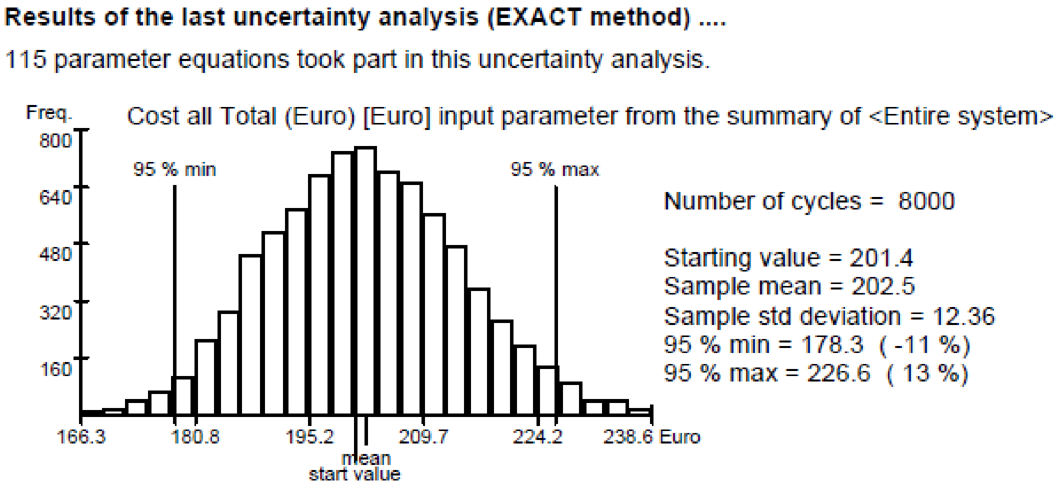
Results of the last uncertainty analysis (EXACT method) ....

430 parameter equations took part in this uncertainty analysis.

Number of cycles = 8000

Starting value = 84.61
Sample mean = 85.11
Sample std deviation = 7.217
95 % min = 71.13 (-16 %)
95 % max = 99.11 (17 %)

Figure 24 **Results from a sensitivity analysis of CO_2 fossil emissions from the Rockdrain model.**



Results of the last uncertainty analysis (EXACT method) ....

115 parameter equations took part in this uncertainty analysis.

Number of cycles = 8000

Starting value = 201.4
Sample mean = 202.5
Sample std deviation = 12.36
95 % min = 178.3 (-11 %)
95 % max = 226.6 (13 %)

Figure 25 **Results from a sensitivity analysis of the total cost per m^2 in the Rockdrain model.**

6.2 The Conventional drainage system

The technical aspects of the conventional drainage system used today are described in chapter 2.2. Due to the technical design of the conventional system, this system requires more space in the tunnel, therefore an extra 200 mm of the tunnel wall has to be excavated. This extra tunnel driving requires energy and is more costly for the tunnel. This additional tunnel driving is not a part of the drainage system but a consequence of the system and must thus be considered in the analysis. In this result chapter, the effect of the extra tunnel driving has been included but is shown separately in the figures.

6.2.1 Energy resource use analysis

This chapter shows the primary energy resources for the conventional drainage system per m^2 and 60 years. The results from the energy analysis of the conventional system are shown in two bar charts. The first bar chart, presented in Figure 26, shows the primary energy resource use for the entire system and divided into construction, maintenance and operation. The second bar chart, presented in Figure 27, shows the different energy resources divided into the individual processes that build up the conventional drainage system.

As shown in Figure 26, the total use of primary energy during a 60 years calculation period is 1421 MJ/m^2 drainage and of that, the construction phase is 643.6 MJ/m^2. The maintenance is calculated mainly as a demolition and new construction after the lifetime of the drainage but the activity is calculated as a yearly contribution which is 100 % at the end of the lifetime. One can also see this as a yearly wear and tear. This means that, at the end of the lifetime, the energy use should be slightly larger than the construction phase due to the demolition activity. In this case, the lifetime of the conventional system is estimated to 60 years and the calculation period is 60 years so the maintenance is slightly larger than the construction phase.

The primary energy use for operation of the conventional system (inspection activity) is relatively small, only 44.23 MJ/m^2 and related to diesel use for a boom lift. For the conventional drainage system, two different types of inspections are needed.
Overview inspection: One inspection per year with an inspection rate of 500 m^2/h has been assumed.
Detailed inspection: One inspection each 10 years with an inspection rate of 50 m^2/h has been assumed. This inspection includes inspection behind the drainage.

As shown in Figure 27, the main primary energy resource for the conventional drainage system is crude oil. The oil is mainly used for production of cement, polyethene plastics and for operation of diesel engines. Electric power is also used in the system and that is mainly shown as a use of nuclear and hydro power due to the Swedish electric power production mix. Natural gas is mainly used for production of polyethene plastics (61.6 %) and steel (24.6 %).

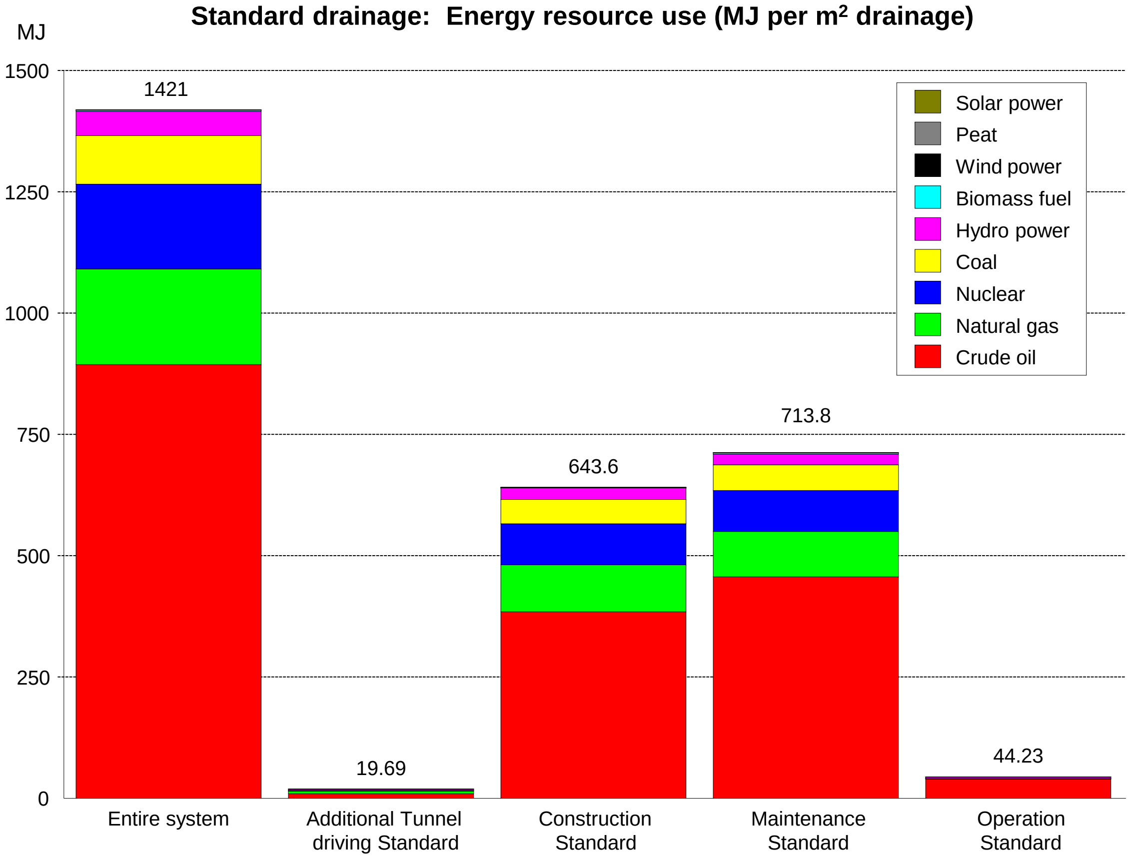


Figure 26 The figure shows primary energy resource use in MJ/m^2 installed drainage for the standard drainage system. The figure shows the energy use for the entire system and divided into construction, maintenance and operation during 60 years. Both non-renewable and renewable energy resources are included. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method.

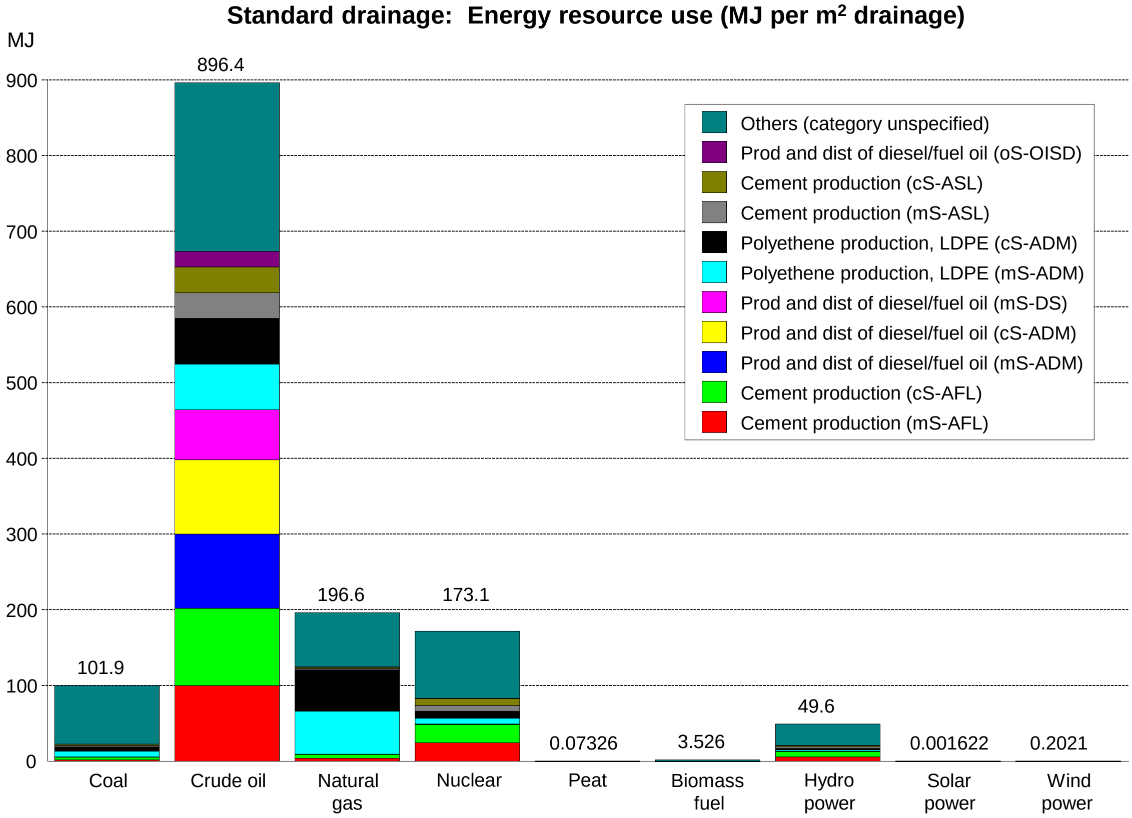


Figure 27 The figure shows the main use for the different energy resources used in the standard drainage system. The energy use is shown in MJ/m² installed drainage. Both non-renewable and renewable energy resources are included in the figure.

6.2.2 Material resource use analysis

As shown in Figure 28, the main non-renewable material resources used for the conventional system are solid rock and limestone. Both are used for shotcrete which is the main material used. The crude oil resource used for production of polyethene plastic to the drainage mats is accounted as an energy resource use and thus not included in this figure. The weight of iron in the construction is significant but small compared to the weight of the concrete layer. Recycled steel is also mainly used for the construction. The iron resource use from ore (Fe(res)) is calculated to 1.8 kg/m^2 drainage while the recycled iron scrap use is calculated to 21.2 kg/m^2 drainage. The iron is mainly used for threaded rods, steel fiber reinforcement of shotcrete and attachment materials for the plastic drainage mats.

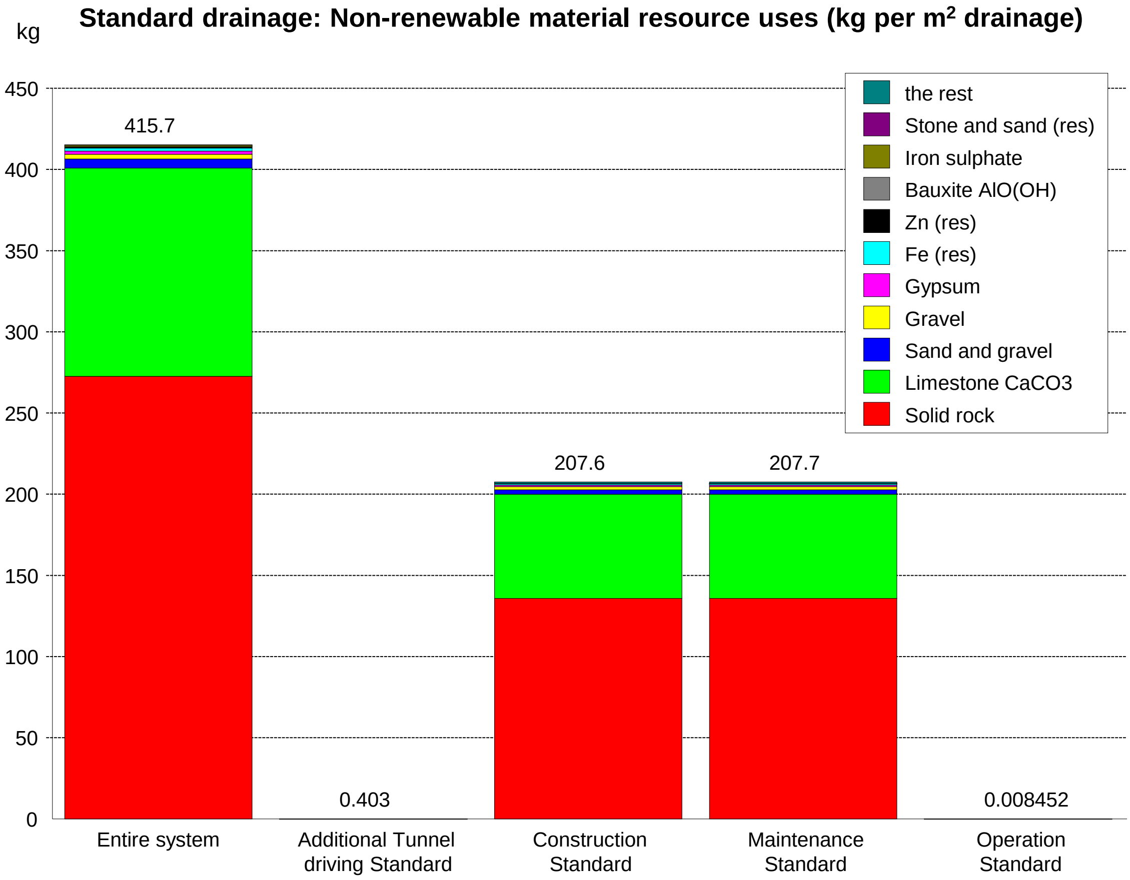


Figure 28 The figure shows non-renewable primary material resource uses in kg/m^2 installed drainage for the standard drainage system. The figure shows the material uses for the entire system and divided into construction, maintenance and operation. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method.

6.2.3 Emission and impact assessment

6.2.3.1 Greenhouse gases

In Figure 29, the Global Warming Potential (GWP) for the entire system and divided in construction, maintenance and operation is shown per m^2 drainage for the conventional system during a calculation period of 60 years. As shown in the figure, the emission of fossil based carbon dioxide CO_2 is the most important source for GWP. Methane (CH_4) emissions give only a small contribution. A small contribution of N_2O also comes from additional tunnel driving (from explosives). The other emissions in the figure are so small that they cannot be quantified in the figure.

The CO_2 uptake in concrete (carbonation) during product use has been estimated for the calculation period (60 years) to 20 % of the CO_2 that was driven of the stone material (mainly lime stone) in the cement production (cement kiln). This represents a carbonation depth in the shotcrete of ~16-17 mm. In addition, the shotcrete will continue to take up CO_2 as long as it is used in the tunnel and it will also continue to take up more CO_2 when the shotcrete is demolished and stored (e.g. crushed and used as aggregates). In fact, the CO_2 uptake rate will increase when the concrete is crushed due to the formation of many more concrete surfaces provided that CO_2 is available. In a very long time perspective one can expect that most of the CO_2 will be taken up. However, in this study, only the CO_2 uptake during the calculation period of 60 years has been taken into account. The CO_2 uptake is shown as negative emissions in the figure.

In Figure 30, the process contribution to GWP is shown. As expected, only fossil based CO_2 emissions will make a significant contribution. Of that emission approximately 57.6 % emanates from production of cement, 19.5 % from diesel use in machines, 9 % from steel production and 4.8 % from polyethene plastic production. The emissions come both from construction and maintenance.

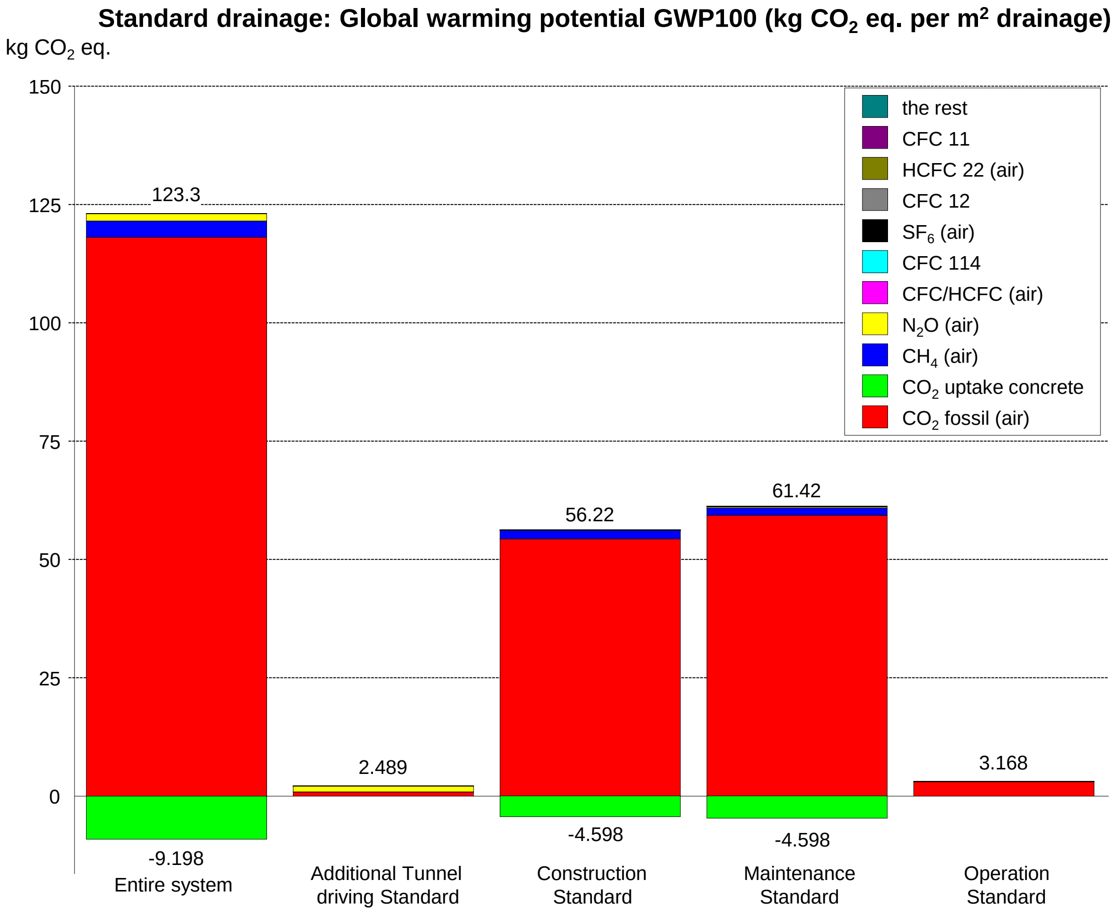


Figure 29 The figure shows the Global Warming Potential (GWP) in kg CO_2 eq./m^2 installed drainage for the standard drainage system. The figure shows the GWP for the entire system and divided into construction, maintenance and operation. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method. The figure also shows the expected CO_2 uptake in the concrete due to carbonation during the calculation period of the product. CO_2 uptake during the waste phase is thus not included.

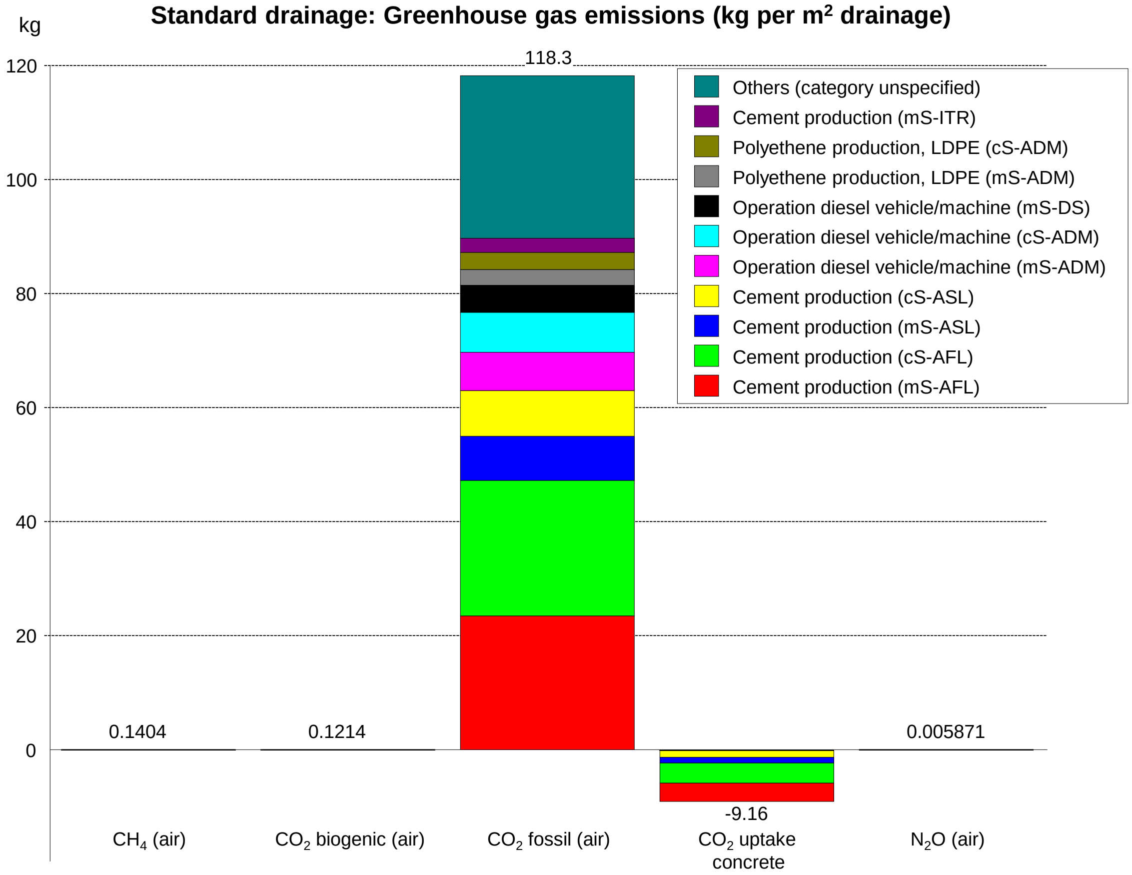


Figure 30 **The figure shows the main emissions of greenhouse gases from different parts of the standard drainage system. The emissions are shown in kg/m² installed drainage. The uptake of CO_2 in concrete due to carbonation is also shown in the figure. The CO_2 uptake as well as the cement production data are calculated and shown in the cement production module so the codes (e.g. cS-ASL) have to be used to identify the actual construction process.**

6.2.3.2 Acidification potential

In this chapter, the acidification potential (AP) is shown in kg SO_2 equivalents per m^2 drainage for the conventional drainage system. As shown in Figure 31, the acidification potential is in total 0.408 kg SO_2 eq./m^2 and is almost entirely caused by the emissions of SO_2 and NO_X. The contribution of NO_X to AP is approximately 65 % in the entire system. Figure 32 shows the origin of NO_X and SO_2 emissions. For the NO_X emissions, diesel engine operation accounts for 42 % and cement production for 25 %. For the SO_2 emissions, cement production accounts for 38 %, steel production for 23 % and polyethene plastics production for 13 %. Note the difference in acidification potential and the actual emission. The difference is caused by a stronger acidification potential for SO_2 compared to NO_X.

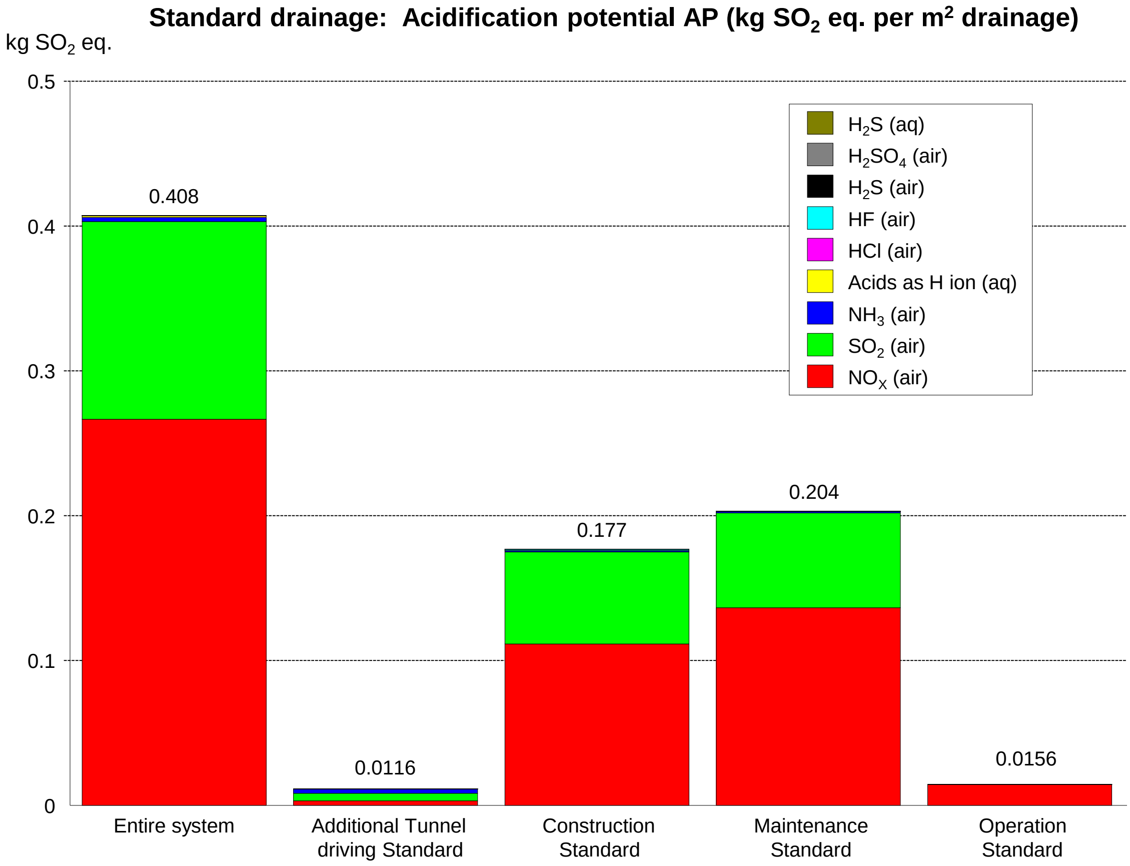


Figure 31 The figure shows the acidification potential (AP) in kg SO_2 eq./m^2 installed drainage for the standard drainage system. The figure shows AP for the entire system and divided into construction, maintenance and operation. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method.

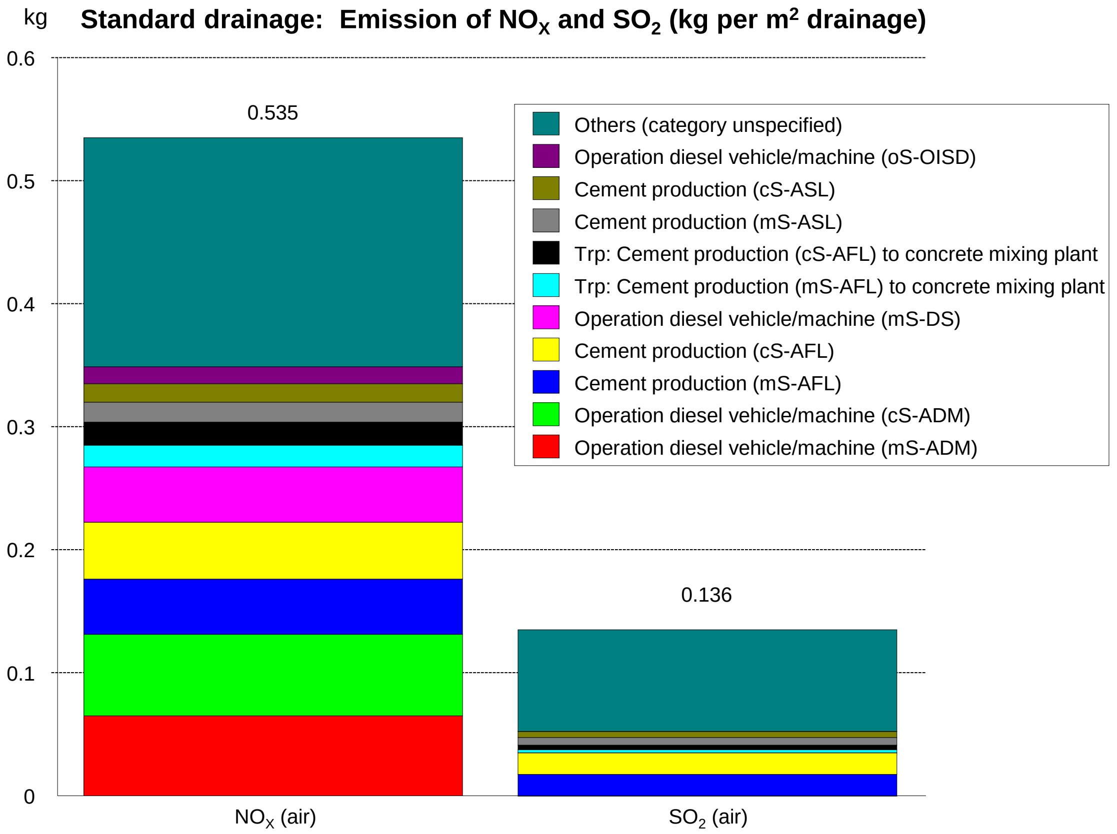


Figure 32 The figure shows the main emissions (NO_X and SO_2) of the acidification potential from different parts of the standard drainage system. The emissions are shown in kg/m^2 installed drainage.

6.2.3.3 Eutrophication potential

The eutrophication potential (EP) is calculated in kg PO_4 equivalents/m² installed drainage. The EP results are shown in Figure 33 and of these results one can see that the emission of NO_X is definitely the most important factor. The origin of the NO_X emissions is of course the same as for the acidification potential and is thus shown in Figure 32.

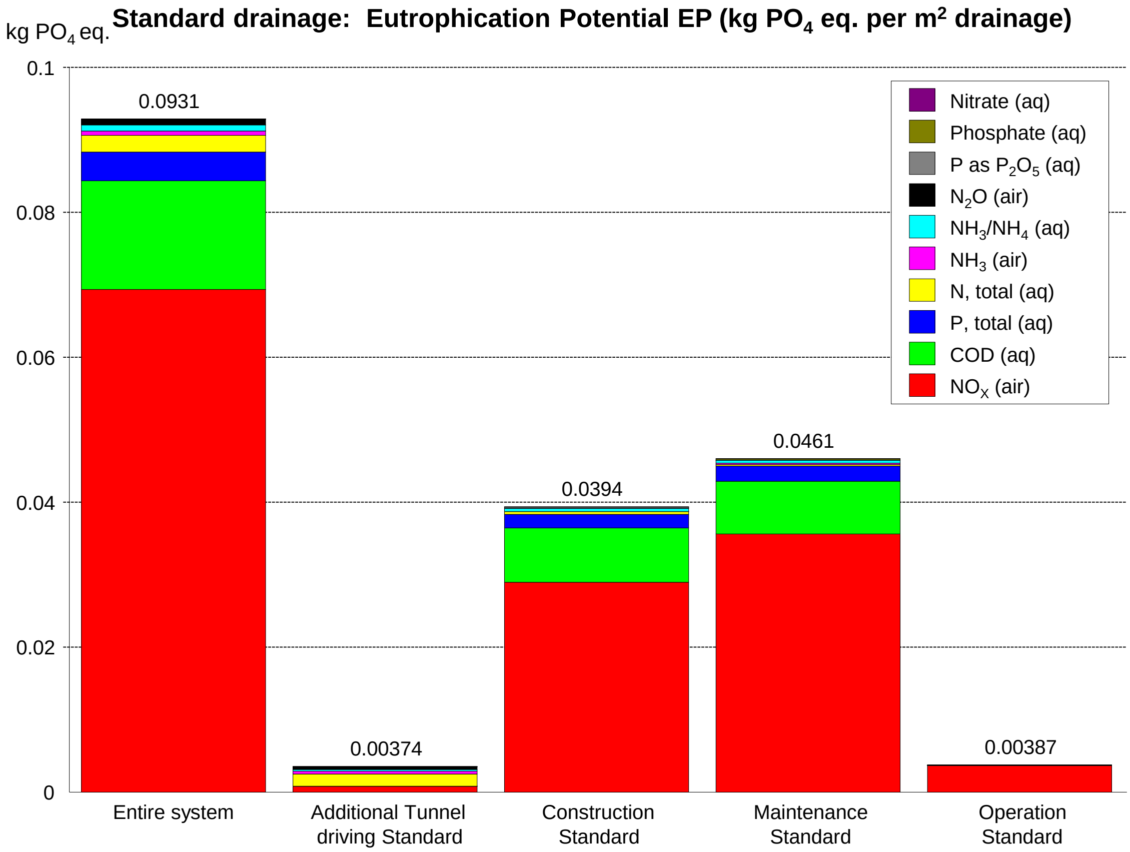


Figure 33 The figure shows the eutrophication potential (EP) in kg PO_4 eq./m² installed drainage for the standard drainage system. The figure shows EP for the entire system and divided into construction, maintenance and operation. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method.

6.2.3.4 Photochemical Ozone Creation Potential

The Photochemical Ozone Creation Potential (POCP)[8] is calculated in kg ethene equivalents per m² installed conventional drainage. The results from the POCP calculations are shown in Figure 34 and as shown in the figure, the emissions are relatively small but significant. The main sources for emissions taken place in the POCP reactions are production of cement (contribution 50-70 %) but other processes such as diesel engines and polyethene plastics production can also play a significant role.

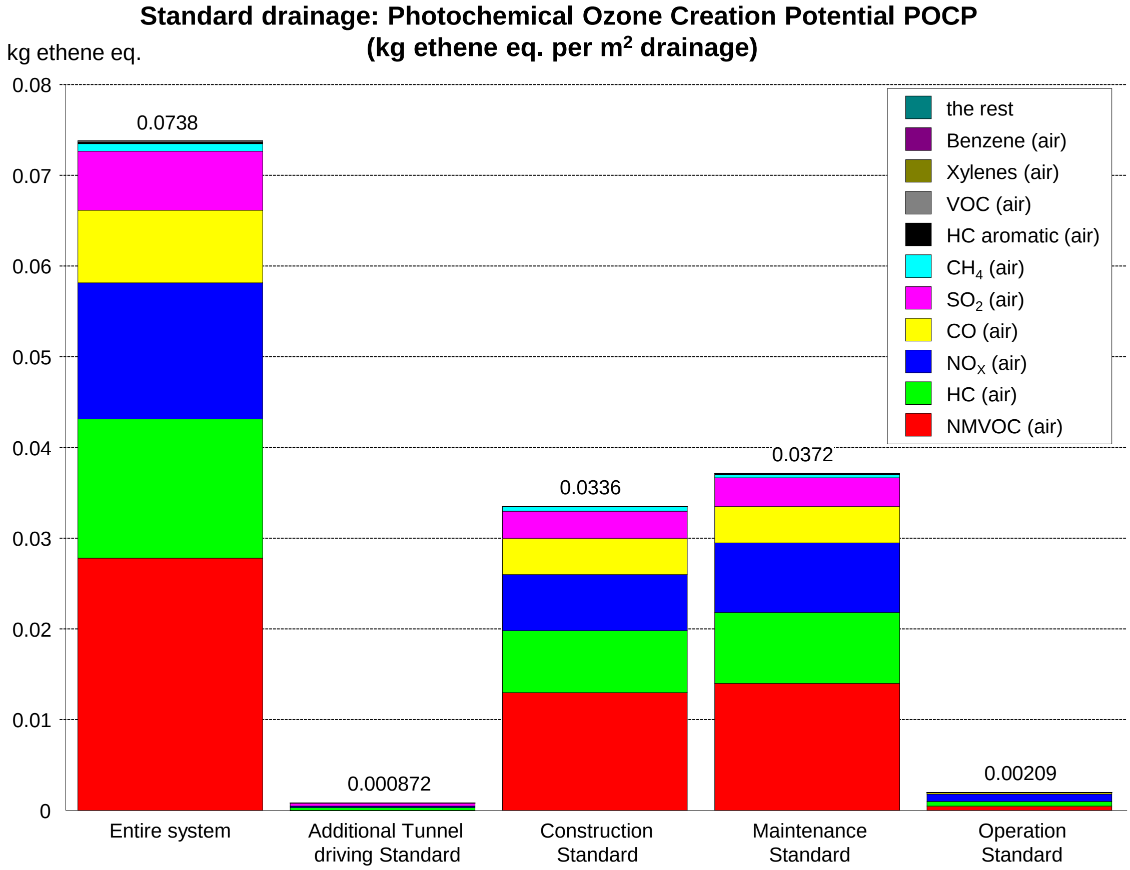


Figure 34 The figure shows the Photochemical Ozone Creation Potential POCP in kg ethene eq. per m² drainage for the standard drainage system. The figure shows POCP for the entire system and divided into construction, maintenance and operation. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method.

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[8] A short description and explanation can be found in chapter 6.1.3.4.

6.2.4 Waste analysis

The waste from the conventional drainage system during 60 years is shown in Figure 35. As shown in the figure, the main waste is generated as demolition waste when the drainage system is replaced after the lifetime. However, some extra drilling water is also generated in the additional tunnel driving that the conventional drainage system requires. The main waste material is concrete. In the model, the drainage replacement is distributed during the lifetime of the product which, in this case, means that a full replacement of the drainage is included in the model because the lifetime of the conventional system is estimated to 60 years which is equal to the calculation period used in the model. Packaging from building materials has not been included in the model due to lack of information. However, the amount of packaging materials are relatively small and sometimes also recyclable containers and packagings are used. It is also worth noting that what we here call waste can be new products, for example, the concrete can be crushed and used as aggregates in different constructions.

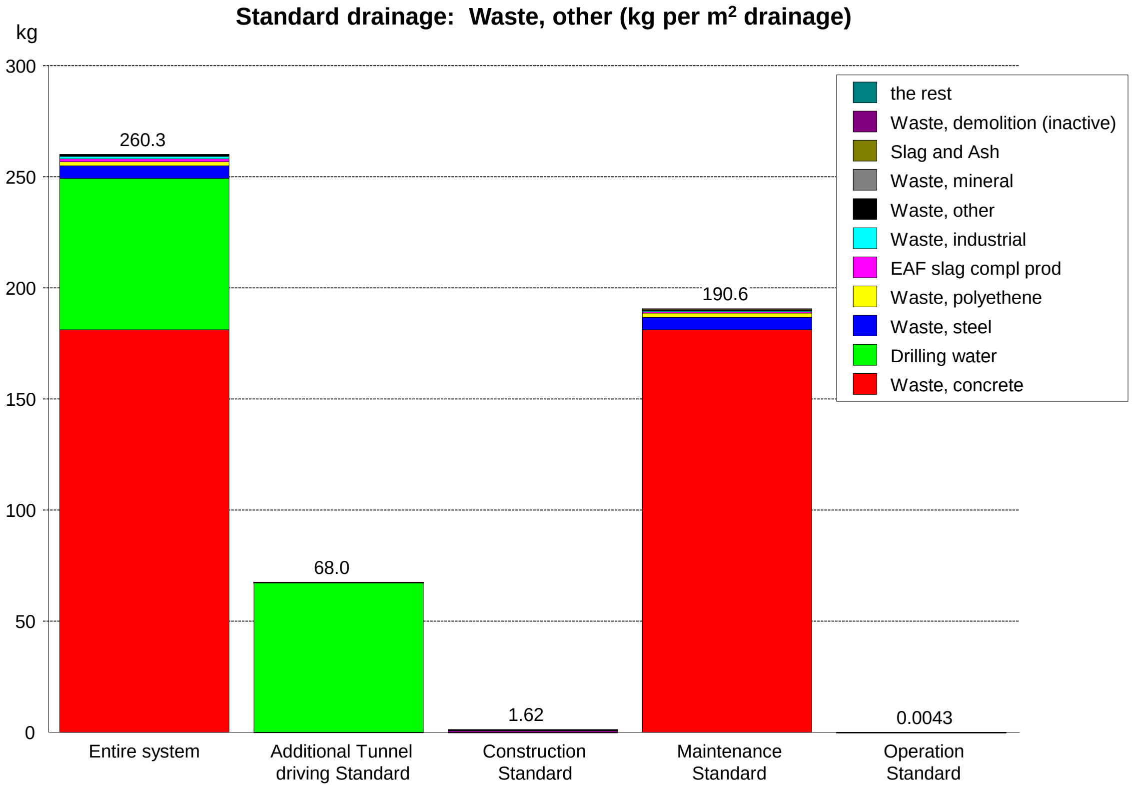


Figure 35 The figure shows generated waste in kg per m² drainage for the standard drainage system. The figure shows waste for the entire system and divided into construction, maintenance and operation.

6.2.5 Economic analysis

The Life Cycle Cost (LCC) has been calculated for the entire system as well as for construction, maintenance and operation. In this case, economic data has been collected from the entire system and the different production processes have been studied in order to calculate the labor cost based on man-hours. Also for the conventional system, data from the tunnel at Kattleberg has been used. Both the drainage systems are used at that tunnel.

In Figure 36, the costs in Euro per m^2 drainage during 60 years are shown for the conventional drainage system. The total cost is calculated to 449.6 Euro per m^2. Of the total cost, 160.2 Euro is costs for materials, 186.3 Euro is costs for man-hours, 97.5 Euro is machine costs and 5.6 Euro is transport costs. The construction cost is calculated to 188.1 Euro per m^2 plus 10 for the extra tunnel excavation. The maintenance cost is calculated to 215.2 Euro per m^2 i.e. slightly more than the construction cost because this cost also includes demolition costs and due to the lifetime of the conventional system which is set to 60 years (see the discussion in Chapter 6.1.1). The cost for operation (inspections) is calculated to 36.4 Euro per m^2. The higher inspection cost compared to the Rockdrain system is caused by the increased need for inspection due to the technical design of the conventional system. As shown in the figure, the costs for materials are relatively equal compared to the Rockdrain system but the costs for man-hours and machines are much higher. This cost pattern between materials, man-hours and machines illustrate one of the problems with the conventional drainage system i.e. the time and work intensity for installation. The aim of the Rockdrain system is thus to create a more efficient drainage system with respect to installation work, maintenance and lifetime.

Figure 37, shows were the different costs arise both for the entire system and for the different cost items. Of the total costs, the costs for assembly of the drainage on the threaded rods are the most significant and account for 52.6 % of the total costs. This is a manual process and is performed by two persons on a boom lift. In the figure we can also see that the shotcrete mixing plant, installation of threaded rods, different inspections and production of the plastic drainage mats also play a significant role.

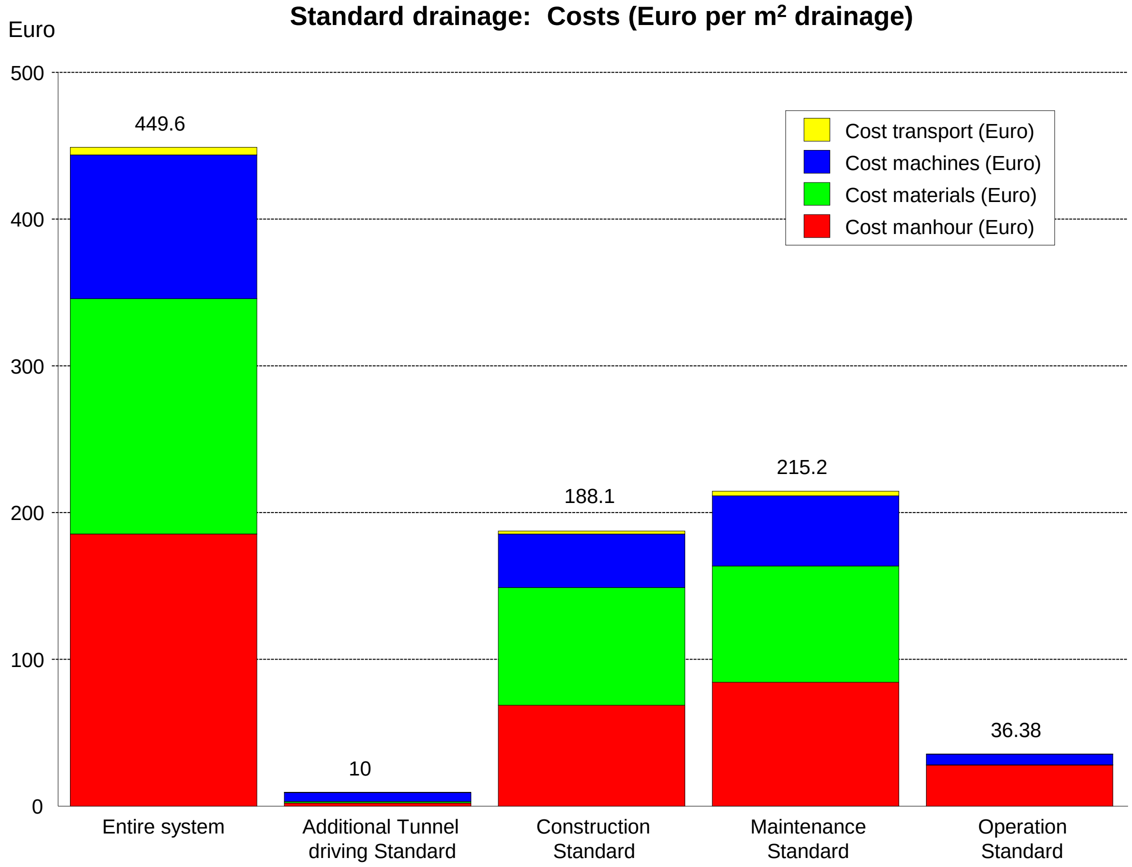


Figure 36 **Cost analysis for the standard drainage method divided into construction, maintenance and operation during 60 years. The figure shows types of costs in Euro. Additional tunnel driving is not a part of the drainage system but represents the extra tunnel excavation (extra space) that this method requires in relation to the Rockdrain method. The costs are shown per m^2 of installed drainage.**

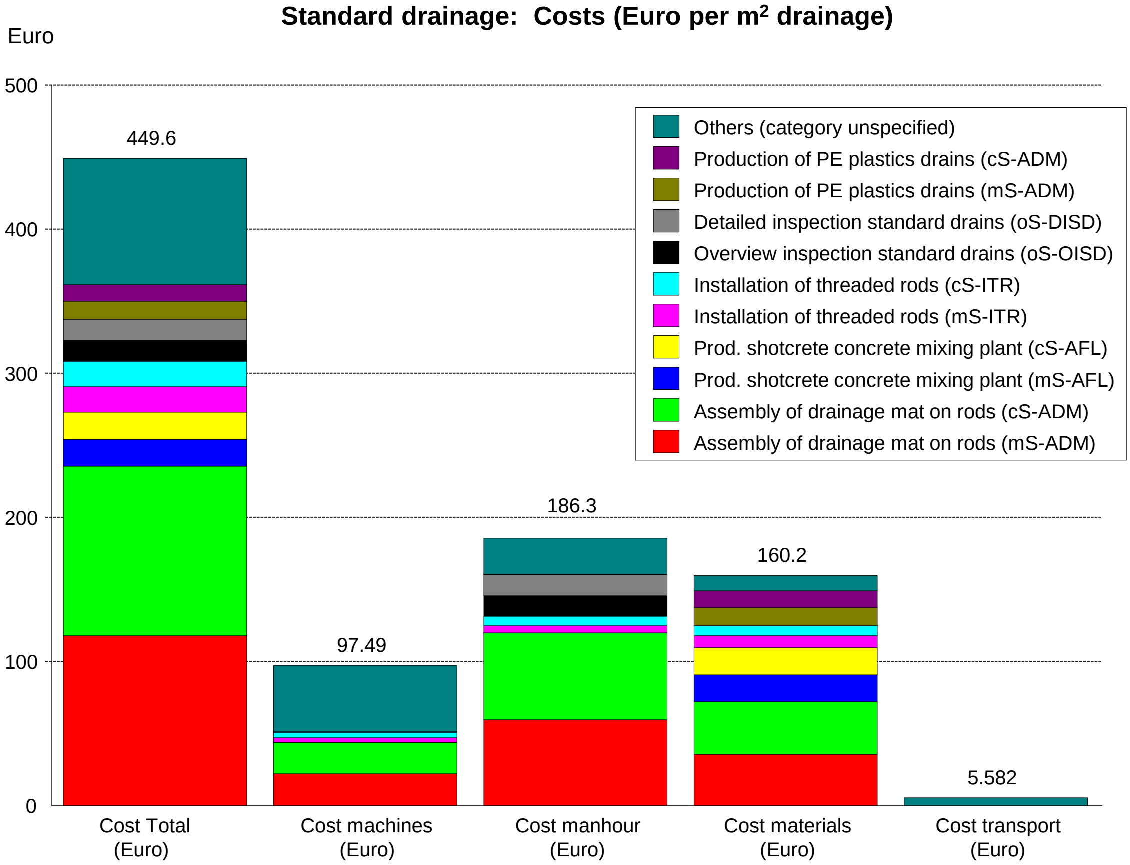
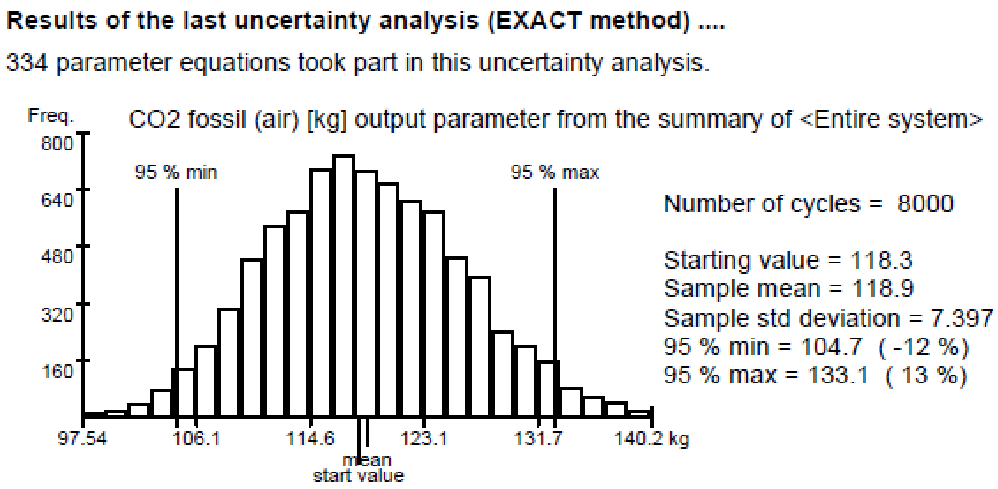


Figure 37 Cost analysis for the standard drainage method showing cost items for different types of costs. The costs are shown per m^2 of installed drainage.

6.2.6 Sensitivity analysis

A sensitivity analysis was also performed of the conventional tunnel drainage system. The general aspects of the sensitivity analysis have already been presented in Chapter 6.1.6. Here we present only the results of the sensitivity analysis of the model itself.

Direct sensitivity analyses have been made of two model results (CO_2 fossil fuel emissions and total cost). For each of these results, the computer model has selected all of the equations that have an impact on the results and added a variation of ±10 % to the input data and run the model 8000 times with different randomly selected values within the variation range of ±10 %. The results from the simulation calculations are then presented in a frequency diagram. These diagrams can be found in Figure 38 and Figure 39. As shown by the calculations, there is a fairly good agreement between the input and output variation and deviations are moderate. This indicates a relatively robust mathematical model. However, this says nothing about whether a variation of ±10 % reflects a real variation.



Results of the last uncertainty analysis (EXACT method) ....

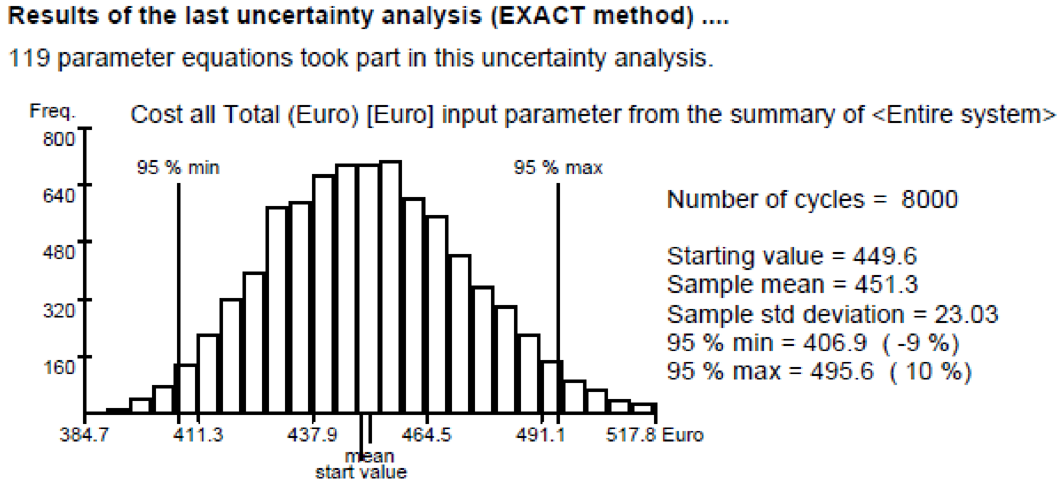
334 parameter equations took part in this uncertainty analysis.

CO2 fossil (air) [kg] output parameter from the summary of <Entire system>

Number of cycles = 8000

Starting value = 118.3
Sample mean = 118.9
Sample std deviation = 7.397
95 % min = 104.7 (-12 %)
95 % max = 133.1 (13 %)

Figure 38 Results from a sensitivity analysis of CO_2 fossil emissions from the model of the conventional drainage system.



Results of the last uncertainty analysis (EXACT method) ....

119 parameter equations took part in this uncertainty analysis.

Cost all Total (Euro) [Euro] input parameter from the summary of <Entire system>

Number of cycles = 8000

Starting value = 449.6
Sample mean = 451.3
Sample std deviation = 23.03
95 % min = 406.9 (-9 %)
95 % max = 495.6 (10 %)

Figure 39 Results from a sensitivity analysis of the total cost per m^2 in the model of the conventional drainage system.

6.3 Comparative analysis – Rockdrain versus conventional drainage

In this chapter, the two drainage methods are compared and the results are analyzed and discussed. The energy use is essential for all type of processes and a comparison can be found in Figure 40. As shown in the figure, the total use of primary energy is 1421 MJ/m² drainage during 60 years for the conventional drainage compared to 813.8 MJ/m² for the Rockdrain system. This is an energy reduction of 43 %. A part of this reduction (~291 MJ/m²) can be referred to the expected longer lifetime for the Rockdrain system. However, if the Rockdrain system meets all the technical expectations and requirements, this is expected to be a real energy reduction. Other reasons for the energy difference are of course differences in the process but also the reduced need for inspections and for tunnel excavation. If only the construction part is considered, the energy use for the conventional system is 663.3 MJ/m² (construction+additional tunnel driving) compared to 515.5 MJ/m² for Rockdrain. This is an energy reduction of 22.3 %. The maintenance, which in this case is estimated with the new construction after the lifetime, is reduced from 713.8 MJ/m² to 276.2 MJ/m². This is an energy reduction of 61.3 %. As shown above, a part of this reduction depends on the expected longer lifetime for the Rockdrain system.

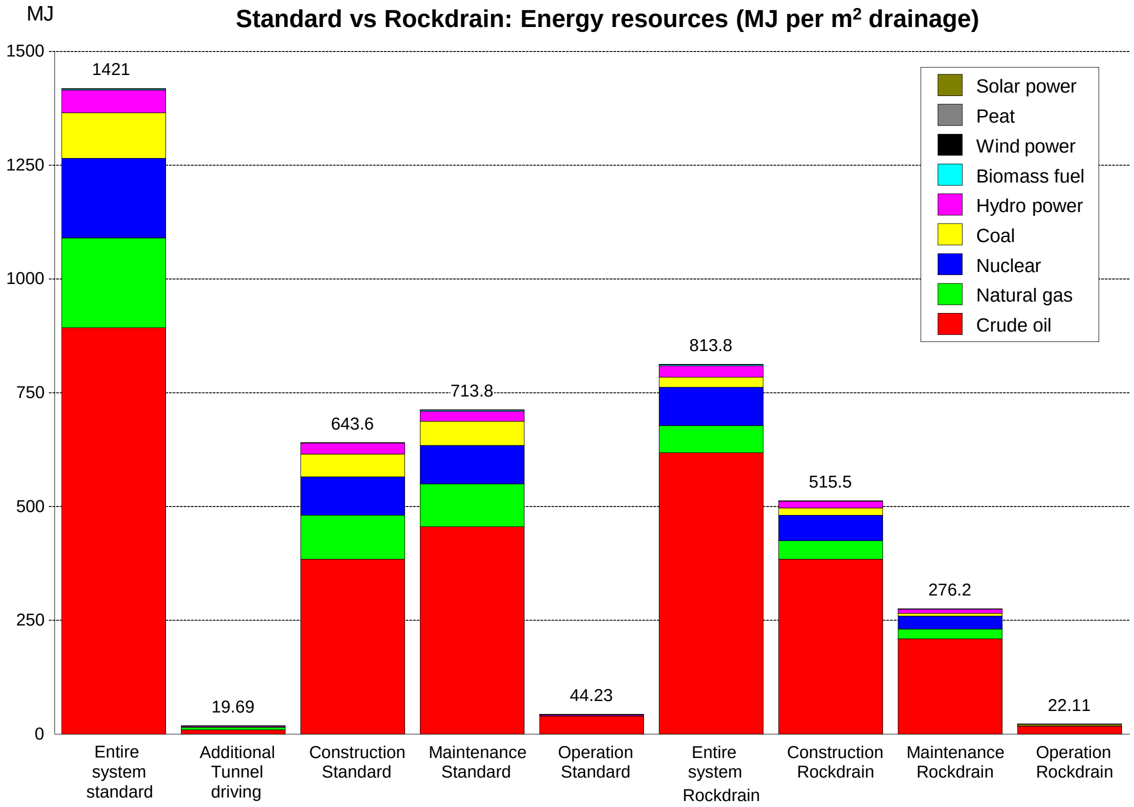


Figure 40 The figure shows a comparative energy analysis between the Rockdrain system and a conventional drainage system. The analysis is based on primary energy resource use in MJ/m² installed drainage during 60 years in the same way as the previous energy analyses. The figure shows the energy use for the entire system and divided into construction, maintenance and operation for both the drainage systems. Both non-renewable and renewable energy resources are included. The additional tunnel driving for the conventional system is also included.

The difference in global warming potential (GWP) for the two systems is shown in Figure 41. If the CO_2 uptake is taken into account, the net GWP for the entire systems will be 114.1 kg CO_2 eq./m^2 drainage during 60 years for the conventional drainage and 78.8 kg CO_2 eq./m^2 for the Rockdrain system. This is a reduction of 31 %. The reduction effect due to the increased lifetime for the Rockdrain system is ~32 kg CO_2 eq./m$^{2.}$. Note that the potential CO_2 uptake is included also for the maintenance even if that uptake mainly will occur after the 60 years. GWP for the construction phase for the two systems are relatively equal, 56.2 kg CO_2 eq./m^2 for the conventional system and 56.2 kg CO_2 eq./m^2 for Rockdrain. GWP for maintenance is higher for the conventional system compared to the Rockdrain system, mainly due to the lifetime effect. The CO_2 balance for the two systems depends mainly on the material use and to a minor part also on the process (e.g. machine use).

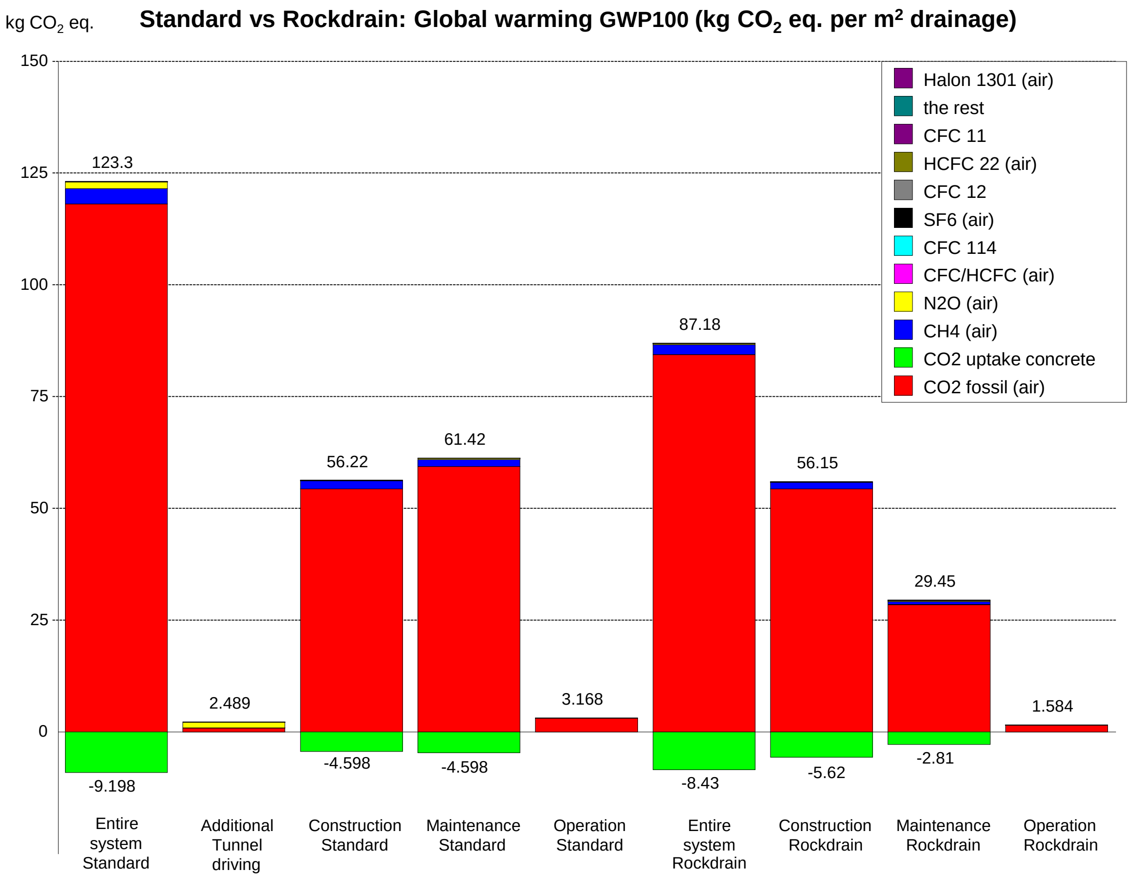


Figure 41 The figure shows a comparative analysis of global warming potential (GWP) between the Rockdrain system and a conventional drainage system. The figure shows GWP (kg CO_2 eq. per m^2 drainage during 60 years) for the entire system and divided into construction, maintenance and operation for both the drainage systems. The additional tunnel driving for the conventional system is also included.

The difference in costs between the two systems is obviously of great interest. It should be noted that the reliability and the technical quality of the systems also play a big role when it often can be very costly and cause huge problems to repair the system during operation or to renew the systems before the expected lifetime. These aspects have been difficult to judge in this project and have therefore been omitted. Likewise, the effect of preventive installation of tunnel drainage has neither been taken into account. If larger areas can be treated as a preventive measure by a simpler and less costly system, this could mean that costly additional measures can be avoided.

Figure 42 shows the combined LCC results for the two systems. The entire cost for the conventional system (449.6 Euro/m^2 drainage and 60 years) is significantly higher compared to the Rockdrain system (201.4 Euro/m^2 drainage and 60 years). The construction cost has been calculated to 198.1 Euro/m^2 (construction+additional tunnel excavation) for the conventional system and 118.8 Euro/m^2 for Rockdrain. This is a cost reduction of 40 %. The cost for maintenance is calculated to 215.2 Euro/m^2 for the conventional system and 64.4 Euro/m^2 for Rockdrain, a cost reduction of 70 %. Approximately 66 Euro/m^2 (44 %) of the cost reduction can be referred to the difference in lifetime for the two systems. The cost for the additional tunnel driving is small, approximately 5.3 % of the cost for the conventional drainage. The cost for operation is also lower for the Rockdrain system due to decreased inspection activities. The cost reduction in operation is calculated to 18.2 Euro/m^2 during 60 years. It is however worth to notice that it is very difficult to predict and cover all the different activities in maintenance and operation during 60 years. The calculation model used for these calculations is relatively simple and based on a few activities. Most likely, the model will underestimate the activities. However, the conventional system consists of a more complex and less solid construction which can result in more maintenance and operation activities compared to the Rockdrain system, provided however, that the Rockdrain system meets the technical requirements and expectations. Further technical evaluations of the Rockdrain system will show its true potential.

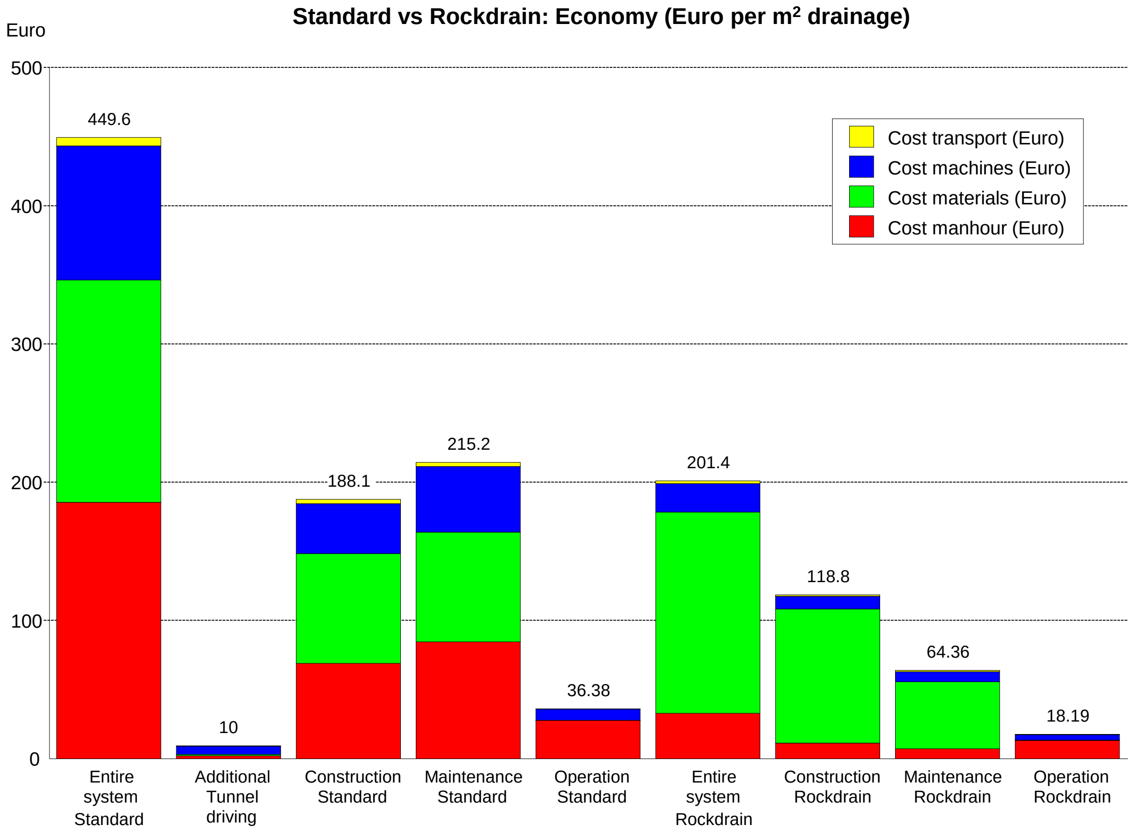


Figure 42 The figure shows a comparative analysis of the life cycle costs (LCC) between the Rockdrain system and a conventional drainage system. The figure shows LCC in Euro per m² drainage during 60 years for the entire system and divided into construction, maintenance and operation for both the drainage systems. The additional tunnel driving for the conventional system is also included.

7 Comments on work environment aspects

This study does not include any real analysis of the work environment or work efficiency, but nevertheless it has emerged a lot of information in this area especially from the Life Cycle Cost (LCC) analysis which can be worth mentioning. In both the LCA and LCC study the manufacturing process has been studied in detail and the operations have been analyzed in terms of both content and time. This is therefore a good starting point to comment on the differences in work environment between the two systems.

Figure 42 show a comparative picture of the LCC for the two drainage systems. It also shows the use of man-hours for the system respectively. It is obvious that the Rockdrain system requires significantly fewer man-hours than the standard system. This in itself represents a significant improvement. The work operation that is most time consuming for the standard system is the assembly of the drainage mats on the tunnel wall. The assembly is done by two persons on a lift mounting the drainage mats manually. This also includes the assembly of various types of brackets of steel and different splicing work of the mats. The attachments in the rock must also be drilled and mounted which can be a hard work especially if you are using smaller drilling machines. In addition, there is also the application work of the shotcrete.

The Rockdrain system has much less of manual work and the manual work that exists is relatively easy. Application of the drainage lattice performed by two persons on a boom lift and application of shotcrete are the most significant manual works. Each lattice weighs only 450 grams and is set with a nail gun in underlying shotcrete. The nail gun work is perhaps the most demanding work from a work environment perspective.

8 Comparative installation study at the tunnel in Hallandsås

To obtain additional reference material about the installation of the Rockdrain system, a test surface with the Rockdrain system has been installed in the tunnel at Hallandsås in south Sweden. The installation work of the drainage system has been followed both from an LCA and LCC perspective. The installation work at the Hallandsås was then compared with the installation in the tunnel at Kattleberg. Three different work operations in the tunnel have been followed.

1. Application of the drainage lattice.
2. Application of water permeable shotcrete (regular shotcrete) on the drainage lattice.
3. Application of a less water permeable shotcrete (Solbruk T).

Results and comments: Application of the drainage lattice

The mounting of the drainage channel lattice was done during a total period of about 3 weeks due to shift changes in the staff and that it was important to use the same personnel for the entire assembly. Therefore, the work took a relatively long time. This time period also included the training of personnel. The research project followed the mounting work but was not on site all the time. Time reporting was handled by the company that did the work. During the mounting process, there were some minor technical problems for example with the nail guns and the work was also delayed by other work in the tunnel. It has therefore been difficult to accurately calculate the amount of hours actually worked and thus also the mounting rate. A questionable time reporting was also provided by the installation company. An estimation of the effective assembly time has been made. The effective work time has been estimated at about 150 man-hours. Two persons have been working on the assembly providing an effective mounting time of 150/2 = 75 hours for the 690 m^2 drainage channel lattice. An additional adjustment was also made after the quality control/inspection.

The estimated effective working time result in the following mounting rate:
690/150 = 4.6 m^2/man-hour
690/75 = 9.2 m^2/hour and 2 persons

This can be compared with the values obtained during the installation in the tunnel at Kattleberg:

Installation rate of the channel lattice per man-hour: 6.25 m^2/man-hour
Installation rate of the channel lattice per 2 persons: 12.5 m^2/hour with 2 persons

As shown above, the mounting rate was somewhat higher during the installation in Kattleberg but the uncertainties are large so it is difficult to draw any firm conclusions concerning the mounting rate. The tunnel rock surface was much more uneven in the tunnel at Hallandsås compared to the conditions in Kattleberg where the mounting was done on a relatively smooth rock surface covered with shotcrete. The reason for the irregularities in the tunnel rock wall contour may be several such the rock structures or the performance of the blasting process. The importance of the rock surface structure for the installation of the channel lattice is difficult to say but the mounting will be slightly more difficult on an uneven rock surface resulting in longer mounting times.

Results and comments: Application of water permeable shotcrete (regular shotcrete) on the drainage lattice

After installation of the channel lattice, ordinary water permeable shotcrete is applied. This process is not different from normal application of shotcrete. Some caution may be required to prevent the channel lattice from damages. For the application of shotcrete on the 690 m^2 Rockdrain area, 20 m^3 of shotcrete was used. Reported application time was 18 hours. This gives an application rate of about 690 m^2/18 hours = 38 m^2/hour or 20 m^3/18 hours = 1.1 m^3 shotcrete/hour. This is a relatively low application rate and may be caused by several smaller application areas and therefore, time was required to move the spraying equipment. Normal application rate can be 50 m^3 of shotcrete per 8 hour shift (6.25 m^3/hour). The technical capacity of the shotcrete spraying equipment is about 15 m^3 shotcrete/hour. The application rate must in this case be regarded as specific to this area, and not representative of a normal industrial application on a large scale.

Results and comments: Application of a less permeable shotcrete (Solbruk T)

The spraying of the less permeable shotcrete (Solbruk T), which is the outermost layer in the Rockdrain system, caused some inexplicable difficulties during the installation at the tunnel in Kattleberg. An important goal for the installation in the tunnel at Hallandsås was thus to perform a very controlled shotcrete spraying where all operations were carried out according to the instructions, which of course always should be the normal case. In this case, it meant that the mixing of Solbruk T shotcrete on site was controlled by weighing the components (in this case only water was added but concrete additives can exist) as specified and that the mixing was performed in a paddle mixer, located near the spraying site. A too long distance/time between mixing and spraying may cause some risk of separation in the Solbruk T shotcrete. That the spraying was carried out with the right equipment which, in this case, was a spraying robot with a screw pump for the shotcrete. That the staff was properly trained, had long experience of spraying shotcrete and was motivated to perform a high quality product.

The reason for the installation difficulties at the tunnel in Kattleberg has not been possible to clarify completely but some causes can be identified, such as: technical reasons (poor mixing control, wrong shotcrete pump "piston pump", poor operation handling of the spraying equipment such as poor machine settings), low level of knowledge and skills of the executors of the spraying process, lack of interest or intentional obstruction of the Rockdrain system. Whatever the reason, these are serious problems that result in significant production problems which must be avoided in future applications.

The installation in the tunnel at Hallandsås began with a series of administrative difficulties which caused considerable disruption before work could begin, and also split the installation work into two phases. The team that carried out the spraying of Solbruk T shotcrete was very experienced and had the knowledge and motivation necessary to carry out high quality work. The technical execution was carried out according to plan with accurate weighing of concrete contents and a screw pump for the shotcrete was used. The screw pump provides a uniform spray jet. The application is a bit slower than traditional wet spraying but is more controlled, which is required to achieve a good final product.

The production worked now without any problems. The quality of the shotcrete product in the tunnel was also excellent with a very smooth and even surface. From this installation, one can most likely conclude that the difficulties involved in the installation at Kattleberg can be attributed to external problems not directly related to Solbruk T or to the Rockdrain system. Competence, motivation and correct equipments are also essential to achieve a good final result.

The spraying robot used was an AMV of older model on a truck chassis. A mono pump S8 putsmeister screw pump was used. The pump has a maximum capacity of about 18 m^3/h and an estimated actual pump rate of 6-8 m^3/h. The spraying of the shotcrete is relatively fast, but due to logistical reasons, mainly transport distance between the mixer and the robot, the application rate is slower and determines the total production rate. In this test area, the overall application rate has been estimated at about 4 m^3/h. On the walls, which constituted the main part of the test area, a shotcrete thickness of 70 mm was applied in one layer.

The shotcrete (Solbruket T) was found to have very good adhesion to the substrate, and the adhesion was rated as equal to or better than "regular" shotcrete. A test area of approximately 68 m^2 (approx. 75 m^2 sprayed surface) was applied in Phase 1 and the total consumed Solbruk T shotcrete was about 7.3 m^3. Excluding estimated spraying losses and produced test samples, about 6.7 m^3 Solbruk T shotcrete was used. In total, the entire work took 2 hours and 15 minutes. Estimated effective spraying capacity was about 4 m^3/h, which is slightly lower than the value used in the model for a large normal industrial application which has been estimated at 6.25 m^3/h. This application rate may well be reached in a normal large application and improved logistics at the application site (e.g. use of concrete truck for transport). In this application, dusting when filling the shotcrete mixer was relatively strong and a better mixer design is needed. Excessive dust in the tunnel is a health and safety problems and reduce visibility in the tunnel and can therefore affect the quality of spraying. However, this is a practical problem that can be solved easily in a normal industrial application.

Application of Solbruk T shotcrete on Phase 2 of the test area at the tunnel in Hallandsås was carried out some weeks later. Due to technical and economic reasons, the application was not performed by the same installation team and with different equipment. The same mixing equipment was used but with a different spraying robot. In this case, only a large piston pump was available. No concrete additives were used, only water was added to Solbruk T. The staff was not trained for this new process. There were many doubts about this installation, but at the same time, the situation meant that a new procedure was tested, which could provide additional information for the research project. However, the installation failed completely and the spraying robot with the piston pump was not able to pump and spray Solbruk T shotcrete. This shows clearly the importance of correct equipment and a trained staff. The contrast to Phase 1, where an almost perfect result was achieved, was obvious. No further installation of Phase 2 was made in the research project.

9 Discussion and conclusions

Finally remains the crucial question which is to assess whether Rockdrain may be a better option to drain the tunnels than today's standard systems. In this report, the two drainage options are analyzed from several aspects such as the use of primary energy, different emissions and costs. The analysis was done in a 60 year perspective with an assumed lifetime of 60 years for today's standard system and 120 years for the Rockdrain system. No ongoing maintenance is assumed. The maintenance is performed by installing new drainage at the end of the lifetime of the old drainage. However, this maintenance has been allocated annually. In addition, some inspection work has been assumed for the two systems.

In the project, the Rockdrain system has partly been used in a tunnel near Gothenburg (the Kattleberg tunnel) which thus includes both today's standard drainage system and the new Rockdrain system. One can use the test tunnel at Kattleberg as an example of implementation of the Rockdrain system in a tunnel. This tunnel is a 1.8 km long double track train tunnel. The total amount of installed drainage is estimated to 20 895 m^2 of which 18 745 m^2 is conventional drainage and 2 150 m^2 is Rockdrain. The maximum possible drainage area in the tunnel (total area of walls and roof) is 52 490 m^2 which means that 39.8 % of the maximum possible drainage area is covered with drainage in this tunnel.

In Table 2 below, a summary comparison of the two systems are shown including different parameters. The table shows the results for both the systems, if they were to be implemented on the total drainage area (20 895 m^2) of the tunnel. The table also shows the effect of switching from a conventional system to Rockdrain both in absolute values and in percent. As shown in the table, there are significant reductions in all parameters. A cost reduction of more than 5 million euros or 55 % can be expected. An energy reduction of more than 12 million MJ or 42 % representing an energy content of 349.5 m^3 crude oil. This is indeed very promising results. One should however keep in mind that this is calculated model values and the real industrial implementation will show the accuracy of the model results. The assumed lifetime of the systems of course influence the results to some extent and both 60 years and 120 years are very long time for technical products. The biggest question marks, however, has been for the conventional system. There are no such old systems today as 60 years, but significant age problems have been detected at much newer installations.

The technical long term properties of the Rockdrain system are still relatively untested, but so far, technical tests show very promising results. Provided that the Rockdrain system also meets the technical requirements, the Rockdrain system must be regarded as a very good alternative to the current tunnel drainage system. Future industrial applications of the Rockdrain system will show its true potential.

Table 2 The table uses the tunnel in Kattleberg as an example and shows the effect of a change from conventional drainage to Rockdrain. A drainage area of 20 895 m² has been used in the model. The table shows the entire model results for a calculation period of 60 years. Please note that one can not deduce any relative importance between the different parameters, only compare the two drainage systems for each parameter.

Parameter	Unit	Conventional drainage	Rockdrain	Difference when switching to Rockdrain	Percent change
Cost	Euro	9 394 000	4 208 000	-5 186 000	-55.2%
Energy	MJ	29 692 000	17 004 000	-12 688 000	-42.7%
GWP	kg CO_2 eq.	2 384 000	1 645 000	-739 000	-31.0%
Acidification	kg SO_2 eq.	8 500	5 500	-3 000	-35.3%
Eutrofication	kg PO_4 eq.	1 900	880	-1 020	-53.7%
POCP	kg ethene eq.	1 500	1 100	-400	-26.7%
Waste	kg	5 439 000	1 624 000	-3 815 000	-70.1%

Appendix

Appendix 1 – Flow chart codes

Codes for the Rockdrain LCA model

R = Rockdrain
S = Standard drainage

c = construction
m = maintenance
o = operation

(cR-ACN) = Rockdrain Application Chanel Lattice (net)
(cR-ASNC) = Rockdrain Application Shotcrete Lattice (net) Cover
(cR-SP) = Solbruk T production
(cR-AS) = Rockdrain Application Solbruk T
(cR-ASWet) = Rockdrain Application Solbruk T Wet method
(cR-ASDry) = Rockdrain Application Solbruk T Dry method
(cR-OECD) = OECD electric power production mix
(cR-SA) = Swedish electric power production mix

(oR-OIRD) = Overview inspection of the Rockdrain system
(oR-SA) = Operation Rockdrain - Swedish electric power production mix

(mR-DR) = maintenance Rockdrain - Demolition of Rockdrain
(mR-ACN) = maintenance Rockdrain Application Chanel Lattice (net)
(mR-ASNC) = maintenance Rockdrain Application Shotcrete Lattice (net) Cover
(mR-SP) = maintenance Solbruk T production
(mR-AS) = maintenance Rockdrain Application Solbruk T
(mR-ASWet) = maintenance Rockdrain Application Solbruk T Wet method
(mR-ASDry) = maintenance Rockdrain Application Solbruk T Dry method
(mR-OECD) = maintenance OECD electric power production mix
(mR-SA) = maintenance Swedish electric power production mix

Codes for the conventional LCA model

R = Rockdrain
S = Standard drainage

c = construction
m = maintenance
o = operation

(cS-RD) = construction Standard drainage - Rock Drilling
(cS-ITR) = construction Standard drainage - Installation Threaded Rods
(cS-ADM) = construction Standard drainage - Assembly of drainage mat on rods
(cS-AFL) = construction Standard drainage - Application First Layer
(cS-ASL) = construction Standard drainage - Application Second Layer
(cS-OECD) = construction Standard drainage - OECD electric power production mix
(cS-SA) = construction Standard drainage - Swedish electric power production mix
(cS ATD) = construction Standard drainage - Additional tunnel driving

(oS-OISD) = operation Standard drainage - Overview inspection of standard drainage
(oS-DISD) = operation Standard drainage - Detailed inspection of standard drainage
(oS-SA) = operation Standard drainage - Swedish electric power production mix

(mS-DS) = maintenance Standard drainage - Demolition of Standard drainage
(mS-RD) = maintenance Standard drainage - Rock Drilling
(mS-ITR) = maintenance Standard drainage - Installation Threaded Rods
(mS-ADM) = maintenance Standard drainage - Assembly of drainage mat on rods
(mS-AFL) = maintenance Standard drainage - Application First Layer
(mS-ASL) = maintenance Standard drainage - Application Second Layer
(mS-OECD) = maintenance Standard drainage - OECD electric power production mix
(mS-SA) = maintenance Standard drainage - Swedish electric power production mix