REPORT

Life cycle assessment of railways and rail transports

- Application in environmental product declarations (EPDs) for the Bothnia Line

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Report Summary

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Life cycle assessment of railways and rail transports - Application in environmental product declarations (EPDs) for the Bothnia Line

Summary

Environmental aspects are today highly important issues in the transport sector especially from a society perspective. Most likely, our society is facing considerable changes in the transport sector due to changes in the energy/environmental situation in the future. Strategic decisions concerning the development of the transport sector must be based on solid facts concerning both the transport infrastructure and the transport traffic on the infrastructure. The transport infrastructure is often complex and difficult to analyse but of great interest in a society perspective. In this project, we have performed a comprehensive view of a modern railway infrastructure system including the traffic on the infrastructure. A Life Cycle Assessment (LCA) methodology has been used for the study and several LCA models of the railway system have been designed. Due to the complexity of the models, several general railway component models have been developed. The component models can then be integrated to form a large model of an entire railway system. The component models (sub-models) are:

- Railway track foundation model
- Railway track model
- Railway electric power and control system model
- Railway tunnel model
- Railway bridge model
- Railway passenger station and freight terminal model
- Passenger and freight train model including train operation

The LCA models have then been used to analyse the environmental performance of the Bothnia Line and to develop Environmental Product Declarations (EPDs) for the Bothnia Line.

Keyword

Environment, Railway, Railroad, LCA, Life cycle assessment, Infrastructure, Tunnel, Bridge, EPD

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Preface

Environmental aspects are today highly important issues in the transport sector especially from a society perspective. Most likely, our society is facing considerable changes in the transport sector due to changes in the energy/environmental situation in the future. Strategic decisions concerning the development of the transport sector must be based on solid facts concerning both the transport infrastructure and the transport traffic on the infrastructure. Environmental transport research has, in many cases, focused on the vehicles and the traffic (freight and passenger transport). The transport infrastructure is often complex and difficult to analyse but of great interest in a society perspective. In this project, we have performed a comprehensive view of a modern railway infrastructure system including the traffic on the infrastructure.

The Bothnia Line is a newly constructed single-track railway in the north of Sweden being laid from the bridge over Ångermanälven, north of Kramfors airport, via the cities of Örnsköldsvik, Husum, Nordmaling, to Umeå. Botniabanan AB has been responsible for the financing, detailed planning and building of the Bothnia Line. Environmental issues have been in focus during the entire construction work and environmental data have been collected during the entire construction phase. This circumstance has opened up an opportunity for a detailed analysis of a modern railway infrastructure. Botniabanan AB has since the start of the Bothnia Line project planned to develop a certified environmental product declaration (EPD), based on LCA, for the railway. Botniabanan AB has thus initiated a research project in order to study the railway infrastructure from an energy and environmental perspective and to develop methods and data for the EPDs. The project has involved three different organisations; IVL Swedish Environmental Research Institute, Botniabanan AB and the Swedish Rail Administration. IVL Swedish Environmental Research Institute has been responsible for the research project and the practical performance. The project has also been a research co-operation project between the three organisations. Botniabanan AB and the Swedish Rail Administration have provided technical support and technical data for the railway systems covering construction, maintenance and operation.

The project is financed by Botniabanan AB, the Swedish Rail Administration and IVL Swedish Environmental Research Institutes research fund. The project and reference group include the following persons and organisations.

Marie Berglund, Botniabanan AB
Stefan Uppenberg, Botniabanan AB
Malin Kotake, Swedish Rail Administration (Banverket)
Håkan Stripple, IVL Swedish Environmental Research Institute

Many other railway experts and organisations have contributed with technical information, data and valuable comments. In this way, we would like to thank those persons for their contribution to the project.

Gothenburg and Örnsköldsvik, September 2010

Håkan Stripple Stefan Uppenberg

Summary

Environmental aspects are today highly important issues in the transport sector especially from a society perspective. Most likely, our society is facing considerable changes in the transport sector due to changes in the energy/environmental situation in the future. Strategic decisions concerning the development of the transport sector must be based on solid facts concerning both the transport infrastructure and the transport traffic on the infrastructure. Environmental transport research has, in many cases, focused on the vehicles and the traffic (freight and passenger transport). The transport infrastructure is often complex and difficult to analyse but of great interest in a society perspective. In this project, we have performed a comprehensive view of a modern railway infrastructure system including the traffic on the infrastructure.

To be able to give as complete a description as possible of the environmental problems related to transports, the entire transport system has to be analysed in a holistic way, which include a life cycle approach. Such life cycle approached analytic system includes not only the transport vehicle, but also the entire infrastructure needed by the transport logistics. For a road transport, such a system can for example consist of: construction, operation and maintenance of the road, manufacturing of vehicles, operation of the vehicle, loading and unloading operations, production and distribution of the fuel, production of electric power etc. It is obvious that such a system is very complex and the analysis of such a system requires both a structured methodology and analytical tools. A common and reliable tool for such analyses is Life Cycle Assessment (LCA), which also has been used in this study.

A railway system is not only just the railway. It consists of many parts and process operations. Different terrain conditions along the railway require many different technical solutions, which will give different results in energy use and environmental performance. In this study, we have developed LCA models to calculate and analyse the railway system. It is very important to design flexible models that can meet the different railway constructions. Different ground stability requires for example different stabilisation methods (concrete piles or cement/lime columns). In some terrain conditions, railway tunnels and railway bridges are needed. A railway model must have the ability and flexibility to handle all those conditions and situations. A railway is thus not a static product with a constant design but a flexible system with a tailor made unique design.

Due to the complexity of the models, several general railway component models have been developed. The component models can then be integrated to form a large model of an entire railway system. The component models (sub-models) are:

- Railway track foundation model
- Railway track model
- Railway electric power and control system model
- Railway tunnel model
- Railway bridge model
- Railway passenger station and freight terminal model
- Passenger and freight train model including train operation

In an ordinary LCA for a product, the products life cycle is studied i.e. the product is analysed in production, use and waste handling. Transport infrastructures differ slightly from this concept in such a way that it can be difficult to define a start and/or an end of the lifetime for an

infrastructure. It is therefore more useful to work with a calculation period for the infrastructure rather than a lifetime.

For the railway, a calculation period is set to 60 years. All activities from construction start to the following 60 years are included in the calculations. 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 transport and infrastructure 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 railway system. The calculation period is set to a time-period close to the lifetime of the majority of railway components (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.

The Bothnia Line is a newly constructed single-track railway in the north of Sweden located from the bridge over Ångermanälven, north of Kramfors airport to Umeå. Environmental issues have been in focus during the entire construction work and environmental data have been collected during the entire construction phase. This circumstance has opened up an opportunity for a detailed analysis of a modern railway infrastructure. The Bothnia Line has thus been used in much of the LCA model work. Botniabanan AB has since the start of the Bothnia Line project planned to develop a certified environmental product declaration (EPD), based on LCA, for the railway. The developed LCA models have thus been used for both the research work and for modelling of data to the EPDs.

LCA model results have been calculated for the different subsystems, the entire infrastructure of the Bothnia Line and for transports of both passenger and goods on the Bothnia Line. The transport calculations combine the railway infrastructure with the train traffic used for the transport. Below, some of the transport calculations for passenger and goods are presented.

To be able to distinguish between freight and passenger transports, the infrastructure has to be allocated to freight and passenger transport respectively. In principle, the total freight and passenger transports work is calculated for the calculation period of 60 years. The infrastructure results over the same calculation period of 60 years are then allocated to the total freight and passenger transport work respectively according to the amount of transport work. Since both the infrastructure and the transport assumptions are specific for each railway line, the transport profile will also be unique for a specific railway line. In this case, with the used traffic assumptions, 31.5 % of the infrastructure has been allocated to the passenger transports and 68.5 % has been allocated to the transport of goods.

The use of primary energy resources for both the entire infrastructure and the train transports at the Bothnia Line is shown in Figure A. In this case, the results are shown for the entire infrastructure with passenger and freight transports divided into construction, maintenance and operation. The results are shown in total for the Bothnia Line and cover the entire calculation period of 60 years. As shown in the figure, the train traffic share stands for 56.7 % of the total primary energy use and thus the infrastructure stand for 43.3 %. We can also see that the operation of the trains stands for a large energy use (52.8 %). Hydropower is the main energy source and this is a result of the use of green electric power. The electric power purchased by the Swedish Rail Administration for the operation of the Swedish railways is so called "Green electric power" based on a selected Swedish electric power production mix. The purchased electric power production mix in year 2008 was 99.2 % hydropower based and 0.8 % based on biomass fuel.

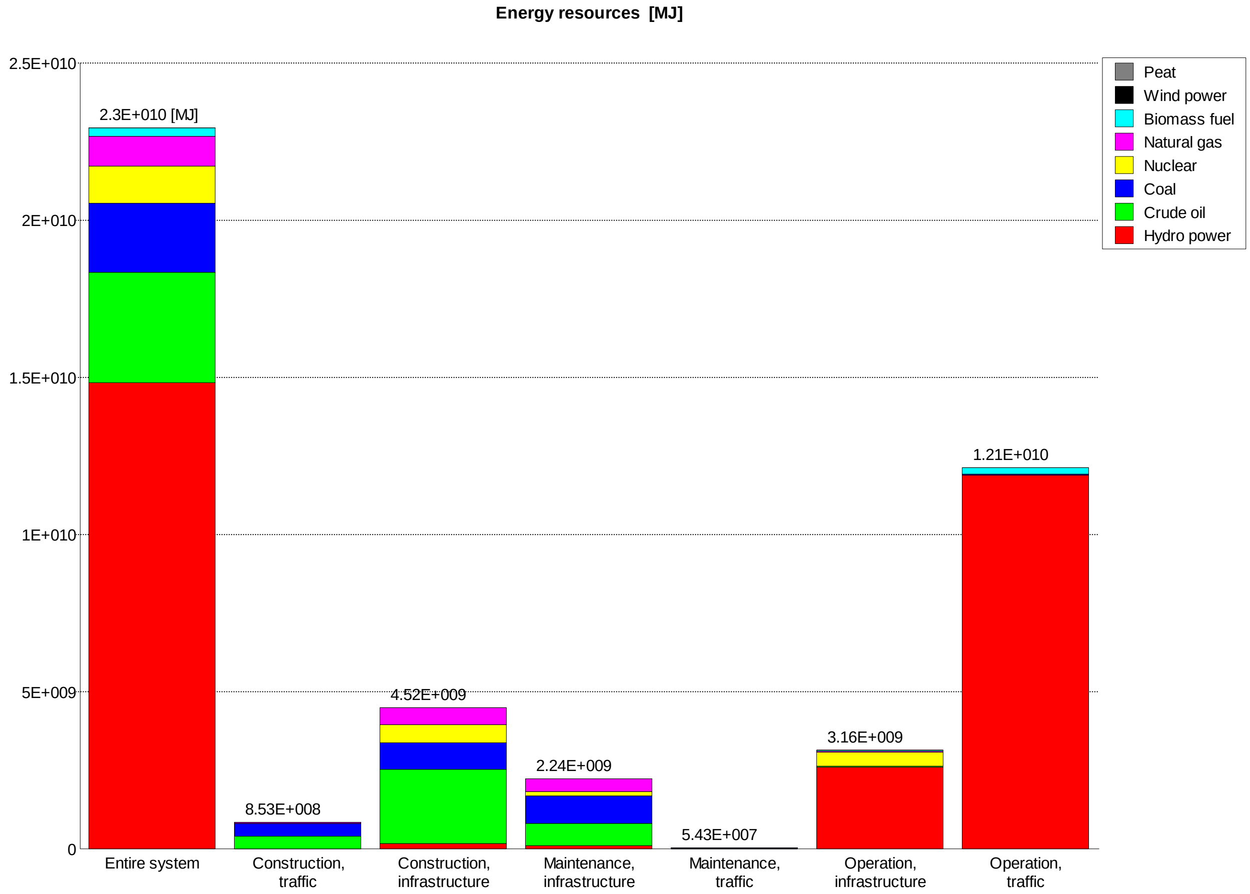

Figure A Use of primary energy resources for the Bothnia Line. The figure shows the total results including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The energy use covers construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the entire energy results over a calculation period of 60 years.

The emissions of greenhouse gases from the entire infrastructure and the total transport work (passenger and goods) of the Bothnia Line are shown in Figure B. Of the total global warming potential (GWP) from the entire transport system, the train traffic contribution is 6.7 % and the contribution from the railway infrastructure is 93.3 %. The main greenhouse gas is fossil-based CO_2 while emissions of N_2O only give a minor contribution.

The infrastructure construction phase stands for the main part of the greenhouse gas emissions while the emissions from infrastructure maintenance are much smaller. Emissions from operation of the trains and the infrastructure are very small due to the use of green electric power (mainly hydropower). The emissions from train production is significant and depends mainly on the use of steel products, while the maintenance of the trains shows a low CO_2 emission due to a generally low energy use for that process. As shown in Figure C, the main source of greenhouse gases is the production of the different materials used in the infrastructure while the actual construction work is smaller. The transport of the different infrastructure materials only gives a smaller contribution.

The CO_2 emission due to deforestation gives a large contribution to the greenhouse gas emissions for this total system view, but note that we have assumed that there originally was forest on more or less the entire railway line area (43 m width around the track). When CO_2 emanates from e.g. combustion of biomass, the emission is normally handled as a biogenic CO_2 emission and accounted as a zero emission since the growing forest after replanting is taking up an equal amount of CO_2 as released in the combustion of the biomass. In an establishment of a railway, no replanting is taking place on the railway area. Therefore, the assumed emissions from the combustion of the removed biomass will not be neutralised by uptake of new, growing forest in the same area. The assumed CO_2 emission from the biomass therefore has to be treated similar to a fossil CO_2 emission. This special CO_2 emission from the new railway area is therefore shown separately as CO_2 deforestation.

The uptake of CO_2 in concrete (carbonation) during product use (service life) is also shown in the figures as hatched negative values. The CO_2 uptake in concrete is relatively small compared to the emissions from the entire railway infrastructure. The reason for this is mainly that only a fraction of the infrastructure materials and work is related to concrete and that a large part of the concrete is used for sleepers with a low uptake of CO_2 (slow carbonation, high concrete quality) during service life. The secondary use of concrete for example crushed waste sleepers is not included in the railway model. In the secondary use stage of the concrete, a lot more CO_2 can be taken up by the concrete.

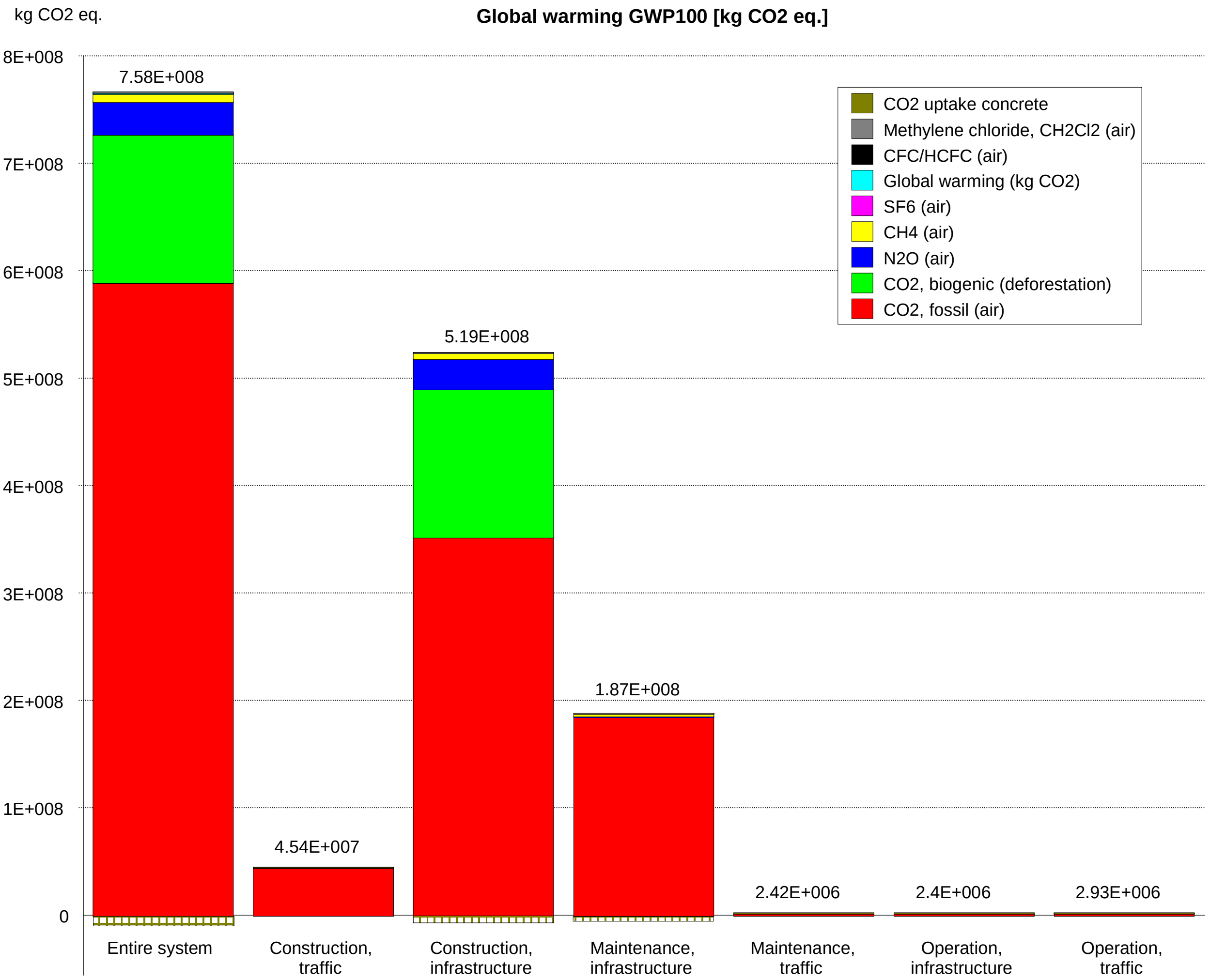

Figure B Emissions of greenhouse gases for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted. Note that so-called green electric power has been used for the train traffic calculations and applicable parts of the railway infrastructure operation.

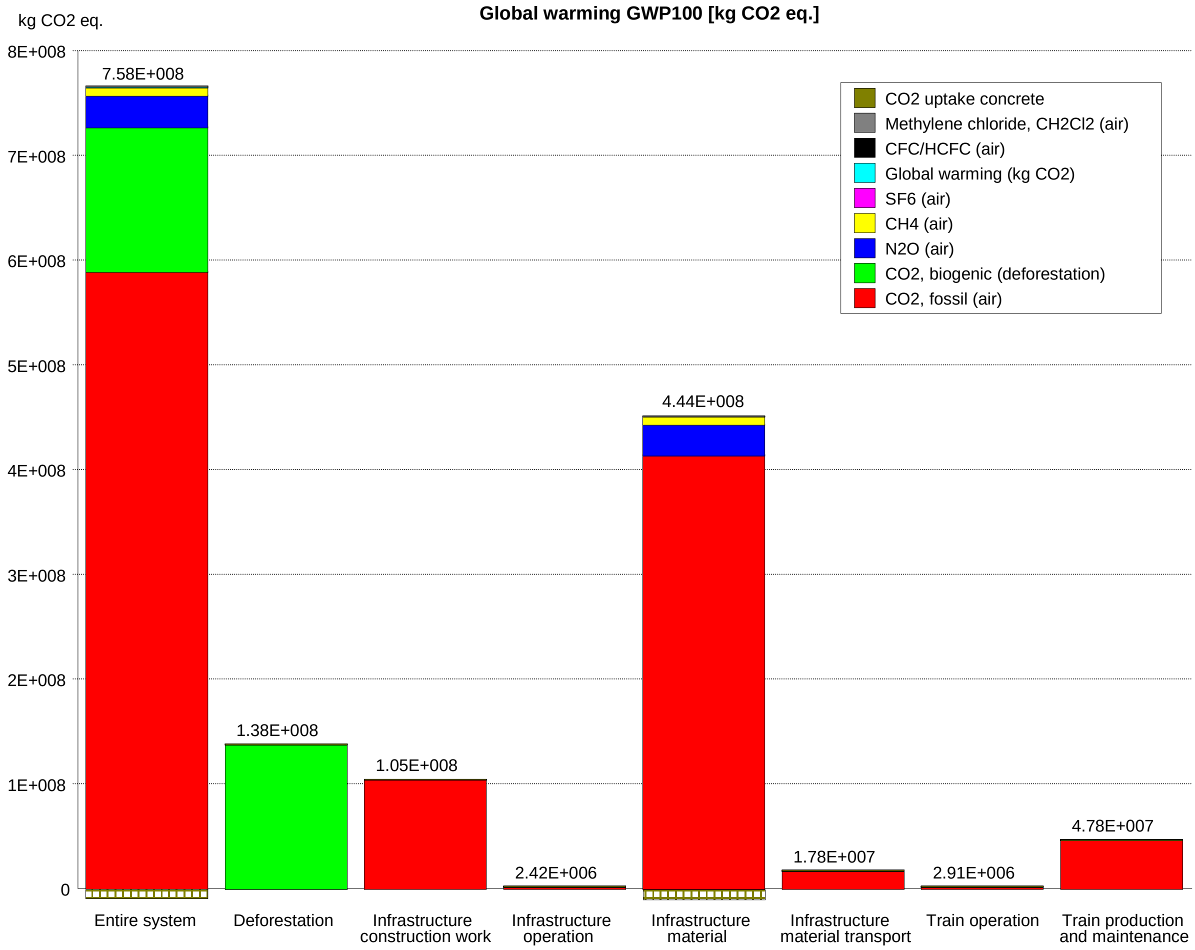

Figure C Emissions of greenhouse gases for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted. The results are here divided into different activity groups. Note that so-called green electric power has been used for the train traffic calculations and applicable parts of the railway infrastructure operation.

The emissions of acidifying pollutants are shown in Figure D and E. Of the total acidifying pollutants from the entire transport system, the train traffic contribution is 9.8 % and the contribution from the railway infrastructure is 90.2 %. As shown from the figure, the emissions show the same emission pattern as the CO_2 emissions except of course for the CO_2 uptake and the emissions from deforestation. The main sources of acidification are the emissions of NO_X and SO_2.

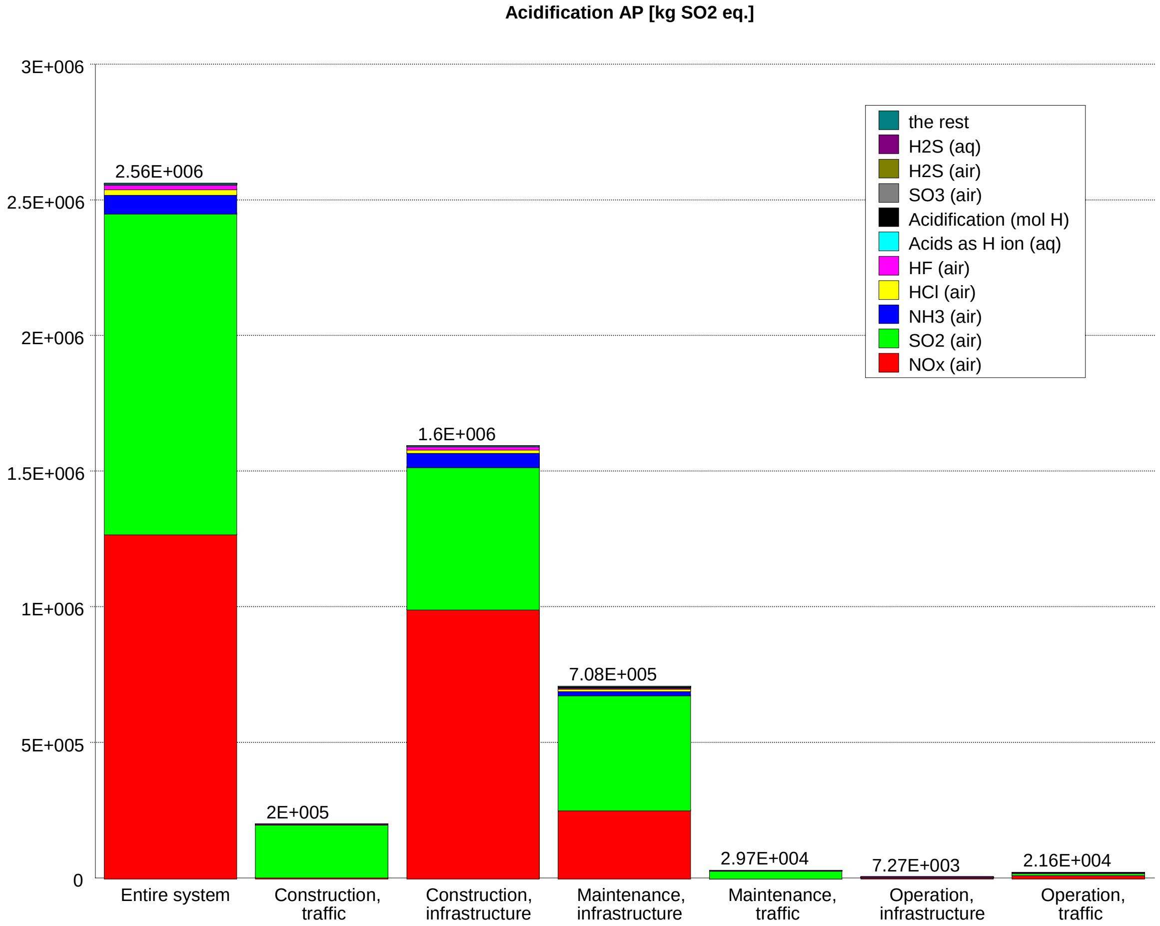

Figure D Emissions of acidifying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Note that so-called green electric power has been used for the train traffic calculations.

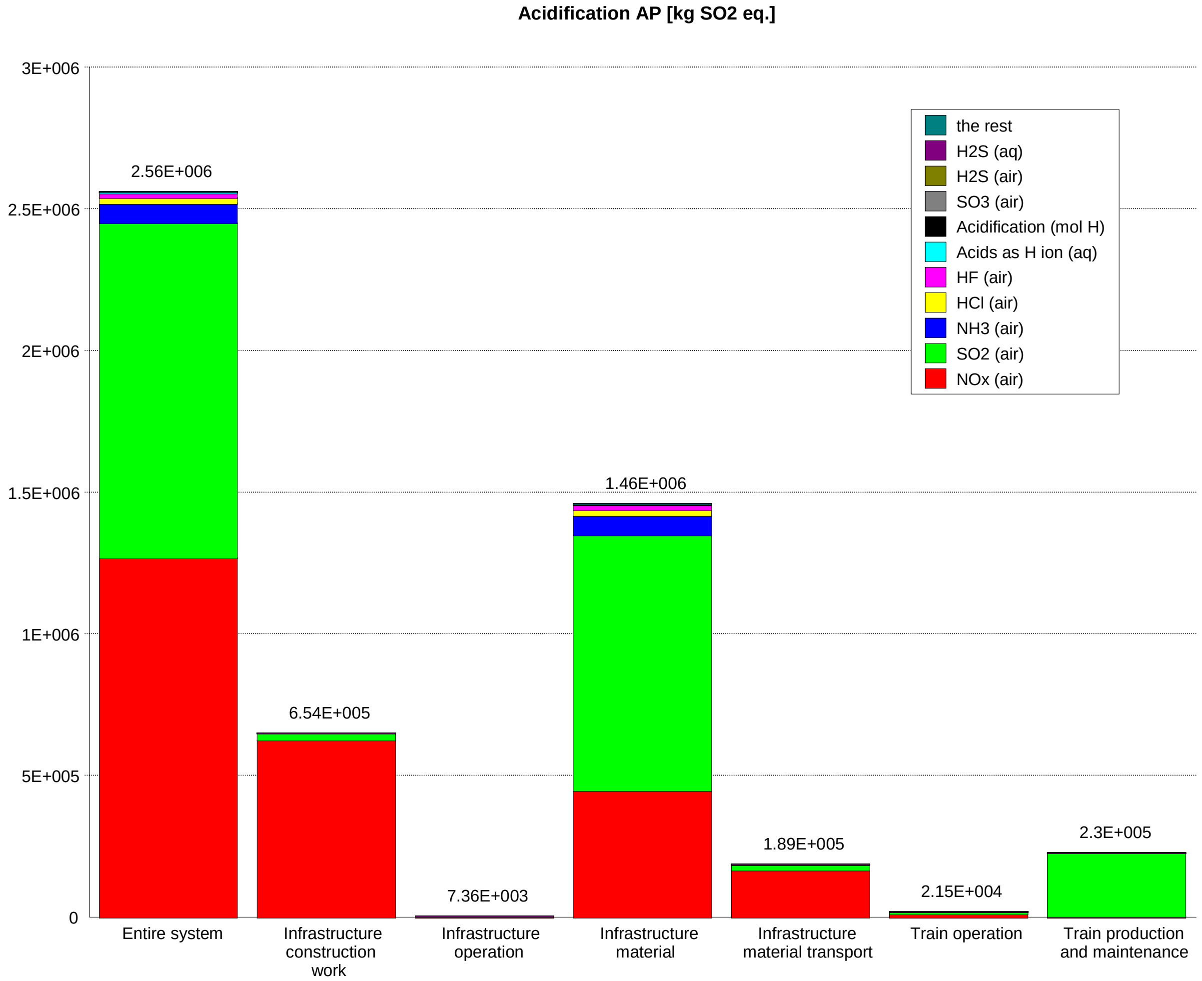

Figure E Emissions of acidifying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. The results are here divided into different activity groups. Note that so-called green electric power has been used for the train traffic calculations.

Finally, an overview impact distribution analysis of a complete train transport is shown in Figure F (passenger transport) and Figure G (freight transport). Here, the contribution distributions of each overview activity areas are shown for the different impact categories.

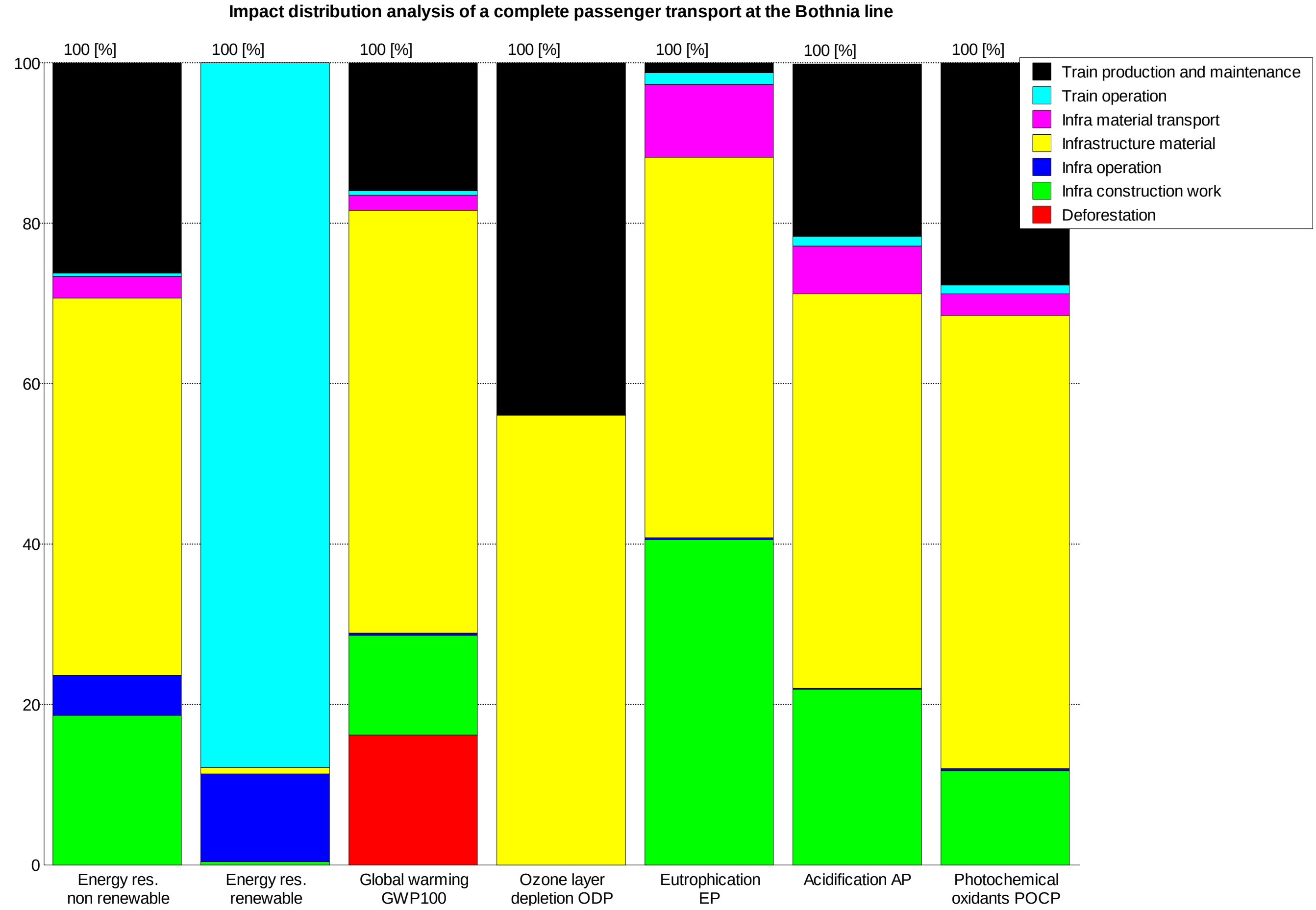

Figure F **Impact distribution analysis of a complete passenger transport at the Bothnia Line.**

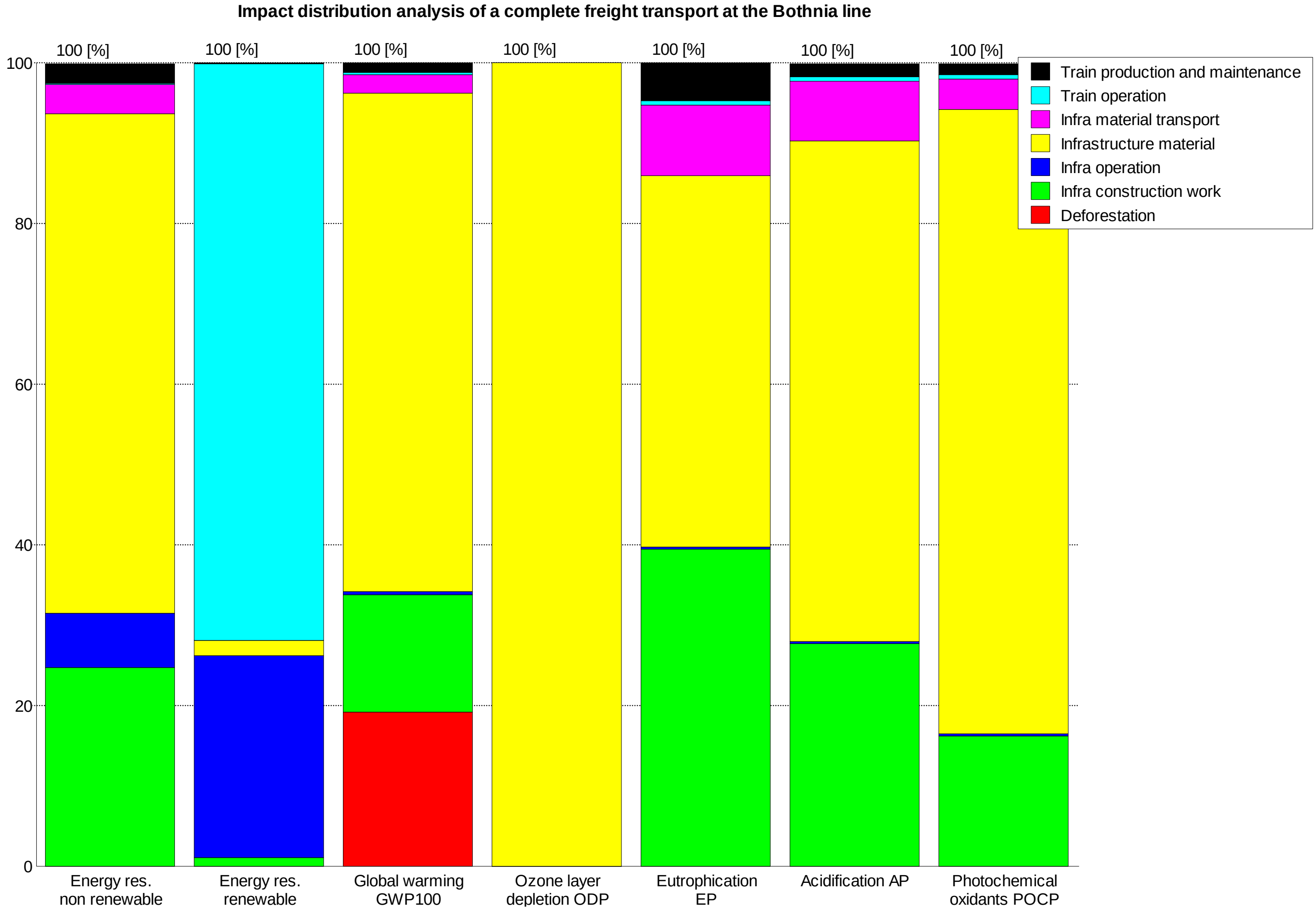

Figure G Impact distribution analysis of a complete freight transport at the Bothnia Line.

The main part of the contributions to all environmental impact categories, except renewable energy resources, comes from raw material acquisition and production of materials used for the construction of the infrastructure, like steel, concrete etc. The contributions from different materials and subsystems to the environmental impact category global warming are described in Table A below. Note that the figures present shares of the contribution to global warming just for infrastructure material, not for the entire transport systems.

Table A Detailed dominance analysis for the contribution of infrastructure material to the environmental impact category Global warming.

Material/subsystem	Track	Tunnels	Bridges	Stations	Track Foundations	Power, signalling, telecom	Total
Steel	29 %	4 %	5 %		3 %	3 %	**43 %**
Cement	6 %	10 %	11 %		5 %	0 %	**32 %**
Buildings				11 %			**11 %**
Aluminium						4 %	**4 %**
Explosives	0 %	2 %			1 %		**3 %**
Plastics	0 %	1 %			1 %	1 %	**2 %**
Copper						1 %	**1 %**
Total	**35 %**	**16 %**	**16 %**	**11 %**	**10 %**	**9 %**	**97 %**

As shown in Table A above, a few materials totally dominate the emissions of carbon dioxide related to production of infrastructure material. Steel and cement together stands for 75 % of the total CO_2 emissions related to infrastructure material. The data for buildings that give a contribution of 11 % are aggregated data for material related emissions and construction work related to the building of stations and freight terminals. The majority of these emissions come from the use of steel and concrete. Therefore, steel and cement can be said to stand for some 85 % of the total material related CO_2 emissions for the Bothnia Line's infrastructure.

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List of abbreviations and explanations

Abbreviation/ Term	**Explanation**
IVL	IVL Swedish Environmental Research Institute/IVL Svenska Miljöinstitutet
Technotope	A category of the Biotope method developed by Vattenfall.
sub	solid under bark, a measure of forest calculated as stem wood under bark. (can also be used as a prefix as in sub model)
Primary energy	Primary energy is energy resources found in nature that has not been subjected to any conversion or transformation process.
GHG	Greenhouse gases (in this case mostly CO_2, CH_4 and N_2O)
Green electric power	The electric power purchased by the Swedish Rail Administration for the operation of the Swedish railways is so called "Green electric power" based on a selected Swedish electric power production mix. The purchased electric power production mix in year 2008 was 99.2 % hydropower based and 0.8 % based on biomass fuel.
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Dinitrogen oxide, Laughing gas
LCA	Life Cycle Assessment
Carbonation	Uptake of CO_2 in concrete.
EIA	Environmental Impact Assessment
EPI	Environmental Performance Indicators

1 Introduction

Transports are essential parts of a modern society. New transport technologies and production methods have dramatically increased the possibilities for long and fast transports in a historical perspective. The need for increased transport capacity has grown constantly and is still growing relatively fast. This situation has also increased the environmental problems related to the transport sector. The transport sector stands today for a significant part of the environmental problems in most part of the world. One of the first environmental problems to be observed was different emissions from the exhaust gases of road vehicles. Later, the emissions from ships, aeroplanes and trains were investigated.

However, to be able to give as complete a description as possible of the environmental problems related to transports, the entire transport system has to be analysed in a holistic way, which include a life cycle approach. Such life cycle approached analytic system includes not only the transport vehicle, but also the entire infrastructure needed by the transport logistics. For a road transport, such a system can for example consist of; construction, operation and maintenance of the road, manufacturing of vehicles, operation of the vehicle, loading and unloading operations, production and distribution of the fuel, production of electric power etc. It is obvious that such a system is very complex and the analysis of such a system requires both a structured methodology and analytical tools. A common and reliable tool for such analyses is Life Cycle Assessment (LCA), which is described in more detail in a later chapter.

The situation of choice between different transport alternatives is very common. In our daily life, we can choose to take the car, the boat, the train or the aeroplane to a certain destination. The choice can also be between different freight alternatives for a company or between different national strategic transport infrastructure solutions, which will have affect for decades. The question is however, which information and criteria that should be used as a base for the decision whether it concerns a single transport or a strategic transport decision. In an overview perspective, there are many different, sometimes also competing alternatives like; economic criteria, regional political aspects, labour market (employment) policy aspects, environmental criteria, energy criteria or travel time aspects. This study covers the energy, resource and environmental aspects for decision-support, and not the multi-criteria problem, which has to be dealt with to actually make the most appropriate choice. In any case, it is however important to have complete and accurate basic information for all decision processes.

The construction of the new railway line, the Bothnia Line, in the north of Sweden was launched in August 1999. From the very beginning of the project, the environmental aspects were in focus. The board of directors of Botniabanan AB decided at the start of the project that an environmental product declaration (EPD) should be developed for the railway, since it was considered important also to have information on the environmental impact related to the infrastructure when discussing the environmental impact from transports in general. An EPD is a standardised method, based on LCA, to communicate environmental performance from products aiming for product choice by the customer.

To realise the development of EPDs, statistic material concerning different energy, resource and environmental parameters was collected during the construction process and the LCA-project was initiated. This gave the opportunity for further environmental research of modern railway systems. It also opened up the possibility to design and construct an advanced computer model of an entire railway system including not only the track but also railway bridges, railway tunnels, electronic systems, railway station and goods terminals etc.

In this project, we have thus analysed an entire modern railway system with many different components. The train traffic on the railway has also been covered in the analyses including both the production of the vehicles and the train traffic operation. A Life Cycle Assessment (LCA) methodology has been used for the analyses and comprehensive LCA models have been designed to implement the construction knowledge into computer models. The project is basically a research project and the developed models have been used to study the railway system and the railway infrastructure and to develop EPDs for the entire railway transport system and for the different railway infrastructure subsystems.

2 Background and description of the work

Railway systems and the railway infrastructure are very large technical systems all over the world. They are important system for the transport in the world. Large investments are made in those systems for construction, maintenance and operation. The lifetime of the railway infrastructure is also relatively long and will thus have an effect on the transport system for a very long time. It is therefore important to study and analyse the railway system in many aspect. In this study, we have focused on the energy, resource and environmental aspects and we have done this with a system perspective hence we have studied the entire railway system from raw material extraction via construction, operation and maintenance of the system to the end of life of the system.

A railway system is not only just the railway. It consists of many parts and process operations. Different terrain conditions along the railway require many different technical solutions, which will give different results in energy use and environmental performance. In this study, we have developed LCA models to calculate and analyse the railway system. It is here very important to design flexible models that can meet the different railway constructions. Different ground stability requires for example different stabilisation methods (concrete piles or cement/lime columns). In some terrain conditions, railway tunnels and railway bridges are needed. A railway model must have the ability and flexibility to handle all these conditions and situations. A railway is thus not a static product with a constant design but a flexible system with a tailor made unique design.

Railway systems are thus very complex and require large LCA computer models. An LCA computer software (KCL-ECO) has been used to develop the railway models. Due to the complexity of the models, several general railway component models have been developed. The component models can then be integrated to form a large model of an entire railway system. The component models (sub-models) are:

- Railway track foundation model
- Railway track model
- Railway electric power and control system model
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- Railway passenger and goods station model
- Passenger and goods train model including train operation.

3 Analytical methods and methodological aspects

3.1 General methodology

Transport infrastructures are complex technical systems with varying design. This requires a solid but flexible strategy. In addition, a system perspective (like LCA) increases the complexity by including the production/handling of all materials, products, processes etc. both upstream and downstream from the construction site. In an ordinary LCA for a product, the products life cycle is studied i.e. the product is analysed in production, use and waste handling. Transport infrastructures differ slightly from this concept in such a way that it can be difficult to define a start and/or an end of the lifetime for an infrastructure. It is therefore more useful to work with a calculation period for the infrastructure rather than a lifetime.

For the railway, a calculation period is set to 60 years. All activities from construction start to the following 60 years are included in the calculations. 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 transport and infrastructure 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 railway system. The calculation period is set to a time-period close to the lifetime of the majority of railway components (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.

The system boundaries used for infrastructures follows in principle the same pattern as for other LCA studies according to the ISO standard. In this study, ISO 14040 and ISO 14044 have been used for the LCA work. A specific PCR for the infrastructure can also be used in the development of EPDs. The LCA performed in this study follows the rules outlined in the Product Category Rules (PCR) for Rail Transport and Railway Infrastructure, PCR 2009:03[1]. The PCR provides the necessary rules for LCA and other assessment methods to make it possible to develop an EPD for a specific product category.

A useful principle for infrastructure analyses has been to divide the activities in three groups: Construction, Maintenance and Operation. In a full transport LCA there are two parts, which have to be combined; the LCA of the infrastructure and the LCA of the actual transport vehicle. The overall layout must be design in such a way that the two parts can be added, Table 1. This requires a uniform way of handling the functional unit and the used parameters. The main structure of a full railway transport LCA, in accordance with PCR 2009:03, is shown in Figure 1 and Figure 2.

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[1] PRODUCT CATEGORY RULES (PCR), for preparing an Environmental Product Declaration (EPD) for Interurban railway transport services of passengers UN CPC 6421, Railway transport services of freight UN CPC 6512 and Railways UN CPC 53212, PCR 2009:03.

Table 1 Main principle of a full transport LCA.

	Construction	Maintenance	Operation
Infrastructure			
Traffic			

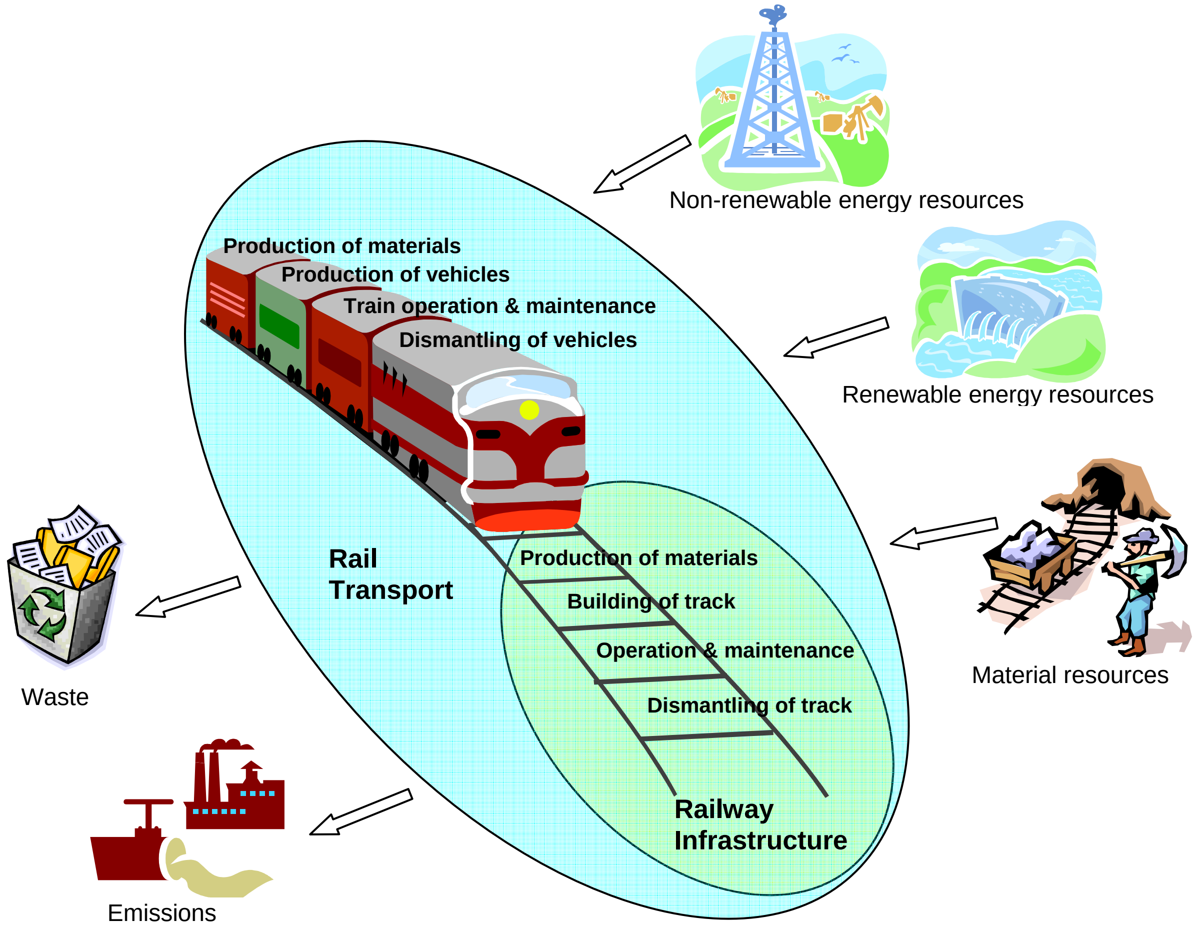

Figure 1 Overview of the product categories Rail Transport and Railway Infrastructure.

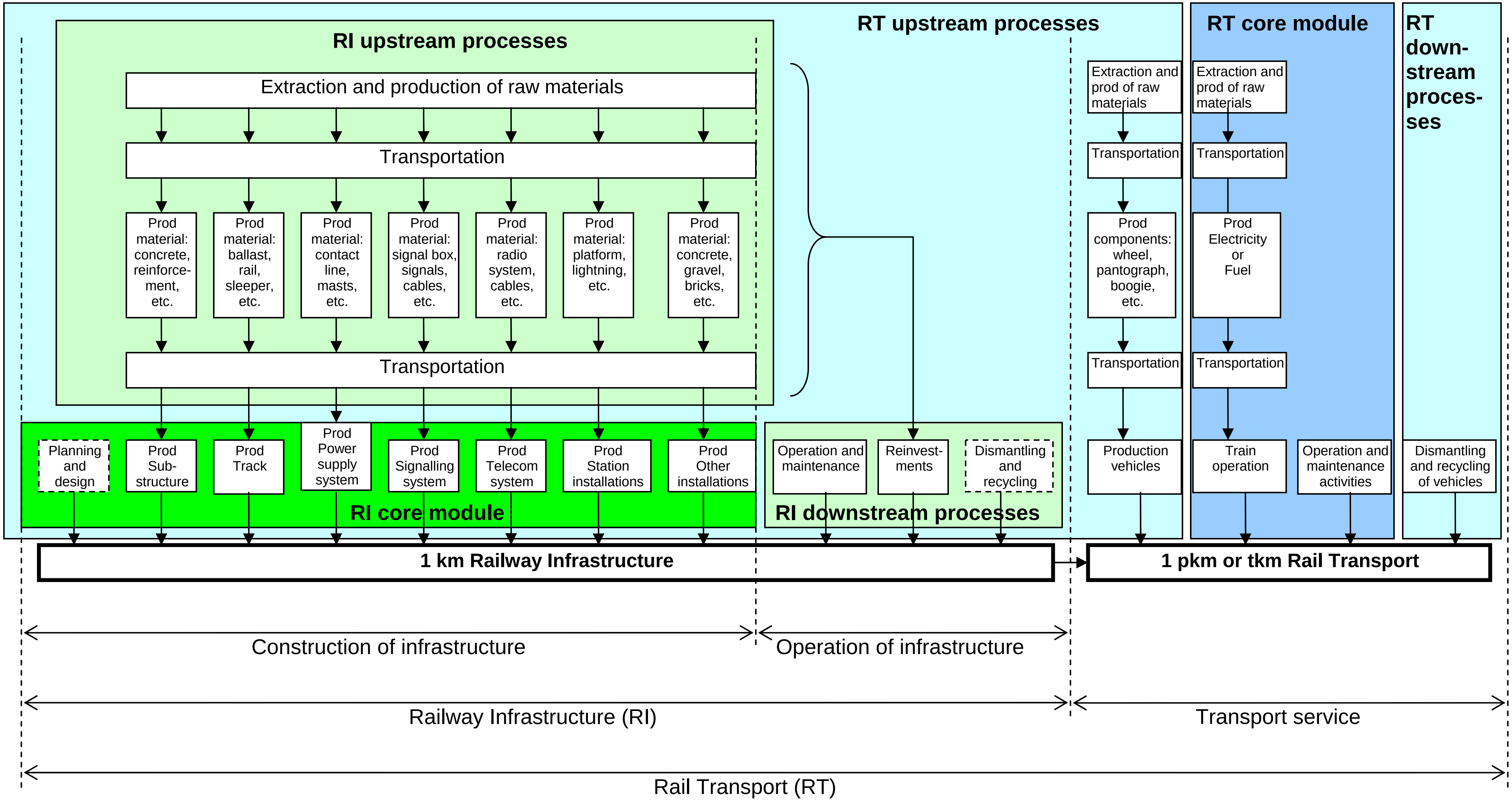

Figure 2 Flow chart of the product system for Rail Transport (RT) and Railway Infrastructure (RI).

Transport operations can include both passenger and goods transports and the same infrastructure can be used for both transport types. In a case when a total transport of a passenger or a tonne of goods shall be analyses and calculated, the infrastructure has to be allocated to passenger and goods transport respectively. In accordance with PCR 2009:03, the transport work, in gross tonne-km (tonnage including both vehicle, freight carriers and passengers/goods), has been used for the allocation. The total transport work (passenger+goods) in gross tonne-km on the infrastructure during the calculation period (60 years) has been calculated. The allocation of the infrastructure on passenger and freight transport has then been performed according to their respective share of the transport work. The infrastructure share for passenger transports has then in a second step been calculated per passenger transport work in passenger-km (1 passenger transported 1 km), and for freight transports to net tonne-km (1 ton of goods, without freight carrier, transported 1 km).

The functional unit is the measure of performance, which the system delivers. For a transport, the functional unit is set to the delivered transport work in passenger-km or tonne-km in this study. However, local functional unit exists for sub-model like railway tunnels, railway bridges or railway tracks. In the later case, the length of the components has for example been used as functional units (e.g. meter tunnel length).

The design of the LCA models is strategically very important. The models need to be accurate and flexible with a good resolution. Resolution in this case means that the models are so detailed that you can use the model in the decision process and for other needs. The data collection for the LCA models is complex and very often, the contractor does not collect data for the different process operations. Generally, there are two methods of model design and data collection that we can call "top-down" and "bottom-up" calculations.

In the "top-down" approach an entire construction site is studied (e.g. a bridge or tunnel construction) and the total material use, energy use, waste and emissions are measured. By dividing the measures by e.g. the length of the tunnels or the bridge, an overview measure of the objects can be obtained. The positive aspect of this approach is that real data for a construction object is used and thereby a good accuracy can be achieved. The negative part is the lack of flexibility and resolution of the model. The model will only be valid for a particular object and no detailed data from the construction can be received.

In the "bottom-up" approach, all activities in construction, maintenance and operation is broken down to small unit operation (e.g. truck transport, excavation, shotcrete application). Each unit operation has its own local unit (e.g. m^3 excavated material, tonne-km truck transport) and its own energy use, emissions etc. per local unit. The LCA models are then build up by the different unit operations together with quantity data for the different processes. This approach will result in a more flexible model with much higher resolution. The model will however be somewhat more theoretical than the "top-down" model and a fear is that this will result in an underestimation of energy use and emission due to the use of theoretical process values that does not reflect a real construction situation.

In this study, the "bottom-up" approach has been chosen due to its flexibility and better resolution. However, for some objects (e.g. bridges) it has been difficult to break down the construction work into unit operation due to lack of detailed data. In those cases, a mixture of "bottom-up" and "top-down" approaches have been used. In the Bothnia Line project, energy and environmental data have been collected for many different construction projects. This has opened up a possibility to verify and test the "bottom-up" based models against real data from construction projects. Such tests have been performed for several objects and models and the result of the tests is presented later on in this report.

An important detail is the emission of CO_2 from deforestation. When CO_2 emanates from e.g. combustion of biomass, the emission is normally handled as a biogenic CO_2 emission and accounted as a zero emission because the growing forest after replanting is taking up an equal amount of CO_2 as released in the combustion of the biomass. In an establishment of a railway, no replanting is taking place on the railway area. Therefore, the assumed emissions from the combustion of the removed biomass will not be neutralised by uptake of new, growing forest in the same area. The assumed CO_2 emission from the biomass therefore has to be treated similar to a fossil CO_2 emission. This special CO_2 emission from the new railway area is shown separately as CO_2 deforestation. The CO_2 deforestation occurs in the construction phase and can give a significant contribution to the greenhouse gases. However, note that if less forest exists on the construction site, the CO_2 deforestation emission will be reduced.

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[2]. In a life cycle assessment, a mathematical model of the system is designed. This model is of course a representation of the real system, including various approximations and assumptions. The 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 (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 characterisation have been included in the impact assessment part. Here, the same classification and characterisation scheme as proposed in the EPD system have been used.

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

3.3 Environmental Product Declaration - EPD

An environmental product declaration, EPD, is defined as "quantified environmental data for a product with pre-set categories of parameters based on the ISO 14040 series of standards, but not excluding additional environmental information". An EPD is short summary information of the environmental performance of a product or service aiming for comparison of different products or services with the same function. An EPD shall contain objective, credible, neutral and comparable information and shall be based on an LCA model (ISO 14040 and ISO 14044) to achieve a solid objective technical base.

To make an EPD (environmental information) comparable it is important that the environmental information is calculated uniformly within the product category. It is therefore necessary to have Product Category Rules (PCR) for that product or service, agreed upon by the branch for the specific product or service. These calculation rules are developed for a line of business in cooperation between the different industrial producers. In the PCR 2009:03[3] for Rail Transports and Railway Infrastructure it is described how the underlying LCA shall be performed, but also how environmental aspects shall be assessed that is not possible to include in the LCA, like impacts on biological diversity, noise disturbance etc.

Eight different EPDs have been developed for the Bothnia Line. The EPDs include both the railway infrastructure and the railway transport on the infrastructure. The EPDs have also been certified by Bureau Veritas in an independent verification process. In this process the background materials, the LCA models and the calculations have been checked. This verification process is mandatory for the international EPD system and intends to strengthen the credibility of the EPDs.

4 The Bothnia Line – an overview description

The Bothnia Line is the biggest railway project of modern times in Sweden. It is a single-track railway with sidings being laid from the bridge over Ångermanälven, north of Kramfors airport, via Örnsköldsvik, Husum, Nordmaling, to Umeå. The opening of the railway line will be in august 2010. The Bothnia Line will carry both passenger and freight traffic and is designed for speeds up to 250 km/h. As regards freight transport, the Bothnia Line is designed to take trains of up to 1400 tonnes. The Bothnia Line replaces and complements the old trunk line. The new railway is located near the cost and connects the cities, which also are located near the cost. The new location of the railway will significantly reduce the travel time between the cities compared to the old trunk line, which is located some 30 km from the coast where the terrain is more flat. Both the new and the old railway will be in operation in the future, which can compensate the reduced capacity due to the single-track construction of the Bothnia Line.

The traffic forecast for the new line indicate a number of passenger to 12 294 000 per year in total for the different parts of the line. The passenger transport work has been estimated to 343 771 000 passenger-km per year. The goods volume has been estimated to 2 623 665 tonnes per year giving a total freight transport work of 506 367 424 tonne-km per year. The regional passenger transports will mainly be carried out by an Alstom train of type Coradia Lirex. The actual train used for

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[3] PRODUCT CATEGORY RULES (PCR), for preparing an Environmental Product Declaration (EPD) for Interurban railway transport services of passengers UN CPC 6421, Railway transport services of freight UN CPC 6512 and Railways UN CPC 53212, PCR 2009:03 version 1.0, 2009-08-18.

operation at Botniabanan is a 4-car train with 208 seats. The freight transports will be carried out by different operators and different vehicles (locomotives+goods wagons). For goods handling there is one large freight terminal located in Umeå with hoisting capacity and a storage capacity of 130 000 m^2 and a smaller container terminal in Arnäsvall just north of Örnsköldsvik. For passengers there are 7 railway stations along the entire railway with a total building area of 6505 m^2.

A plan map and a profile diagram of the Bothnia Line are shown in Figure 3. Notice the direction of north in the map and that the figure is simplified and thus do not show all details. As shown in the figure, some parts (especially in the south) of the Bothnia Line are relatively hilly and thus require a large number of tunnels and bridges and a significant amount of excavation.

The length specifications of the Bothnia Line are as follows:

Total railway track length: 209 000 m
(of which main railway track is 183 000 m, side tracks are 23 000 m and shunting yard tracks are 3000 m)
Total railway bridge length: 10 930 m
Total railway tunnel length: 24 538 m
Total track foundation length: 209 000-10 930-24 538 = 173 532 m

The Bothnia railway line is a modern Swedish electrified railway designed for 15 kV AC 16 2/3 Hz and with overhead contact lines made of copper with a cross section area of 200 mm^2 including support wire (auxiliary, droppers). Current-carrying droppers are used. For the operation of the Bothnia Line, Swedish railway electric power production mix is used (electric power purchased by Banverket, the Swedish Rail Administration). The electric power purchased by the Swedish Rail Administration for the operation of the Swedish railways is so called "Green electric power" based on a selected Swedish electric power production mix. The purchased electric power production mix in year 2008 was 99.2 % hydropower based and 0.8 % based on biomass fuel.

Modern tracks in Sweden have rails of type UIC 60 and concrete sleepers with e-clips for attachment of rails. Distance between sleepers is 0.60 m. UIC 60 is mainly used at the Bothnia Line even if short distances with UIC 54 exist. The new railway is equipped with a modern signal system, ERTMS (European Rail Traffic Management System) level 2 and ETCS (European Train Control System). In addition, there are also several other telecommunication and safety equipments.

At the Bothnia Line, there are 16 main railway tunnels. The total length of main tunnels with railway is 24 538 m. The length of the tunnels varies and long tunnels (> 1000 m) are equipped with service and access tunnels for emergency evacuation and construction reasons. The total length of service tunnels is 14 360 m and total length of access tunnels is 2 107 m.

The Bothnia Line has three different types of bridges:

- Concrete portal frame bridges (small bridges with two piers)
- Steel girder bridges (large bridges with several piers and a superstructure made of a steel girder with an overlay structure of concrete)
- Concrete beam bridges (large bridges with several piers and a superstructure made of concrete)

The bridge specifications for the Bothnia Line are as follows:
Total number of railway bridges: 90
Total railway bridge length: 10 930 m
Total number of concrete bridge piers: 391
Total length of steel girder superstructures: 3513 m
Total length of concrete beam superstructures: 5367 m
Total length of superstructure for other bridges (e.g. concrete portal frame bridges): 2050 m
Total length of concrete bridge piers for all bridges at the Bothnia Line: 3164 m (estimated value based on calculations)

In addition, there are also 53 road bridges with a total length of 1959 m build in the Bothnia Line project. These road bridges are not included in the calculations of the railroad infrastructure but thus allocated to the road traffic infrastructure.

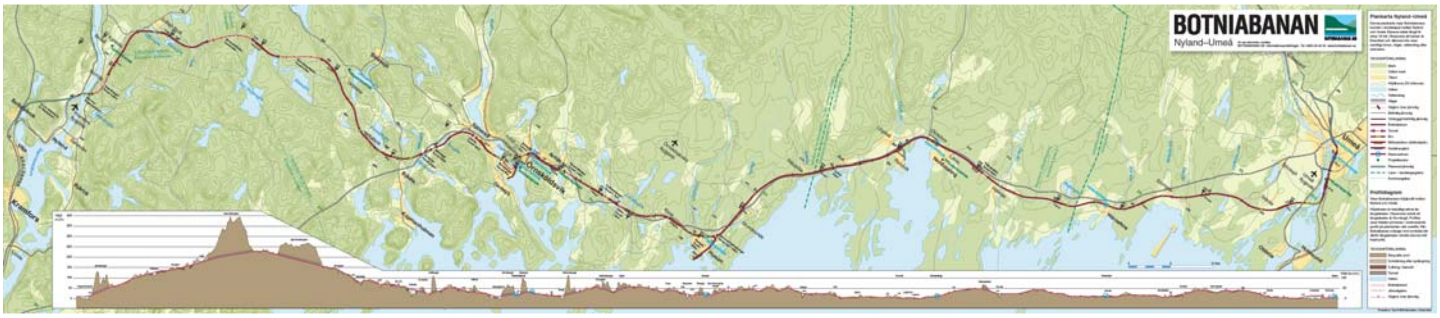

Figure 3 Plan map and profile diagram for the entire Bothnia Line. The figure is simplified and do not show all details. (Use pdf file and read figure from screen for improved readability).

5 Technical description of railway infrastructure components

LCA models are mathematical models of technical systems. It is therefore important to have a good technical description of the system with the various components and quantities. In this chapter, you will found a technical description of the system with its different components and design solutions. As far as possible, we have tried to use pictures to explain the technical systems, which we hope, will improve the understanding of the railway systems. All the technical descriptions are based on the system design for the Bothnia Line.

5.1 Railway track foundation

In the LCA models, a distinction has been made between the actual railway track and the railway track foundation. In a construction site, these operations are usually performed as separate construction operations. The function of the railway track foundation is to carry the railway track and to form a stable base for the track. The foundation operations can vary significantly depending on ground condition. The operations include all operations from ground stabilisation with concrete piles or cement/lime columns, excavation of soil material, filling of stabilisation materials (e.g. blast stone) to formation of the actual track foundation made of different types of ballast. To form a balanced railway (almost horizontal), excavations in both soil (earth cut) and hard rock (rock cut) is required. Figure 9 shows an example of a rock cutting at the Bothnia Line. The excavation masses are usually used internally in the construction and the masses are transported along the foundation. Mass-balance within the construction contract is often a prerequisite for the planning of the railway. Several other process operations are involved in the foundation construction. The main operations are listed below:

- Geotechnical surveys for track foundation.
- Establishment of construction site.
- Forest felling.
- Clearing of soil
- Open soil excavation
- Erosion protection
- Open hard rock excavation.
- Rock bolting reinforcement (in rock cuts).
- Application of protecting wire netting for rock.
- Application of cement/lime columns or concrete piles.
- Geotextile application.
- Construction of unbound base course, unbound subbase course and unbound subbase course for frost protection.
- Application of water and wildlife culverts, see Figure 8.
- Application of different cable man-holes.
- Application of different noise protections (steel, wooden, glass)
- Application of protection and wildlife fences.
- Application of different cable channels.
- Application of various foundations for e.g. contact poles, noise protections, stay anchors.

Schematic figures of railway foundations on flat land and in rock and earth cuttings are shown in Figure 4 to Figure 6.

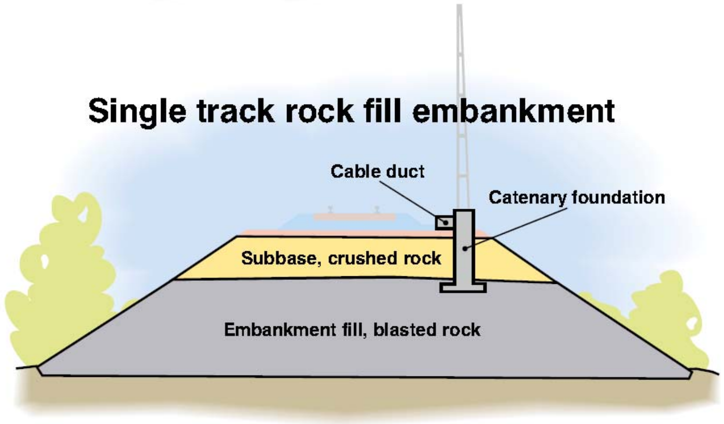

Figure 4 **Schematic figure showing a railway foundation on flat land.**

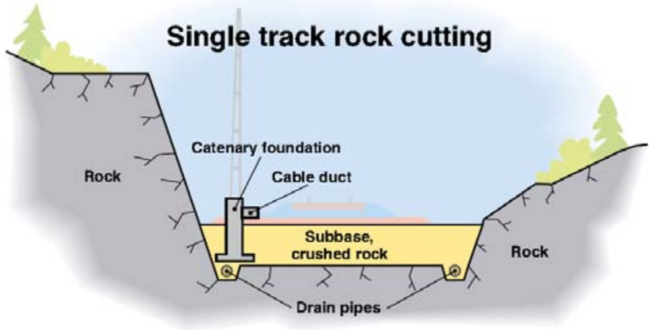

Figure 5 **Schematic figure showing a railway foundation in a rock cutting.**

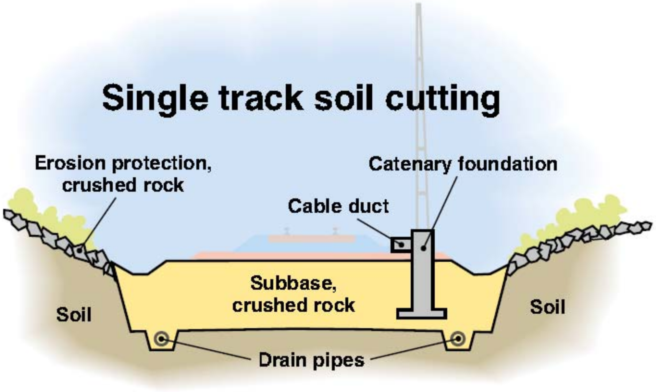

Figure 6 **Schematic figure showing a railway foundation in an earth cutting.**

A typical design (used in the models) of a railway track foundation on flat land is shown below.

Unbound base course (single track)	The unbound base course is the ballast material just under the sleepers. This layer is ca 0.3 m thick with an average width of 4 m (3.5m+slopes). The cross section is: 4*0.3=1.2 m^2. For the compaction process general: The models work with a compaction area. The compaction area is the total area compacted for all layers. The maximum compaction thickness is 0.5 m for each layer. This means that e.g. if the thickness of the layer is 0.8 m, two compaction operations is needed and thus the compaction area has to be double. The density of ballast is set to 1620 kg/m^3 loose volume.
Unbound subbase course (single track)	The unbound subbase course is the ballast layer under the base course. The subbase course is 0.8 m thick and the average width is 9.5 m. (7.5m+1m+1m for slopes). The cross section is: 9.5*0.8=7.6 m^2.
Unbound subbase course for ground frost protection (single track)	This subbase course is a ballast layer for ground frost protection. This layer is only used where frost protection is needed. The subbase course is 0.8 m thick and the average width is 10.5 m (7.5+1.5m+1.5m for slopes). The cross section is: 10.5*0.8=8.4 m^2.

In Figure 7 a picture of a railway track foundation is shown. The next step in the construction work is here laying of rails, which is covered in the next chapter. To the left in the picture, the service road is shown. For construction, service and other purposes there are always a service road parallel to the railway. The service road is a simple road build during the construction phase of the railway. The cross section structure of the service road is specified below:

Width of service road is 4 m, including slopes an average construction width is estimated to 5 m.

<u>On rock foundation:</u>
Gravel wearing course: 50 mm (0-20 mm gravel)
Base course: 200 mm (0-50 mm gravel)
Erosion protection: 300 mm (0-100 mm gravel)

<u>On soil foundation:</u>
Gravel wearing course: 50 mm (0-20 mm gravel)
Base course: 200 mm (0-50 mm gravel)
Sub base course: 300 mm (0-100 mm gravel)
Erosion protection (slopes): 300 mm (0-100 mm gravel)

Service roads can also need ground stabilisation, mainly blast stone filling.

Figure 7 To the right, a typical railway track foundation. The service road parallel to the railway is shown to the left.

Figure 8 Culverts are needed in the track foundation for water and wildlife. The picture shows a culvert for a water course (large) and a separate, dry wildlife passage (small).

Figure 9 **The railway track do not usually follow the landscape. In this case, excavations are needed. This picture shows an example of a hard rock excavation (a rock cutting).**

5.2 Railway track

The railway track consists of two rails attached to sleepers. The sleepers rest on the top of the track foundation. The space between and around the sleepers are filled with track ballast. The railway track construction (laying process) is carried out by a fully automated train that handles the sleepers, rails and fill the track with track aggregates. This train is diesel driven. A similar train is also used for the replacement of old tracks in the maintenance process. The tracks also include railway switches and drivers for the switches. To increase the lifetime and to give the rails a smooth surface, a rail milling process is used.

Modern tracks in Sweden have rails of type UIC 60 and concrete sleepers with e-clips for attachment of rails. Different rail types have different weight per meter. UIC 60 has a specific weight of 60.4 kg/m rail. UIC 54 has a specific weight of 54.4 kg/m rail. UIC 60 is mainly used at the Bothnia Line. The rails are welded with a thermite welding process. The lifetime of the railway track is estimated to 45 years with head-hardened rails and rail milling maintenance.

Normally, concrete sleepers are used but wooden sleepers can exist and are included in the LCA model as an option. The distance between sleepers is 0.60 m.

Material use for one sleeper is:
Concrete: 250 kg
Steel reinforcement: 6.1 kg
Steel blocks for attachment: 4 units per sleeper and 1.3 kg per block (total 5.2 kg per sleeper).
E-clips for attachment: 4 clips per sleeper, 0.6 kg steel per clip gives 2.4 kg steel per sleeper.
Neoprene (polychloroprene) pads: 2 units per sleeper with dimension 150x150x5 mm (density 1230 kg/m^3) gives 0.277 kg per sleeper.
Isolator of nylon 66: 0.046 kg nylon/isolator, 4 isolators per sleeper gives 0.184 kg nylon per sleeper.

Rail milling is a process in which the rails are initially milled to improve performance and quality and thus reduce maintenance intervals. The milling depth is 0.7 mm and the milling width is approximately 70 mm. The process is performed with a service train. During maintenance, the rails are milled each second year[4].

A picture of a typical modern Swedish railway track under construction is shown below in Figure 10.

Figure 10 The picture shows a typical railway track with rails attached to concrete sleepers with rail fastening. The space between sleepers are filled with track ballast.

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[4] Stahlberg-Roensch Scandinavia and Bothnia Line.

5.3 Railway electrical power and control systems

The electric power and control systems can be divided into three different systems:

- The electric power supply for train operation.
- Train control systems.
- Telecommunication systems.

In addition to the direct work with the electric and electronic systems, there can also be general work to prepare for the electric and electronic systems such as forest felling for cables, service roads for housing for electronics and other excavation work. The power and control systems in this study reflect a modern Swedish railway system.

The power supply for train operation is thus 15 kV and 16 2/3 Hz. The power feed is through airborne cables. The overhead contact lines are made of copper with a cross section area of 200 mm^2 including support wire (auxillary, droppers). Current-carrying droppers are used. For insulation of power line from the contact line pole, 8 insulators of 0.5 m length per pole are used. The insulators are made of a composite material and the weight is 5 kg/insulator.

Overhead contact line poles are used to carry the contact lines and other power equipments. Different poles are used in Sweden. A common and typical pole is "BV linjestolpe 120"[5]. This type of pole has been used in this study as a typical example of a standard pole. This pole is 8.1 m high and made of galvanized steel. The pole itself has a weight of 316.3 kg steel and 14.2 kg zinc. In addition to the pole, there is also a contact line holder (ca 50 kg). In total, the construction has been assumed to have a weight of 380 kg galvanized steel. The distance between poles is normally 60-65 m but decreased in e.g. curves. The average distance for the Bothnia Line is 54 m. For stabilisation, contact line poles can be equipped with stay wires. An example of electric power supply lines for train operation is shown in Figure 11.

The contact line carrying system is somewhat different in tunnels compared to other parts. However, the differences in material use and applications have been assumed too small to affect the results and therefore the same data have been used for the entire track.

In addition, there are different types of transformers (AT transformer, pole transformer, isolation transformer, local transformer, RM6 transformer, Trafo 11/22); there are UPS batteries; there are electronics and houses for electronic; there are many types of cables, both copper cables and aluminium cables. The cable isolation can be of different types but plastics of polyethene type are mainly used.

For train control, an EU standardised system, ERTMS/ETCS[6] level 2, has been used. ETCS level 2 is a digital radio-based signal and train protection system. Movement authority and other signal

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[5] Nielsen B., Bydén S., Holmberg L., LCA av kontaktledningsstolpar. Rapport från Melica på uppdrag av Banverket. LCA of contact line poles. Report from Melica on behalf of Swedish Rail Administration.

[6] European Rail Traffic Management System/European Train Control System.

aspects are displayed in the cab for the driver. No optical signals are required as the driver receives all essential information via GSM-R radio, the railways' own wireless communication system. The system consists physically of electronic balises on the track, electronics, UPS batteries and cables. For radio communication, tele-towers are used. In Figure 12 an example of houses for electronics and tele-towers for the train control system. Figure 13 show other types of houses for electronics in train tunnels.

Figure 11 The picture shows power supply line for train operation. On the pole to the right a pole transformer is shown.

Figure 12 The picture shows houses for electronic equipment used for train operation control (signal and telecommunication). On the right a telecommunication tower is shown.

Figure 13 Houses for electronic equipments.

5.4 Railway tunnels

Railway tunnels are used for passage through massive barrier of different materials when cuttings are not possible. The most common tunnels are rock tunnels but earth tunnels also exist. Earth tunnels are usually reinforced with a concrete lining. If the stability of earth is low, a freezing technique can be used. It is a relatively rare technique and energy consuming when the ground is artificial frozen during a year before the construction operation is taken place. Another technique that is used is the so-called cut and cover technique where a concrete tunnel is build in a cut and then covered with soil materials. In this study, only rock tunnels are analysed.

There are different techniques for construction of rock tunnels. The traditional method is by drilling and blasting. In addition to this method, there is also tunnel boring. This study covers only the traditional drilling and blasting techniques and not tunnel boring.

A railway tunnel consists of a main tunnel for the train traffic. In addition, there can be a service tunnel parallel to the main tunnel for e.g. evacuation of passenger in case of fire in the railway tunnel. There can also be an access tunnel. The access tunnel connects the service tunnel with the surrounding approximately half way of the tunnel length. The access tunnel is used for evacuation of the service tunnel and to create additional tunnel driving fronts during tunnel construction. Service and access tunnels are used for main railway tunnels longer than 600 m. Fire doors are used to connect the main tunnel with the service tunnel. Usually, there is one fire door each 500 m.

A railway tunnel has a relatively standardized geometry however depending on if it is a tunnel for single track or double track. The cross section area of a main railway tunnel is approximately 70 m^2. The installations in the tunnels are also relatively standardised. A schematic picture of a main railway tunnel is shown in Figure 14. The figure shows different tunnel components and tunnel dimensions. After drilling and blasting of the rock, the blasted rock is transported out of the tunnel and stored for internal use in the construction work or for external use. The tunnel walls are sealed with cement slurry to prevent leakage and reinforced with rock bolts. The tunnel walls are then covered with steel reinforced shotcrete (a type of concrete). Where water leakages exist, the walls are covered with foamed polyethene drains, which are also covered with shotcrete. The thickness of the shotcrete layer is approximately 80 mm but thinner layer exists. The shotcrete layer and the drains are then fixed to the tunnel wall with rock bolts.

The track rests on a bed of ballast. The base course under the sleepers has a thickness of approximately 0.3 m and a width of 6 m. The sub-base course of the ballast is 0.8 m thick (ballast type 0-150 mm). Below the sub-base course, there can be an additional sub-base course for frost protection. The frost protection layer is also 0.8 m thick (ballast type 0-150 mm). This layer is only used where frost protection is needed. The frost protection layer is used 0-600 m from each mouth of the tunnel. Thus, if the tunnel is shorter than 1200 m, the frost protection layer is used in the entire tunnel. The width of the sub-base courses is 8 m. Track ballast is used around the sleepers.

The design of service and access tunnels is relatively equal compared to main tunnels. The cross section area is smaller compared to the main tunnel (25.6 m^2 for service tunnels and 35.7 m^2 for access tunnels). The interior installations are mainly electric installation such as lightning, cables and cable suspension bridges.

Pictures showing an example of a main tunnel, a service tunnel and an access tunnel can be found below in Figure 15 - Figure 17.

Several other process operations are involved in the tunnel construction. The main operations are listed below:

- Geotechnical surveys for track foundation.
- Establishment of construction site.
- Forest felling.
- Clearing of soil.
- Open soil excavation.
- Construction of service roads.
- Erosion protection outside of the tunnel.
- Open hard rock excavation.
- Geotextile application outside of the tunnel.
- Application of protecting wire netting for rock outside the tunnels.
- Tunnel driving (blast hole drilling, cement injection, injection of explosives, blasting, post cement injection).
- Rock bolting reinforcement.
- Application of tunnel vault drains.
- Application of shotcrete.
- Construction of unbound base course and unbound sub-base course for frost protection.
- Application of tunnel portals.
- Application of fire doors from main tunnel to service tunnel.
- Application of cable channels with lids.
- Application of different cable man-holes.
- Application of fire water pipes and tank (steel tank or blast rock tank).
- Application of drainage water systems.
- Application of surface water systems.
- Application of footpath.
- Application of various foundations for e.g. contact poles, noise protections, stay anchors.
- Ventilation during construction.
- Water pumping during construction.
- Application of different electronic equipments for tunnel operation.
- Application of cable suspension bridges, handrails etc.

Railway tunnels are constructed relatively flat, usually with a minor fall. In this way, leaked water from the rock and surface water can pass the tunnel without pumping. Such a construction saves electric energy during operation of the tunnel. The energy use for lightning during operation of the tunnel is also very small because the train uses its own headlights.

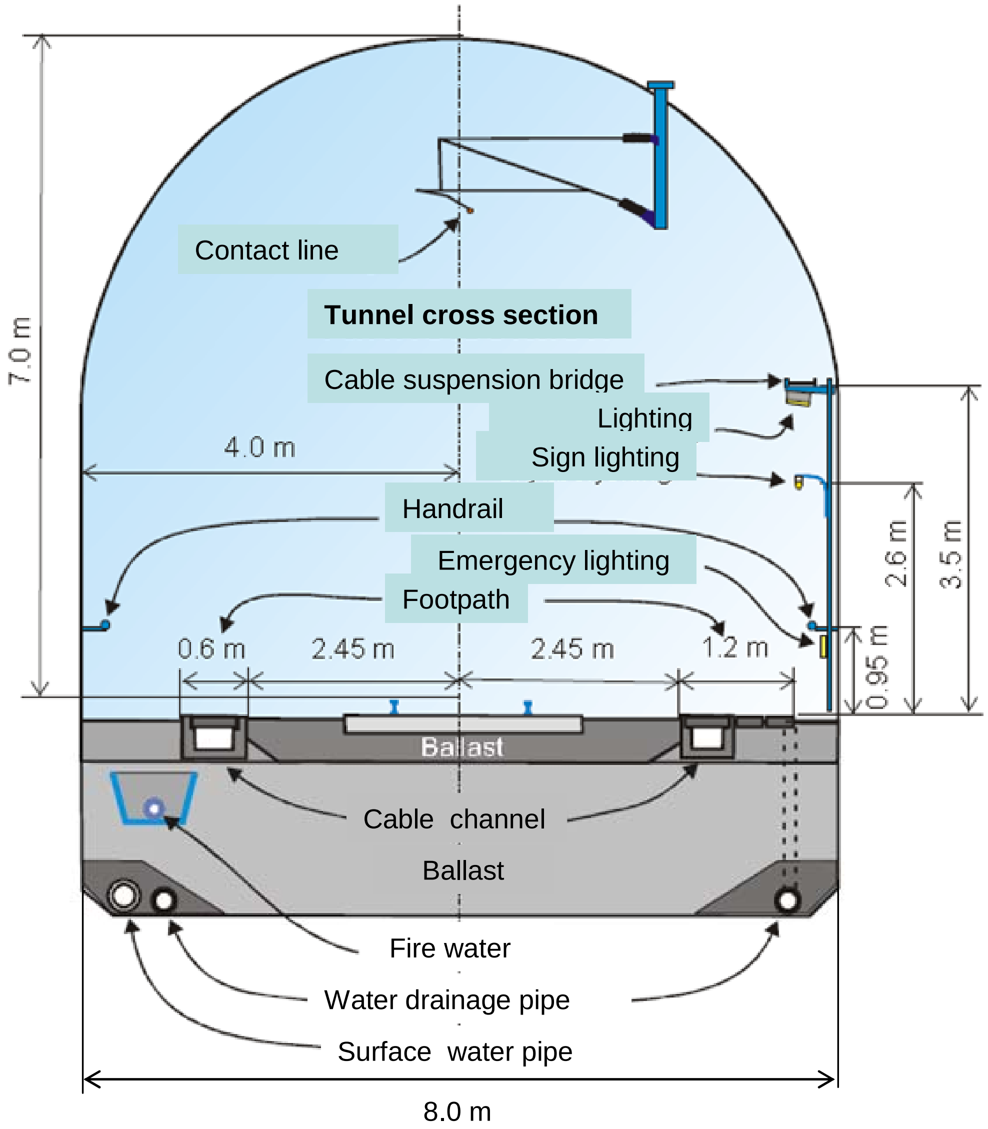

Figure 14 Cross section figure of a single track railway tunnel. The figure shows the main components and dimensions of a main railway tunnel (train tunnel). Ref. figure from the Bothnia Line.

Figure 15 The picture shows an example of a main tunnel (train tunnel) with the different equipments.

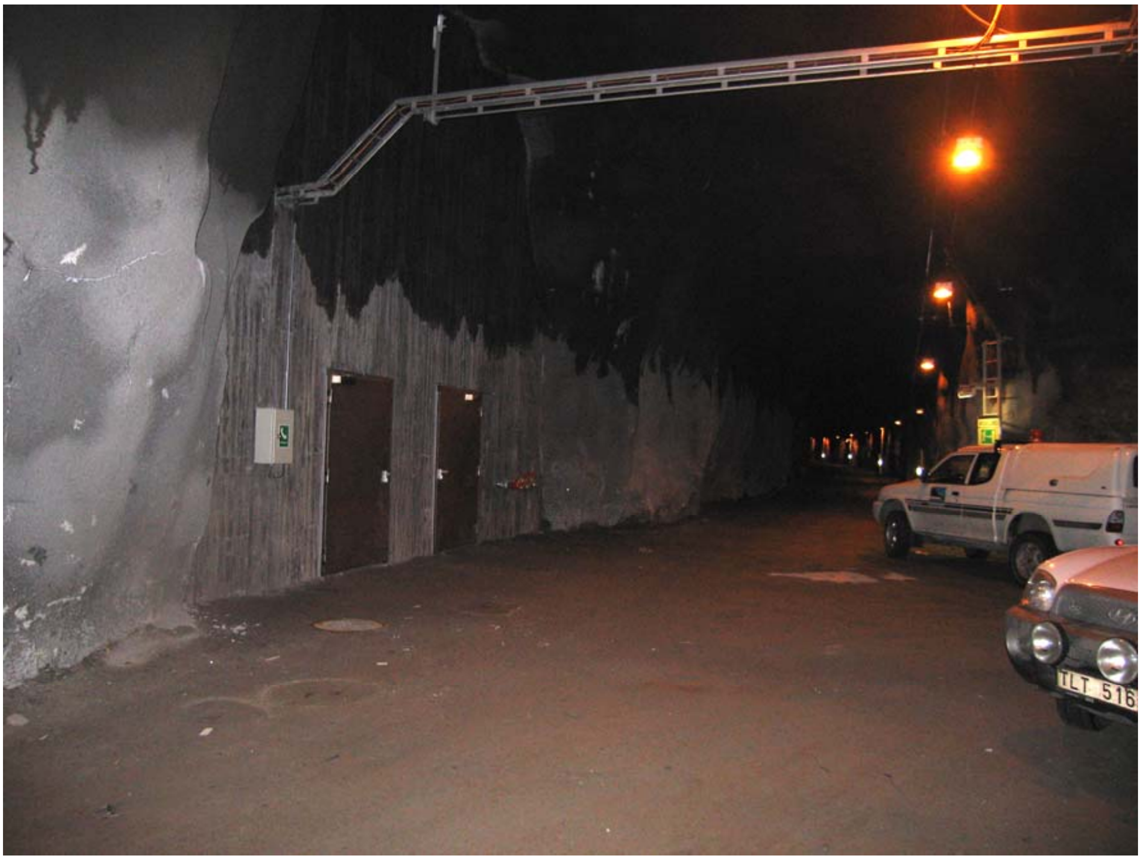

Figure 16 Example of a service tunnel. The doors are a part of the evacuation lock from the main tunnel to the service tunnel.

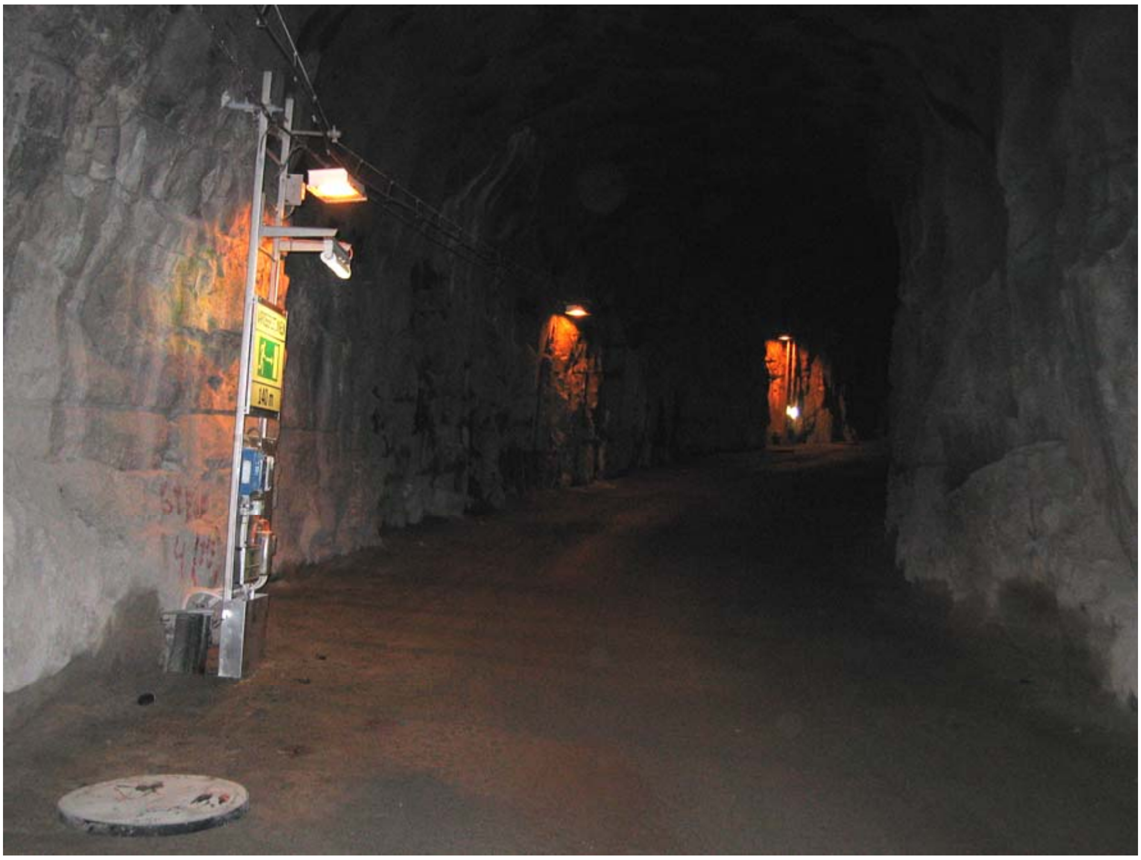

Figure 17 Example of an access tunnel.

5.5 Railway bridges

There are several types of bridges used for railway applications. A railway bridge needs to be a strong and solid construction. Three bridge types are commonly used in Sweden for railway applications.

- Concrete portal frame bridge (small bridges with two piers).
- Steel girder bridge (large bridges with several concrete piers and a superstructure made of a steel girder with an overlay structure of concrete).
- Concrete beam bridge (large bridges with several concrete piers and a superstructure made of concrete).

The LCA model of railway bridges is based on a relatively simple physical model, as default and where the material use can be changed if necessary (for more exact analysis of a specific bridge). This will provide a relatively good approximation even if many bridge designs are unique. The base input to the model is length of steel girder superstructure, length of concrete beam superstructure and total length of supporting piers for the bridge. The model can also combine calculations of several different bridges at the same time when calculating an entire railway with several bridges. In that case, the total length of the different bridge components is given. The calculation of the Bothnia Line is an example of such a method.

Examples of different bridge types and construction operations are shown in Figure 18 - Figure 21 below.

A LCA model of a railway bridge consists mainly of production of the different materials/products used for the bridge and the on-site construction of the bridge. The on-site construction consists mainly of many different small operations including construction of the concrete mould. The on-site construction is thus difficult to calculate using a bottom-up method. Instead different bridge construction projects have been analysed for material use, diesel use, electric power use etc. The LCA model for railway bridges is then based on a combination of top-down and bottom-up calculation.

The process operations that form the LCA model of the railway bridges are listed below:

- Geotechnical surveys for railway bridge (ground stability).
- Establishment of construction site.
- Forest felling.
- Clearing of soil.
- Open soil excavation.
- Construction of service roads.
- Open hard rock excavation.
- Application of concrete piles.
- Foundation construction and other filling.
- Construction of concrete pier foundations.
- Construction of concrete bridge superstructure.
- Construction of steel girder/concrete bridge superstructure.
- Construction of bridge parapet.
- Erosion protection at bridge abutments.
- Application of noise protection (steel, glass or wooden).
- Application of unbound track base course.
- Application of other ballast except ballast for track base course e.g. for bridge abutments.
- Application of cable channels with lid.

The operation activities for railway bridges are few. The operation activities are usually related to the tracks or signalling and telecommunication systems and thus not included in the bridge model. Maintenance activities for railway bridges are also few. Only replacement of certain components such as noise protections and cable channels exists.

Figure 18 A steel girder railway bridge. To the right in the picture, the erosion protection of the slope is shown.

Figure 19 A concrete beam railway bridge under construction. The slipform is shown in the foreground and the finished bridge is shown in the background.

Figure 20 The picture shows an example of foundation work for a bridge pier. In this case, the ground has been excavated, stabilized by precast concrete piles and a concrete foundation has been cast.

Figure 21 Casting of a railway bridge pier on top of the foundation. In the picture, the concrete mould with the steel reinforcement is shown.

5.6 Passenger stations and freight terminals

For passenger and goods transports, different types of buildings (railway stations and freight terminals) are needed for loading, unloading and as transfer stations. The construction of the different type of buildings is, in general, not different from ordinary buildings and storages. This means that standard LCA data for buildings can be used if no specific LCA data exist for the stations. Heating and electric power is needed for operation of the stations. Different type of heating systems can of course be used with different environmental performance. For freight terminals, loading equipment is also needed. The energy use for the loading equipment consists mainly of diesel oil and electric power. For especially railway passenger stations, many other activities can be found such as different shops and restaurants. Such activities that are not directly involved in the railway transport shall not be included in the railway infrastructure. In addition, there are also buildings for train maintenance, train traffic control, administration etc. Some of those activities can be common for e.g. an entire country and can thus be difficult to allocate to a specific railway line.

The number and size of stations on a railway route depends on local conditions around the railway and the transport work on the railway. The amount of buildings used can be described as area per railway distance (m^2 building/m railway). Along the Bothnia Line, there are seven passenger railway stations (area span of 45-2850 m^2), one large freight terminal (in Umeå, 130 000 m^2) and a smaller container terminal in Arnäsvall, just north of Örnsköldsvik. For the Bothnia Line as an example, the railway passenger stations have been calculated to 36 m^2 station per 1000 m main railway. Freight terminals have been calculated to 710 m^2 per 1000 m main railway. In total, there are 746 m^2 building area per 1000 m main railway at the Bothnia Line.

5.7 Passenger and freight trains

An entire transport of a passenger or a tonne of goods consists of both a share of the railway infrastructure and the actual transport i.e. construction, operation and maintenance of the transport vehicle (the train in this case). Thus, to be able to analyse an entire transport, full data for the trains have to be included in the LCA model.

Several different train types exist. Today many countries have also opened the railways for different train operators to increase competition. This implies that many different train types can operate a railway line. However, even if different train types exist, their basic design is relatively equal for a standard passenger train and goods train respectively. For passenger trains, the development during the last 30 years has focused on high speed trains with increased comfort. For goods trains, there are many different types of wagons depending on the type of goods. A very important factor for the environmental performance of the train transport is the energy use during operation of the train in terms of both quantity and type. The crucial factor is if the train is electrified or not and how the electric power is produced.

Life cycle assessment of trains is complex and usually LCA data sets from train manufacturer have to be used. The LCA data for the vehicle are also divided into construction, operation and maintenance. One passenger train and one goods train have been used in this study as examples of the vehicle and transport part. For the passenger train, a Coradia Lirex train has been used and for the goods train a locomotive of type RE460 with standard good wagons has been used.

The *Coradia Lirex* is an electric driven modern passenger train. The train type is chosen for operation at the Bothnia Line. The Coradia Lirex is produced by Alstom, Salzgitter and is a state-of-the-art single-level six-car EMU (Electric Multiple Unit) train. The vehicle is operated in suburban or similar traffic according to the Swedish regulations, rules and standards. The LCA data for the model are obtained from an EPD (Environmental Product Declaration) of the train[7]. The weight of the train is 206 tonnes. Maximum speed is 160 km/h. Number of seats are 374. Standing

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[7] Environmental Product Declaration: A Presentation of Quantified Product Information on the Life Cycle of the CORADIA LIREX Commuter Train for Stockholm/Sweden. Alstom.

passenger room: 544 (5 passenger/m^2). The data has been calculated for seating passenger only, because most of Swedish trains (including the Bothnia Line) are regional train operation in low populated areas. The data cover operation of the train with an average transport distance of 180 000 km per year and a lifetime of the train of 30 years. The transport work achieved by the train during its lifetime is thus 180 000*30*374*0.4=807 840 000 passenger-km assuming a load factor of 40 %. A 40 % load factor has been estimated for the Bothnia Line. (The actual train used for operation at the Bothnia Line is a 4-car train with 208 seats.) The larger train used in the EPD is used as an approximation of impact per passenger-km. This approximation can be a minor underestimation while a smaller train normally gives slightly lower transport efficiency.

The *Re 460* (also known as the Lok 2000) series are four-axle electric locomotives of the Swiss Federal Railways. Builders of the locomotive are SLM, Winterthur and ABB, Zürich. Build years are: 1991–1996. Length: 18 500 mm. Width: 3000 mm. Height: 4310 mm. Locomotive weight: 84 tonnes. Electric system: 15 kV 16 2/3 Hz AC. Top speed: 230 km/h. Power output: 6100 kW (8180 hp). Tractive effort: 275 kN, Continuous: 300 kN Max.

The inventory data (LCI)[8] includes material production, representing the material composition of one locomotive. For manufacturing, electricity and light oil burned in industrial furnace are included. For the transportation of materials, standard distances are applied. The life span of the locomotive Re 460 is assumed to be 40 years, resulting in a life-time performance of 9.6 million kilometres. Materials with a weight above 200 kg are accounted for. Manufacturing data represents a locomotive produced in Germany.

The goods transport prediction for Bothnia Line is 2 623 665 tonnes/year and 7679 train/year giving 2 623 665/7679=341.7 tonne goods/train. This gives a total lifetime transport work for the locomotive at the Bothnia Line of 341.7*9 600 000=3 280 320 000 tonne-km.

An ordinary goods wagon for 70 tonne load and an empty weight of 20 tonnes (in total 90 tonne) has been assumed in the study. Further, it is assumed that the wagon is made of steel only. A very rough estimation of the production of the wagon from raw steel has been made. The energy is assumed to be supplied by electric power and an electric energy consumption of 100 000 MJ electric energy per produced wagon has been used as an estimation including energy for the entire industrial production.

6 LCA models of railway infrastructure and railway traffic

A very important part of the system analysis is the development of the computer models used for the calculations in the analysis. For that purpose, LCA models of railway infrastructure and railway traffic have been developed in the project. The LCA models are made with the LCA software, KCL-ECO. A primary objective of the project work is to make flexible models that can be used to calculate an energy and environmental profile for an entire railway transport, including both the railway infrastructure and the railway traffic. Other field of applications are e.g. in the analysis of the design of the railway infrastructure in order to improve the construction. To meet these requirements, the LCA model has been made in different model units. The units can then be put together to form an entire railway transport model. The LCA model units are:

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[8] Ecoinvent database, 2006. Locomotive RER. Data representing year 1993.

- Railway track foundation model
- Railway track model
- Model of electric power and control systems for railways
- Railway tunnels model
- Railway bridges model
- Model of passenger stations and freight terminals
- Model of passenger and freight trains including train operation

All models are divided in construction, operation and maintenance. The construction part covers the initial construction of the new railway. The operation part includes the on-going operations during the lifetime of the railway such as electric power use for operation of the trains, for heating of railway switches or for operation of control electronics. The maintenance includes replacement of old railway components when the lifetime of the components has expired. The layout of the model structure has been chosen to reflect the order in which the railway is constructed. The different models are shown in appendix A, Figure 90 - Figure 101. Unfortunately, it is very difficult to show an entire model with a readable format in a report. Even the unit models are to complex to be readable in the report; they can easily be read as pdf-file on the computer screen using the zoom enlargement of the Acrobat Reader.

7 Technical model data - LCI

Many different environmental parameters can be covered in a life cycle inventory. A comprehensive number of consistent parameters have thus been selected for the study. The parameters cover energy resource use, material resource use, emissions and wastes. In Table 2 below, the main parameters covered in the model are shown. The different waste categories have no unambiguous definition. Radioactive waste is however strictly related to the production of nuclear power. Mineral waste is here defined as relatively inert materials usually from mining operations. If possible, wastes have been specified by the material in the waste e.g. waste, concrete or waste, polyethene.

Table 2 Main parameters included in the study.

Variables
<Emissions to air>
Acetylene (air)
Aldehydes (air)
As (air)
Benzene (air)
Benzo(a)pyrene (air)
C4 and alkene (air)
Cd (air)
CFC/HCFC (air)
CH4 (air)
CH4 (CO2 equivalent)
Chromtrioxid (air)
Cl2 (air)
CO (air)
Co, metal (air)
CO2 uptake concrete
CO2, biogenic (air)
CO2, biogenic (deforestation)
CO2, fossil (air)
Cr (air)
Cr VI (air)
CS2 (air)
Cu (air)
Dichloroethane (air)
Ethane (air)
Ethene (air)
Ethylbenzene (air)
Ethylene (air)
F2 (air)
H2, air
H2S (air)
H2SO4 (air)
HC (air)
HC aromatic (air)
HC chlorinated (air)
HCl (air)
HCN (air)
Hexachlorobenzene (air)
HF (air)
Hg (air)
Methylene chloride, CH2Cl2 (air)
Mn (air)
Mo (air)
N2O (air)
N2O (CO2 equivalent)
NH3 (air)
Ni (air)
NMVOC (air)
NOx (air)
O3 (air)
organics (air)
Other organics
PAH (air)
Particles (air)
Particles 2.5 to10 (air)
Particles <2.5 (air)
Particles >10 (air)
Pb (air)
Phenol (air)
Propane (air)
Propene (air)
Propylene (air)
Radioactive emiss.
Radioactive emissions
Radon 222 (air)
Rn-222
Se (air)
SF6 (air)
Sn (air)
SO2 (air)
SO3 (air)
Styrene (air)
TCDD eqv. (air)
Tl (air)
Toluene (air)
V (air)
VCM (air)
VOC (air)
Xylenes (air)
Zn (air)
<Emissions to soil>
As (soil)
Cd (soil)
Cr (soil)
Cr VI (soil)
Hg (soil)
Ni (soil)
Oil, unspec. (soil)
Pb (soil)
Sn (soil)
Zn (soil)
<Emissions to water>
Acids as H ion (aq)
Al (aq)
AOX (aq)
As (aq)
Benzene (aq)
BOD (aq)
Br (aq)
Ca (aq)
Carbonate ions (aq)
Cd (aq)
Chloride ions (aq)
Chromtrioxid (aq)
Cl (aq)
Cl ions (aq)
ClO3-- (aq)
CN ions (aq)
Co (aq)
COD (aq)
Cr (aq)
Cr VI (aq)
Creosol (aq)
Cu (aq)
Detergent/oil (aq)
Dichloroethane (aq)
dissolved Cl2
Dissolved organics (aq)
Dissolved solids (aq)
DOC (aq)
F (aq)
Fe (aq)
H2S (aq)
HC (aq)
HC aromatic (aq)
HC chlorinated (aq)
Hg (aq)
K (aq)
Lead Pb (aq)
LS (aq)
Mg (aq)
Mn (aq)
Mo (aq)
N, excl. NH3 (aq)
N, total (aq)
Na (aq)
NH3/NH4 (aq)
Ni (aq)
Nitrate (aq)
Nitrite (aq)
Oil, unspec. (aq)
Organics (aq)
Other nitrogen but NO3
other organics not specified elsewhere (aq)
P as P2O5 (aq)
P, total (aq)
PAH (aq)
Pb (aq)
Phenol (aq)
Phosphate (aq)
Phosphate as P2O5 (aq)
PO4 (aq)
Radioactive emissions (aq)
S, total (aq)
Sb (aq)
SiO2 (aq)
Sn (aq)
SO3 ions (aq)
SO4 ions (aq)
Sodium, Na (aq)
Sr (aq)
Sulphate (aq)
Sulphides (aq)
Sulphur/sulphide
Suspended solids (aq)
TOC (aq)
TSS (aq)
V (aq)
VCM (aq)
waste, oil (aq)
Zn (aq)
<Energy resources-non renewable>
Coal
Crude oil
Natural gas
Nuclear
Peat
<Energy resources-renewable>
Biomass fuel
Hydro power
Wind power
<Resources-non renewable>
Ag (res)
Al (res)
Anhydrite CaSO4
Au (res)
Baryte BaSO4
Basalt
Bauxite AlO(OH)
Bentonite
Calcite, CaCO3
Calcium sulphate (CaSO4)
Clay mineral
Cr (res)
Cu (res)
Dolomite CaMg(CO3)2
Fe (res)
Feldspar
Ferromanganese

Fluorspar CaF2
Gravel
Gypsum
Hg (res)
Iron sulphate
KCl (res)
Limestone CaCO3
Magnesite MgCO3
Mg (res)
Mn (res)
Mo (res)
NaCl (res)
Natural sand and gravel
Ni (res)
Olivine (Mg,Fe)2SiO4
Pb (res)
Pd (res)
Phosphate as P2O5 (ore)
Pt (res)
Rutile, TiO2
Sand and gravel
Shale
Silica sand SiO2
Solid rock
Zn (res)
<Resources-renewable>
Biomass
Land use

Water
Water, cooling
Water, fresh
Water, salt
Wood kg (res)
Wood kg DS (res)
Wood m3 (res)
<Wastes, liquid>
Drilling water
Waste oil
<Wastes, solid>
Chlorinated rubber
Concrete to landfill (waste)
EAF slag
High radioactive
Inert chemicals
Low radioactive
Medium radioactive
Mineral wool to landfill (waste)
Municipal solid waste (W)
Regulated chemicals
Slag and Ash
Waste to incineration
Waste to landfill
Waste to recycling
Waste, Al
Waste, concrete

Waste, construction
Waste, Cu
Waste, demolition (inactive)
Waste, drains
Waste, glass
Waste, hazardous
Waste, highly radioactive
Waste, industrial
Waste, mineral
Waste, other
Waste, Pb
Waste, plastics
Waste, polyethene
Waste, radioactive
Waste, reg. chem.
Waste, shotcrete
Waste, steel
Waste, unreg. chem.
Waste, unspecified
Waste, wood
Waste, wood sleeper

An important criterion for the selection of data and system boundaries is the strategic choice of data representation. LCI data in a model can represent different types of data e.g. data for a specific process, average data for a number of processes (European average, country average etc.), data for a certain technology standard or data for a certain type of plant. The selected strategy depends for example on the aim of the study and data availability. The choice of data strategy will also influence the data quality achieved. Reliable average data, e.g. European average, are usually very difficult to achieve and evaluate. It is usually difficult to define the technology level because the data represent different types of processes and different technology levels. Therefore, average data are best used in background processes in a LCI study where no detailed evaluation of the process will be performed. The overall data selection criterion for this study has been to identify and specify certain technology levels of processes and based on that defines energy, resource and emission data. This is achieved by studying a modern newly build railway line (the Bothnia Line). In this way, reliable technical data can be obtained. The disadvantage is of course that the results will reflect a specific railway line but results are always specific in some way or another so in this case we have chosen to carefully comment and identify the unique local aspects (e.g. use of green electric power) in the results so that the reader can valuate the results. In this way we hope that the results will be both reliable and generally useful for many applications not directly related to the Bothnia Line or to Sweden.

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 (soil conditions, rock quality in tunnels) etc. Generally for this model, the accuracy is relatively high for the energy resource use and for the material resource use under the assumed conditions. The precision for the emissions varies with substance. Generally, the precision is higher for the most common and best mapped emittants (CO_2, SO_2 and NO_X) compared to the other emittants. The accuracy for the waste components are relatively low but quantities of specific demolition wastes from the railway infrastructure is well defined.

LCI data for this project have been obtained from different sources such as literature data, data from single plants and processes in operation, data from equipment supplier, data from legislation and directives. Process data for the different parts of the railway infrastructure (tunnels, bridges, foundations, tracks etc.) has been obtained from Botniabanan AB or its building contractors. Transport data (per tonne-km) for external transports (e.g. to the construction site) has been obtained from NTM[9], Sweden. All data sets have been described carefully in the models with references. However, in total all the models include approximately 32 000 variables and it is thus not possible to give a detailed specification of all variables in the entire model in this report. Based on the requirements in the ISO standard the following general information can be given concerning the data quality, see Table 3 below.

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 electric power production mix has been used. For operations driven by the Swedish Rail Administration (such as train operation and operation of the rail infrastructure) a specific "green" electric power production mix has been used since the Swedish Rail Administration purchase that type of specific electric power as a part of their environmental strategy. The purchased "green" electric power production mix in year 2008 was 99.2 % hydropower based and 0.8 % biomass fuel based. All electric power supply calculations include production of the electric power and distribution losses in the electric power grid. The distribution losses have been estimated to 4 % in the electric power grid to industrial applications. For the power supply to the trains, the distribution losses have been estimated to 12 % in the electric power grid for the Swedish railways. All energy use is calculated back to primary energy resource use. 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 and distribution losses.

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

Table 3 General specification of inventory data.

Data quality subject	Coverage and strategies for inventory data
Time-related coverage	Data for a newly build railway with modern technology (completed 2010). Most of other data (foreground and background) represent the most reason and applicable LCA data available. A goal is to use data not older than 5 years, but for LCA data that is a fairly short time and LCA data are not updated that often. Older LCA data than 5 years has thus been used but only for data that has not undergone any significant changes during the time period until today. The model covers construction, operation and maintenance of the railway (Bothnia Line) during a calculation period of 60 years.
Geographic coverage	The focus in the study has been on the Bothnia Line which is a railway situated in the north of Sweden. Some of the data reflects the geographic location such as use of frost protection in the construction, use of Swedish green electric power, transport of materials to the construction site. The topography at the Bothnia Line (many tunnels and bridges) also plays a significant role. Generally, we have tried to use specific production data for materials as much as possible (e.g. Austrian production of rails). Some data are however general data such as production of plastics which mostly represent European average data.
Technology coverage	Modern railway technology has been used as well as modern production data of the railway (Swedish production). The design of the railway is described in chapter 4 and 5. The specific material used at the Bothnia Line has also been used in the model. Normal but high quality materials have also been assumed. For the material production the existing LCA data level has been used for the different materials. These data covers normally an environmentally good but ordinary production in a specific plant or European average.
Precision, completeness and representativeness of the data	The model together with the included base data represents an example of a railway and a selection of data and processes. The LCA data are calculated from the original resource use to the waste handling of the demolition waste during 60 years. Data for production of production equipment such as steel plants, cement and concrete plants, trucks, rollers etc. have not been included. A yearly maintenance share is used in the model so the model results always show the results for a maintained railway.
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 railway line is relatively unique due to topography, soil conditions, transport distances, processes and materials used etc. and the overall results reflects the specific conditions at the defined production site.
Sources of the data and their representativeness	Almost all quantity data regarding material and construction are obtained from the Bothnia Line. Material production data are obtained from general LCA data sets or producers of the materials. Specific data have been used for materials used in large quantities.
Uncertainty of the information	Exact figures of the uncertainty of the data are not possible to achieve.

8 LCA model tests and verifications

The calculation methodology used in the LCA model calculations is already described in chapter 3.1. In general, a “top-down” approach has been used for the model calculations. This means that the models are built up by different smaller sub-processes that can be specified in terms of energy and environmental parameters. However, such a “top-down” model tends to model a complex process in a theoretical perfect schematic way. In a real process situation, the construction work may differ from the theoretical model scheme. It can therefore be useful to verify the model calculation with real construction data if possible. In this case, the Bothnia Line comprises many different construction projects for e.g. railway foundations, tunnels and bridges that can be used for verification and where process data have been collected during the construction phase. Such verifications have thus been performed to test and eventually calibrate the LCA models. In this type of verification, it has only been possible to verify the construction phase and not the maintenance and operation phase. Verifications have been performed of three railway foundation projects and three tunnel projects. In addition, the LCA model for railway bridges is based on real construction projects because it was not possible to break down an on-site bridge concreting process in sub-processes to make a “top-down” model. Instead real bridge construction data for diesel and electric power use have been used in the model. For general purpose, the energy use has been scaled to the length of the bridge (energy use per meter bridge has been used in the model).

In the verification of the railway foundation model, three different foundations were tested. The foundations represent a heavy work foundation with much excavation and ground stabilisation work, a light foundation with a minimum of excavation and stabilisation work and one medium foundation with a work level in-between the two other foundations. The technical quantities of e.g. excavated materials etc. were inserted in the model for the three types of foundations and the use of electric power and fuels (mainly diesel) from the model calculations were compared with the actual use reported in the foundation projects. The model calculations for the diesel use show a good compliance for the medium work foundation. The diesel use for the heavy work foundation show an underestimation while the diesel use for the light work foundation show an overestimation. No obvious explanation of this has been found and no action was taken to adjust the model concerning diesel use. The electric power use was also compared in the same way as the diesel use. The model includes very little of the general energy use at the construction site. Thus, the model is using a general electric power use taken from the light and heavy work foundations. The general electric power use has been calculated to 46.5 MJ/m foundation.

Railway tunnels have been studied in the same way as railway foundations. Three different tunnel types have been studied representing a short (only main tunnel), medium (with access tunnel), and long tunnel type (with service and access tunnel). The different construction project has been studied with respect to energy use (electric energy, diesel and gasoline consumption). All three models underestimate the diesel use. An adjustment of 25.9 MJ diesel/m^3 tunnel has been used. The models show also a small underestimation of the electric power use. An extra general electric power use of 11.7 MJ/m^3 tunnel has been added.

In addition to the technical verification mentioned above, an external verification process has also been used. In accordance with the EPD system regulations, the LCA models/data, additional environmental information and the EPDs have passed an external verification process by a third party verifier (Bureau Veritas, Sweden).

9 Results from scenario analyses

As shown in the previous chapters, different LCA models have been developed for both specified railway components (such as tracks, tunnels, bridges etc.) and for entire railway lines where the different components have been put together to form an entire railway line. The models have then been used in different railway scenarios to show the performance and technical details of a railway system. In this chapter, the results from the scenario analyses are presented for both the railway components and an entire railway line. In the railway component analyses, general model scenarios have been used to give as general and useful information as possible. In this analyse part we have tried to set up a scenario that will reflects many different details of the components and then we have tried to present the results from different perspectives. For the railway line analysis, the Bothnia Line has been used as an example. Results from the EPD calculations are also shown in this chapter. The LCA data used in the EPDs are entirely based on the LCA railway models presented in this report. Small differences between the results used in the EPDs and the results presented in this research study can exist due to updated and different assumptions of some material use and some transport distances. The differences only reflect a further development of the models and the latest results are used in this research presentation.

9.1 Railway track foundation analysis

9.1.1 Analysis and scenario description

The railway track foundation model covers all the processes that form the foundation of the railway track. This includes preparation of the land area (such as forest felling, soil removal and planing), ground stabilisation activities, formation of the different base courses, soil cut excavation, rock cut excavation etc. It is thus of importance to create a scenario that can exemplify these activities. A general description of railway track foundations can be found in chapter 5.1. A one kilometre long, track foundation has been studied. The results are then presented both divided in construction, maintenance and operation and in different separate process steps. The specification of the scenario foundation is shown below in Table 4.

Table 4 Specification of the railway track foundation scenario used in chapter 9.1.2.

Activity/Process	Description
Foundation length	1000 m
Width of railway area (technotope[10])	43 m
Geotechnical survey	Yes
Forest felling	An initial forest landscape is assumed with 112 m^3 sub/hectare. Forest harvest area is thus 43*1000=43000 m^2. This gives a total forest amount of 481.6 m^3 sub.
Clearing of top soil	5000 m^3
Ground stabilisation (cement/lime columns)	50 m stabilisation length. 1.5 m distance between columns giving 132 columns. 10 m length of each column gives a total column length of 1320 m.
Ground stabilisation (concrete piles)	50 m stabilisation length. 3 m distance between piles giving 51 piles. 10 m length of each pile gives a total pile length of 510 m.
Earth cut	100 m length of foundation giving 20 000 m^3 soil excavation. Geotextile used in earth cut foundation (1200 m^2).
Rock cut	100 m length of foundation giving 20 000 m^3 rock excavation.
Erosion protection	Along the 100 m earth cut giving 4000 m^2 erosion protection.
Rock bolting area	800 m^2
Protecting steel net	800 m^2
Noise protection length	200 m (37.7% in steel design, 10.1% in glass design and 52.2% in wood design) same distribution as in the Bothnia Line
Protection fences	200 m
Blast stone filling	15 m^3/m railway foundation (15 000 m^3 in total)
Soil filling	10 m^3/m railway foundation (10 000 m^3 in total)
Crushed aggregate filling	1.5 m^3/m railway foundation (1500 m^3 in total)
Unbound base course	1.2 m^3/m railway foundation (1200 m^3 in total)
Unbound subbase course	7.6 m^3/m railway foundation (7600 m^3 in total)
Unbound subbase course for ground frost protection	8.4 m^3/m railway foundation (8400 m^3 in total)
Equipments	Concrete culverts and manholes are used. Power pole foundations are included.
Service road	1000 m
Cable channels	1000 m
Water drainage	200 m used in earth and rock cuts
Transports	Transports covering different materials in construction, operation and maintenance. Distances and transport type reflects the situation at the Bothnia Line.
General electric energy use (heating of offices and other localities, illumination of construction site etc. during construction.)	46.5 MJ/m foundation

In addition to this fictive track foundation, the results from the Bothnia Line foundation are shown in chapter 9.1.3.

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[10] A category of the Biotope method developed by Vattenfall. Ref. The biotope method 2005 - a method to assess the impact of land use on biodiversity. (2005) Vattenfall AB.

9.1.2 Results from the analysis

9.1.2.1 Energy results

The use of both non-renewable and renewable energy resources is shown in Figure 22. The energy use is shown over a 60 years calculation period. As shown in the figure, the use of non-renewable energy is much larger than the renewable energy (hydro, wind and biomass power) use. The construction phase is also larger than the maintenance phase concerning energy resource use. No operation energy is required for the track foundation. The overall main energy resource is crude oil. The reason for this can of course be found in the use of many different diesel driven heavy machines for construction work and transports. Coal is mainly used in steel production and for production of lime and cement.

In Figure 23 the total energy resource use has been divided into different sub-processes to show the distribution of the energy use. The electric power calculated is however here shown separately as a lump sum. The used electric power is Swedish production (mainly hydropower and nuclear power). As shown in the figure there is no dominating energy process but the energy use is well distributed among the sub-processes even if some processes show a significant energy use. It is however worth to note that some energy use is of a more constant nature while others depend very much on the local conditions. For example clearing of top soil, culverts and pipes, general construction site, foundation construction and service road are relatively constant per km of railway foundation while others such as fences and noise protection, ground stabilisation, earth and rock cuts depends very much on the local conditions and can thus be much less or much more. Forest felling can be treated as a maximum or high level because the example is assuming an area completely covered with forest.

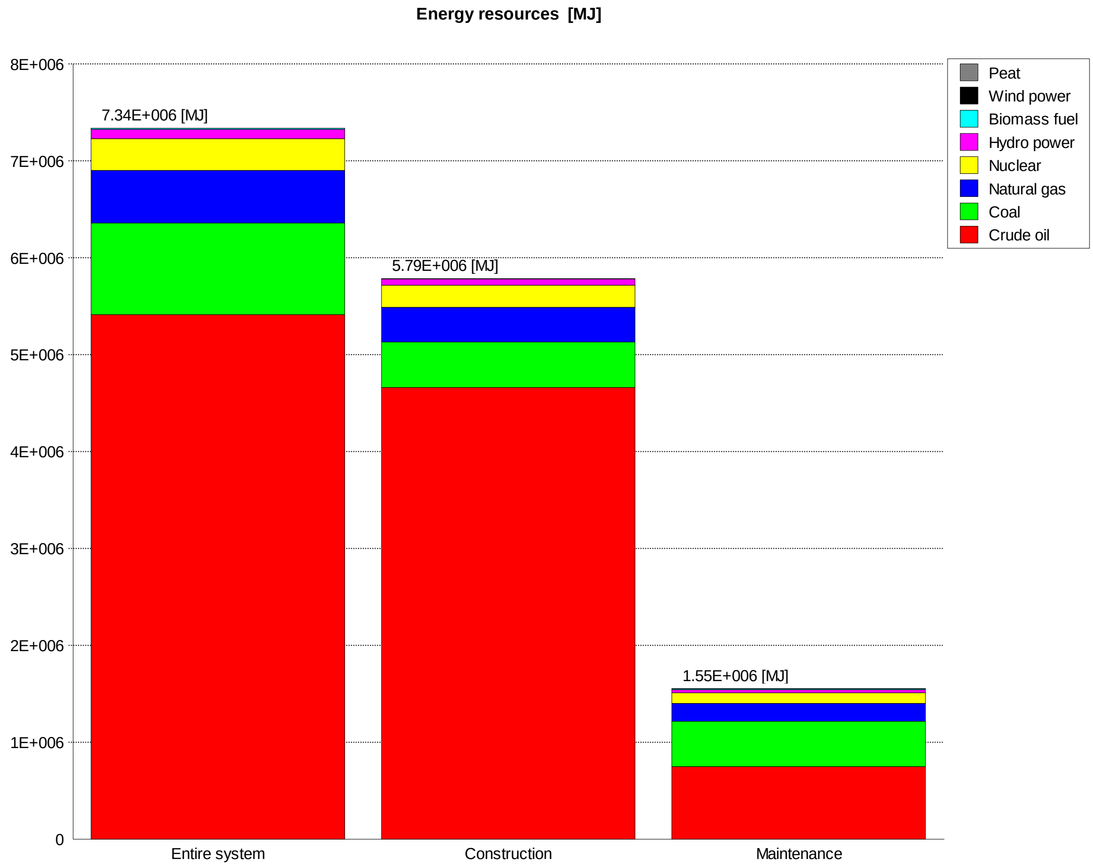

Figure 22 Use of primary energy resources for 1 km track foundation. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. The track foundation has no energy use for operation.

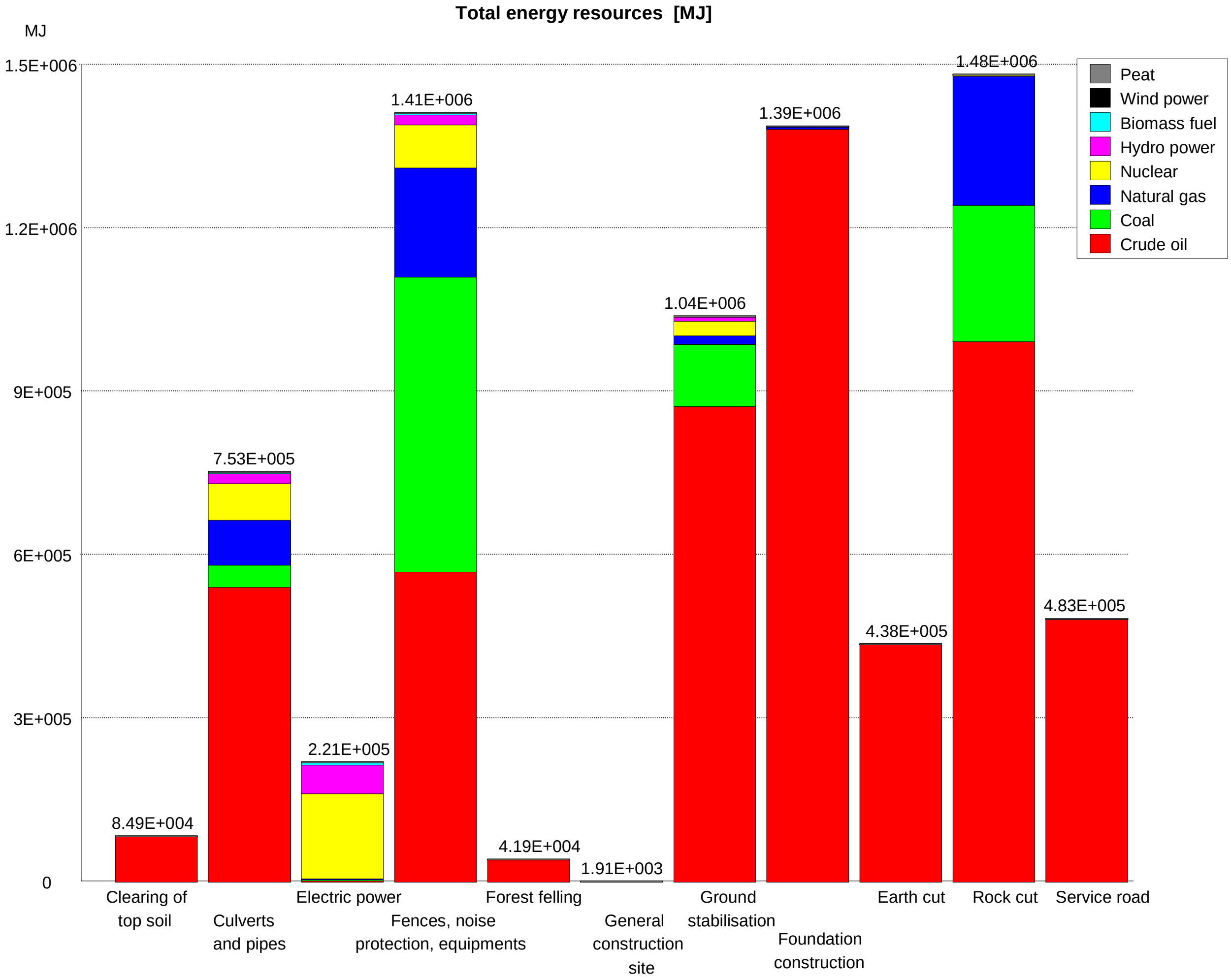

Figure 23 Use of primary energy resources for 1 km track foundation divided into different sub-processes. The figure includes construction, maintenance and operation over a calculation period of 60 years. The electric power use calculated in the model is shown separately.

9.1.2.2 Emission results

There are many different emissions and other parameters in the model and it is not possible to analyse the results for every parameter. The focus has been to show some central examples in order to give a picture of the model dynamics. A more complete picture of the results is shown in the next chapter covering the Bothnia Line example.

The emission of greenhouse gases for the railway foundation is shown in Figure 24 and Figure 25. The emission pattern of the greenhouse gases is similar to the energy use shown in the previous chapter. The reason for this is of course that the greenhouse gases emanate from combustion in energy production. An important difference is however the emission of CO_2 from deforestation. When CO_2 emanates from e.g. combustion of biomass, the emission is handled as biogenic CO_2 and accounted as a zero emission because the growing forest after replanting is taking up an equal amount of CO_2 as released in the combustion of the biomass. In an establishment of a railway, no replanting is taking place on the railway area. Therefore, the assumed emissions from the combustion of the removed biomass will not be neutralised by uptake of new, growing forest in the same area. The assumed CO_2 emission from the biomass therefore has to be treated similar to a fossil CO_2 emission. This special CO_2 emission from the new railway area is shown separately as CO_2 deforestation. The CO_2 deforestation occurs in the construction phase and stands, in this case, for a significant contribution to the greenhouse gases. However, note that if less forest exists on the construction site, the CO_2 deforestation emission will be reduced. This model example assumes a large amount of forest on the construction site. Concerning the greenhouse gases in general, we can conclude that the emission of CO_2 is by far the most important. A small amount of N_2O exists, mostly at the rock cut excavation. This emission occurs mostly in the production of ANFO explosives.

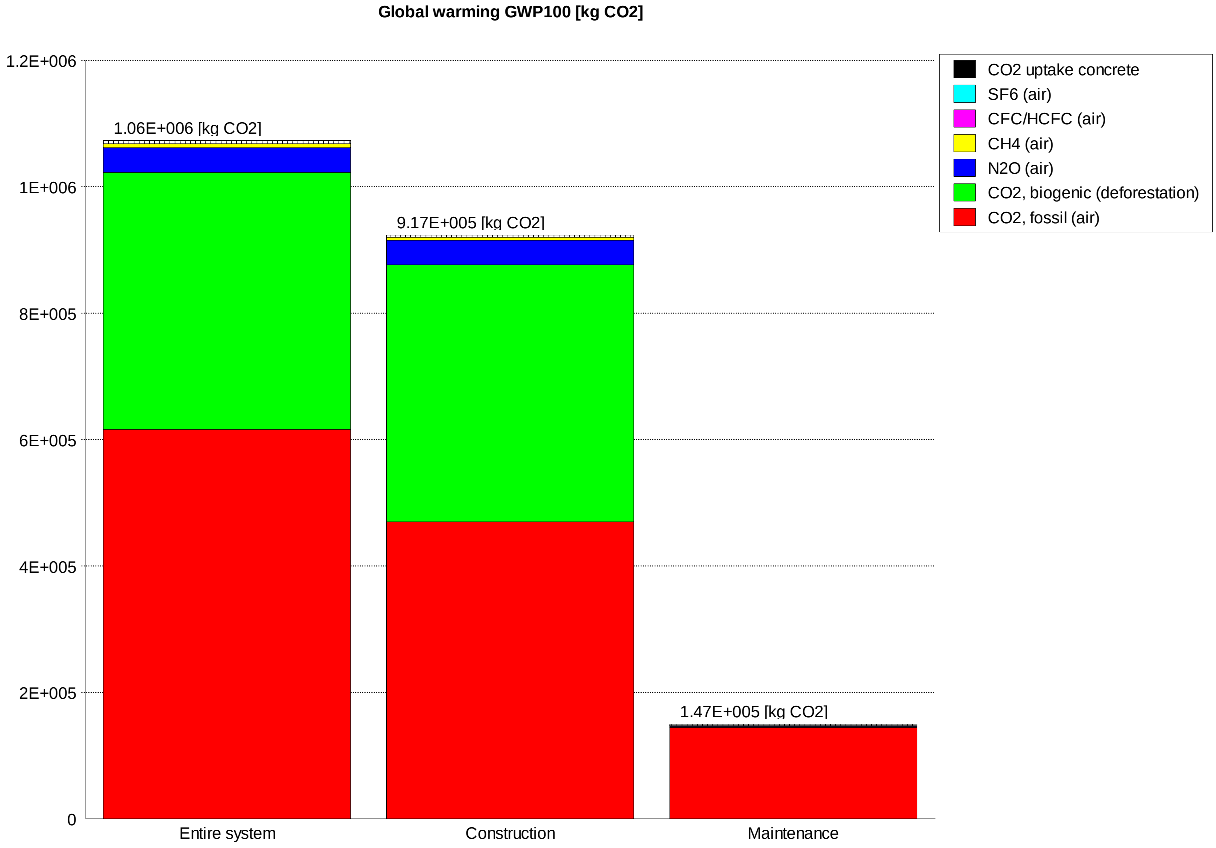

Figure 24 Greenhouse gas emissions from 1 km track foundation expressed as global warming potential (GWP). The figure shows the entire life-cycle (entire system) and GWP divided into construction, maintenance and operation over a calculation period of 60 years.

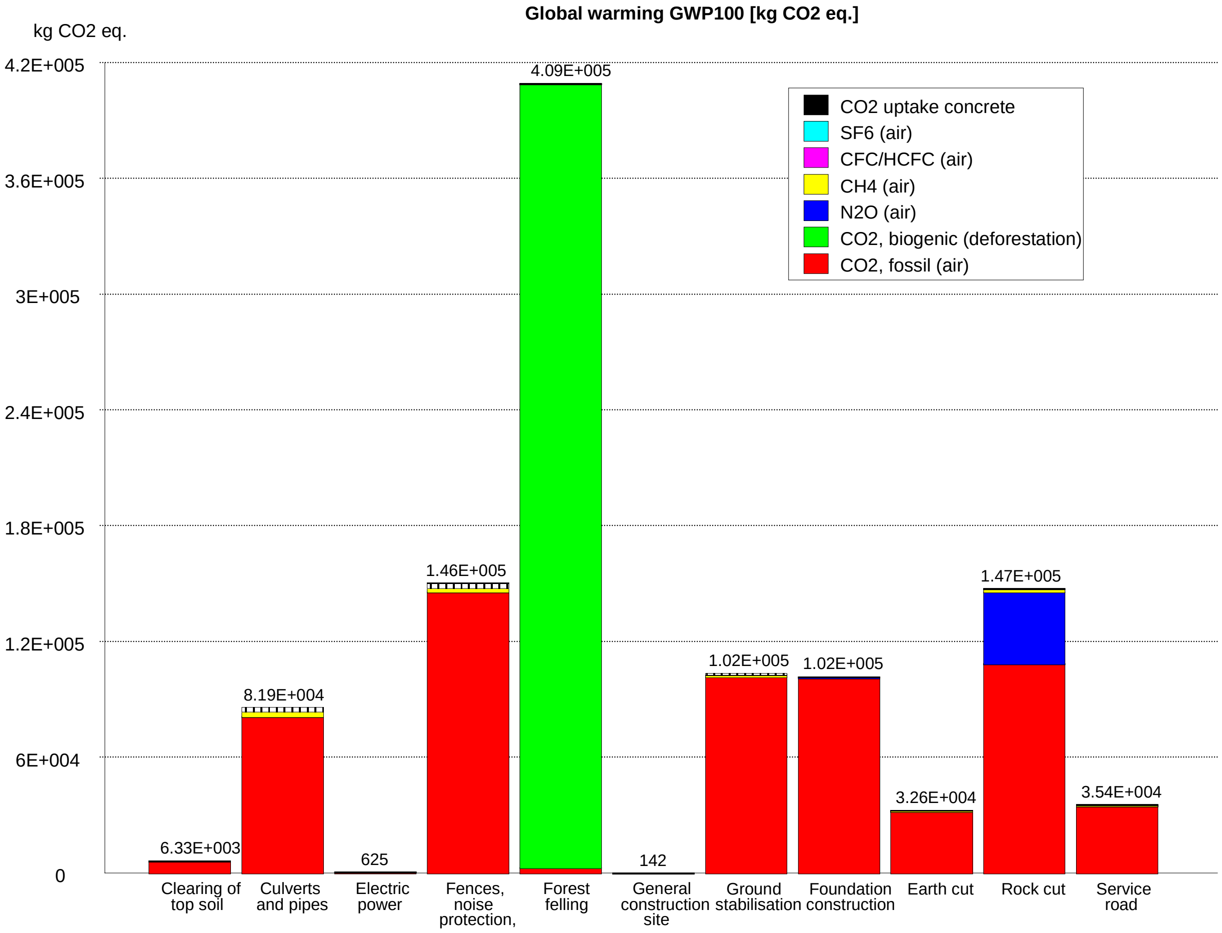

Figure 25 Greenhouse gas emissions from 1 km track foundation expressed as global warming potential (GWP). The figure shows GWP divided into different sub-processes. The results covers the entire life-cycle including construction, maintenance and operation over a calculation period of 60 years.

Also the acidification potential and the eutrophication potential show the same pattern as for the energy use as shown in Figure 26 and Figure 27. The acidification potential is calculated in kg SO_2 equivalents. The dominant contributors to the acidification potential are NO_X- and SO_2-emissions. Some small amount of NH_3 from production of explosives also contributes. The eutrophication potential is calculated in kg PO_4 equivalents and the dominating emittant is NO_X. We can conclude that the NO_X emission is important in many sub-processes and the source of the NO_X emission is mainly diesel engines and other combustion processes.

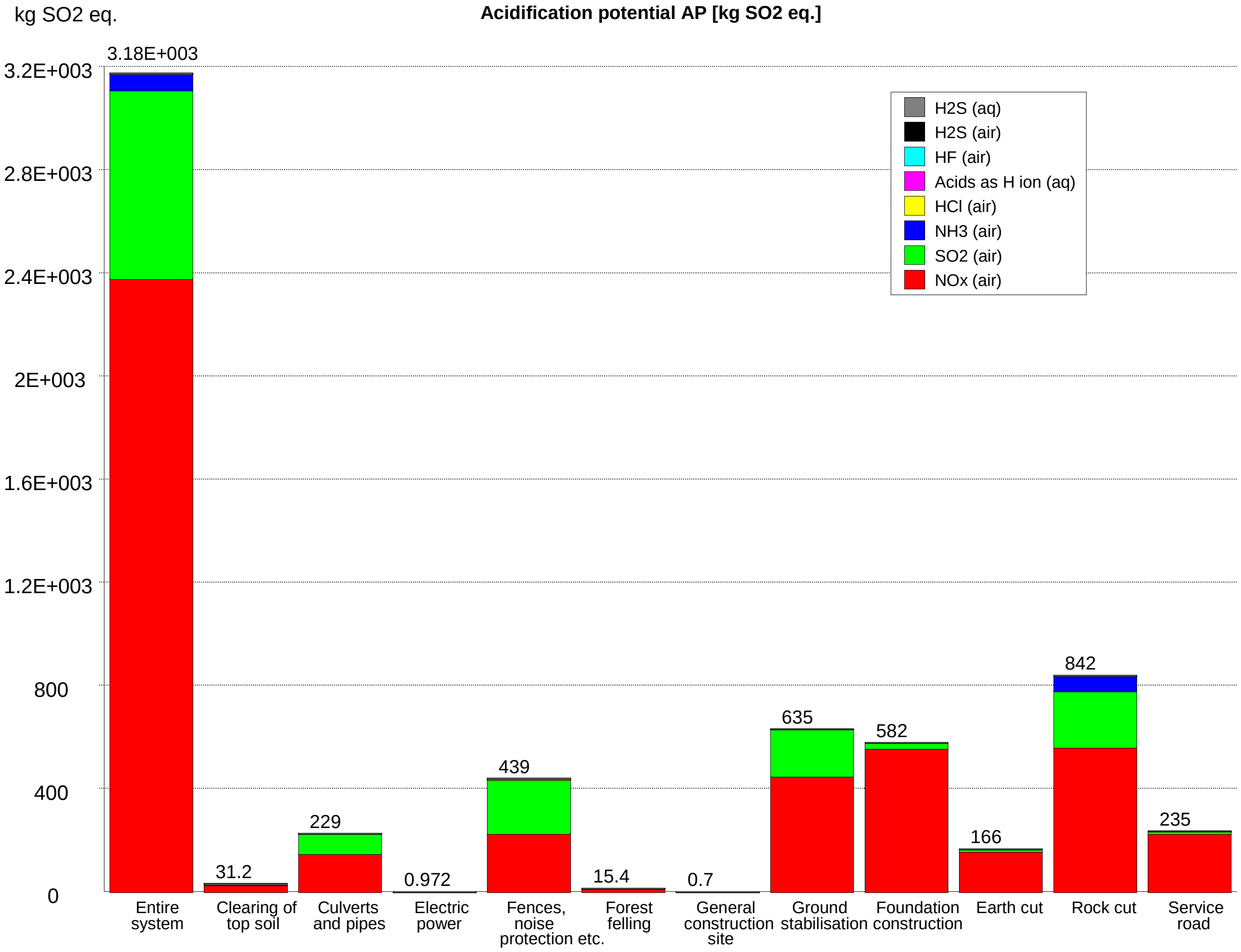

Figure 26 Emission of acidifying substances from 1 km track foundation expressed as acidification potential (kg SO_2 equivalents). The figure shows AP divided into different sub-processes. The results covers the entire life-cycle including construction, maintenance and operation over a calculation period of 60 years.

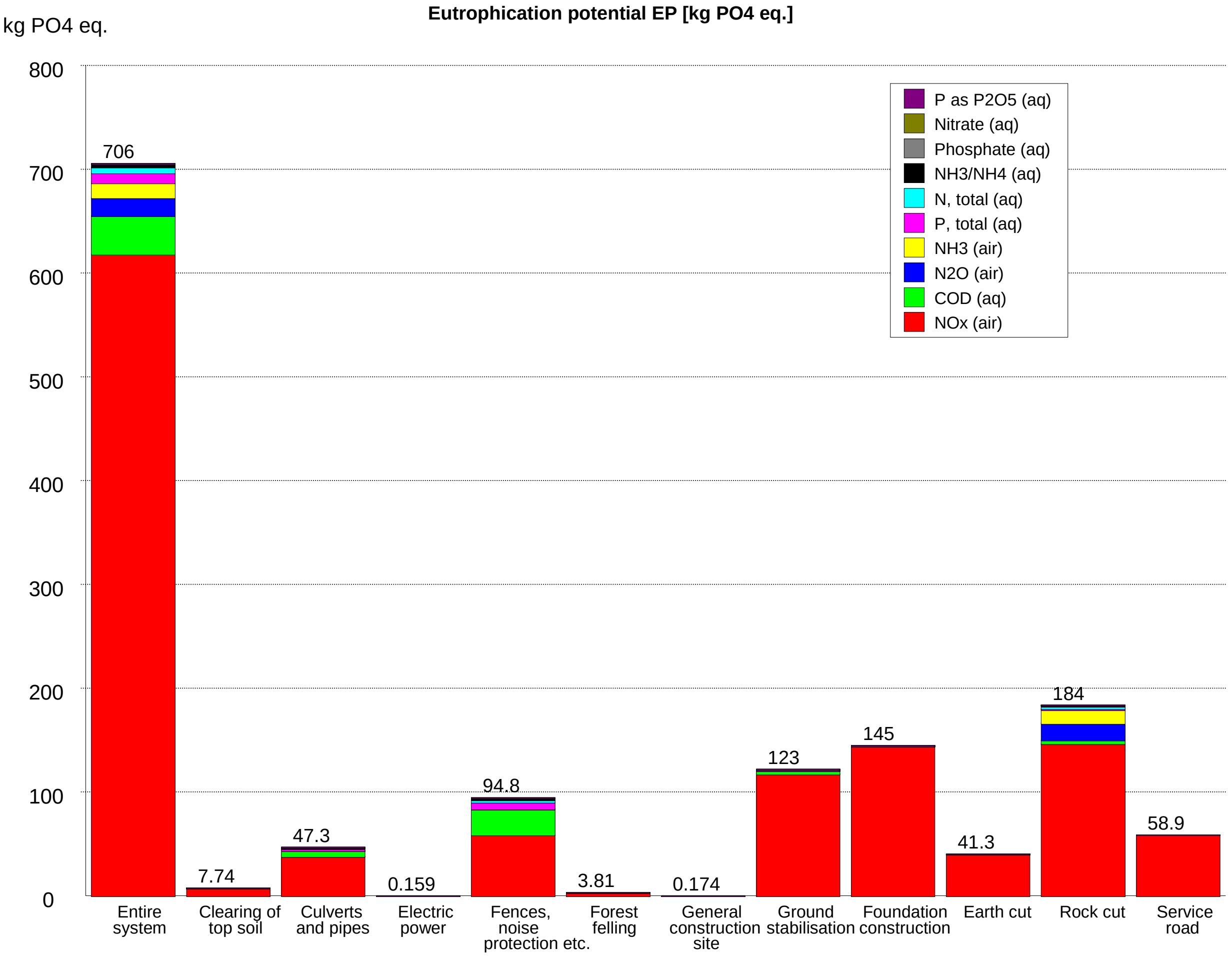

Figure 27 Emission of eutrophying pollutants from 1 km track foundation expressed as eutrophication potential EP (kg PO_4 equivalents). The figure shows EP divided into different sub-processes. The results covers the entire life-cycle including construction, maintenance and operation over a calculation period of 60 years.

9.1.3 Results from the Bothnia Line example

The railway track foundation model has been used in a real calculation for modelling of data to an Environmental Product Declaration (EPD) for railway track foundations on the Bothnia Line[11]. The input data for the model is real data for the Bothnia Line or calculated data for the Bothnia Line. A full set of impact categories are calculated and the results are presented in Table 5. These data covers only the foundation work. The results are given per km foundation and include construction, maintenance and operation over a calculation period of 60 years. No operation activities exist for the foundation.

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[11] EPD Railway track foundations, Environmental Product Declaration for railway track foundations on the Bothnia Line., Reg. no. S-P-00198, UN CPC 53212, Date 2010-03-19.

In Table 6, the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 6. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are shown and explained below. The distribution of the emission impact categories in the overview activity areas are shown in Table 7.

Infrastructure material = Emissions from raw material acquisition and production of materials such as steel, concrete, plastics etc.

Infrastructure construction work = Emissions from machines (excavators, dumpers, trucks, drilling rigs, etc.) used in constructing the infrastructure. This also includes transport of excavated soil and rock on or in close connection to the construction site. Note that maintenance construction work is also included here.

Infrastructure material transport = Emissions from vehicles (e.g. trucks and trains) used for transporting infrastructure material (e.g. sleepers and cables) from suppliers to the construction site.

Infrastructure operation = Regularly activities for the operation over the calculation period of 60 years. Mainly emissions from production of electricity used for operation of the infrastructure (e.g. tunnel illumination and railway switch heating).

Deforestation = Net emissions of CO_2 resulting from forest land being permanently changed to railway land.

Finally, a graphic overview impact distribution analysis of track foundation has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is presented in Figure 28.

Table 5 Environmental impact of 1 km of railway track foundations (main line) on the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the track foundations infrastructure. However, note that track, power, signalling and telecom systems are not included here.

Impact category	**Unit/km track foundation at main railway**	**Construction**	**Operation**	**Maintenance**	**Total**
Resource use					
Non-renewable materials	kg/km	138 083 263	0	578 466	138 661 730
Renewable materials	kg/km	10 640	0	15 956	26 596
Non-renewable energy	MJ/km	9 352 954	0	1 716 821	11 069 775
Renewable energy	MJ/km	76 750	0	43 006	119 756
Recycled resources	kg/km	30 730	0	23 632	54 362
Water	kg/km	493 582	0	576 860	1 070 442
Land use	m^2/km	51 053	0	176	51 228
Emissions					
Global warming	kg CO_2 eq./km	1 660 081	0	148 669	1 808 749
Acidification	kg SO_2 eq./km	4 475	0	440	4 915
Ozone depletion	kg CFC-11 eq./km	0.00042	0	0.00017	0.00059
POCP (Photochemical Ozone Creation Potential)	kg ethene-eq./km	306	0	50	356
Eutrophication	kg PO_4^{2-}eq./km	1 062	0	86	1 148
Other					
Output of materials for recycling	kg/km	0	0	35 043	35 043
Waste, hazardous	kg/km	324	0	131	455
Waste, excess soil	kg/km	105 167 692	0	0	105 167 692
Waste, other	kg/km	7 243	0	585 684	592 927

Table 6 Specification of resources making the largest contributions to the different resource use categories for the railway track foundation.

Resource category	**Unit**	**Largest contributors**
Non-renewable materials	kg	Solid rock: 99.5%, Sand and gravel: 0.241%, Limestone $CaCO_3$: 0.194%, Fe (res): 0.035%
Renewable materials	kg	Wood 100%
Non-renewable energy	MJ	Crude oil: 80.8%, Natural gas: 8.7%, Coal: 7.1%, Nuclear: 3.4%
Renewable energy	MJ	Hydro power: 91.9%, Biomass fuel: 7.8%, Wind power: 0.3%
Recycled resources	kg	Ferrous scraps 100%

Table 7 Main process contributors to the different impact categories for the railway track foundation.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 22.0 % Infrastructure construction work: 28.7 % Infrastructure material transport: 1.1 % Infrastructure operation: 0.0 % Deforestation: 48.3 %
Acidification	kg SO_2-eq.	Infrastructure material: 25.5 % Infrastructure construction work: 70.4 % Infrastructure material transport: 4.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 32.4 % Infrastructure construction work: 64.1 % Infrastructure material transport: 3.5 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 20.4 % Infrastructure construction work: 75.6 % Infrastructure material transport: 4.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %

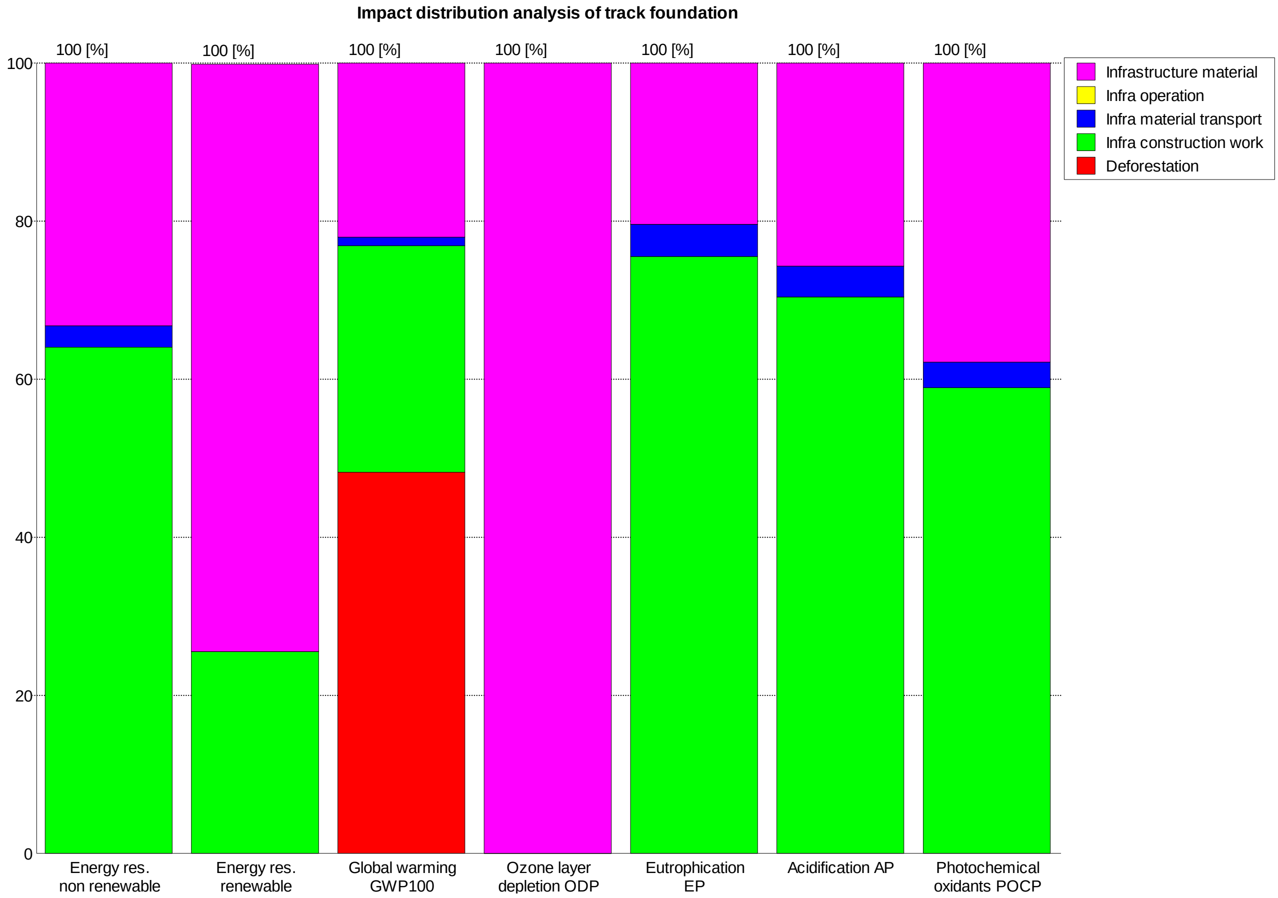

Figure 28 Impact distribution analysis of track foundation at the Bothnia Line.

9.2 Railway track analysis

9.2.1 Analysis and scenario description

The railway track analysis covers the track laying process with a track laying train for a single track. The track design used in the analysis represents a modern Swedish standard railway and the laying process is also a standard method for railway tracks. A general description of the railway track can be found in chapter 5.2. For the operation of the tracks, two main energy users exist; illumination of railway depots and operation and heating of railway switches (both electric energy use).

Railway depots are illuminated during darkness. Yearly average illumination time is set to 12 hours per day. The power use for illumination has been measured to 500 W/60 m of railway depot. This corresponds to 2190 kWh/60 m and year or 131.4 MJ electric energy/m railway depot and year. The switches use electric power for frost protection (heating) during wintertime. Data from the Bothnia Line indicates an energy use of 30 000 kWh (108 000 MJ) per switch and year. The switches are temperature controlled and the energy value can of course vary with geographic location and outdoor temperature, 30 000 kWh represent a location in central Sweden. A railway switch driver use electric power for its mechanical operation. In the EPD for a switch, the energy use is set to 243 kWh for 20 years of operation. This gives 43.74 MJ electric power per year and switch. This value can of course vary due to e.g. traffic intensity.

In addition to the main maintenance with a service train, rail milling is also assumed. Rail milling is a process in which the rails are initially milled to improve performance and quality and thus reduce maintenance intervals. The milling depth is 0.7 mm and the milling width is approximately 70 mm. The process is performed with a service train. Energy data has been obtained from an operator to 700 litre diesel per 6 km railway which corresponds to 1 day of operation[12]. This gives: 700*35.9/6000=4.188 MJ diesel/m railway (single track). The rails are milled each second year. The production and maintenance of the service train is not included, only the operation of the service train is included.

The electric power supply (power production) to the railway track model depends on the power user. The actual power production mix is used to a large extent. Rails are produced in Austria by Voestalpine and thus an Austrian electric power production mix is used[13]. For the operation of the railway (e.g. train operation, heating of switches etc.) a Swedish railway electric power production mix is used. (Electric power purchased by Swedish Rail Administration, see chapter 4 and 7). The purchased "green electric power" production mix in year 2008 was 99.2 % hydropower based and 0.8 % biomass fuel based. The remaining electric power supply is a Swedish average power production mix.

In Table 8 below, the general technical specifications used in the scenario is presented. The specifications are general and thus used both for the scenario specification and for the Bothnia Line example.

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[12] Reference: Stahlberg-Roensch Scandinavia and the Bothnia Line.

[13] Used Austrian electric power production mix (year 2006): Hydro power: 59.3 %, Natural gas back pressure: 16.9 %, coal back pressure: 1.3 %, Fuel oil back pressure: 2.1 %, Wind power 2.7 %, Biomass back pressure: 5.3 %, Fuel oil condensing power 12.4 %.

Table 8 Technical scenario specification of the railway track (single track) and the track laying process.

Activity/Process	**Description**
Rail type	UIC 60 with e-clips
Rail weight	60.4 kg/m rail
Rail joining	Thermite welding
Sleeper type	Concrete sleepers
Distance between sleepers	0.6 m
Track ballast	1.7 m^3/m track
Diesel use for laying train	117 MJ/m track
Illumination of railway depot	131.4 MJ electric energy/m railway depot and year
Heating of railway switches	30 000 kWh (108 000 MJ) electric energy per switch and year (Bothnia Line value)
Switch driver	43.74 MJ electric energy per year and switch
Assumed number of railway switches	1.51 switches/km railway (the Bothnia Line value)
Rail milling	4.188 MJ diesel/m railway (single track)
Transports	Transports covering different materials in construction, operation and maintenance. Distances and transport type reflects the situation at the Bothnia Line. Rails from Austria. Sleepers from local producers near the Bothnia Line.
Assumed life-time of the track	45 years

9.2.2 Results from the analysis

9.2.2.1 Energy results

In Figure 29 the energy resource use for 1 km railway track is presented. The results are divided in construction, maintenance and operation over a calculation period of 60 years. A railway track design is standardised so the results are relatively general for a typical Swedish railway track. However, as shown in the figure, the energy use for the operation is large. This energy use emanates from heating of railway switches to remove snow and ice in wintertime. This is an essential part to maintain the train traffic during the winter. In this case, the energy is almost entirely supplied by hydropower. The reason for this is that “green electric power” purchased by Swedish Rail Administration is used. The switch heating electric power use reflects a climate in mid Sweden. In countries with mild winters, this energy use will be zero. For the coal use, the steel production is completely dominating. For the crude oil use, the cement production plays a significant role (30.2 %). Natural gas is also mainly used in the steel and rail production.

In Figure 30, the energy use is divided in different sub-processes. As shown in the figure, the operation of the track is very much dominating but apart from this, the production of rails and sleepers play a significant role. The operation of the laying train and the rail milling process play a minor role.

Transport energy (crude oil and electric power) calculated in the models stands for approximately 2.52 % of the total primary energy used in the example. Other transports, for example integrated in the production of different materials, also exist. These transports cannot be shown separately in the model but are included in the overall results. The contribution from these transports is probably very small.

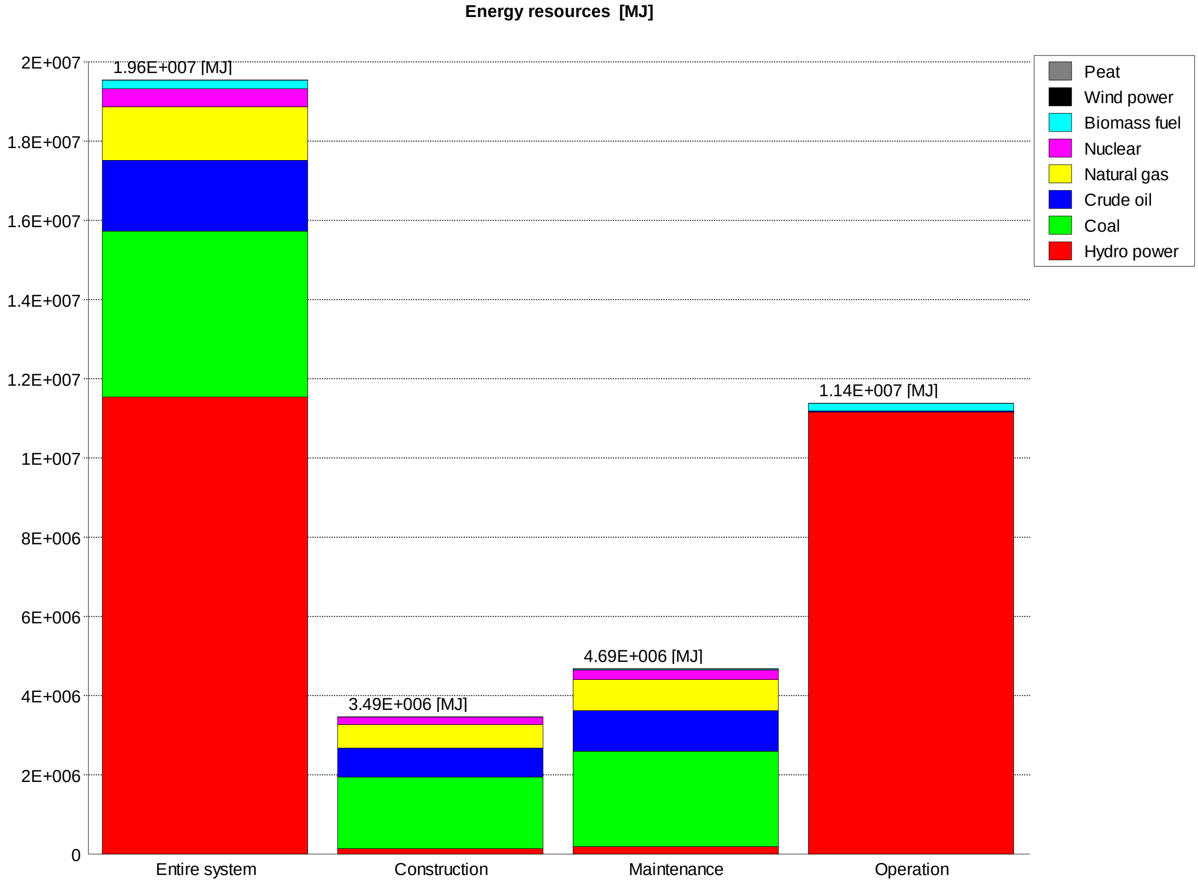

Figure 29 Use of primary energy resources for 1 km railway track. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

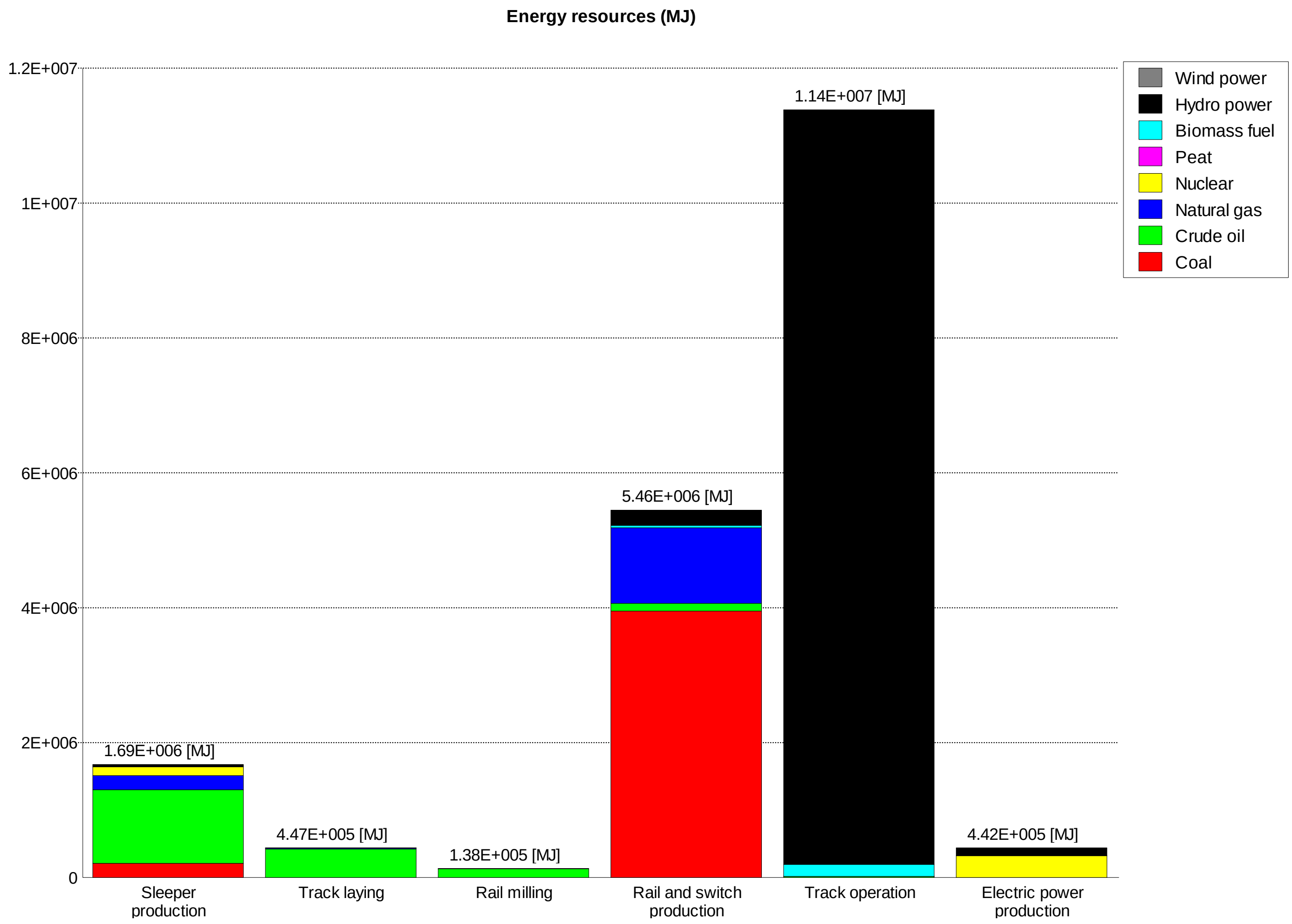

Figure 30 Use of primary energy resources for 1 km railway track divided into different sub-processes. The figure includes construction, maintenance and operation over the calculation period of 60 years. The electric power use calculated in the model for on site use (construction and maintenance) is shown separately.

9.2.2.2 Emission results

Even if the heating of the switches stands for a large energy use, the emission of CO_2 is small because of the use of green electric power. In Figure 31, the greenhouse gas emissions from construction, maintenance and operation is shown. As shown in the figure, the emission of greenhouse gases is low from the operation of the railway track. We can also see that fossil-based CO_2 is the main greenhouse gas from the system. Of the fossil-based CO_2, 70.1 % emanates from steel production and 15.1 % emanates from production of cement. We can also see that the emission from maintenance is higher than from the construction. The reason for this can be found in the lifetime of the track combined with the calculation strategy. The lifetime of the track is estimated to 45 years and the maintenance strategy is to cover the maintenance every year. After 45 years, the track is thus completely replaced. The calculation period is however, set to 60 years so after 60 years, the maintenance (in principle) is 60/45 times larger than the construction. In addition to this, some maintenance activities are performed more often than each 45 year.

In Figure 32, the greenhouse gas emission is divided in the different sub-processes. As shown in the figure, the emissions from production of rails and sleepers are dominating while the emissions from track laying and rail milling are relatively low. The emissions from track operation are low in this example because a green electric power is used. However, the emissions can increase significantly if another production mix of electric power is assumed. The contribution from model-calculated transports is calculated to 3.64 % of the total GWP.

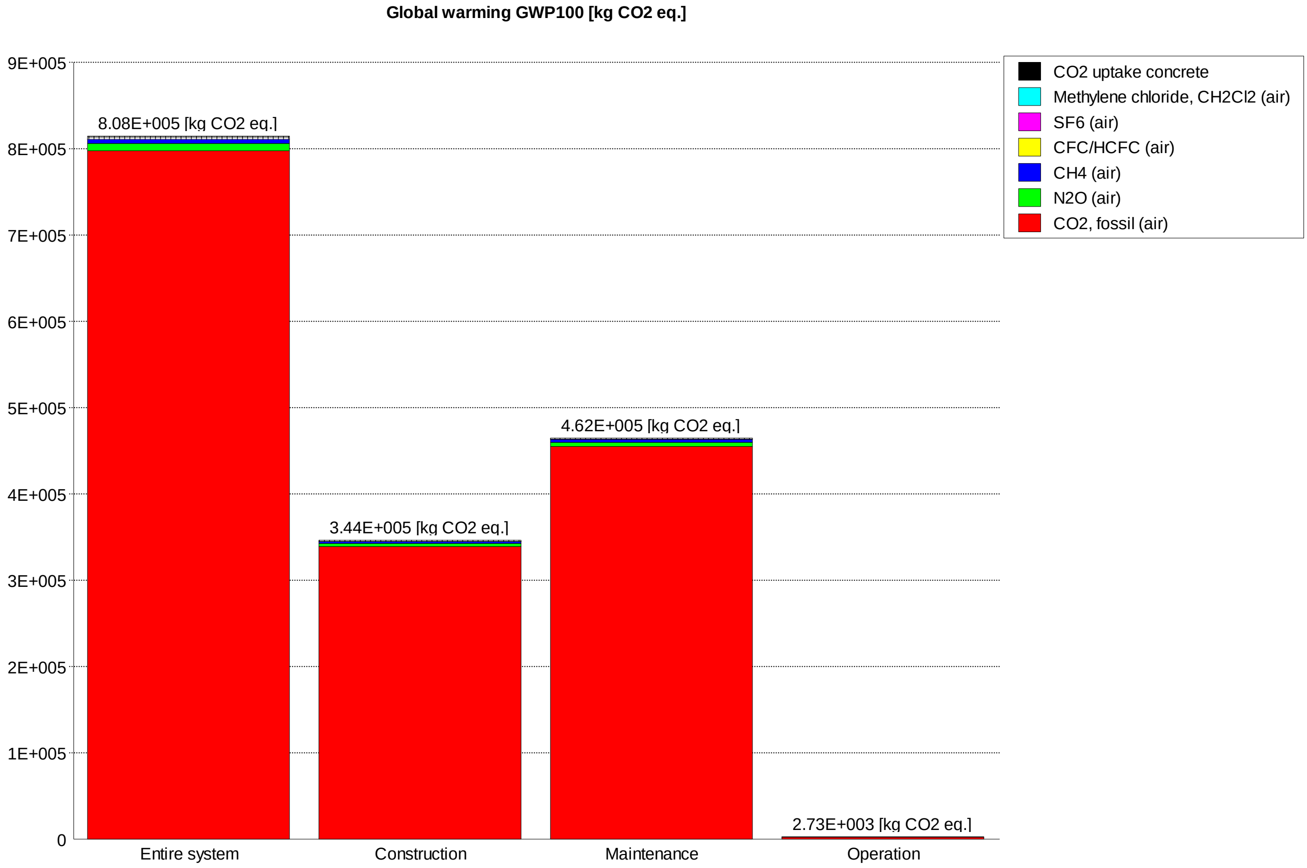

Figure 31 Greenhouse gas emissions from 1 km railway track. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

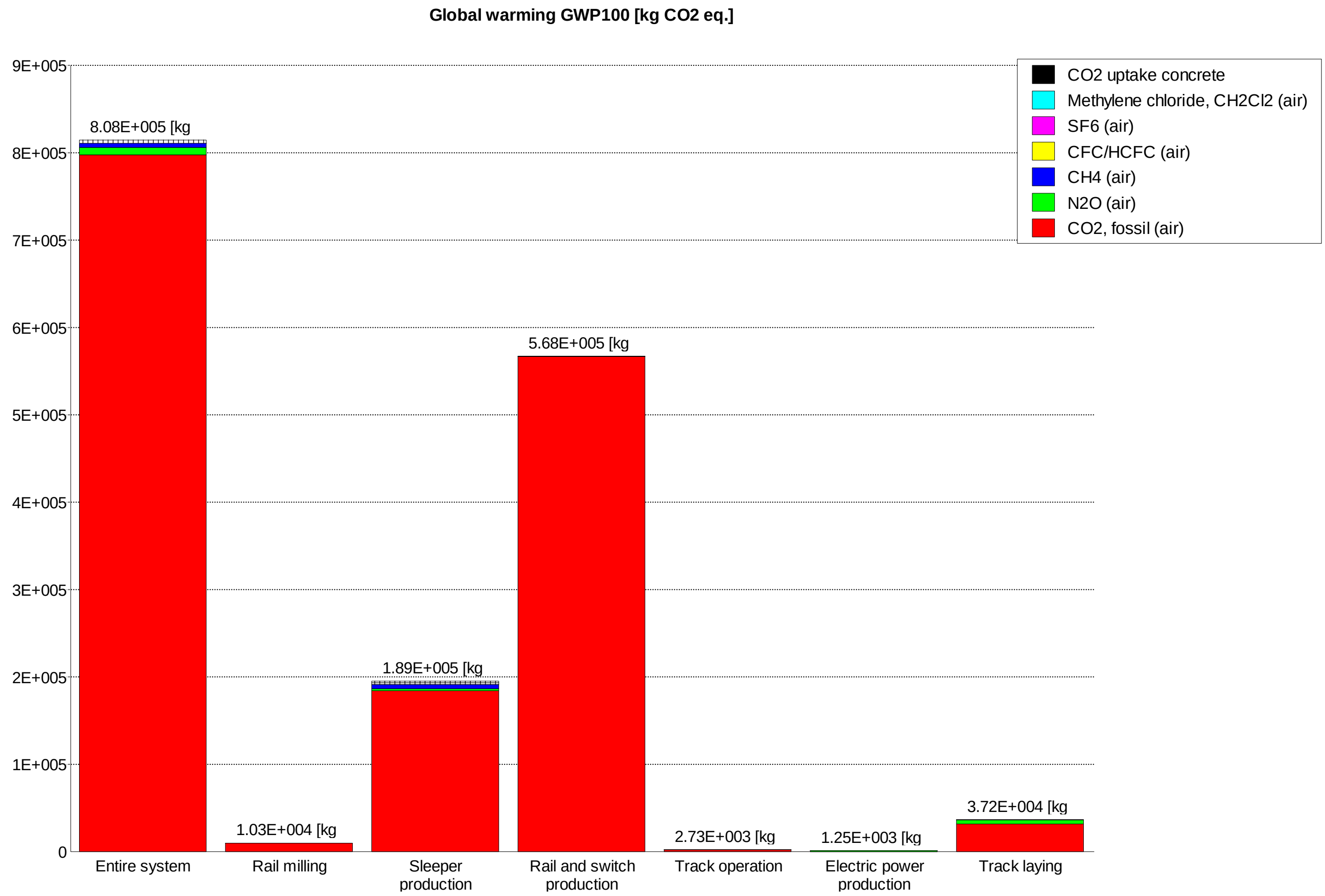

Figure 32 Greenhouse gas emissions from 1 km railway track divided into different sub-processes. The figure includes construction, maintenance and operation over a calculation period of 60 years. The electric power use calculated in the model for on site use (construction and maintenance) is shown separately.

The acidification potential is shown in Figure 33 and as shown in the figure, it is mainly driven by the emissions of NO_X and SO_2. The main contributing processes are sleeper and rail production and the track laying process. The contribution from rail milling and track operation is small. For the track operation, the result reflects the use of green electric power. The main sources of NO_X are transport of sleepers and rails, production of cement and production of steel. The main sources of SO_2 are the production of steel and cement.

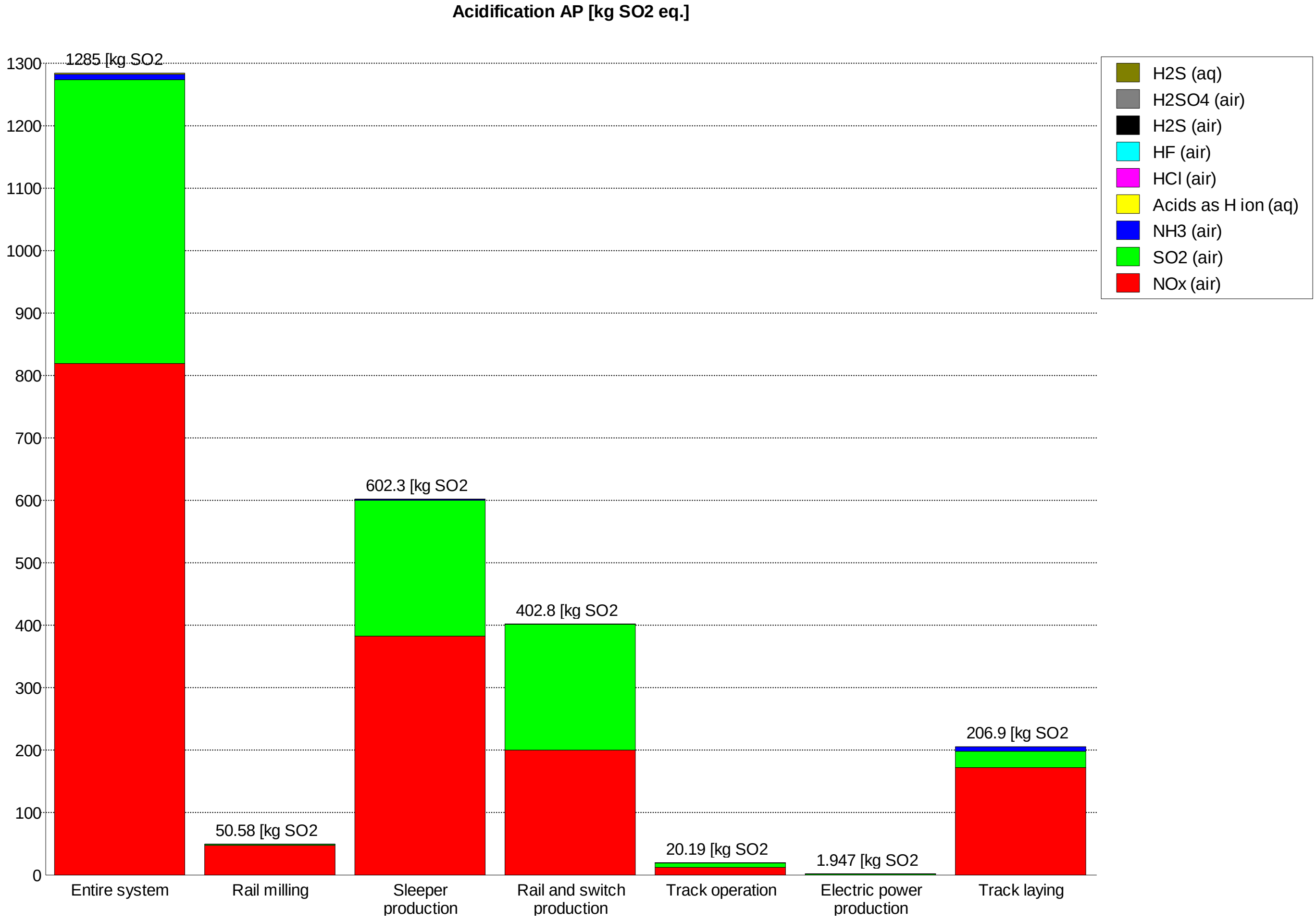

Figure 33 Emission of acidifying pollutants from 1 km railway track expressed as acidification potential, AP (kg SO_2 equivalents). The figure shows AP divided into different sub-processes. The results covers the entire life-cycle including construction, maintenance and operation over a calculation period of 60 years. The electric power use calculated in the model for on site use (construction and maintenance) is shown separately.

The eutrophication potential is shown in Figure 34. Also here, the main contributors to the eutrophication potential is production of sleepers and rails and the track laying process while rail milling and track operation give a minor contribution. The emission of NO_X, COD and P, total is the main emission contributors. The main sources of NO_X are transport of sleepers and rails, production of cement and production of steel. The main source of both COD and P, total is the production of steel.

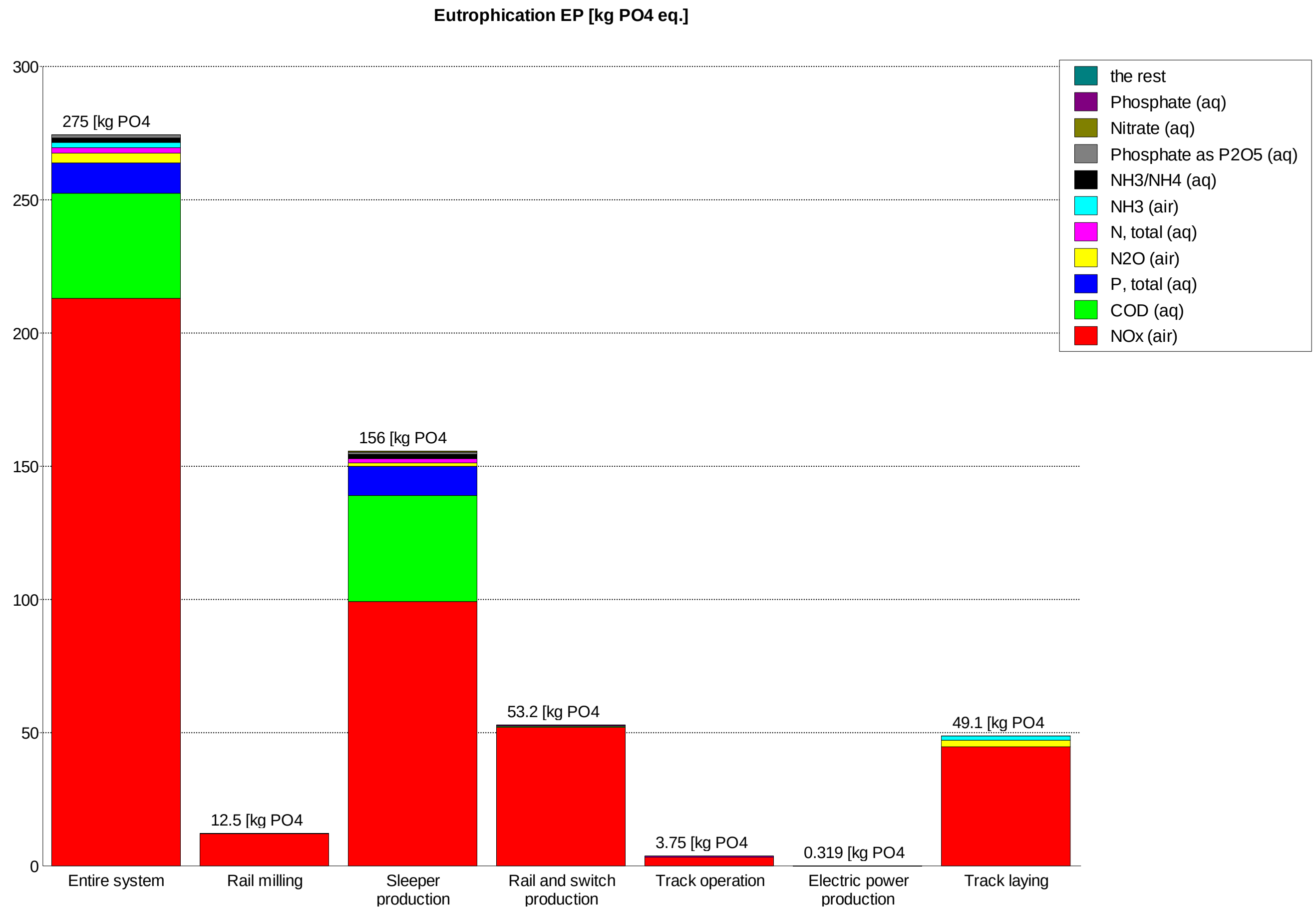

Figure 34 Emission of eutrophying pollutants from 1 km railway track expressed as eutrophication potential, EP (kg PO_4 equivalents). The figure shows EP divided into different sub-processes. The results covers the entire life-cycle including construction, maintenance and operation over a calculation period of 60 years. The electric power use calculated in the model for on site use (construction and maintenance) is shown separately.

9.2.3 Results from the Bothnia Line example

The railway track model has been used in a real calculation for modelling of data to an Environmental Product Declaration (EPD) for railway tracks[14]. The input data for the model is real data for the Bothnia Line or calculated data for the Bothnia Line. A full set of impact categories are calculated and the results are presented in Table 9. These data cover only the railway track and thus not the underlying foundation. The results are given per km main railway track and include construction, maintenance and operation over a calculation period of 60 years. This means that the side tracks in this single track line are included in the calculations but distributed per main line.

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[14] EPD Railway track, Environmental Product Declaration for railway track on the Bothnia Line., Reg. no. S-P-00200, UN CPC 53212, Date 2010-03-19.

In Table 10 the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 10. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are shown and explained in chapter 9.1.1. The distribution of the emission impact categories in the overview activity areas are shown in Table 11.

Finally, a graphic overview impact distribution analysis of the railway track has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is presented in Figure 35.

Table 9 Environmental impact of 1 km of railway track (main line) on the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the track infrastructure. However, note that substructure (track foundation), power, signalling and telecom systems are not included here.

Impact category	Unit/km main track	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	4 482 306	1 825	5 919 180	10 403 312
Renewable materials	kg/km	5.8	0	7.6	13.3
Non-renewable energy	MJ/km	3 776 760	24 444	5 087 760	8 888 964
Renewable energy	MJ/km	204 646	12 977 486	271 011	13 453 143
Recycled resources	kg/km	28 421	0	37 642	66 063
Water	kg/km	3 680 399	0	4 891 978	8 572 377
Land use	m^2/km	2 021	20 200	2 673	24 894
Emissions					
Global warming	kg CO_2 eq./km	393 021	3 118	527 158	923 298
Acidification	kg SO_2 eq./km	620	23	825	1 467
Ozone depletion	kg CFC-11 eq./km	0.000030	0	0.000040	0.000070
POCP (Photochemical oxidant formation)	kg ethene eq./km	214	3	283	500
Eutrophication	kg PO_4^{2-}eq./km	133	4	176	314
Other					
Ouput of materials for recycling	kg/km	393	0	209 364	209 757
Waste, hazardous	kg/km	377	0	501	878
Waste, excess soil	kg/km	0	0	0	0
Waste, other	kg/km	18 322	191	886 066	904 579

Table 10Specification of resources making the largest contributions to the different resource use categories for the railway track.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 91.0%, Sand and gravel: 3.2% Fe (res): 3.2%, Limestone $CaCO_3$: 2.5%
Renewable materials	kg	Wood 100%
Non-renewable energy	MJ	Coal: 53.8% , Crude oil: 23.0%, Natural gas: 17.5% , Nuclear: 5.8%
Renewable energy	MJ	Hydro power: 98.1% Biomass fuel: 1.8% Wind power: 0.1%
Recycled resources	kg	Ferrous scraps 100%

Table 11 Main process contributors to the different impact categories for the railway track.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 90.9 % Infrastructure construction work: 5.1 % Infrastructure material transport: 3.6 % Infrastructure operation: 0.3 %
Acidification	kg SO_2-eq.	Infrastructure material: 57.8 % Infrastructure construction work: 17.4 % Infrastructure material transport: 23.2 % Infrastructure operation: 1.6 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 91.2 % Infrastructure construction work: 4.1 % Infrastructure material transport: 4.2 % Infrastructure operation: 0.5 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 52.2 % Infrastructure construction work: 20.3 % Infrastructure material transport: 26.1 % Infrastructure operation: 1.4 %

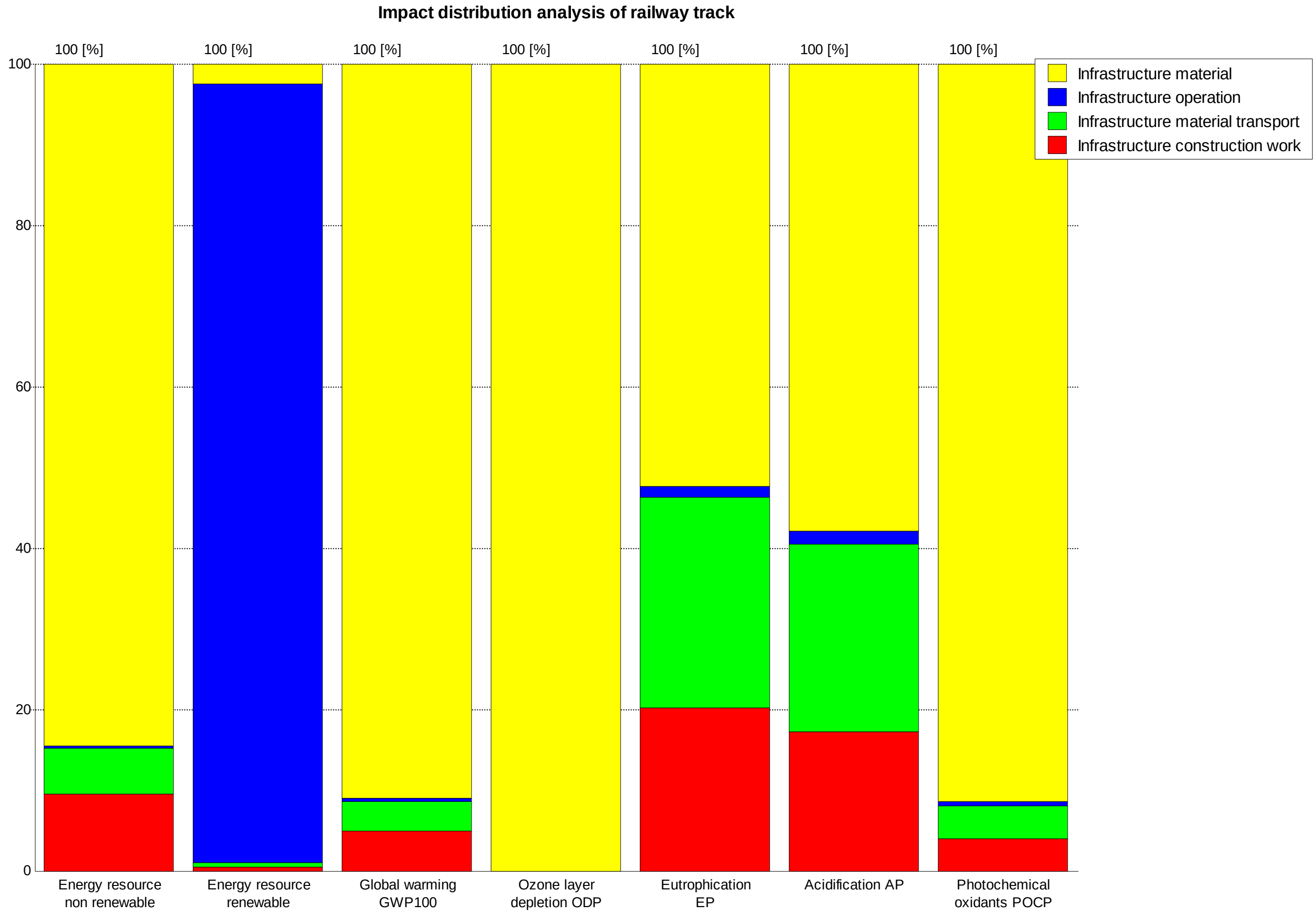

Figure 35 Impact distribution analysis of railway track at the Bothnia Line.

9.3 Railway electric power and control system analysis

9.3.1 Analysis and scenario description

This analysis and model cover the electric power systems for operation of the trains, train control and signalling system and finally the telecommunication system. An overview technical description of the systems can be found in chapter 5.3. The model reflects a modern standardised system in Sweden. Over time, these systems have developed rapidly, especially the train control and signalling system, so a modern system can differ significantly compared to an ordinary Swedish installation. The power supply systems for the trains are however more similar over time. The model is also developed in modules where the power supply system can be separated from the train control and signalling system in order to make it possible to analyse a non-electrified railway. The example scenario covers a 1 km electrified single-track railway. The example comprises construction, maintenance and operation and shows the results over a calculation period of 60 years. Note that the results do not include the electric power distributed by the system. Only the auxiliary power for the system is included. The power to the trains is included in the train transport models presented in chapter 9.7 and 9.9. The train control and signalling systems are today computer based and it is often difficult to collect LCI data for complex electronic systems. General and estimated data, based on material use and estimated electricity consumption, have thus been used. This also implies an increased uncertainty of the results.

9.3.2 Results from the analysis

9.3.2.1 Energy results

Figure 36 shows the energy use divided into construction, maintenance and operation. The energy use is mainly divided between construction and maintenance while the energy use for operation is small. Figure 37 show the same energy use but divided into Infrastructure material, Infrastructure construction work, Infrastructure material transport and Infrastructure operation. As shown in the figure, the main energy use is related to the different materials (from raw material extraction to forming of different products) in the systems. May be even the energy use for production of different electronic and computer systems are underestimated. The remaining activities are rather small.

The primary energy resource use shows the following distribution, Table 12:

Table 12 Origin of primary energy resource use for the electric power and control system.

Primary energy resource	Origin of use
Coal	Aluminium production: 56.2 %, Steel production: 28.4 %, Copper production: 10.5 %.
Crude oil	Aluminium production: 33.1 %, Polyethene production: 36.5 %, Steel production: 5.2 %, Copper production: 7.7 %.
Natural gas	Polyethene production: 52.7 %, Aluminium production: 21.5 %, Steel production: 12.1 %, Copper production: 10.6 %.
Nuclear	Aluminium production: 69 %, Polyethene production: 2.3 %, Copper production: 15.4 %.
Hydropower	Aluminium production: 60 %, Polyethene production: 1.4 %, Copper production: 12.7 %.

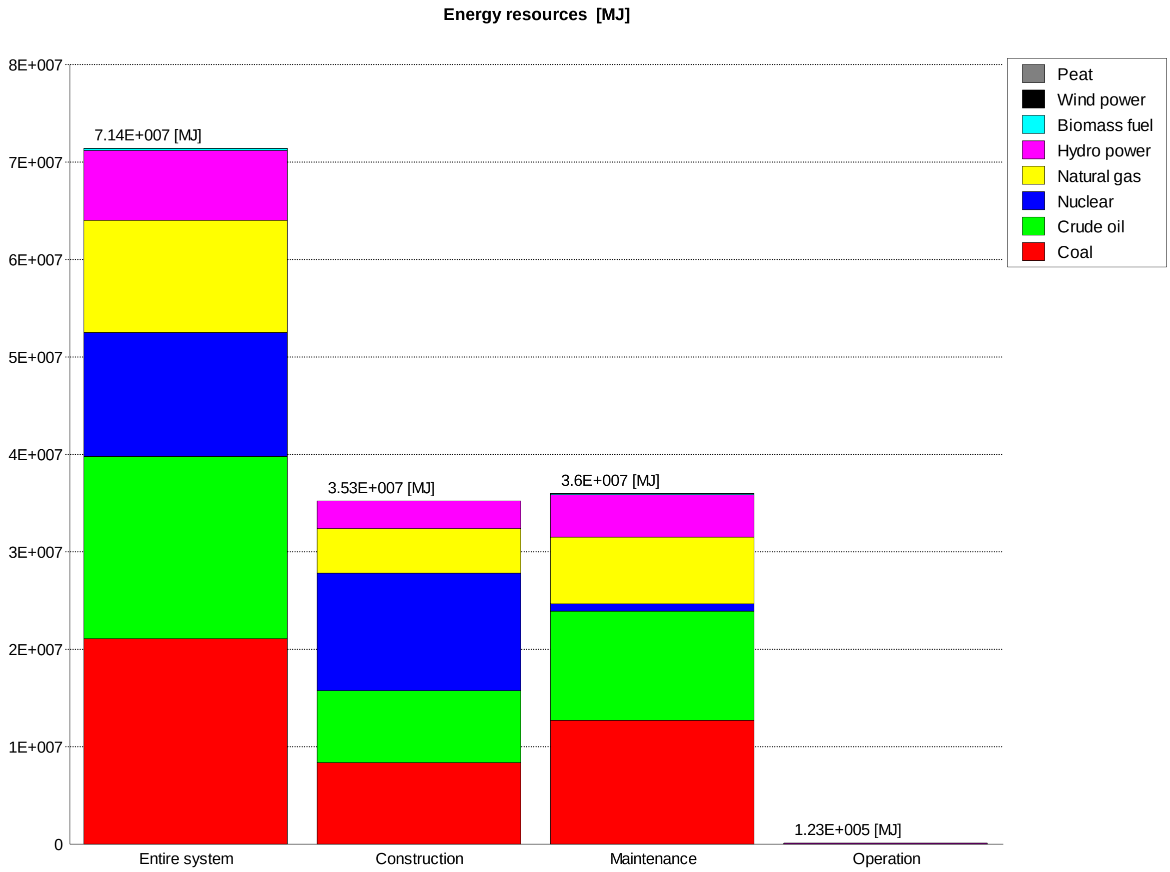

Figure 36 Use of primary energy resources for electric power and control systems at 1 km electrified railway (single track). The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. Note that the results do not include the electric power distributed by the system. Only the auxiliary power for the system is included.

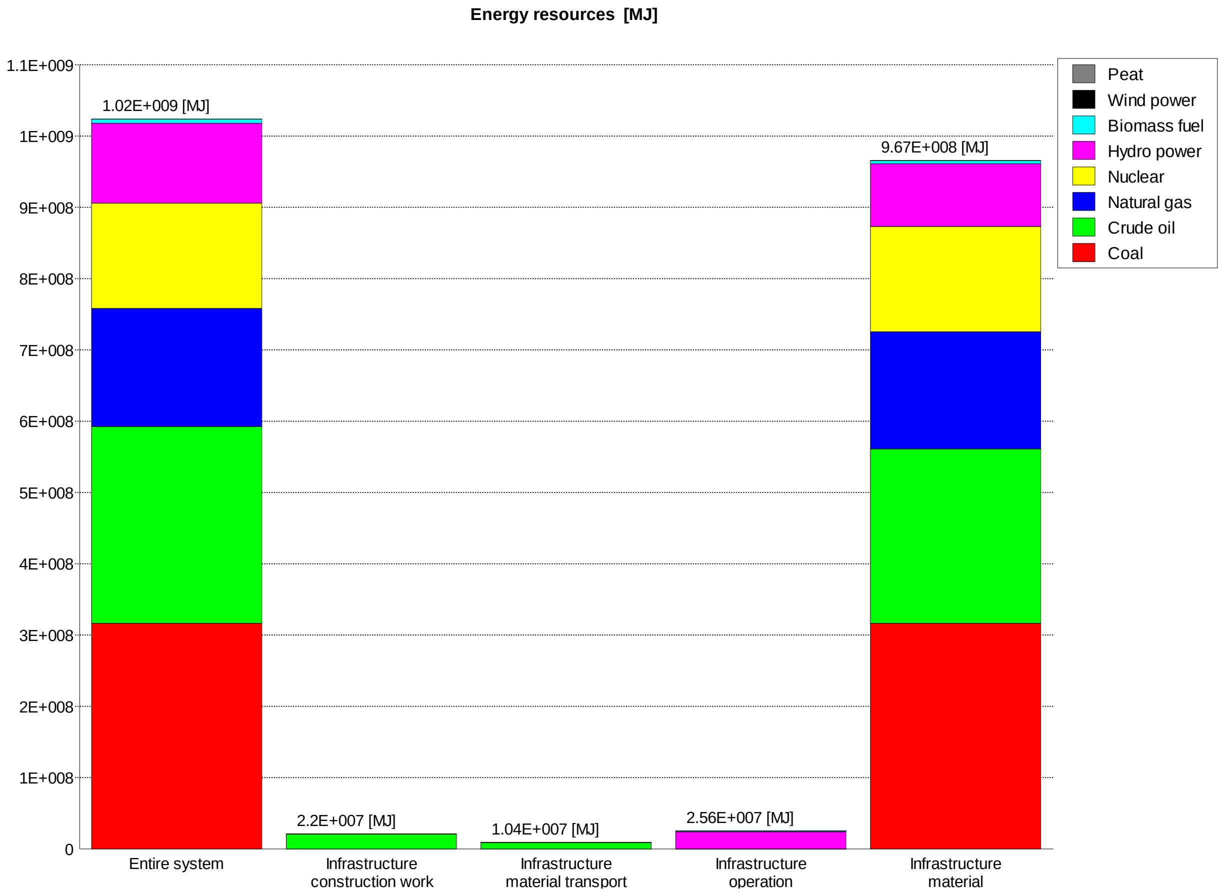

Figure 37 Use of primary energy resources for electric power and control systems at 1 km electrified railway (single track). The energy use is divided into different sub-activities and shows the results over a calculation period of 60 years including construction, maintenance and operation. Note that the results do not include the electric power distributed by the system. Only the auxiliary power for the system is included.

9.3.2.2 Emission results

The emission of greenhouse gases shows the same patterns as the energy use and thus the main emissions come from the production of the different materials, see Figure 38 and Figure 39. The emission of fossil-based CO_2 is the overall dominating sources of greenhouse gases. The main sources of the CO_2 fossil emissions are: Aluminium production: 42.1 %, Steel production: 28.3 %, Copper production: 10.7 %, Polyethene production: 10.5 %.

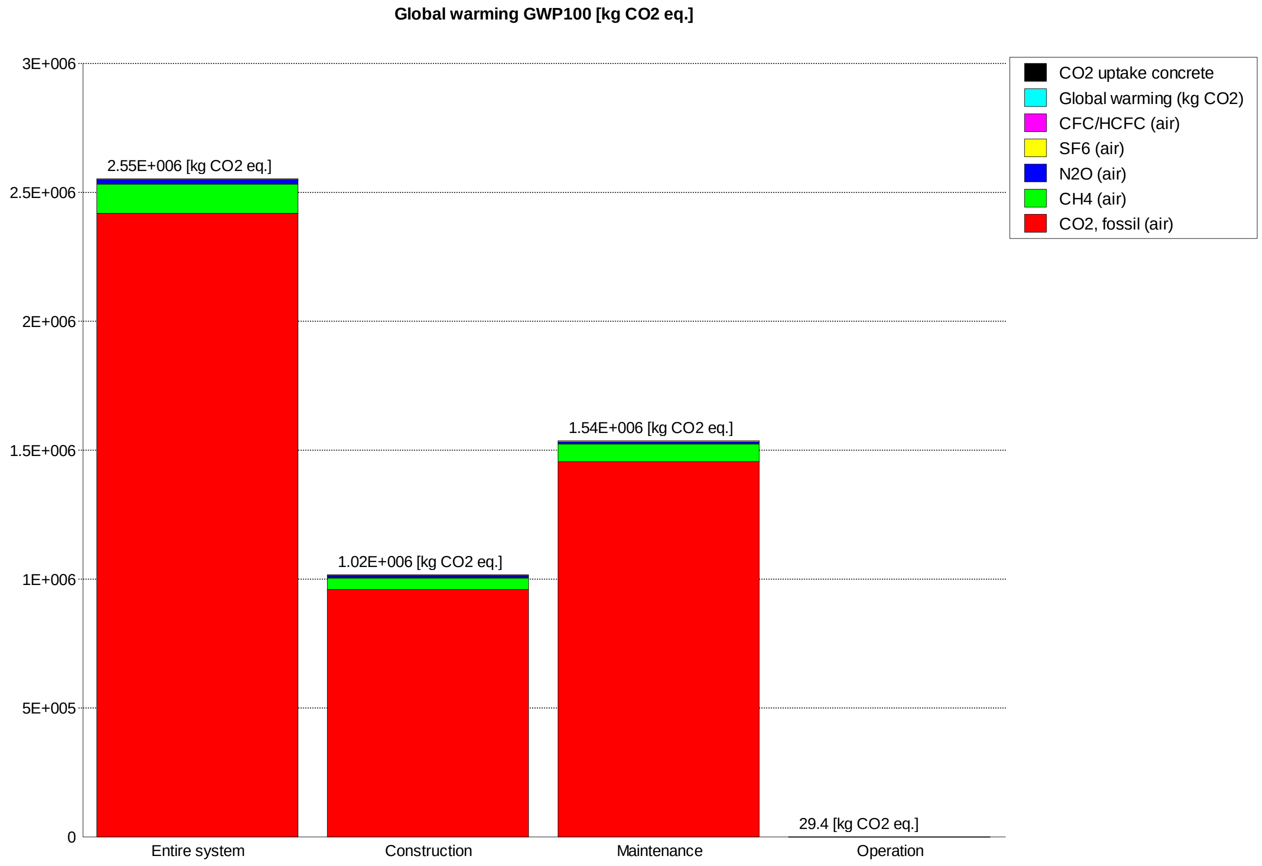

Figure 38 Greenhouse gas emissions from electric power and control systems at 1 km electrified railway (single track) expressed as global warming potential. The GWP is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

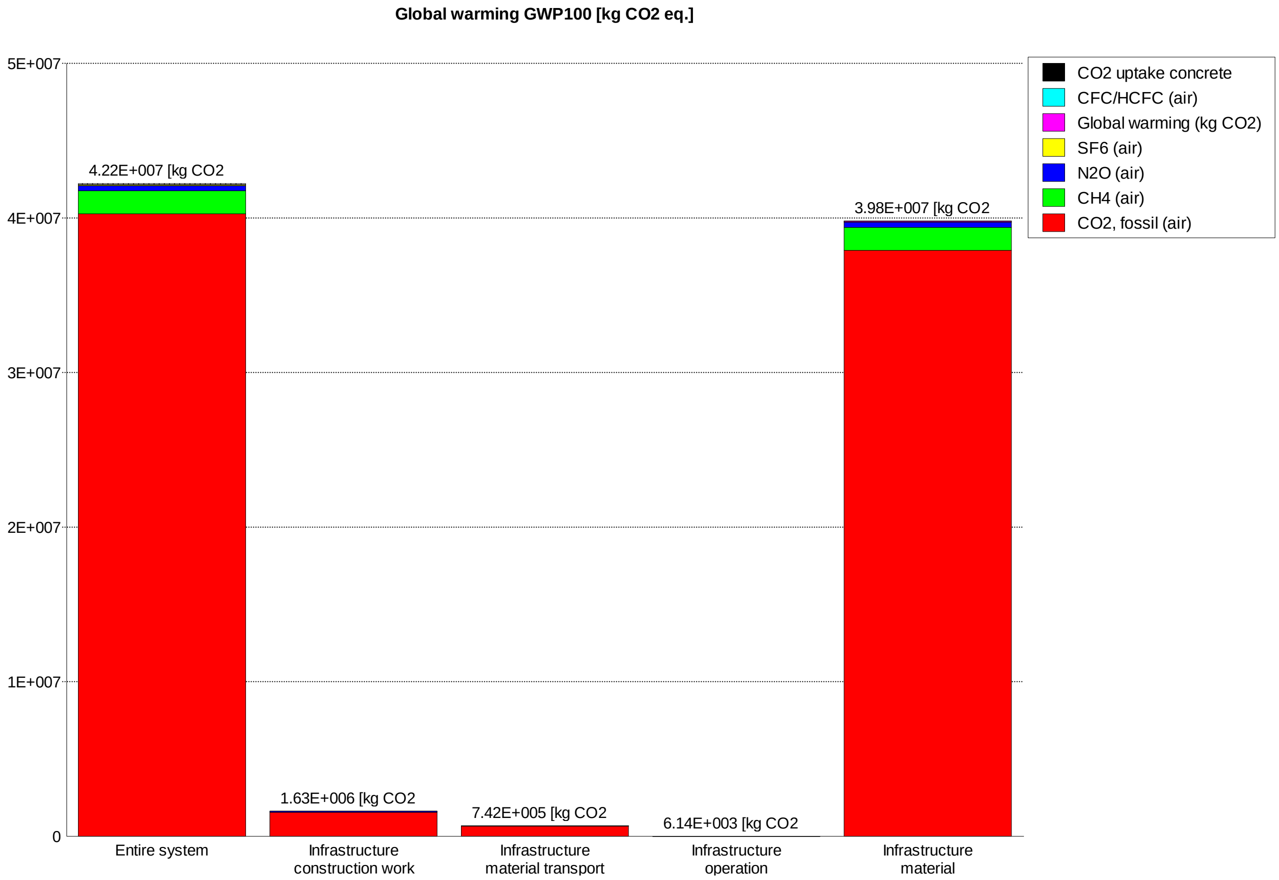

Figure 39 Greenhouse gas emissions from electric power and control systems at 1 km electrified railway (single track) expressed as global warming potential. The GWP is divided into different sub-activities and shows the results over a calculation period of 60 years including construction, maintenance and operation.

Both emissions of acidifying and eutrophying pollutants also show the same emission pattern as the greenhouse gas emissions, see Figure 40 and Figure 41. Thus, the main sources of the emissions are the production of different materials. The main pollutants for acidification are SO_2 and NO_X and the main pollutants for eutrophication are NO_X, phosphate and COD.

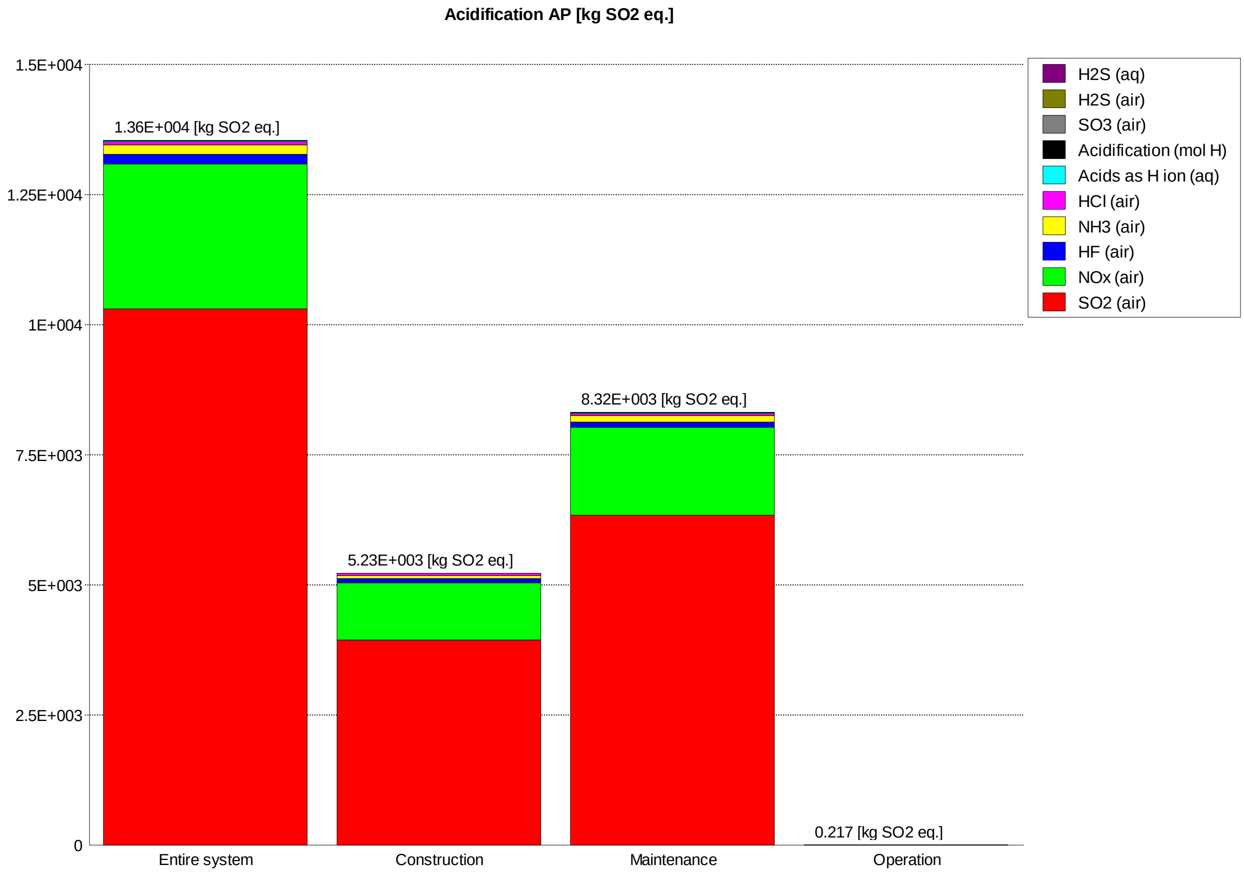

Figure 40 Emission of acidifying pollutants from electric power and control systems, expressed as acidification potential (kg SO_2 equivalents), for 1 km electrified railway. The acidification potential is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

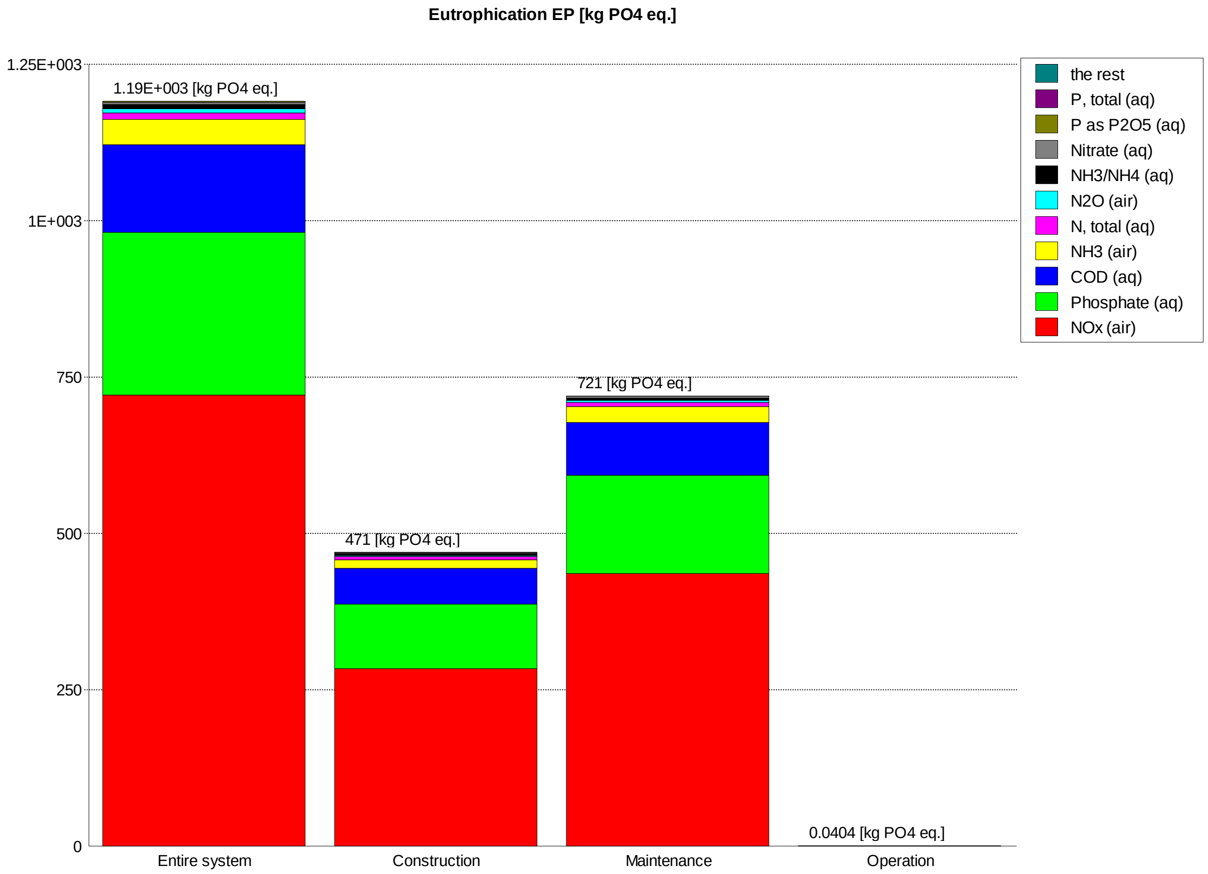

Figure 41 Emission of eutrophying pollutants from electric power and control systems, expressed as eutrophication potential EP (kg PO_4 equivalents), for 1 km electrified railway. The eutrophication potential is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

9.3.3 Results from the Bothnia Line example

The overall results from the electric power and control system model used in the calculation for modelling of data to an Environmental Product Declaration (EPD) for power, signalling and telecom[15] are shown in this chapter. The input data for the model is real data for the Bothnia Line or calculated data for the Bothnia Line. A full set of impact categories are calculated and the results are presented in Table 13. The results are given per km railway (single track) and include construction, maintenance and operation over a calculation period of 60 years.

In Table 14 the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 14. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources

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[15] EPD Power, signalling and telecom, Environmental Product Declaration for power, signalling and telecom systems on the Bothnia Line., Reg. no. S-P-00201, UN CPC 53212, Date 2010-03-19.

of the emissions. The overview activity areas are explained in chapter 9.1.3. The distribution of the emission impact categories in the overview activity areas are shown in Table 15.

Finally, a graphic overview impact distribution analysis of the power, signalling and telecom systems has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is presented in Figure 42.

Table 13Environmental impact of 1 km of power, signalling and telecom systems (main line) on the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the power, signalling and telecom systems. However, note that the substructure (track foundation) and track system are not included here.

Impact category	Unit/km main track	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	43 110	20	68 714	111 843
Renewable materials	kg/km	752	0	451	1 203
Non-renewable energy	MJ/km	2 275 180	263	2 676 650	4 952 094
Renewable energy	MJ/km	174 160	139 699	333 192	647 050
Recycled resources	kg/km	6 332	0	4 623	10 955
Water	kg/km	216 103	0	323 520	539 623
Land use	m^2/km	88	217	155	460
Emissions					
Global warming	kg CO$_2$ eq./km	86 306	34	144 313	230 652
Acidification	kg SO$_2$-eq./km	829	0	1 776	2 605
Ozone depletion	kg CFC-11 eq./km	0.00022	0	0.00041	0.00063
POCP (Photochemical oxidant formation)	kg ethene-eq./km	54	0.021	109	163
Eutrophication	kg PO$_4^{2-}$eq./km	56	0.046	100	156
Other					
Output of materials for recycling	kg/km	0	0	35 765	35 765
Waste, hazardous	kg/km	171	0	312	483
Waste, excess soil	kg/km	0	0	0	0
Waste, other	kg/km	3 147	2.1	62 898	66 048

Table 14Specification of resources making the largest contributions to the different resource use categories for the power, signalling and telecom systems.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Fe (res): 35.4%, Gravel: 19.9%, Al (res): 9.9%, Cu (res): 9.6%, Solid rock: 8.2%, Calcite, $CaCO_3$: 5.9%, Sand and gravel: 4.9%, Limestone $CaCO_3$: 4.0%
Renewable materials	kg	Wood 100%
Non-renewable energy	MJ	Coal: 35.0%, Crude oil: 30.6% , Natural gas: 18.3%, Nuclear: 16.2%
Renewable energy	MJ	Hydro power: 95.3%, Biomass fuel: 4.1%
Recycled resources	kg	Ferrous scraps: 87.3%, Copper scrap: 12.6%

Table 15 Main process contributors to the different impact categories for the power, signalling and telecom systems.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 94.4 % Infrastructure construction work: 3.9 % Infrastructure material transport: 1.8 % Infrastructure operation: 0.01 %
Acidification	kg SO_2-eq.	Infrastructure material: 97.o % Infrastructure construction work: 1.6 % Infrastructure material transport: 1.4 % Infrastructure operation: 0.01 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 95.3 % Infrastructure construction work: 3.0 % Infrastructure material transport: 1.7 % Infrastructure operation: 0.01 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 87.6 % Infrastructure construction work: 6.5 % Infrastructure material transport: 5.8 % Infrastructure operation: 0.03 %

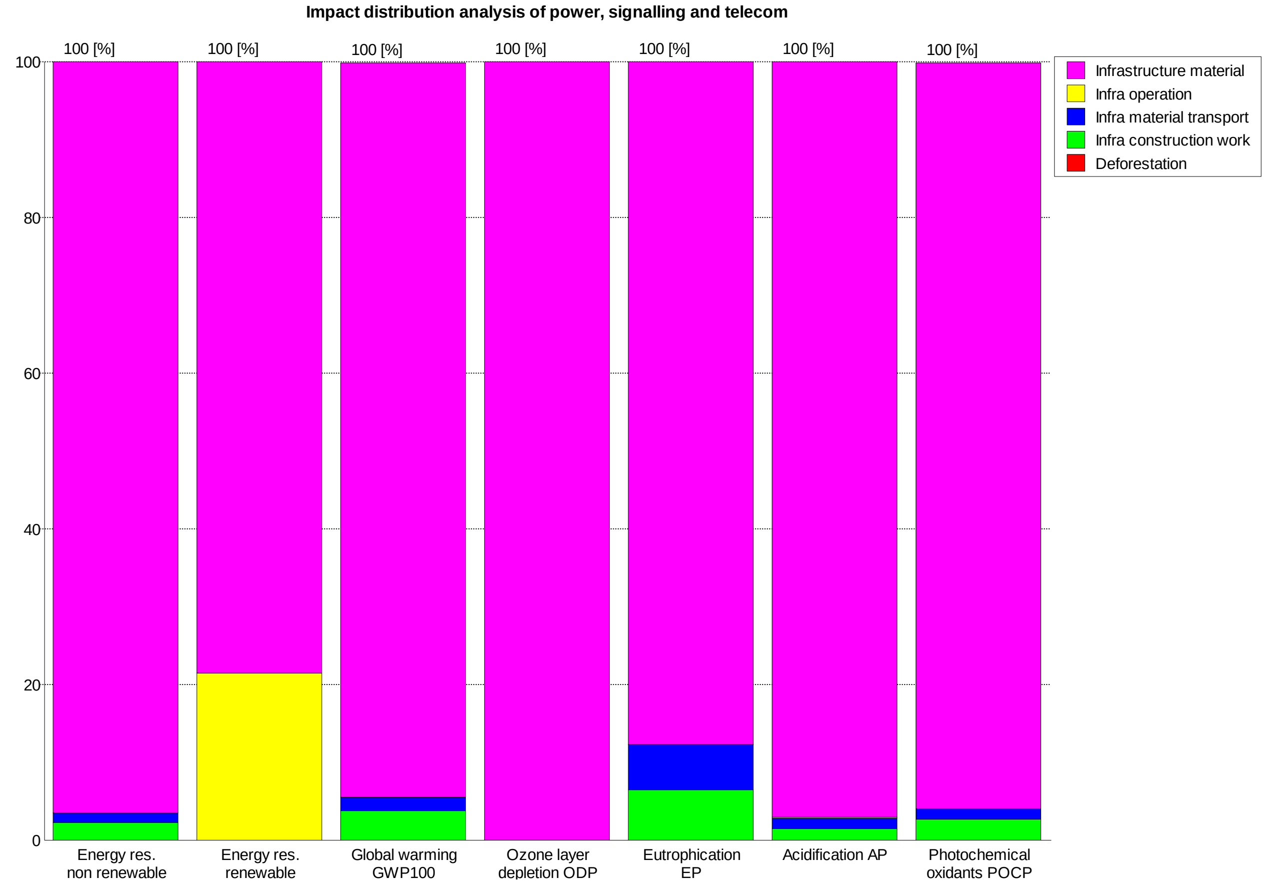

Figure 42 Impact distribution analysis of power, signalling and telecom at the Bothnia Line.

9.4 Railway tunnel analysis

9.4.1 Analysis and scenario description

Railway tunnels are more or less standardised products in terms of technical function and design. The physical geometry of the tunnel is well specified as well as the technical design. However, the local geotechnical conditions can vary. For example, the type and quality of rock as well as occurrence of water can vary significantly. An important design factor is however the length of the tunnel. Short tunnels (< 1000 m) do not require any service or access tunnels for evacuation. Long tunnels require both service and access tunnels while medium length tunnels can manage with only an access tunnel for evacuation. The influence of tunnel length is an importance factor to analyse. It is therefore difficult to give a result per length unit (e.g. meter) of tunnel. The results from the model calculations are thus given for two different example tunnels representing a short and long tunnel. In a way, the results reflect two real tunnels at the Bothnia Line, Håknäs tunnel (short tunnel) and Åskottsberg tunnel (long tunnel). Some data (such as open rock excavation, clearing of soil, soil excavation) has however been estimated and made equal for both tunnels in order to show the influence of long and short tunnel design.

A technical overview description of railway tunnels has already been presented in chapter 5.4. The technical design described in that chapter has been used as a base for the LCA model layout and is also the design used for the Bothnia Line. The detailed tunnel layout/work is specified by the model parameters. These parameters can vary significantly between different tunnel projects and is therefore important to specify and to keep in mind when analysing the model results. In Table 16, the specific project parameters are shown.

Table 16 Technical scenario specification of railway tunnels (single track).

Activity/Process	Description
Geotechnical survey of tunnel rock	Estimation included
Establish construction site	Estimation included
Forest felling	100 m^3 solid wood under bark
Clearing of soil	2000 m^3 per tunnel
Soil excavation	2000 m^3 per tunnel
Ballast (base course)	Thickness: 0.3 m, Width: 6 m
Ballast (sub-base course)	Thickness: 0.8 m, Width: 8 m
Ballast (frost sub-base course)	Thickness: 0.8 m, Width: 8 m , 600 m from each tunnel mouth or in the entire tunnel if the tunnel is longer than 1200 m.
Fire doors	One door each 500 m of main tunnel
Fire water tank	1 steel tank per tunnel
Cable ladders	Along the entire main and service tunnel
Geotextile	200 m^2 per tunnel
Handrails	Along both sides of main tunnel
Manhole (1200 mm) length	5.2 m per tunnel
Manhole (1500 mm) length	10.4 m per tunnel
Manhole (600 mm) length	1.8 m per tunnel
Cable channels	Along both sides of main tunnel
Drainage water at construction	80 m^3 per m of all tunnels
Drainage water system	Along both sides of main tunnel
Drains	10 % of inner area for all tunnels
Erosion protection	100 m^2 per tunnel
Fire water pipes	Along the entire main tunnel
Footpath length	Along the entire main tunnel
Post injection tunnel area	Calculated as value per tunnel inner area
Protecting steel net	100 m^2 per tunnel
Rock bolting tunnel area	Calculated as value per tunnel inner area
Rock excavation (other then tunnel driving)	250 m^3 per tunnel
Service roads	50 m per tunnel
Shotcrete steel fibre reinforced	Calculated as value per tunnel inner area, 70 mm average thickness
Surface water system	Along the entire main tunnel
Tunnel portals	2 for each tunnel (access tunnel port neglected)
Electric equipments for tunnel	Estimation included

9.4.2 Results from the analysis

9.4.2.1 Energy results

The energy use for a short tunnel at the Bothnia Line is shown in Figure 43 and Figure 44. The energy use is given as primary energy. The results are shown both divided in construction, maintenance and operation and divided in sub-activity groups. The sub-activity groups are; Infrastructure material; Infrastructure construction work; Infrastructure material transport; Infrastructure operation and Deforestation. As shown in the figures, the use of nuclear power and crude oil resources are dominating even if hydropower, natural gas and coal also play an essential role. The energy use in construction is large but so is also the use in operation. The crude oil use in construction is used for different diesel engines but also for cement and explosives production. The energy use for operation is mainly electric power use with a Swedish electric power production mix. The excess of nuclear energy resources over hydropower (compared to the actual production mix) is caused by the use of heat production to the turbines as the resource use for nuclear power. The largest electric power consumer in operation is electric power for frost protection of firewater and electronic equipments. Power for illumination is small. Production of materials for the tunnel infrastructure makes a large contribution to the energy use while the tunnel work plays a minor role. Of the infrastructure construction work, the tunnel driving process and the base course construction play and important role.

For the long tunnel, the energy resource use is 6.6 times larger but the main railway tunnel is only 5.6 times longer. The energy resource use per meter main tunnel is thus larger for a longer tunnel. The energy resource use for the long tunnel is shown in Figure 45 and Figure 46. As shown in the figures, the relative contribution from construction is larger for a longer tunnel. As shown in Figure 46, both the tunnel construction work and the material production show a relative increase. The contribution from material transports is small. An analysis of fossil primary energy resource use has also been performed for the long tunnel and the result is shown in Table 18 below.

Table 17 Origin of fossil primary energy resource use for a long tunnel example.

Primary energy resource	Origin of use
Coal	Steel production: 80.4 %
Crude oil	Cement production: 35.4 %, Diesel engine use 22.4 %, Polyethene production: 13.4 %, Production of explosives 11.1 %
Natural gas	Production of explosives 38.2 %, Polyethene production: 31.9 %, Steel production: 23.2 %

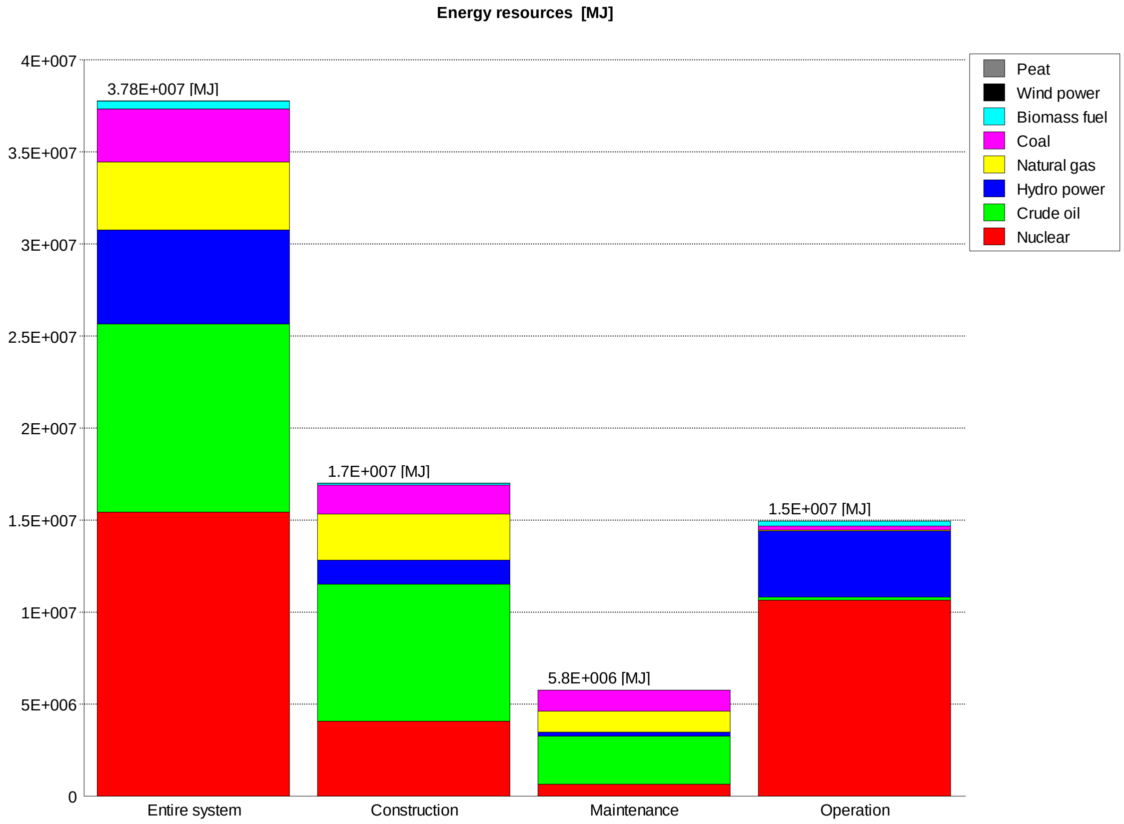

Figure 43 Use of primary energy resources for a short single track railway tunnel (type tunnel: Håknäs). The figure shows the total results for a 586 m long tunnel. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

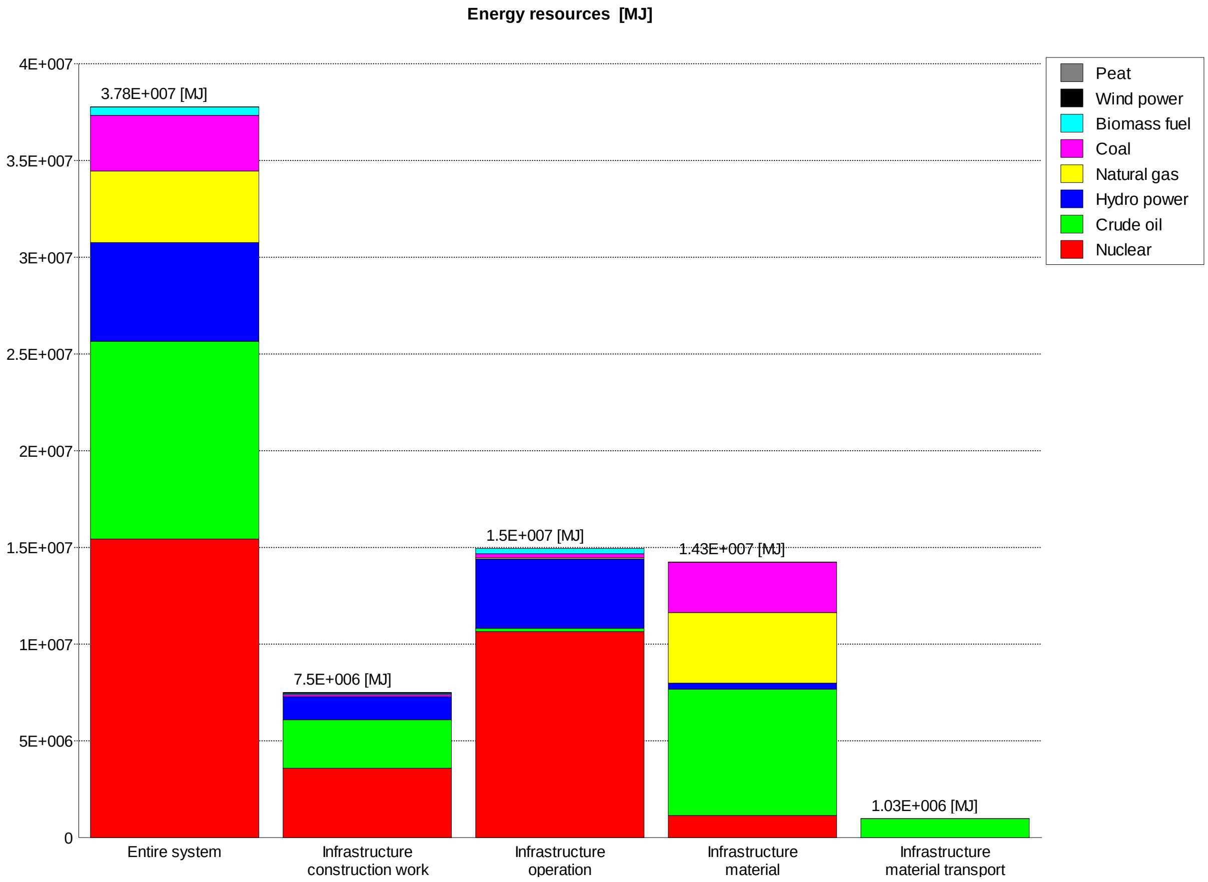

Figure 44 Use of primary energy resources for a short single track railway tunnel (type tunnel: Håknäs). The figure shows the total results for a 586 m long tunnel. The energy use is divided into different activity groups and includes construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

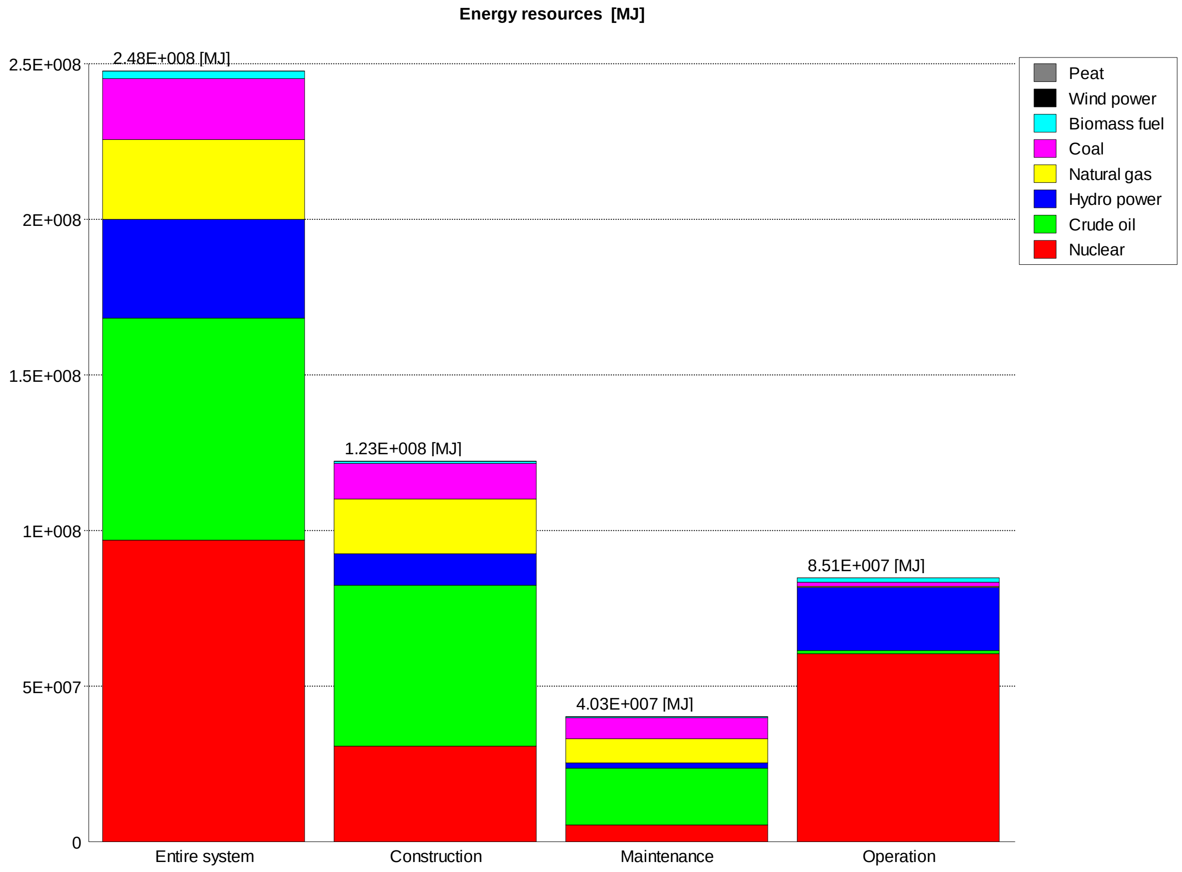

Figure 45 Use of primary energy resources for a long single track railway tunnel (type tunnel: Åskottsberget). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

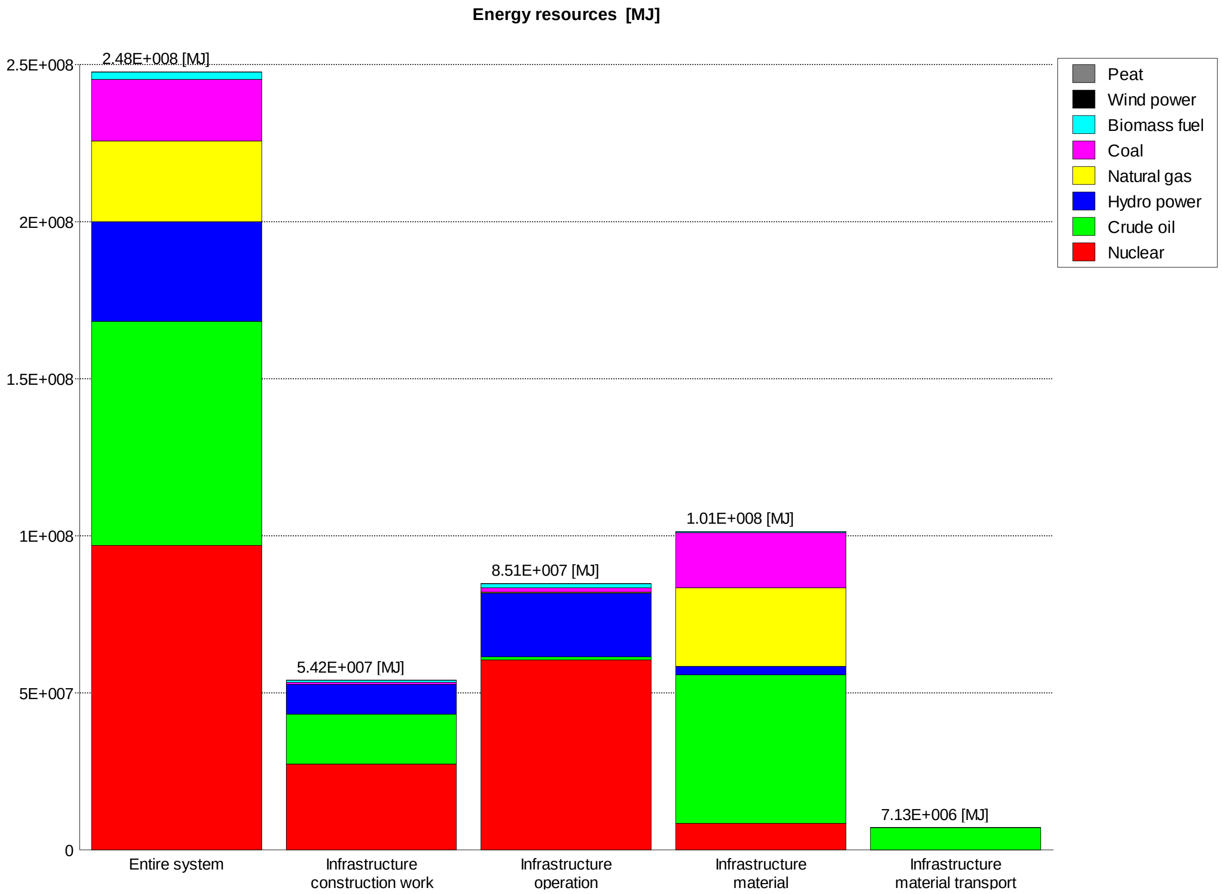

Figure 46 Use of primary energy resources for a long single track railway tunnel (type tunnel: Åskottsberget). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The energy use is divided into different activity groups and includes construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

9.4.2.2 Emission results

The emissions of greenhouse gases divided in construction, maintenance and operation and in different activity groups are shown in Figure 47 and Figure 48 for the short tunnel example. The emission of fossil CO_2 is the dominating emittant but the emission of N_2O plays a significant role. CO_2 caused by deforestation is significant in this example but depends very much on the assumed forest/harvest amounts. The emissions during tunnel construction are the dominating source while the emission during operation is small. Generally, railway tunnels have a low energy use during operation (no ventilation, in many case no water pumping, low illumination level). However, in cold climate electric power is used for frost protection of firewater supply pipes. The electricity used is however produced by low CO_2 power production. Railway tunnels have a relatively low level of maintenance so the emission from maintenance is much smaller than from the construction phase. From Figure 48 we can also conclude that the main emissions emanates from production of different materials while the actual construction work is relatively small. The uptake of CO_2 in concrete occurs mainly in the shotcrete layer. In this case, we have assumed an uptake level of 20 % of maximum uptake. Uptake of CO_2 during waste phase of concrete is not included in the model.

For the long tunnel, the emissions of greenhouse gases are 6.7 times larger but the main railway tunnel is only 5.6 times longer. The emissions show the same pattern as for the short tunnel. Deforestation is proportionally smaller because the same amount of forest has been assumed for the short and long tunnel.

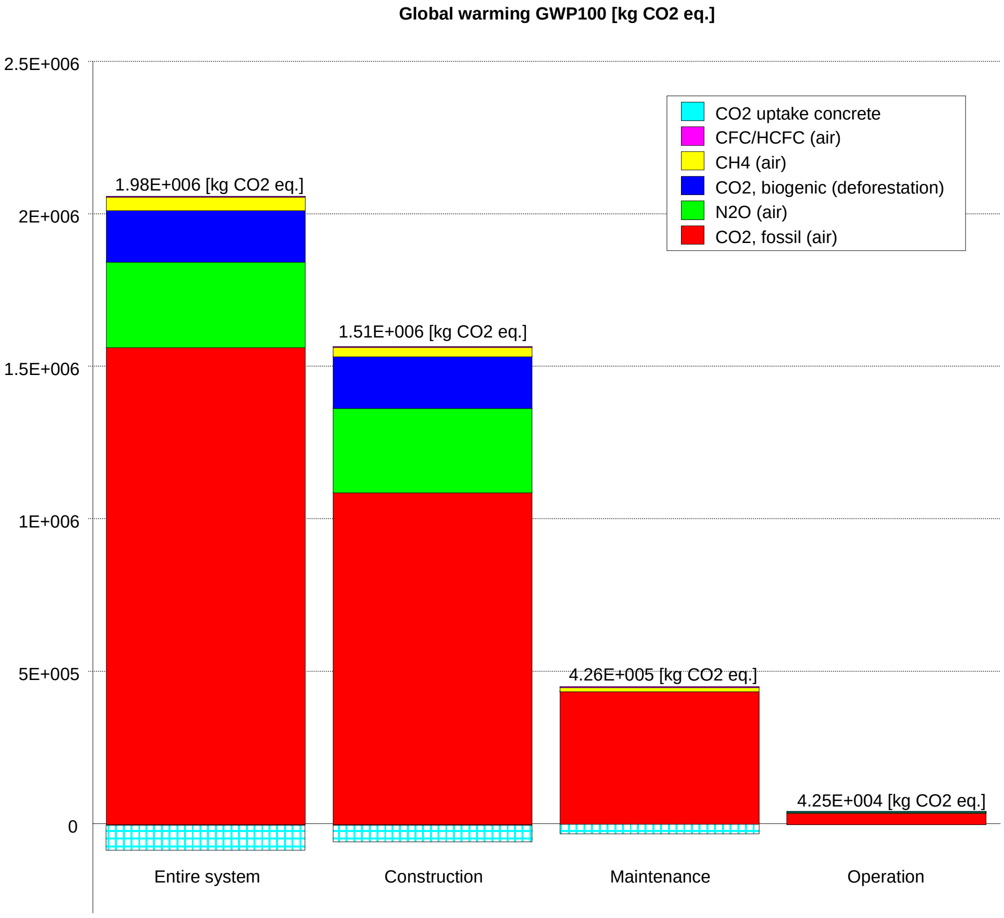

Figure 47 Emissions of greenhouse gases for a short single track railway tunnel (type tunnel: Håknäs). The figure shows the total results for a 586 m long tunnel. The emissions are divided into construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

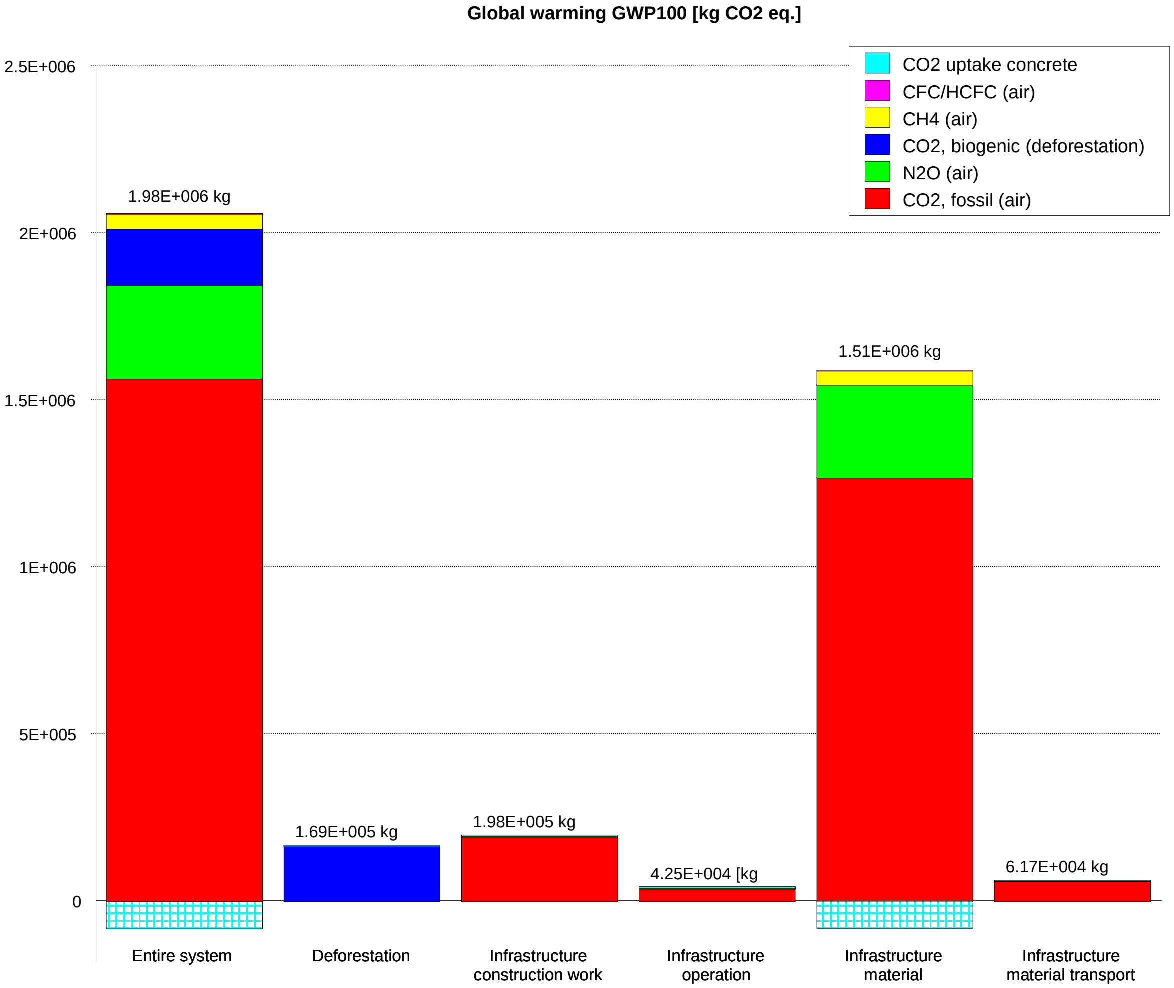

Figure 48 Emissions of greenhouse gases for a short single track railway tunnel (type tunnel: Håknäs). The figure shows the total results for a 586 m long tunnel. The emissions are divided into different activity groups and include construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

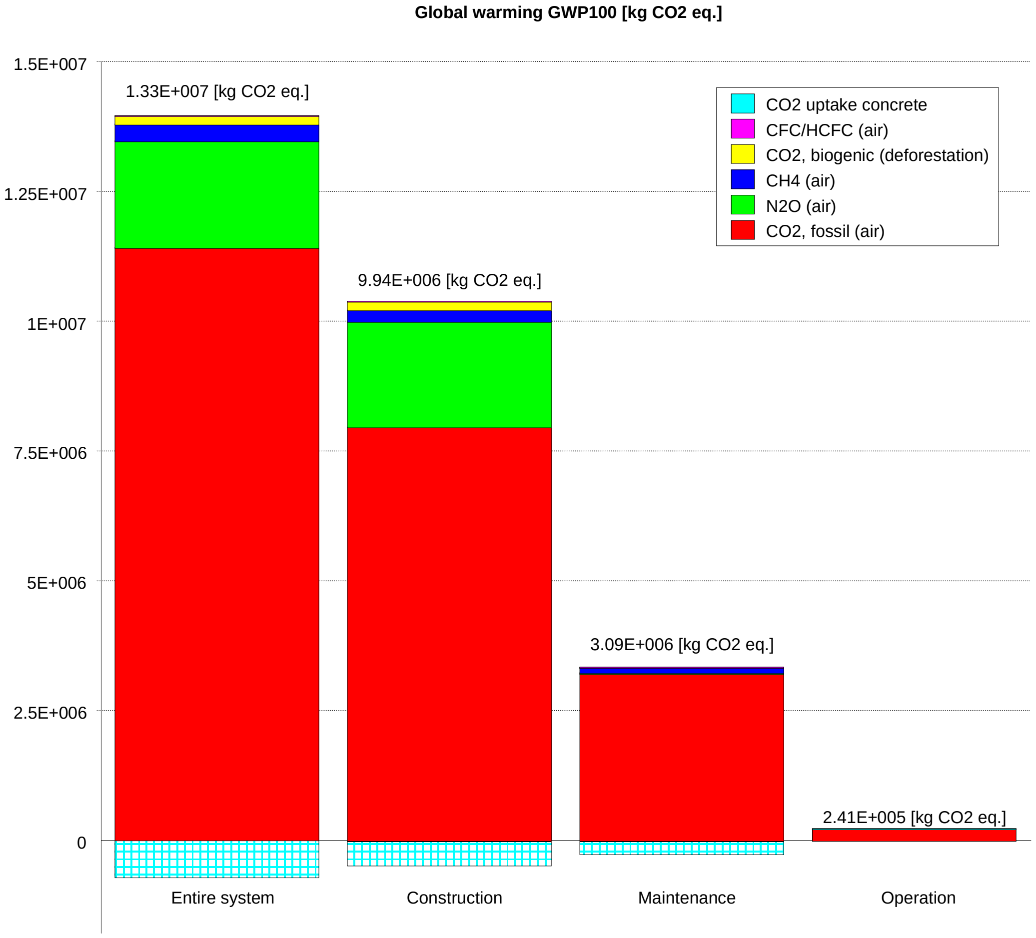

Figure 49 Emissions of greenhouse gases for a long single track railway tunnel (type tunnel: Åskottsberget). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The emissions are divided into construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

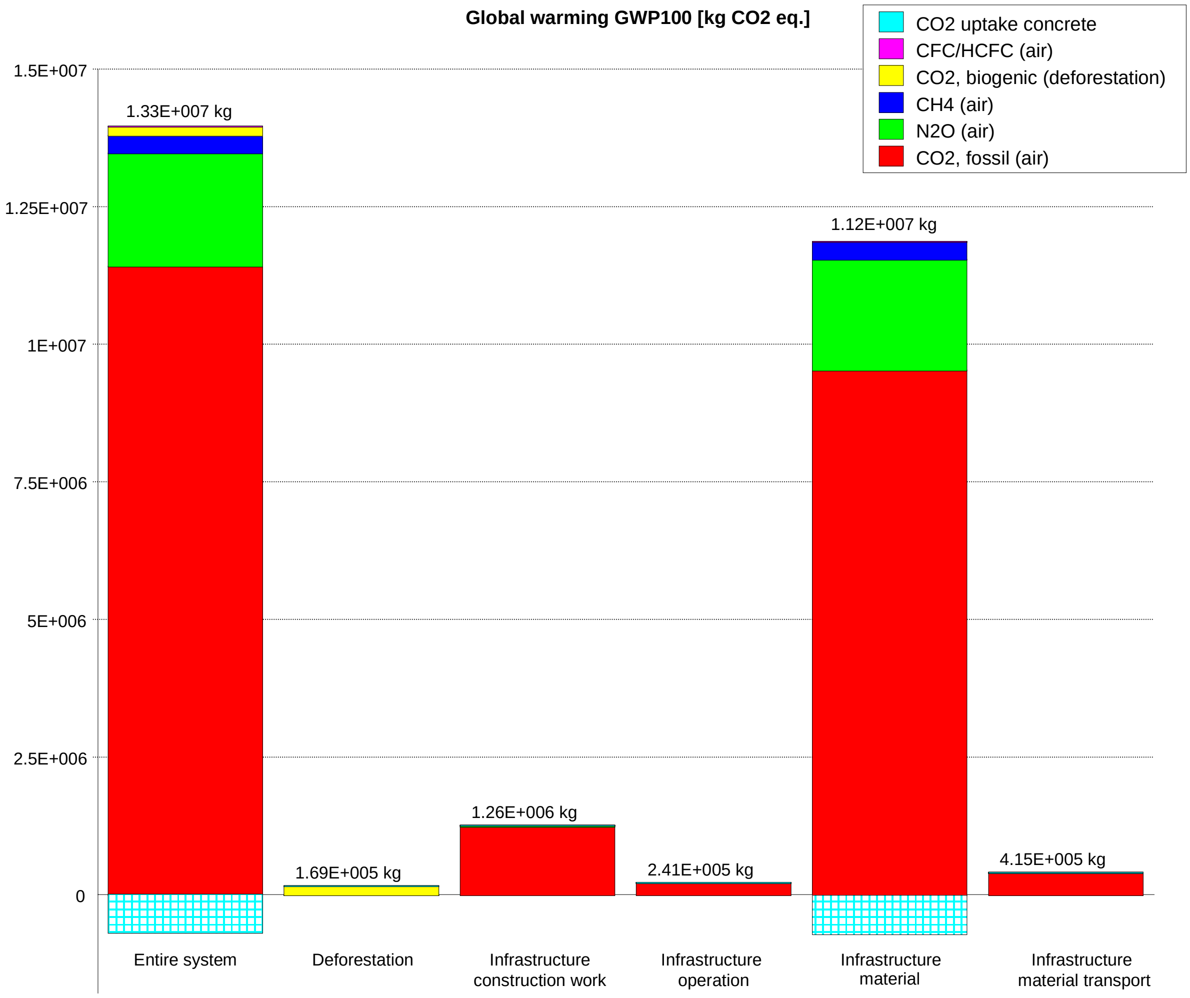

Figure 50 Emissions of greenhouse gases for a long single track railway tunnel (type tunnel: Åskottsberget). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The emissions are divided into activity groups including construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

The acidification potential for the long tunnel divided into activity groups is shown in Figure 51. Also here, the production of materials for the infrastructure is the dominating origin for acidification. In total, the emissions of NO_X and SO_2 play an equal role for the acidification potential. Also the eutrophication potential is driven by production of materials for the infrastructure and NO_X is an important emittant for the eutrophication potential even if other emittants also make a significant contribution, Figure 52.

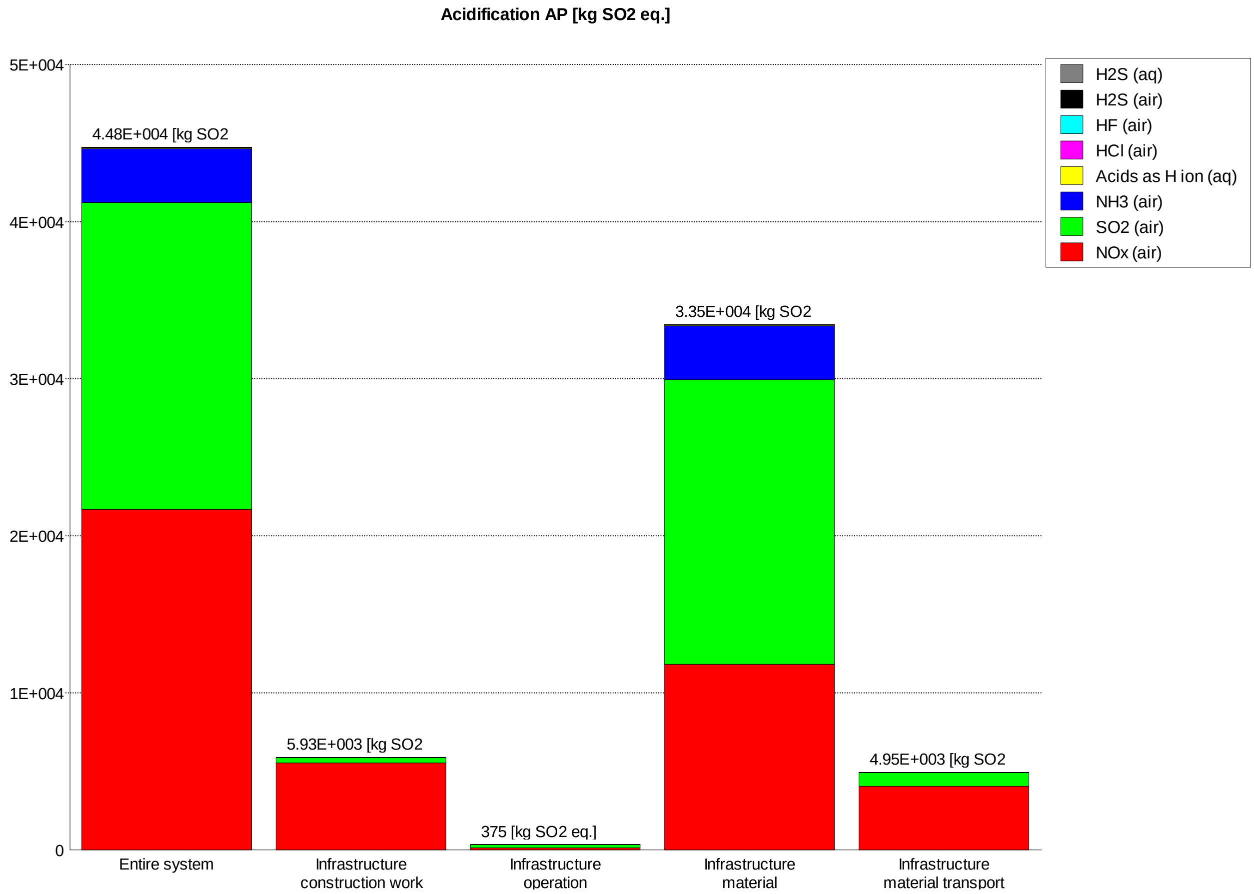

Figure 51 Emissions of acidifying pollutants for a long single track railway tunnel (type tunnel: Åskottsberget), expressed as acidification potential (kg SO_2 equivalents). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The emissions are divided into activity groups including construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

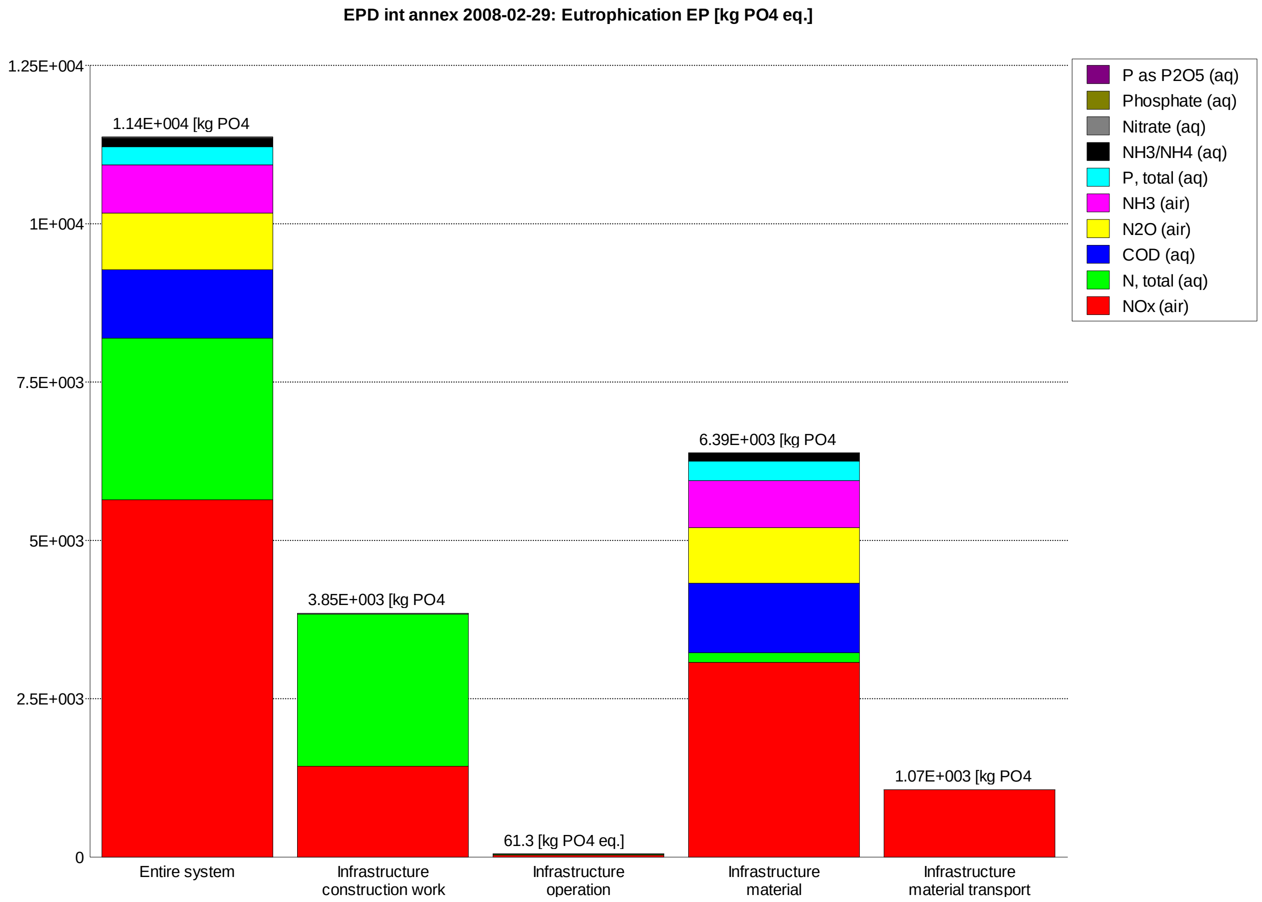

Figure 52 Emissions of eutrophying pollutants for a long single track railway tunnel (type tunnel: Åskottsberget), expressed as eutrophication potential EP (kg PO_4 equivalents). The figure shows the total results for a 3276 m long railway tunnel (main tunnel) including 2265 m service tunnel and 360 m access tunnel. The emissions are divided into activity groups including construction, maintenance and operation over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

9.4.3 Results from the Bothnia Line example

The overall results from the railway tunnel model used in the calculation for modelling of data to the Environmental Product Declaration (EPD) for railway tunnels[16] at the Bothnia Line are shown in this chapter. The input data for the model is real data for the Bothnia Line or calculated data for the Bothnia Line. A full set of impact categories are calculated and the results are presented in Table 18. The results are given per km railway tunnel (single track, main tunnel) and include construction, maintenance and operation over a calculation period of 60 years. The results show average values per km railway tunnel for the 16 tunnels at the Bothnia Line.

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[16] EPD Railway tunnels, Environmental Product Declaration for railway tunnels on the Bothnia Line., Reg. no. S-P-00197, UN CPC 53212, Date 2010-03-19.

In Table 19 the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 19. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are explained in chapter 9.1.3. The distribution of the emission impact categories in the overview activity areas are shown in Table 20.

Finally, a graphic overview impact distribution analysis of the railway tunnels at the Bothnia Line has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is shown in Figure 53.

Table 18 Environmental impact for 1 km railway tunnel (main line) of the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the tunnel infrastructure. Note that the track, power, signalling and telecom systems are not included here .

Impact category	Unit/km main tunnel	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	25 808 501	4 775	3 796 397	29 609 673
Renewable materials	kg/km	111	0	53	164
Non-renewable energy	MJ/km	32 780 178	19 188 361	11 138 601	63 107 140
Renewable energy	MJ/km	3 176 306	6 640 435	507 874	10 324 615
Recycled resources	kg/km	293 831	0	177 053	470 884
Water	kg/km	34 119 529	0	2 885 520	37 005 049
Land use	m^2/km	27 741	66 397	2 998	97 135
Emissions					
Global warming	kg CO_2 eq./km	2 970 984	73 203	877 105	3 921 291
Acidification	kg SO_2-eq./km	10 517	114	2 450	13 081
Ozone depletion	kg CFC-11 eq./km	0.0010	0	0.0016	0.0026
POCP (Photochemical oxidant formation)	kg ethene-eq./km	1 162	18	474	1 653
Eutrophication	kg PO_4^{2-}eq./km	2 810	19	498	3 326
Other					
Output of materials for recycling	kg/km	0	0	81 926	81 926
Waste, hazardous	kg/km	18 164	42 966	2 093	63 222
Waste, excess soil	kg/km	2 971 717	0	0	2 971 717
Waste, other	kg/km	30 020 540	33 332	3 895 550	33 949 421

Table 19 Specification of resources making the largest contributions to the different resource use categories for the railway tunnels.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 85.5%, Limestone $CaCO_3$: 10.7%, Sand and gravel: 2.5%, Iron 1.0%
Renewable materials	kg	Wood: 100%
Non-renewable energy	MJ	Nuclear: 45.6 %, Crude oil: 33.1%, Natural gas 11.9%, Coal: 9.0%
Renewable energy	MJ	Hydro power: 92.5 %, Biomass fuel: 7.0%,
Recycled resources	kg	Ferrous scrap: 96.6%, Steel scrap: 2.7%, Stainless steel scrap: 0.7%

Table 20 Main process contributors to the different impact categories for the railway tunnels.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 82.5 % Infrastructure construction work: 9.7 % Infrastructure material transport: 3.1 % Infrastructure operation: 1.9 % Deforestation: 2.8 %
Acidification	kg SO_2-eq.	Infrastructure material: 74.4 % Infrastructure construction work: 13.7 % Infrastructure material transport: 11.1 % Infrastructure operation: 0.9 % Deforestation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 85.2 % Infrastructure construction work: 8.8 % Infrastructure material transport: 4.9 % Infrastructure operation: 1.1 % Deforestation: 0.0 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 55.7 % Infrastructure construction work: 34.3 % Infrastructure material transport: 9.4 % Infrastructure operation: 0.6 % Deforestation: 0.0 %

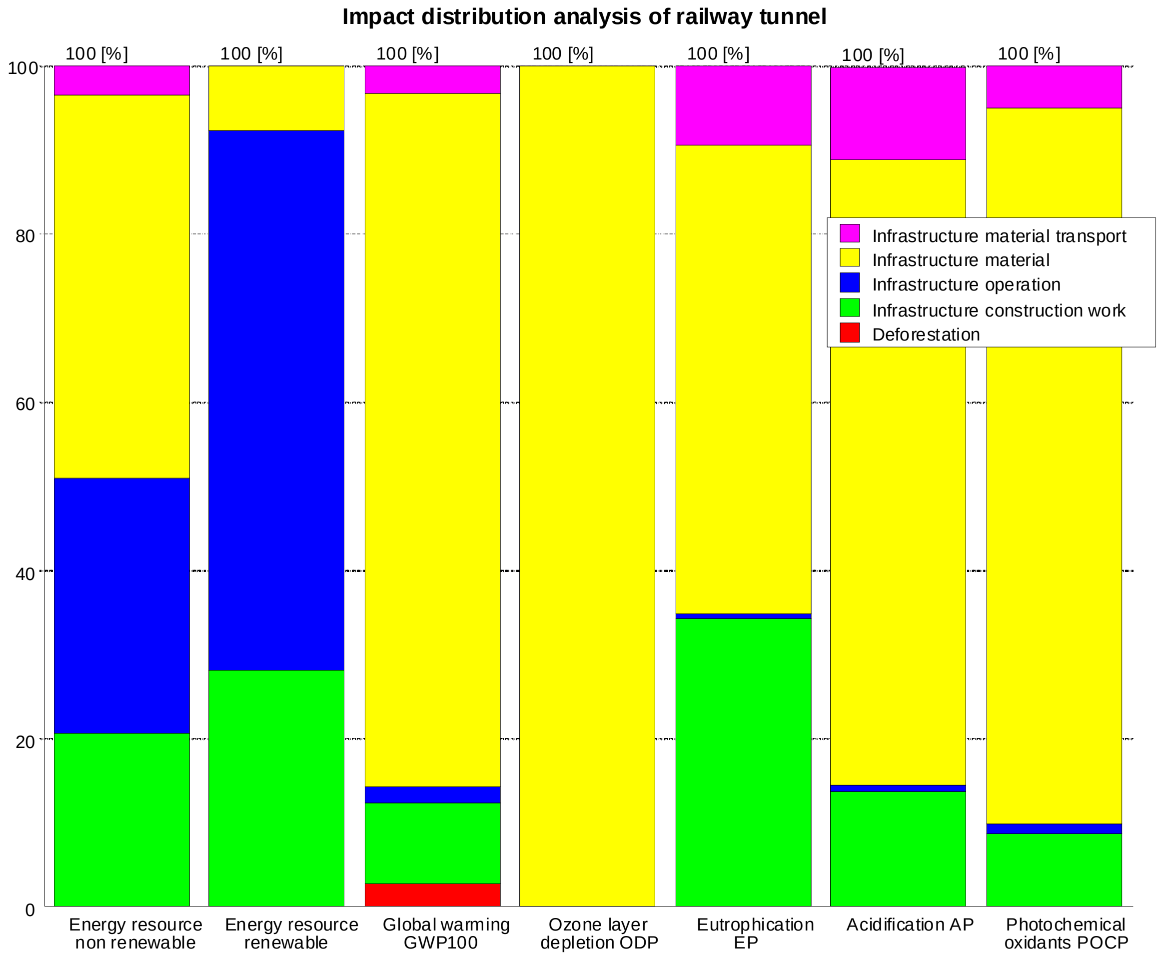

Figure 53 Impact distribution analysis of railway tunnels at the Bothnia Line.

9.5 Railway bridge analysis

9.5.1 Analysis and scenario description

Railway bridges can be designed in many different ways, which is described in the bridge presentation, chapter 5.5. For the analysis, a concrete beam bridge at the Bothnia Line has been used as an example bridge to show the results from the bridge model. Bridges can vary significantly both in design/construction and in terrain conditions even if the technical design is well standardised. For example, the height of the bridge can of course vary significantly and it can therefore be difficult to give a specified value per meter bridge of different energy and environmental parameters. Therefore, we have chosen to show the results for an entire bridge model.

A railway bridge is usually moulded on site. The moulding process consists of construction of concrete moulds and the actual moulding. This process is very difficult to break down in sub-processes and to obtain data from. It has therefore been necessary to use empirical data from real bridge construction projects. This data consist mainly of electric power use and use of diesel oil even if some material use data such as mould form materials also has been included. All materials for the bridge such as concrete, reinforcement steel, noise protections, parapets, erosion protections at bridgeheads etc. are included in the model in the usual way covering also the production of the materials. An uncertainty, with this method is that it can be difficult to know exactly which processes are covered and included in the empirical data. It can therefore be a risk of overlapping or missing process data in the model due to the bridge specification in the model.

In Table 21, a specification of the bridge used for the analysis is presented. The Hörnefors bridge at the Bothnia Line is used as an example bridge. No exact data exist for the bridge for all processes, so estimated data have been used for example for the foundation work.

Table 21 Specification of railway bridge scenario used in chapter 9.5.2. The scenario reflects one bridge, the Hörnefors bridge, at the Bothnia Line.

Activity/Process	**Description**
Bridge type	Concrete beam bridge for single track
Bridge length	389 m
Number of bridge piers	11 + bridge heads
Bridge height	A relatively constant average height of 5 m
Total bridge pier length	70 m
Concrete piles	600 m total length of piles per bridge pier
Foundation filling	144 m^3 per bridge pier
Foundation concrete casting	75 m^3 per bridge pier
Base course ballast in bridge track foundation	1.98 m^3 per m bridge
Cable channel	One channel along the entire bridge
Erosion protection	200 m^2 per bridge (0.3 m thickness)
Noise protection	Glass type along both sides of the bridge
Parapet	Along both sides of the bridge
Service road	Along the entire bridge (bridge length)

In addition to this example bridge, the results from the Bothnia Line are shown in chapter 9.5.3. In this chapter, the overall results from modelling of all 90 railway bridges at the Bothnia Line are shown.

9.5.2 Results from the analysis

9.5.2.1 Energy results

The total primary energy use for the Hörnefors bridge is shown in Figure 54 and Figure 55. As shown in the figures, the construction phase is totally dominating the energy use. Only a small part is used for maintenance and no energy use is assumed for the operation of the bridge. A large part (64 %) of the energy is used in the production of different materials for the bridge, Figure 55. The actual construction work of the bridge stands only for approximately 27 % of the primary energy use. Crude oil is, in this case, the main energy source with a share of 50 %. The crude oil is mainly used for cement production, transport, machinery, heating and steel production.

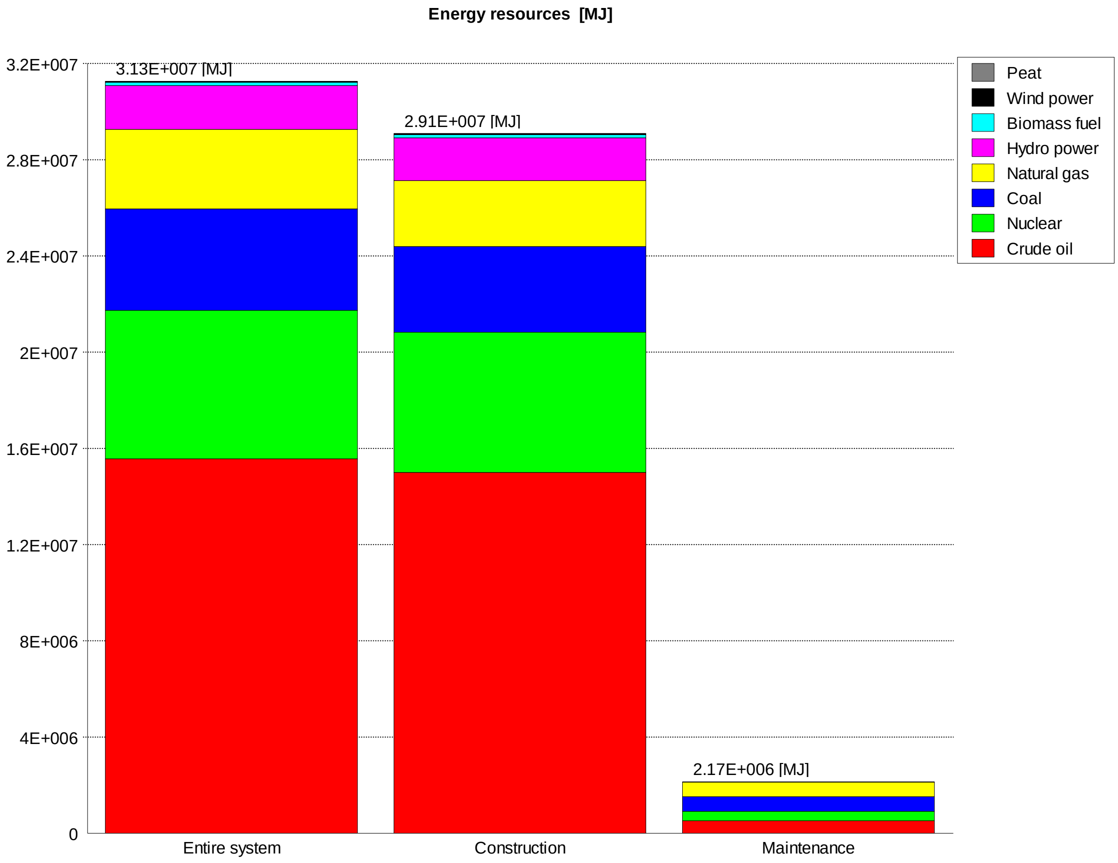

Figure 54 Use of primary energy resources for a concrete beam bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m single track railway bridge. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. No operation data exist for the bridge. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

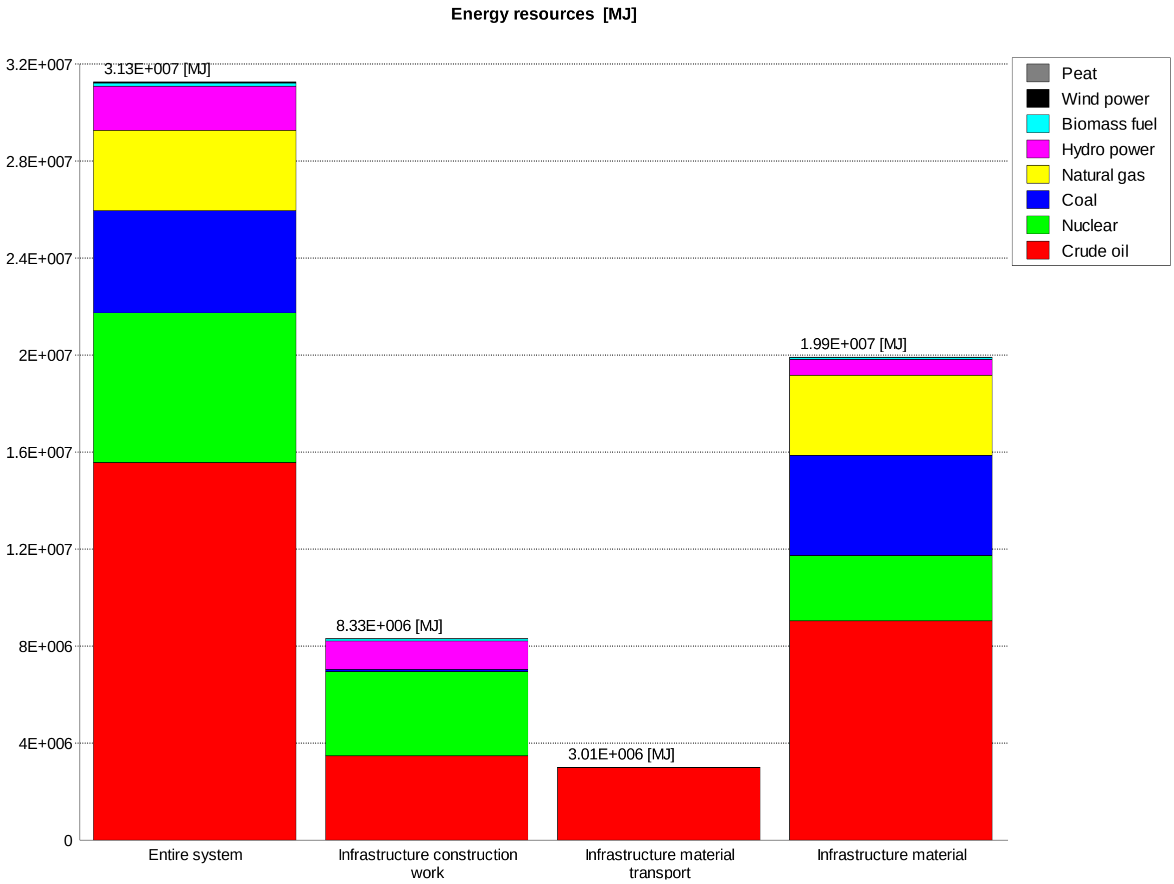

Figure 55 Use of primary energy resources for a concrete beam bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m single track railway bridge. The energy use is divided into activity groups including construction, maintenance and operation and shows the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

9.5.2.2 Emission results

The main emission source for the greenhouse gases is CO_2 from fossil sources. The contribution from CH_4 and N_2O is small, see Figure 56. The uptake of CO_2 in bridge concrete during the lifetime of the bridge has been estimated to 5 % of maximum concrete uptake. The uptake of CO_2 during waste phase of the concrete is not included in the study. The uptake is shown under construction but take, of course, place during the entire lifetime of the bridge. The emission of greenhouse gases is strongly related to the construction phase of the bridge and only small amounts are released during maintenance. No emissions from operation activities have been assumed. Much of the CO_2 emissions take place in the production of materials for the bridge, see Figure 57. The CO_2 emission emanates mainly from cement production (59 %), steel production (18.6 %) and transport/machine use (14.7 %).

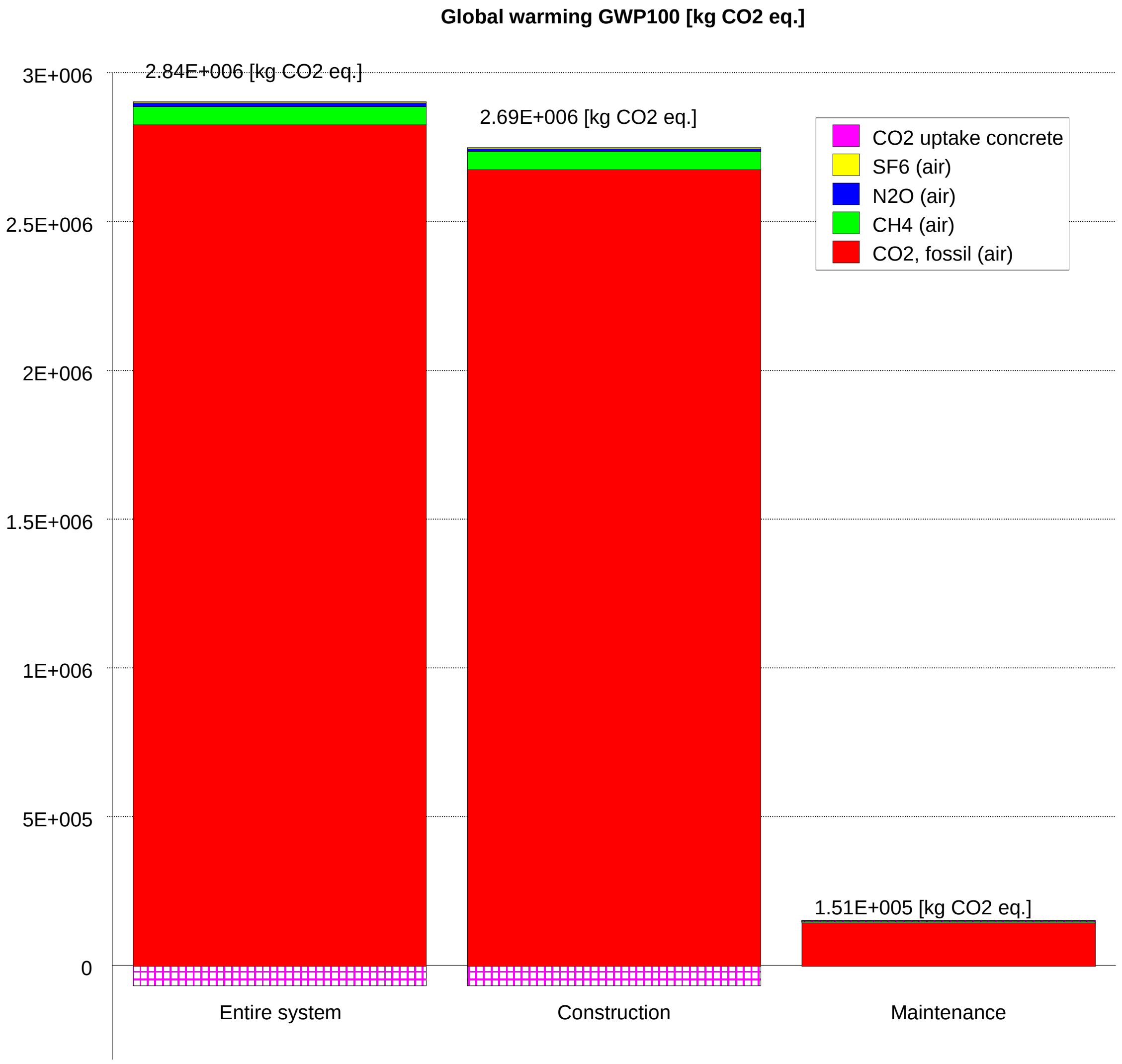

Figure 56 **Emissions of greenhouse gases for a single track railway bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m long bridge. The emissions are divided into construction, maintenance and operation and show the results over a calculation period of 60 years. No operation data exist for the bridge. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.**

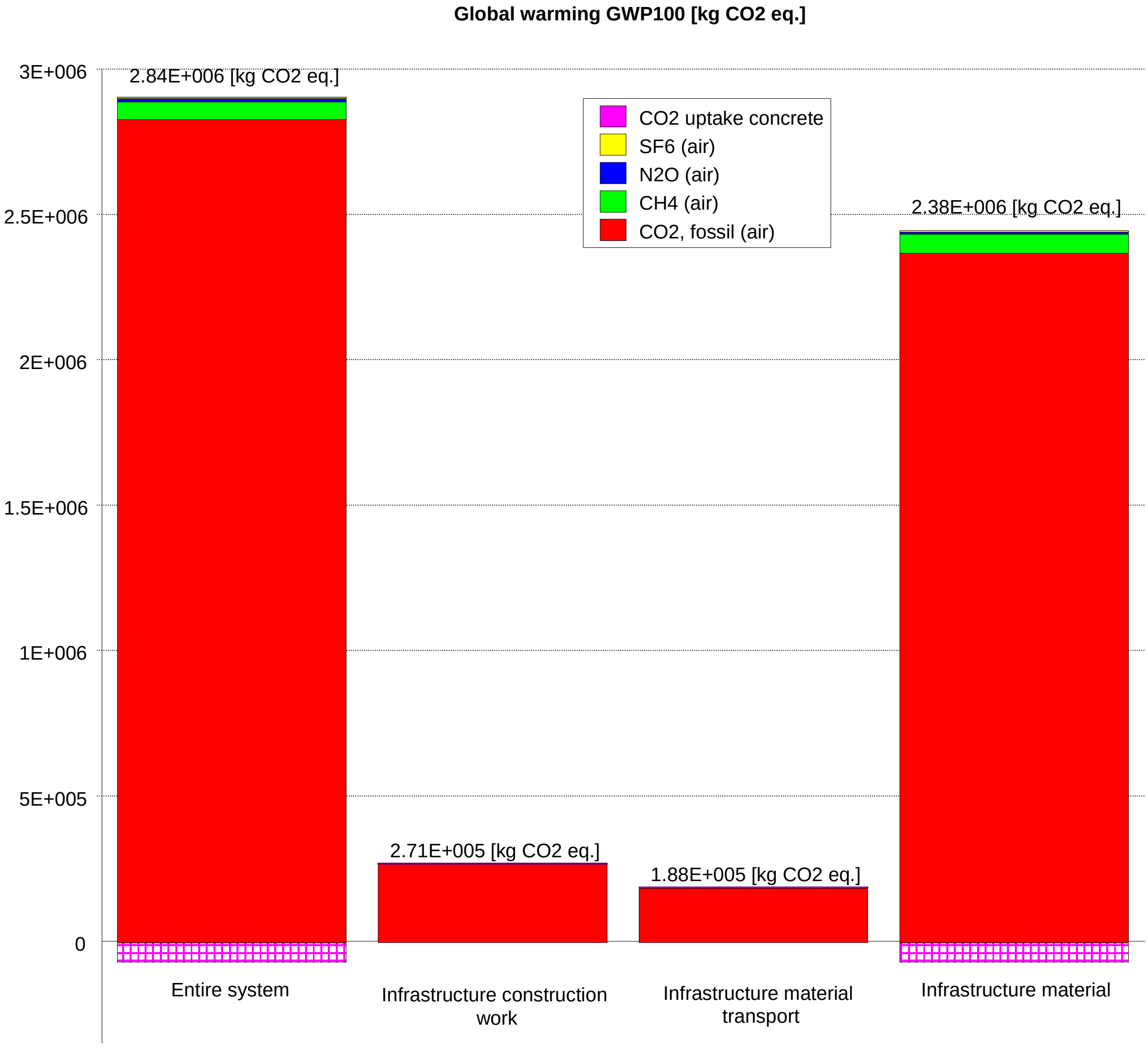

Figure 57 Emissions of greenhouse gases for a single track railway bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m long bridge. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

The emissions of acidifying and eutrophying pollutants are shown in Figure 58 and Figure 59 respectively. The main pollutants for acidification are NO_X and SO_2 and the main pollutants for eutrophication are NO_X, COD and P, total. The production of different materials plays also here an important role. 50.5 % of the NO_X emissions emanate from different transports and machines, 28.9 % comes from cement production and 9.6 % from steel production. Of the SO_2 emission, 34 % originate from cement production (can vary significantly due to sulphur content in fuels), 36.6 % originate from steel production and 19.5 % from glass production.

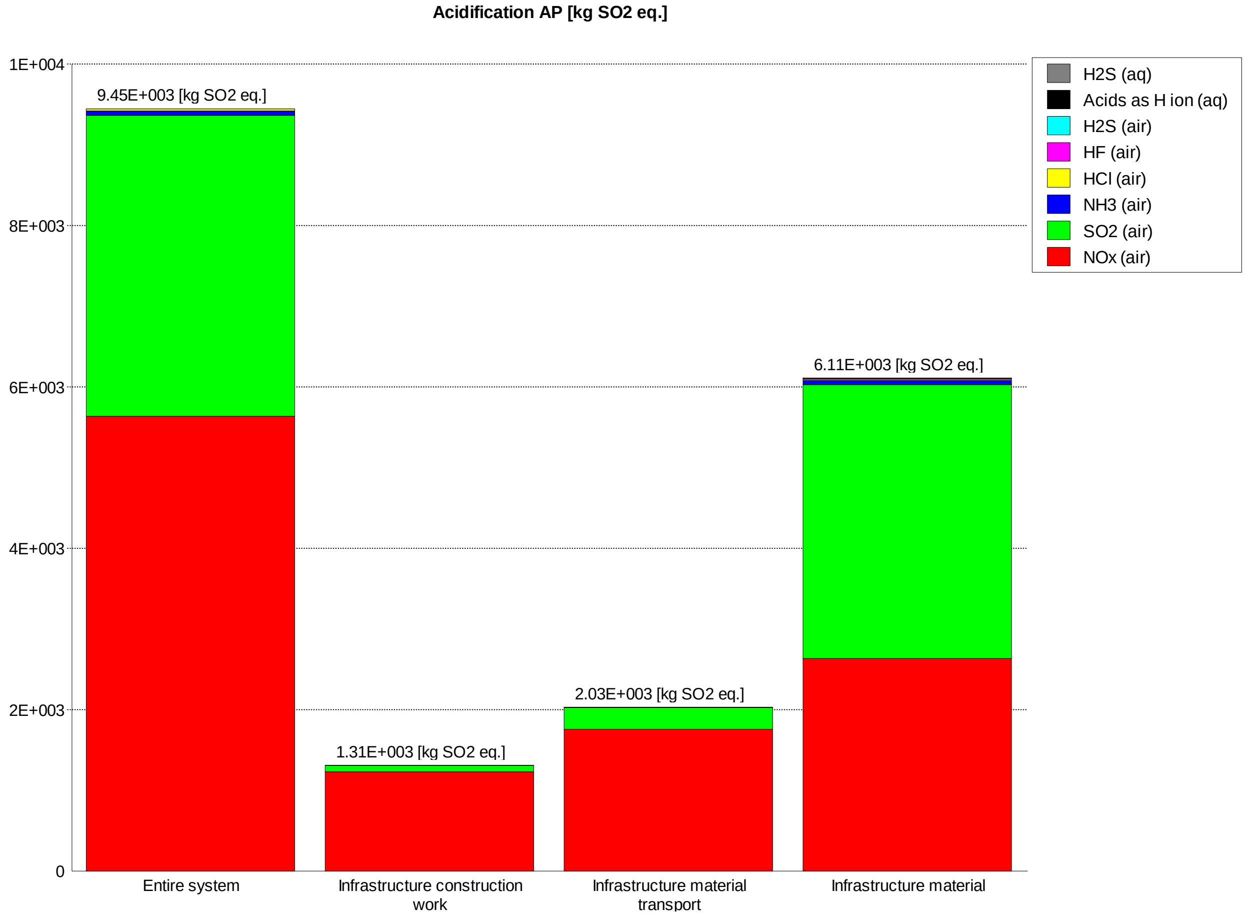

Figure 58 Emissions of acidifying pollutants for a single track railway bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m long bridge. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

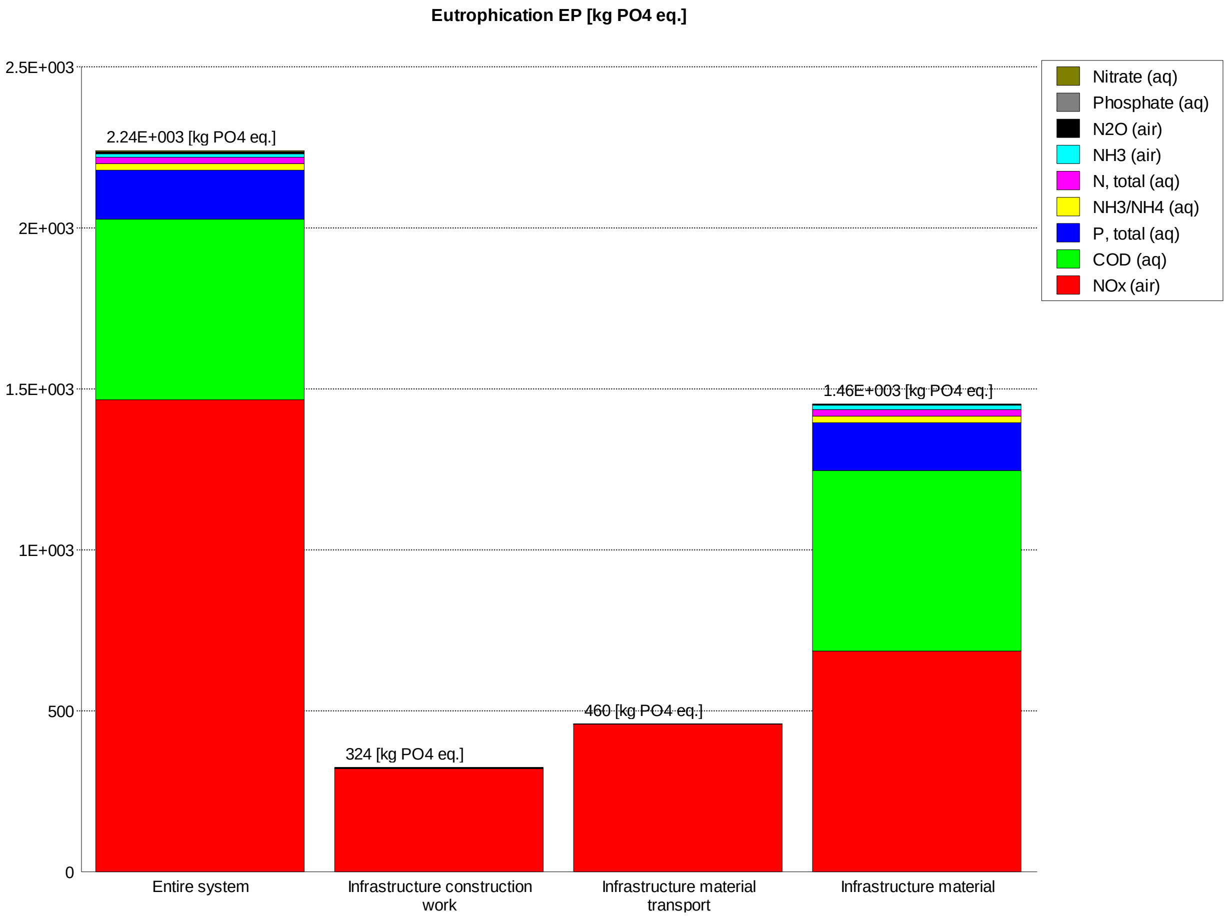

Figure 59 Emissions of eutrophying pollutants for a single track railway bridge (type bridge: Hörnefors). The figure shows the total results for a 389 m long bridge. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the railway track (rail, sleeper and track ballast) and the train power and control systems.

9.5.3 Results from the Bothnia Line example

The overall results from the railway bridge model used in the calculation for modelling of data to the Environmental Product Declaration (EPD) for railway bridges[17] at the Bothnia Line are shown in this chapter. The input data for the model is real data for the Bothnia Line or calculated data for the Bothnia Line. A full set of impact categories are calculated and the results are presented in Table 22. The results are given per km railway bridge (single track) and include construction, maintenance and operation over a calculation period of 60 years. The results show average values per km railway bridge for the 90 railway bridges at the Bothnia Line.

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[17] EPD Railway bridges, Environmental Product Declaration for railway bridges on the Bothnia Line., Reg. no. S-P-00199, UN CPC 53212, Date 2010-03-19.

In Table 23 the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 23. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are explained in chapter 9.1.3. The distribution of the emission impact categories in the overview activity areas are shown in Table 24.

Finally, a graphic overview impact distribution analysis of a railway bridge at the Bothnia Line has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is shown in Figure 60. As shown from the figure, the production of different materials for the bridge is the most important factor for the overall environmental performance. The construction work and transports play some role while operation activities are small. The role of deforestation depends very much on the amount of forest that is removed for the bridge construction.

Table 22 Environmental impact of 1 km of railway bridge (main line) on the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the bridge infrastructure. However, note that track, power, signalling and telecom systems are not included here.

Impact category	Unit/km main track on bridges	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	56 556 542	0	377 618	56 934 159
Renewable materials	kg/km	12 467	0	18 094	30 560
Non-renewable energy	MJ/km	72 705 398	0	3 441 006	76 146 404
Renewable energy	MJ/km	4 895 032	0	19 471	4 914 503
Recycled resources	kg/km	2 638 188	0	11 563	2 649 752
Water	kg/km	8 636 953	0	2 294 035	10 930 988
Land use	m^2/km	78 358	0	44	78 402
Emissions					
Global warming	kg CO_2 eq./km	7 736 185	0	308 742	8 044 927
Acidification	kg SO_2-eq./km	22 892	0	874	23 765
Ozone depletion	kg CFC-11 eq./km	0	0	0	0
POCP (Photochemical oxidant formation)	kg ethene-eq./km	2 612	0	44	2 656
Eutrophication	kg PO_4^{2-}eq./km	6 176	0	105	6 281
Other					
Output of materials for recycling	kg/km	0	0	102 814	102 814
Waste, hazardous	kg/km	23 457	0	31	23 488
Waste, excess soil	kg/km	86 697 896	0	0	86 697 896
Waste, other	kg/km	316 792	0	348 283	665 075

Table 23 Specification of resources making the largest contributions to the different resource use categories for the railway bridges.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 68.8%, Sand and gravel: 15.9%, Limestone $CaCO_3$: 14.1%, Fe (res): 0.9%
Renewable materials	kg	Wood: 100%
Non-renewable energy	MJ	Crude oil: 52.9% , Nuclear: 18.8%, Coal: 17.6% , Natural gas: 10.7%
Renewable energy	MJ	Hydro power: 92.6%, Biomass fuel: 7.1%
Recycled resources	kg	Ferrous scraps: 100%

Table 24 Main process contributors to the different impact categories for the railway bridges.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 76.4 % Infrastructure construction work: 10.2 % Infrastructure material transport: 5.8 % Infrastructure operation: 0.0 % Deforestation: 7.5 %
Acidification	kg SO_2-eq.	Infrastructure material: 61.3 % Infrastructure construction work: 17.5 % Infrastructure material transport: 21.3 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 0.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 76.6 % Infrastructure construction work: 12.1 % Infrastructure material transport: 11.3 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 65.4 % Infrastructure construction work: 16.4 % Infrastructure material transport: 18.2 % Infrastructure operation: 0.0 % Deforestation: 0.0 %

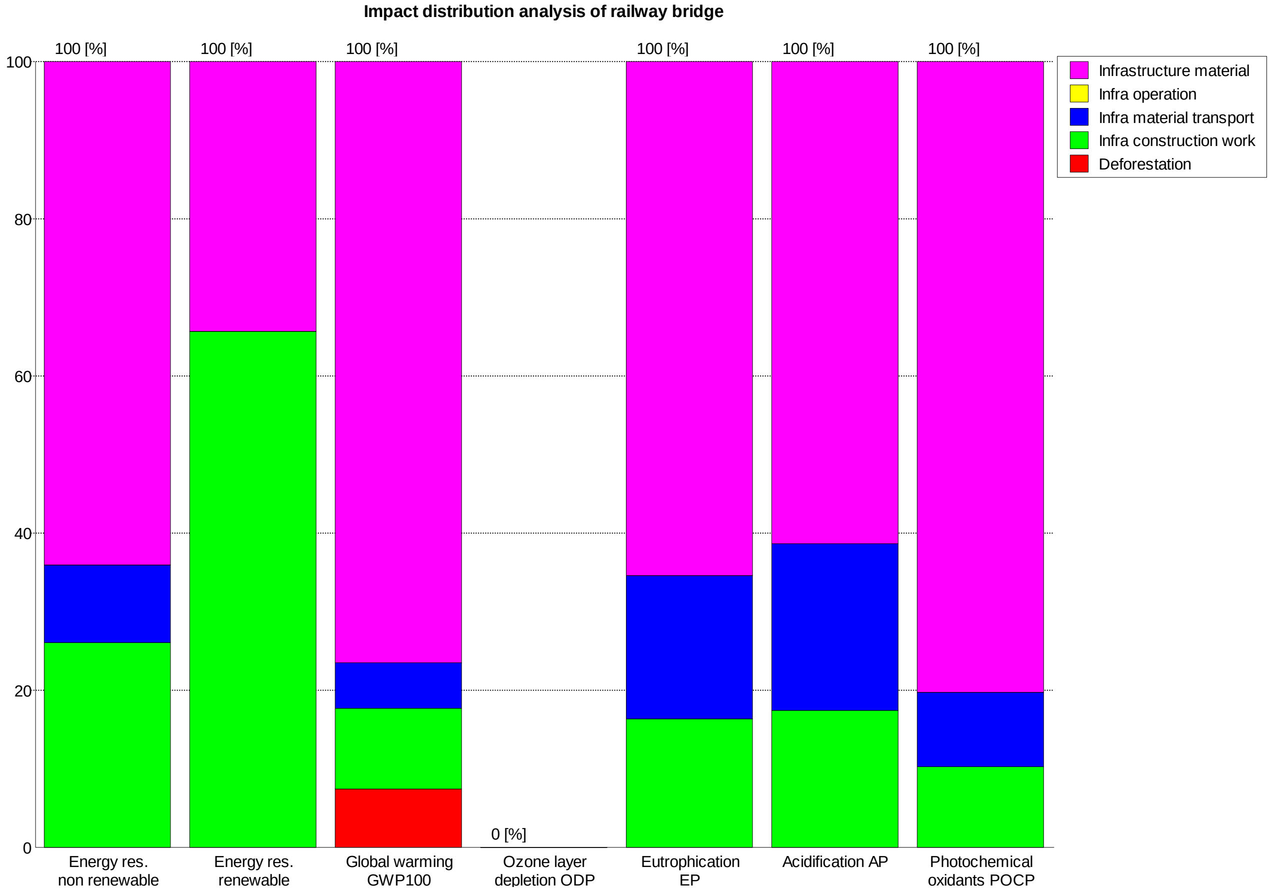

Figure 60 Impact distribution analysis of railway bridges at the Bothnia Line.

9.6 Passenger station and freight terminal analysis

9.6.1 Analysis and scenario description

A railway needs stations and freight terminals for loading, unloading and transfer of passenger and goods. A brief description of this can be found in chapter 5.6. It is almost impossible to describe a typical railway station. The number of railway stations on a railway also varies significantly and as already has been pointed out the stations can be described as m^2 station per km railway. This can form a good measure of the influence of stations on the entire railway. The design of the station buildings can of course vary significantly but in this case, we have assumed that the actual station buildings does not differ very much from ordinary buildings of the same size. Freight terminals can in some cases be of a more simple design especially if it is a non-heated storage. In addition, there are construction elements such as passenger platforms, loading platforms and platform roofs in a railway station. These construction elements have not been included in the analysis.

In this chapter, we have tried to give an example of a passenger railway station with a building area of 1000 m^2. LCA data for an ordinary building has been used. Some excavation work has been added as well as specification of energy use for heating and other operation of the building. The estimated lifetime of the building is set to 100 years. The maintenance activities for the building are estimated as 1/100 part of building construction each year. In Table 26 below, the used specifications are presented.

Table 25 Specification of the railway station scenario used for chapter 9.6.2. The scenario reflects an example passenger station of 1000 m^2 building area.

Activity/Process	**Description**
Building area of station	1000 m^2
Forest felling	11.2 m^3 sub
Clearing of soil	250 m^3
Soil excavation	1000 m^3
Energy for heating	100 kWh/m^2 per year (360 MJ/m^2 per year), electric power used (Swedish railway production mix, green power)
Energy of illumination and other operation	30 kWh/m^2 per year (108 MJ/m^2 per year) electric power used (Swedish railway production mix, green power)
Estimated lifetime of station building	100 years

In addition to this example station, the results from the Bothnia Line are shown in chapter 9.6.3. In this chapter, the overall results from modelling all stations at the Bothnia Line are shown. In that analysis, the results for the stations are shown per km main railway. The Bothnia Line is equipped with 7 passenger stations and two goods station as shown below:

Passenger stations and freight terminals	**Building area (m^2)**
Freight terminal Umeå	130 000
Freight terminal Arnäsvall	Small local terminal
Passenger station Örnsköldsvik	45
Passenger station Örnsköldsvik norra	2850
Passenger station Husum	390
Passenger station Nordmaling	830
Passenger station Hörnefors	390
Passenger station Umeå Ö	2000
Passenger station Umeå C	Existing station
Sum total area	136 505
Sum passenger stations	6505
Sum freight terminals	130 000
Main railway length (meter)	183 000 m

9.6.2 Results from the analysis

9.6.2.1 Energy results

In Figure 61 the energy use for the example railway station is shown. As shown in the figure, the energy use (electric power use) for heating, illumination and other operation activities during 60 years is very important and thus much more dominant than construction and maintenance of the buildings. The use of electric power for heating and the use of Swedish green power production mix (mainly hydropower with some biomass fuel) explain the large use of hydropower.

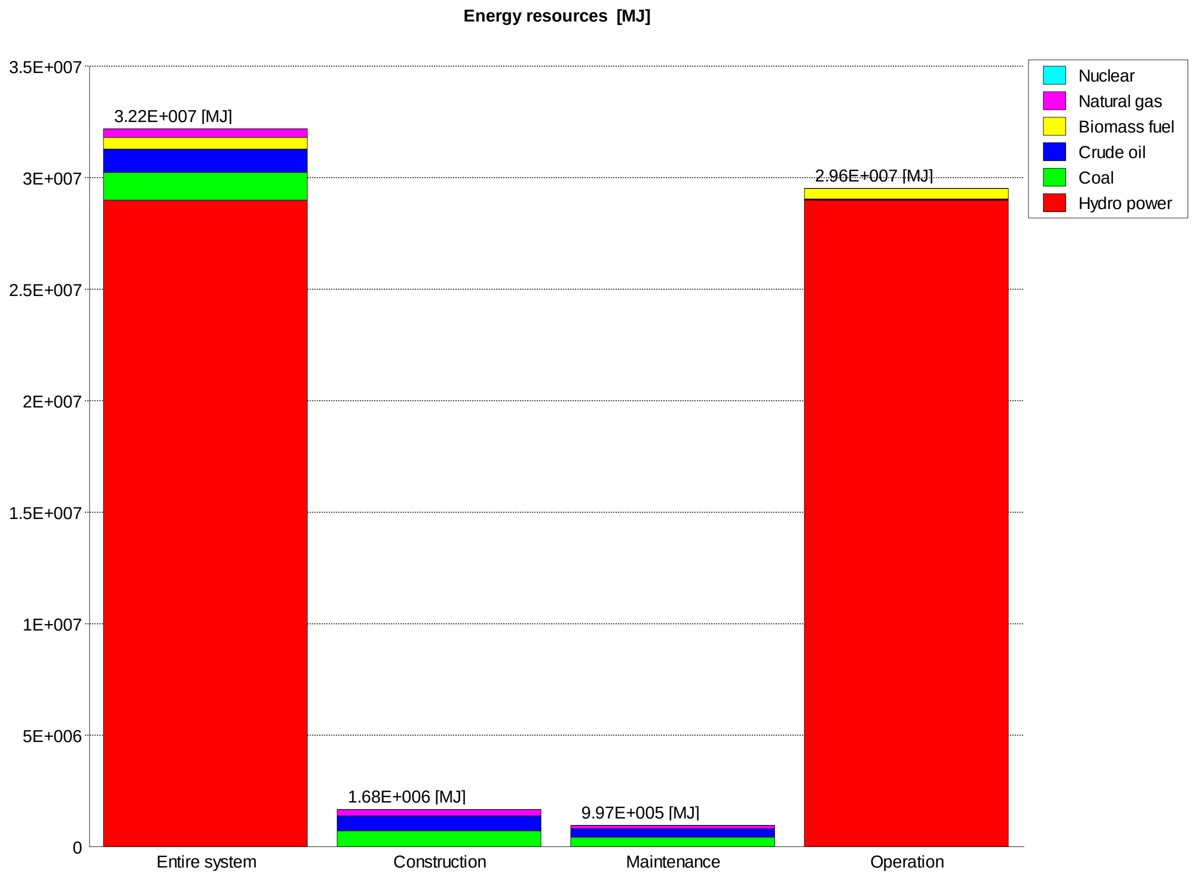

Figure 61 Use of primary energy resources for a railway station. The figure shows the total results for a 1000 m² heated passenger railway station. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. Swedish green railway electric power production mix has been used.

9.6.2.2 Emission results

The emission of greenhouse gases from the example railway station is shown in Figure 62. Unlike the energy use in the previous figure, the operation of the railway station give just a small contribution to the greenhouse gases while construction and maintenance is more dominant. This is of course a result of the emission level from production of used green electric power. The main emittant is fossil-based CO_2. The CO_2 emission caused by deforestation is of course related to how much forest there is on the construction site from the beginning. In this case, we have assumed that the entire construction site was covered with an ordinary Swedish forest (112 m^3 sub per hectare).

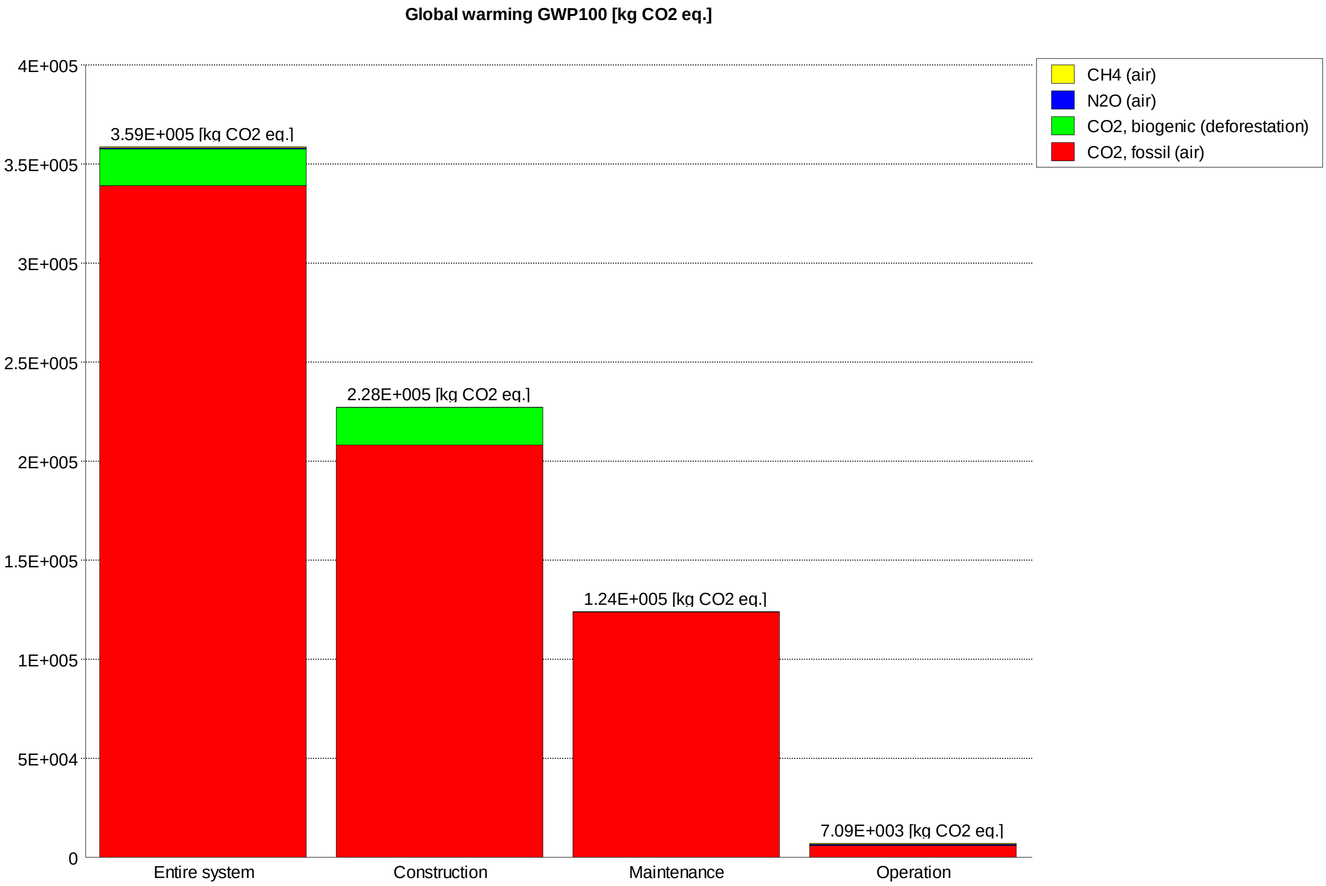

Figure 62 Emissions of greenhouse gases for a railway station. The figure shows the total results for a 1000 m^2 heated passenger railway station. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. Swedish green railway electric power production mix has been used.

The emissions of acidifying pollutants show the same emission pattern as the CO_2 emissions, Figure 63. This is of course also a result of the use of green electric power. NO_X and SO_2 emissions are the main contributing substances for the acidification process. For the eutrophication potential, the emission pattern is similar to the acidification but the emission of NO_X plays an even larger role, Figure 64.

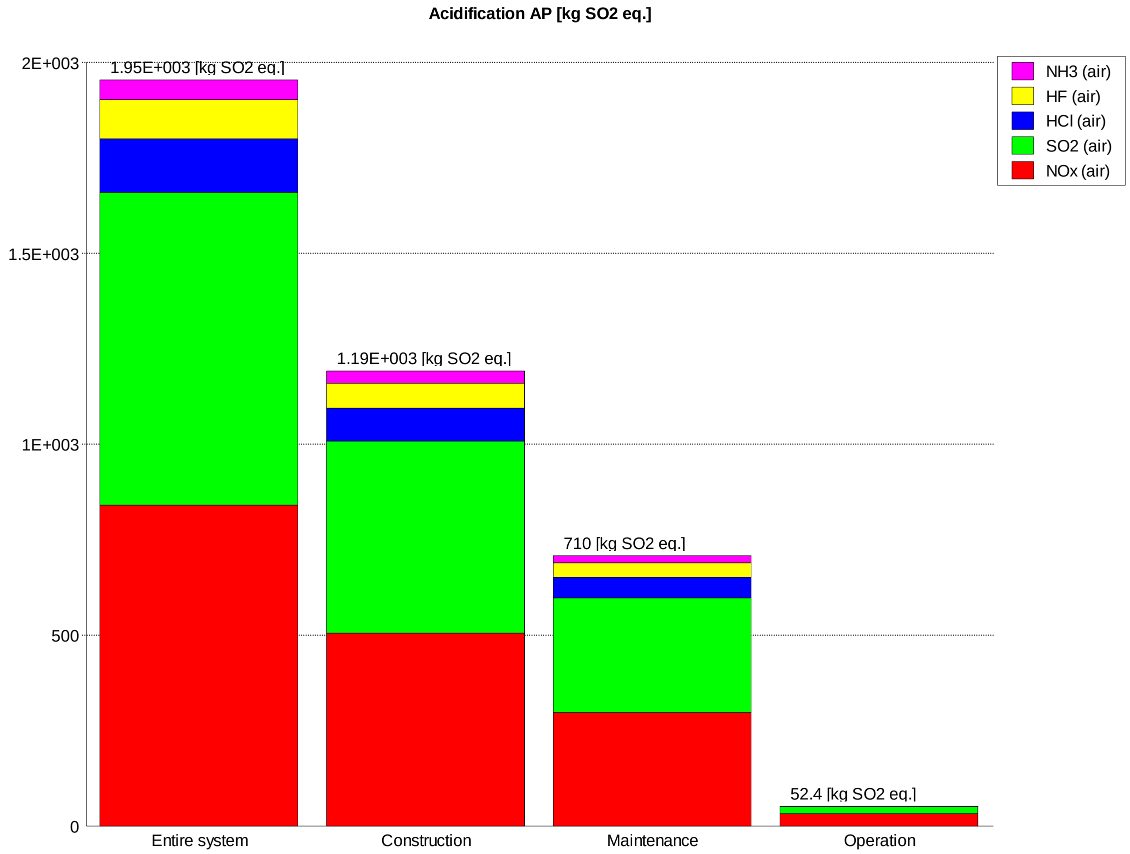

Figure 63 Emissions of acidifying pollutants for a railway station. The figure shows the total results for a 1000 m² heated passenger railway station. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

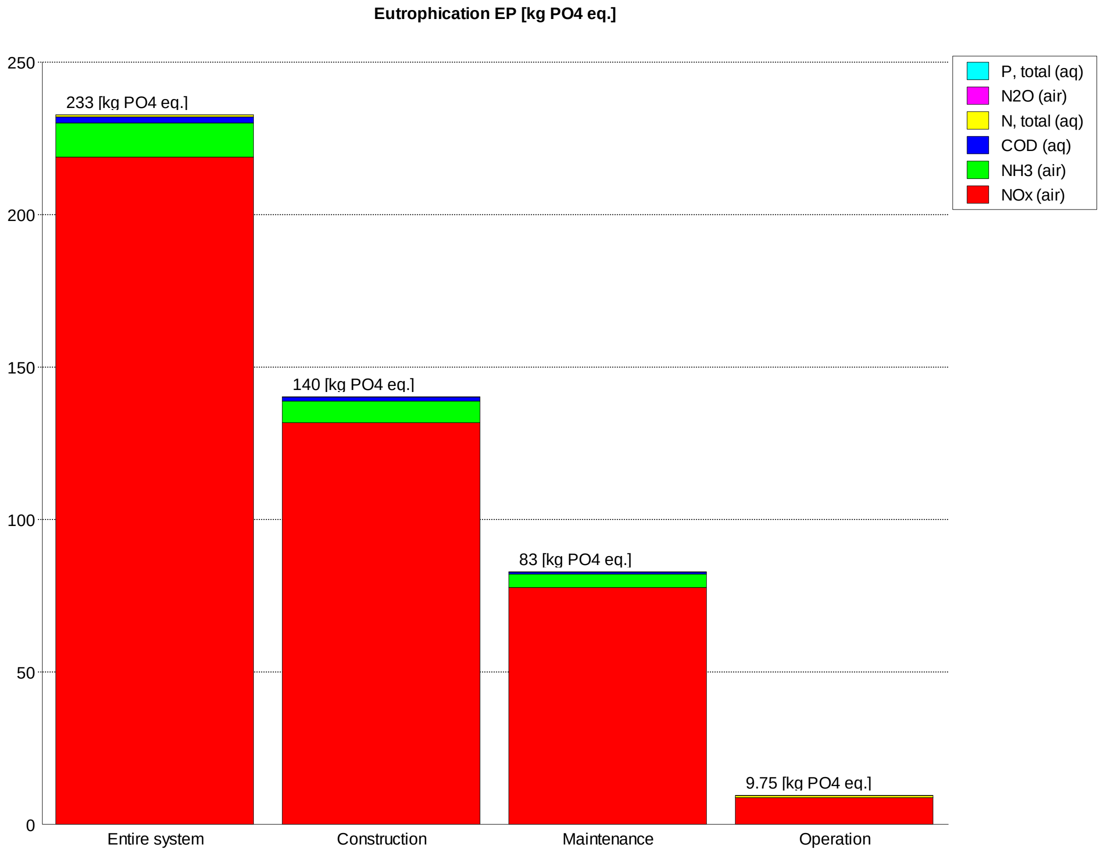

Figure 64 Emissions of eutrophying pollutants for a railway station. The figure shows the total results for a 1000 m^2 heated passenger railway station. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years.

9.6.3 Results from the Bothnia Line example

The overall results from the railway station model used in the calculation for modelling of data for the Environmental Product Declaration (EPD) for the Bothnia Line are shown in this chapter. There is however no separate EPD for stations and terminals at the Bothnia Line. The results presented here are included in the EPDs for passenger transport, freight transport and the total infrastructure of the Bothnia Line. The input data for the model is in general the same data as for the example station but several stations have been modelled and the results have been presented per km main railway, which make it easier to use the data in combination with other railway data. A full set of impact categories are calculated and the results are presented in Table 26. The results are given per km main railway (single track) and include construction, maintenance and operation over a calculation period of 60 years for the stations.

In Table 27 the different resource uses have been broken down into single material uses. The largest contributors are presented in Table 27. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources

of the emissions. The overview activity areas are explained in chapter 9.1.3. The distribution of the emission impact categories in the overview activity areas are shown in Table 28.

Finally, a graphic overview impact distribution analysis of a railway stations at the Bothnia Line has been performed. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. The result of this analysis is shown in Figure 65. As shown from the figure, the production of different materials for the stations is the most important factor for the overall environmental performance. Note however that the construction work is also included in the material production figures due to lack of specific production data for buildings. The hydropower for heating and other purposes is shown in the use of renewable energy.

Table 26 Environmental impact of passenger and goods stations along Bothnia Line calculated and presented per km of main railway line at the Bothnia Line. All construction, operation and maintenance activities over 60 years are included for the passenger and goods stations.

Impact category	Unit/km main track	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	825 077	95.4	495 045	1 320 217
Renewable materials	kg/km	25 364	0	15 218	40 582
Non-renewable energy	MJ/km	1 240 530	1 278	743 732	1 985 540
Renewable energy	MJ/km	0	678 508	0	678 508
Recycled resources	kg/km	22.4	0	13.4	35.8
Water	kg/km	0	0	0	0
Land use	m^2/km	1 492	1 056	0	2 548
Emissions					
Global warming	kg CO_2 eq./km	155 338	163	92 653	248 154
Acidification	kg SO_2-eq./km	884	1.21	530	1 415
Ozone depletion	kg CFC-11 eq./km	0	0	0	0
POCP (Photochemical oxidant formation)	kg ethene-eq./km	53.1	0.103	31.9	85.1
Eutrophication	kg PO_4^{2-}eq./km	103	0.224	61.9	165
Other					
Output of materials for recycling	kg/km	0	0	20 263	20 263
Waste, hazardous	kg/km	7.46	0	4.48	11.9
Waste, excess soil	kg/km	60 500	0	0	60 500
Waste, other	kg/km	15 666	9.98	47 132	62 808

Table 27 Specification of resources making the largest contributions to the different resource use categories for the passenger and goods stations.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Sand and gravel: 75.7%, Limestone CaCO3: 19.6%, Fe (res): 4.5%
Renewable materials	kg	Wood 100%
Non-renewable energy	MJ	Coal: 45.8% , Crude oil: 38.6%, Natural gas: 15.6%
Renewable energy	MJ	Hydro power: 98.4%, Biomass fuel: 1.6%
Recycled resources	kg	Glass, recycled 100%

Table 28 Main process contributors to the different impact categories for the passenger and goods stations.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 99.6 % Infrastructure construction work: 0.0 % Infrastructure operation: 0.1 % Deforestation: 0.3 %
Acidification	kg SO_2 eq.	Infrastructure material: 99.9 % Infrastructure construction work: 0.0 % Infrastructure operation: 0.1 % Deforestation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 0.0 % Infrastructure construction work: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene eq.	Infrastructure material: 99.8 % Infrastructure construction work: 0.0 % Infrastructure operation: 0.1 % Deforestation: 0.0 %
Eutrophication	kg PO_4^{2-} eq.	Infrastructure material: 99.8 % Infrastructure construction work: 0.1 % Infrastructure operation: 0.1 % Deforestation: 0.0 %

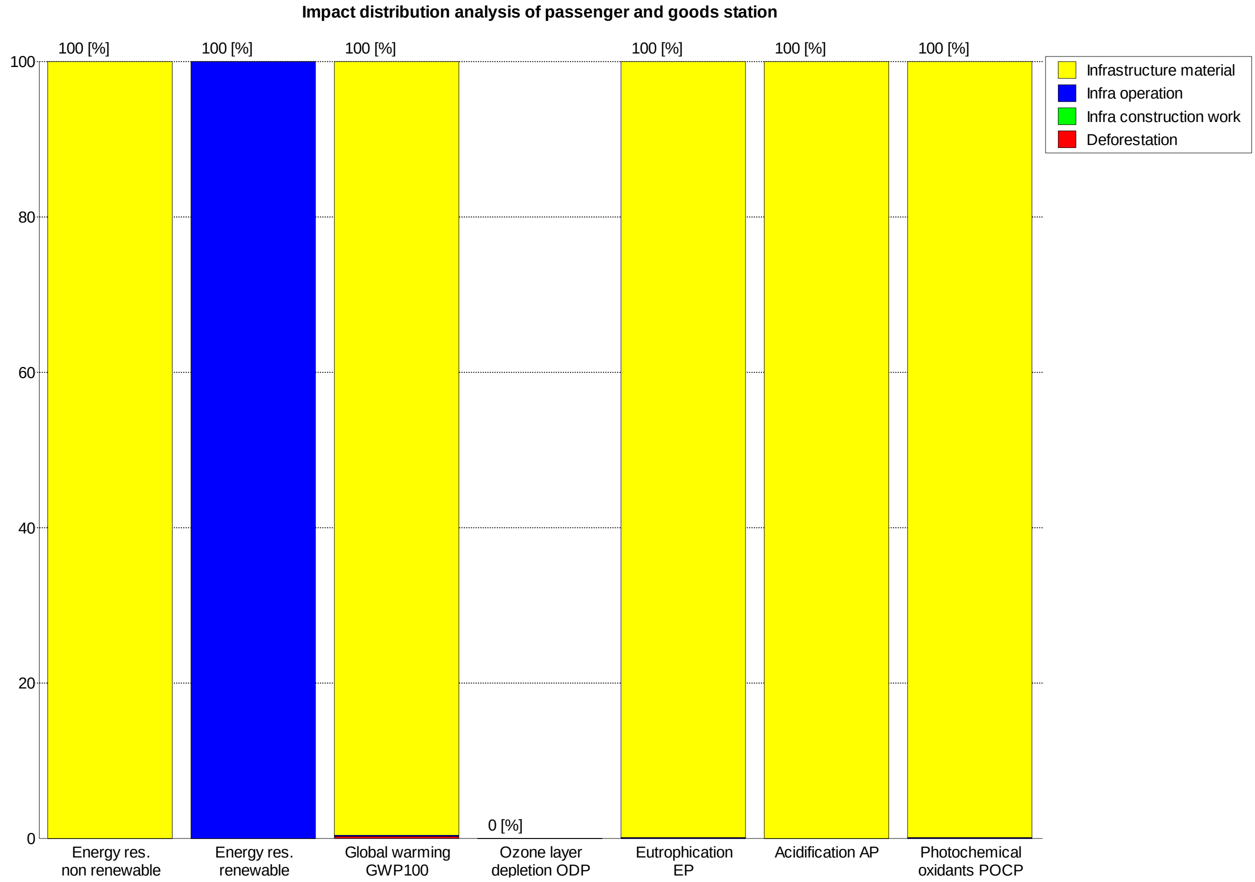

Figure 65 Impact distribution analysis of passenger and goods station at the Bothnia Line. Note that the construction of the buildings is included in the 'Infrastructure material' label and thus not shown separately.

9.7 Passenger and freight train traffic analysis

9.7.1 Analysis and scenario description

This chapter covers the actual transport activities. In this case, it includes construction and maintenance of the trains, energy for operation of the trains and operation of goods handling equipments (diesel driven vehicles). The analysis includes both passenger and freight transports.

The transport work (train traffic) differs significantly from the railway infrastructure. While the railway infrastructure is relatively static, the transport work is dynamic and depends on the amount of goods and passenger, load factor etc. However, standard LCA values can be given for a train transport in e.g. tonne-km or passenger-km. In this case, we have used the developed LCA model for the train transport work and adapted the model for the Bothnia Line. We have thus used forecast transport data for the Bothnia Line covering both passenger and freight transport and calculated the results over the calculation period of 60 years. The results are shown in the next chapter. A background description of the Bothnia Line can be found in chapter 4. In Table 29 below, basic data used in the calculations are shown.

Table 29 Specification of the train transport data used in the model calculations. The data are specific for the Bothnia Line.

Activity/Process	Description
Energy source for the train operation	Green electric power purchased by Swedish Rail Administration
Energy use for goods train transport (operation)	0.1512 MJ/tonne-km
Energy use for passenger train transport (operation)	0.288 MJ/passenger-km (load factor of 40 %)
Load and unload of goods at railway terminals	1.4 MJ/tonne goods
Number of passengers	12 294 000 per year
Passenger transport work	343 771 000 passenger-km per year
Goods volume	2 623 665 tonnes per year
Freight transport work	506 367 424 tonne-km per year
Bothnia Line transport distance	193 km
Estimated lifetime of trains	30 years

9.7.2 Results from the analysis

9.7.2.1 Energy results

The energy use for the passenger and freight transport is shown in Figure 66. The electric power for the operation of the trains stands for the major energy use while the energy use for construction and maintenance of the trains plays a minor role. As shown in the figure, the dominating resource for the electric power is hydropower. This is explained by the use of Swedish green electric power. The trains are mainly produced in central Europe and the energy resource use for train construction thus reflects the electric power production mix used in that geographic area.

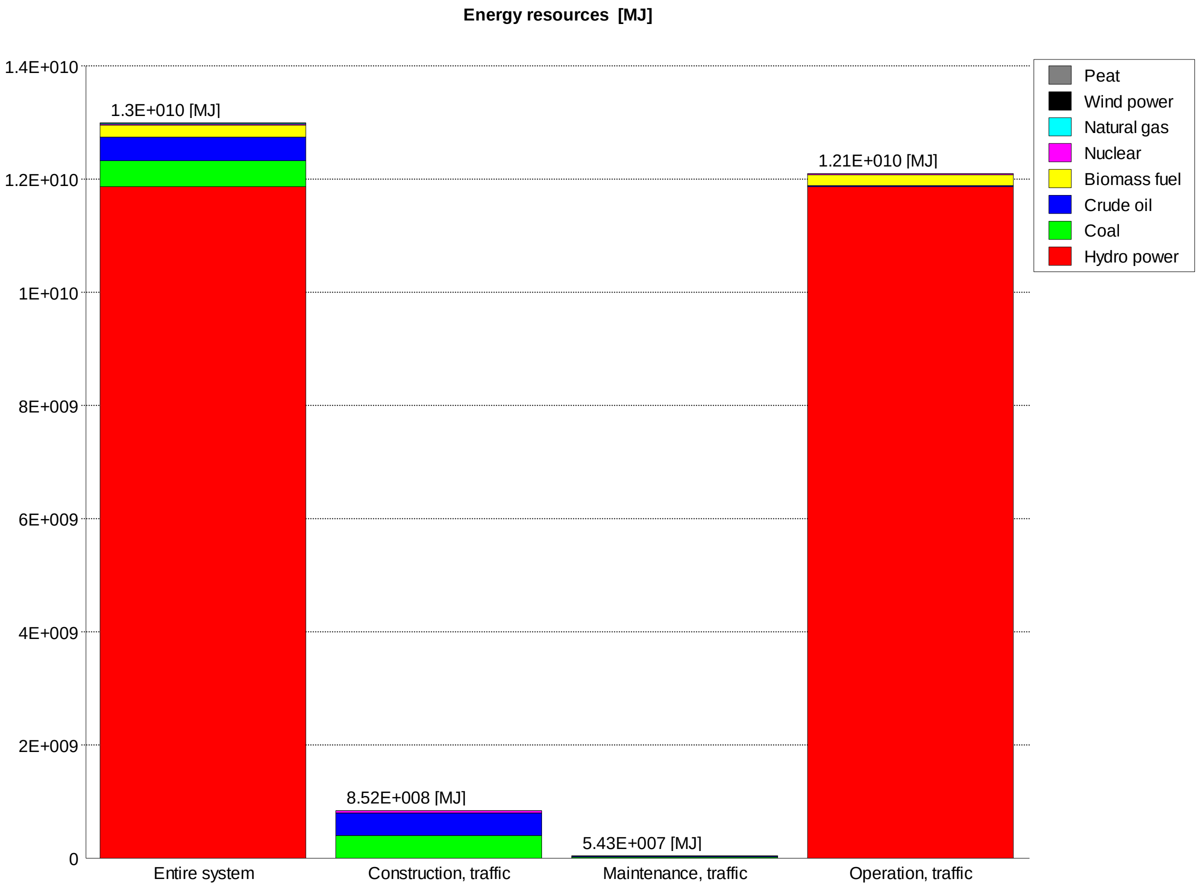

Figure 66 Use of primary energy resources for the train traffic (forecast) at the Bothnia Line. The energy use includes construction, maintenance and operation of the trains (both freight and passenger trains) during the calculation period of 60 years. Note that so-called Green electric power is used for the operation of the trains.

9.7.2.2 Emission results

Even if the energy use for train operation was dominating, the specific emission levels for the Swedish green electric power mix used are low. This result in low emission levels for the operation of the trains and higher emission levels for the construction of the trains due to the emission levels of the used electric power. The emission of greenhouse gases, Figure 67, is dominated by the emission of fossil-based CO_2 and the train construction process shows the highest emissions. The emissions of acidifying and eutrophying substances show the same emission pattern as the greenhouse gas emissions, see Figure 68 and Figure 69.

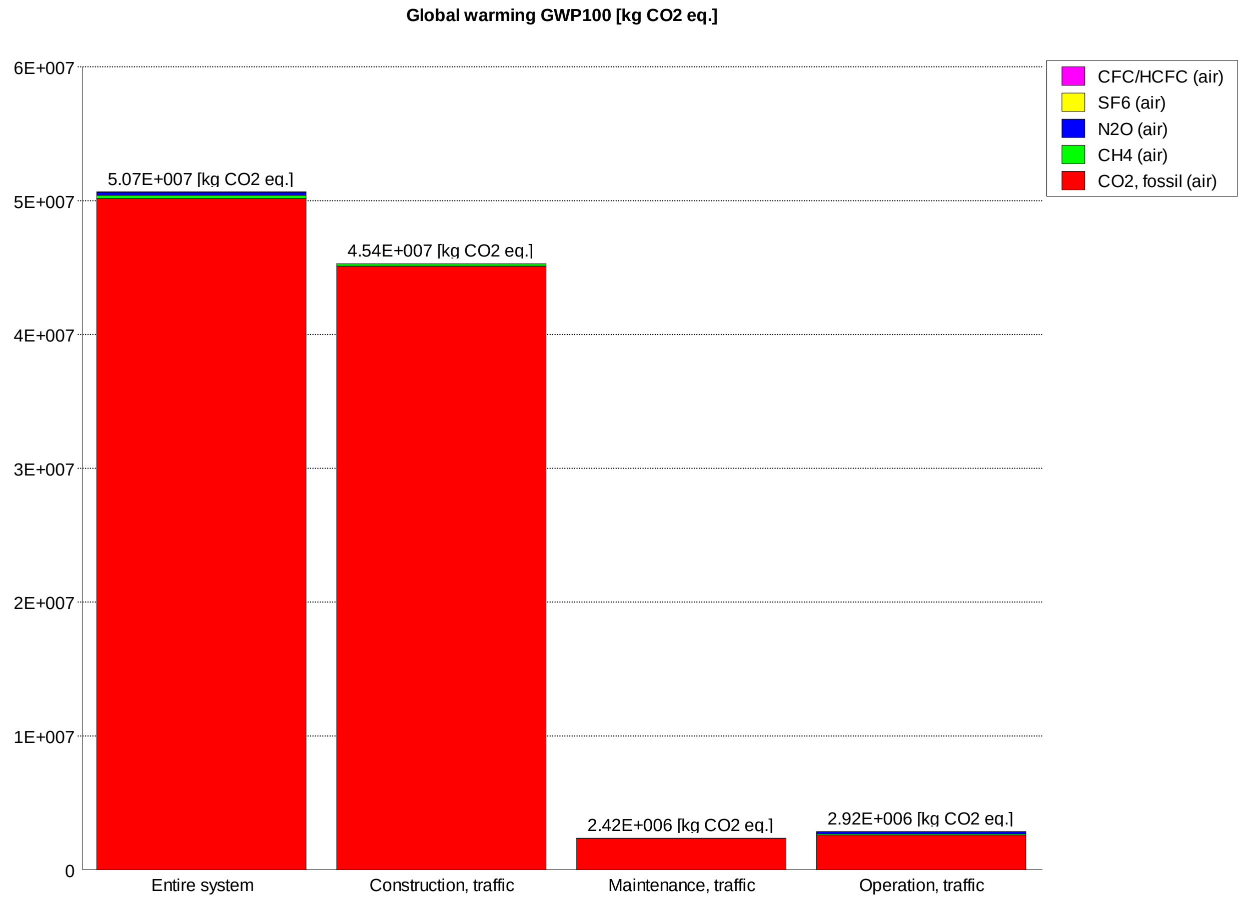

Figure 67 Greenhouse gas emissions from the train traffic (forecast) at the Bothnia Line. The emissions include construction, maintenance and operation of the trains (both freight and passenger trains) during the calculation period of 60 years. Note that so-called Green electric power is used for the operation of the trains.

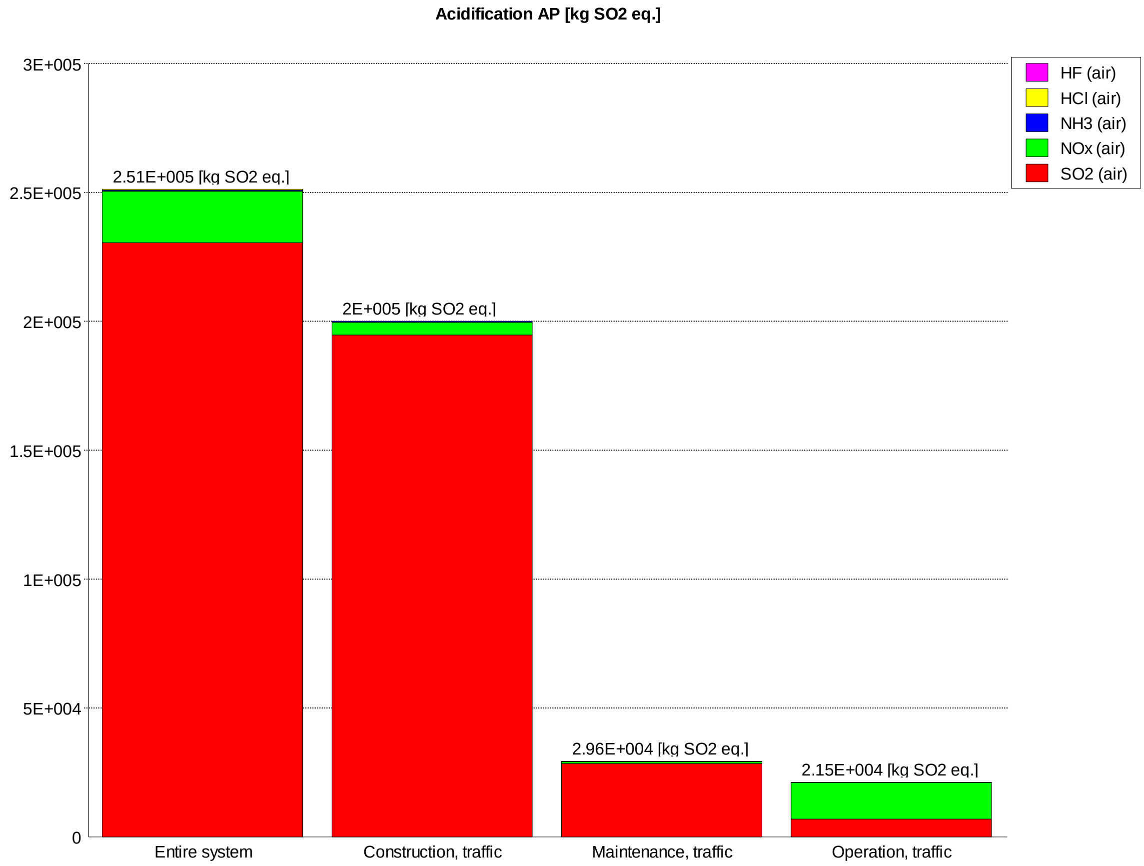

Figure 68 Emissions of acidifying substances from the train traffic (forecast) at the Bothnia Line. The emissions include construction, maintenance and operation of the trains (both freight and passenger trains) during the calculation period of 60 years. Note that so-called Green electric power is used for the operation of the trains.

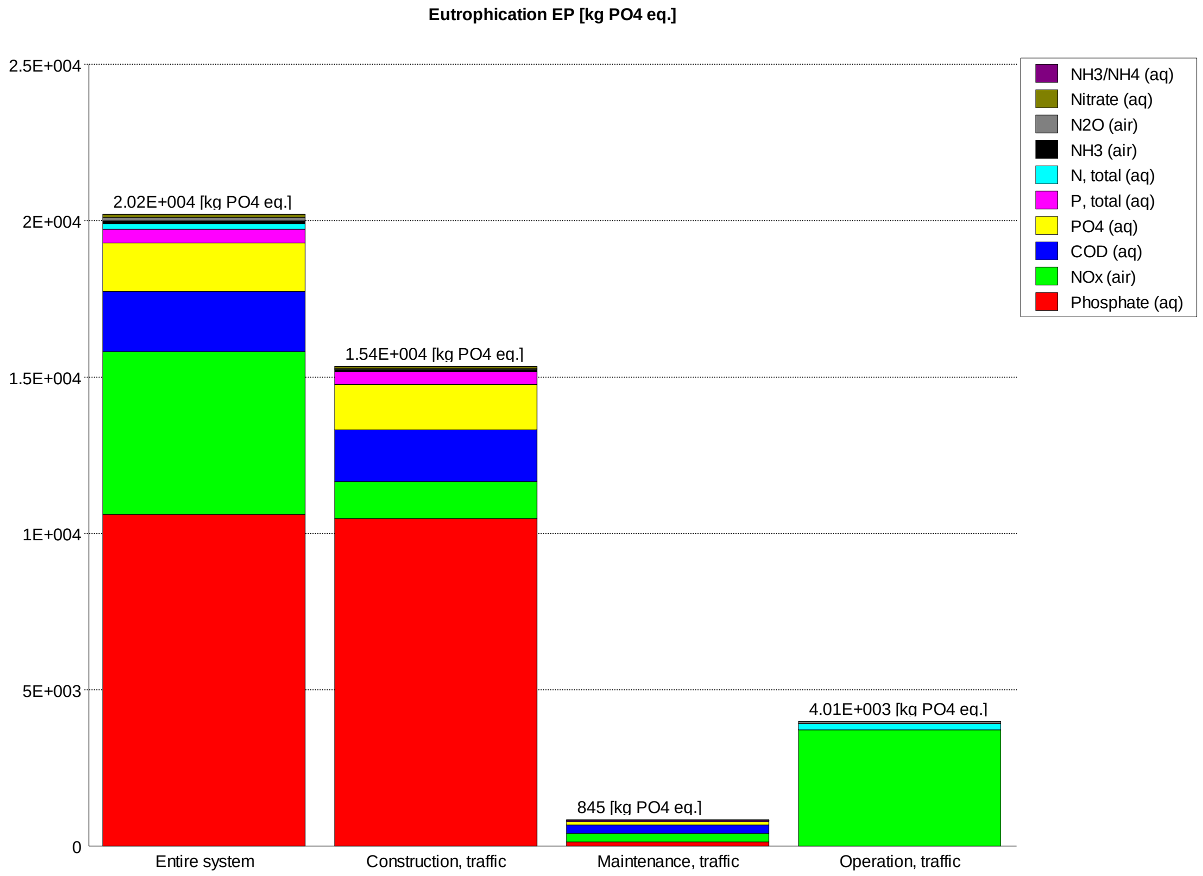

Figure 69 Emissions of eutrophying substances from the train traffic (forecast) at the Bothnia Line. The emissions include construction, maintenance and operation of the trains (both freight and passenger trains) during the calculation period of 60 years. Note that so-called Green electric power is used for the operation of the trains.

9.7.3 Results from the Bothnia Line example

The passenger and freight transport model has in this case been used for the EPD calculations of the passenger and freight transport work at the Bothnia Line. The input data for the model is calculated and estimated data for the Bothnia Line. The results for passenger transport and freight transport are presented separately. A full set of impact categories are calculated and the results are presented in Table 30 and Table 33. The results are given per passenger-km and tonne-km respectively and include construction, maintenance and operation of the trains over a calculation period of 60 years.

In Table 31 and Table 34, the different resource uses have been broken down into single material uses. The largest contributors are presented in the tables. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are explained in chapter 9.1.1. The distribution of the emission impact categories in the overview activity areas are shown in Table 32 and Table 35. The infrastructure operation shown in these tables refer to loading, unloading and handling operations of goods.

The graphic overview impact distribution analysis of the passenger and freight train transports are shown in Figure 70 and Figure 71. Here, the contribution distribution of each overview activity areas is shown for the different impact categories. As shown in the figures, the production and maintenance of the trains gives a larger contribution to the emissions than the operation of the trains. This is explained by the use of so-called green electric power, which in this case consists mainly of hydropower with very low emission levels in general. The hydropower use is shown in the figure as a high use of renewable energy resources for train operation. The production and maintenance of the trains are more dominant for the passenger trains. This can probably be explained by a higher production complexity and many different materials in passenger trains. The production and maintenance of trains are however complex so the results are indicative.

Table 30 Environmental impact of the passenger train traffic (not including the railway infrastructure) at the Bothnia Line calculated and presented per passenger-km over 60 years. All construction, operation and maintenance activities over 60 years are included for the trains.

Impact category	Unit/passenger-km	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/passenger-km	1.72E-04	4.64E-05	0	2.18E-04
Renewable materials	kg/passenger-km	0	0	0	0
Non-renewable energy	MJ/passenger-km	3.61E-02	6.22E-04	1.51E-03	3.83E-02
Renewable energy	MJ/passenger-km	0	3.30E-01	0	3.30E-01
Recycled resources	kg/passenger-km	0	0	0	0
Water	kg/passenger-km	0	0	0	0
Land use	m^2/passenger-km	0	5.14E-04	0	5.14E-04
Emissions					
Global warming	kg CO_2 eq./passenger-km	1.98E-03	7.93E-05	6.96E-05	2.13E-03
Acidification	kg SO_2 eq./passenger-km	8.59E-06	5.86E-07	1.24E-06	1.04E-05
Ozone depletion	kg CFC-11 eq./passenger-km	3.11E-12	0	1.98E-13	3.31E-12
POCP (Photochemical oxidant formation)	kg ethene-eq./passenger-km	1.60E-06	4.99E-08	1.26E-07	1.78E-06
Eutrophication	kg PO_4^{2-}eq./passenger-km	7.04E-08	1.09E-07	4.47E-09	1.84E-07
Other					
Output of materials for recycling	kg/passenger-km	0	0	0	0
Waste, hazardous	kg/passenger-km	0	0	0	0
Waste, excess soil	kg/passenger-km	0	0	0	0
Waste, other	kg/passenger-km	0	4.85E-06	0	4.85E-06

Table 31 Specification of resources making the largest contributions to the different resource use categories for the passenger train traffic.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Fe (res): 71.4%, Cu (res): 18.9%, Cr (res): 4.3% , Silica sand SiO2: 2.1%, Ni (res): 1.9%, Pb (res): 1.2%
Renewable materials	kg	-
Non-renewable energy	MJ	Crude oil: 49.9% , Coal: 49.8%, Nuclear: 0.2%
Renewable energy	MJ	Hydro power: 98.4%, Biomass fuel: 1.6%
Recycled resources	kg	-

Table 32 Main process contributors to the different impact categories for the passenger train traffic.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Train production and maintenance: 96.3 % Train operation: 3.7 % Infrastructure operation: 0.0 %
Acidification	kg SO_2-eq.	Train production and maintenance: 94.4 % Train operation: 5.6 % Infrastructure operation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Train production and maintenance: 100.0 % Train operation: 0.0 % Infrastructure operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Train production and maintenance: 97.2 % Train operation: 2.8 % Infrastructure operation: 0.0 %
Eutrophication	kg PO_4^{2-}eq.	Train production and maintenance: 40.7 % Train operation: 59.3 % Infrastructure operation: 0.0 %

Table 33 Environmental impact of the freight train traffic (not including the railway infrastructure) at the Bothnia Line calculated and presented per tonne-km over 60 years. All construction, operation and maintenance activities over 60 years are included for the trains.

Impact category	Unit/tonne-km	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/tonne-km	4.19E-05	2.44E-05	1.34E-05	7.97E-05
Renewable materials	kg/tonne-km	1.03E-06	0	2.54E-07	1.28E-06
Non-renewable energy	MJ/tonne-km	3.23E-03	3.34E-04	7.26E-04	4.29E-03
Renewable energy	MJ/tonne-km	2.86E-04	1.73E-01	3.55E-05	1.74E-01
Recycled resources	kg/tonne-km	6.90E-05	0	6.90E-06	7.59E-05
Water	kg/tonne-km	2.35E-03	0	5.79E-04	2.93E-03
Land use	m2/tonne-km	4.84E-06	2.70E-04	9.81E-07	2.76E-04
Emissions					
Global warming	kg CO_2 eq./tonne-km	1.48E-04	4.22E-05	3.25E-05	2.22E-04
Acidification	kg SO_2 eq./tonne-km	7.60E-07	3.11E-07	1.29E-07	1.20E-06
Ozone depletion	kg CFC-11 eq./tonne-km	0	0	0	0
POCP (Photochemical oxidant formation)	kg ethene-eq./tonne-km	7.41E-08	3.59E-08	1.78E-08	1.28E-07
Eutrophication	kg PO_4^{2-}eq./tonne-km	4.58E-07	5.80E-08	2.48E-08	5.41E-07
Other					
Output of materials for recycling	kg/tonne-km	0	0	5.71E-06	5.71E-06
Waste, hazardous	kg/tonne-km	1.12E-06	0	1.12E-07	1.23E-06
Waste, excess soil	kg/tonne-km	0	0	0	0
Waste, other	kg/tonne-km	5.62E-06	2.55E-06	6.91E-06	1.51E-05

Table 34 Specification of resources making the largest contributions to the different resource use categories for the freight train traffic.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Fe (res): 40.6%, Cu (res): 20.8%, Limestone $CaCO3$: 16.7% , Pb (res): 1.8%, Al (res) 1.7%, Ni (res) 1.2%, Clay mineral 1.1%, NaCl (res) 0.5%, Cr (res) 0.4%
Renewable materials	kg	Wood: 100%
Non-renewable energy	MJ	Coal: 38.0%, Crude oil: 28.1%, Nuclear: 21.0%, Natural gas: 12.9%
Renewable energy	MJ	Hydro power: 98.3% , Biomass fuel: 1.7%
Recycled resources	kg	Ferrous scraps: 100%

Table 35 Main process contributors to the different impact categories for the freight train traffic.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Train production and maintenance: 81.0 % Train operation: 18.7 % Infrastructure operation: 0.3 %
Acidification	kg SO_2-eq.	Train production and maintenance: 74.1 % Train operation: 25.7 % Infrastructure operation: 0.3 %
Ozone layer depletion	kg CFC-11 eq.	Train production and maintenance: 0.0 % Train operation: 0.0 % Infrastructure operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Train production and maintenance: 71.9 % Train operation: 27.9 % Infrastructure operation: 0.2 %
Eutrophication	kg PO_4^{2-}eq.	Train production and maintenance: 89.3 % Train operation: 10.6 % Infrastructure operation: 0.1 %

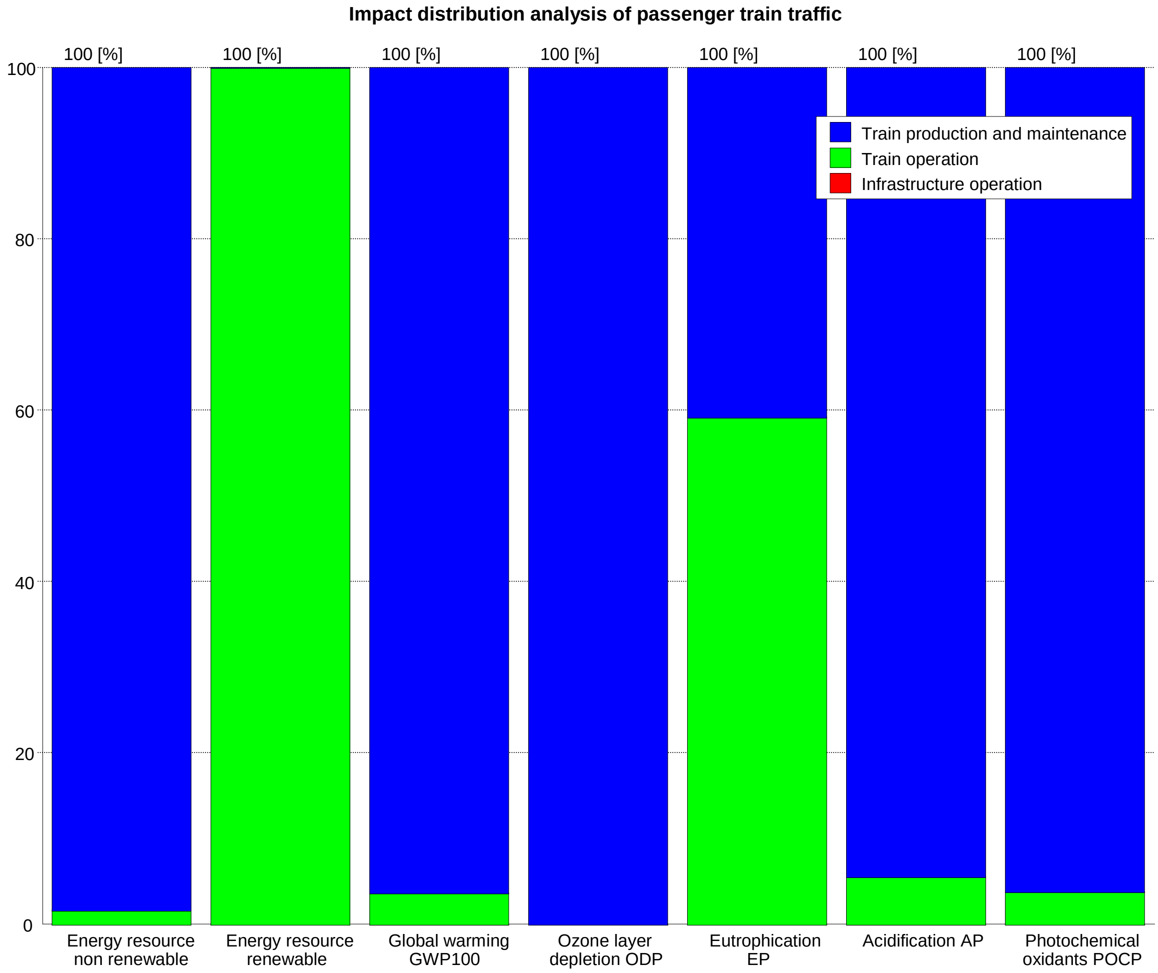

Figure 70 Impact distribution analysis of passenger train traffic at the Bothnia Line. Note that so-called Green electric power is used for the operation of the trains.

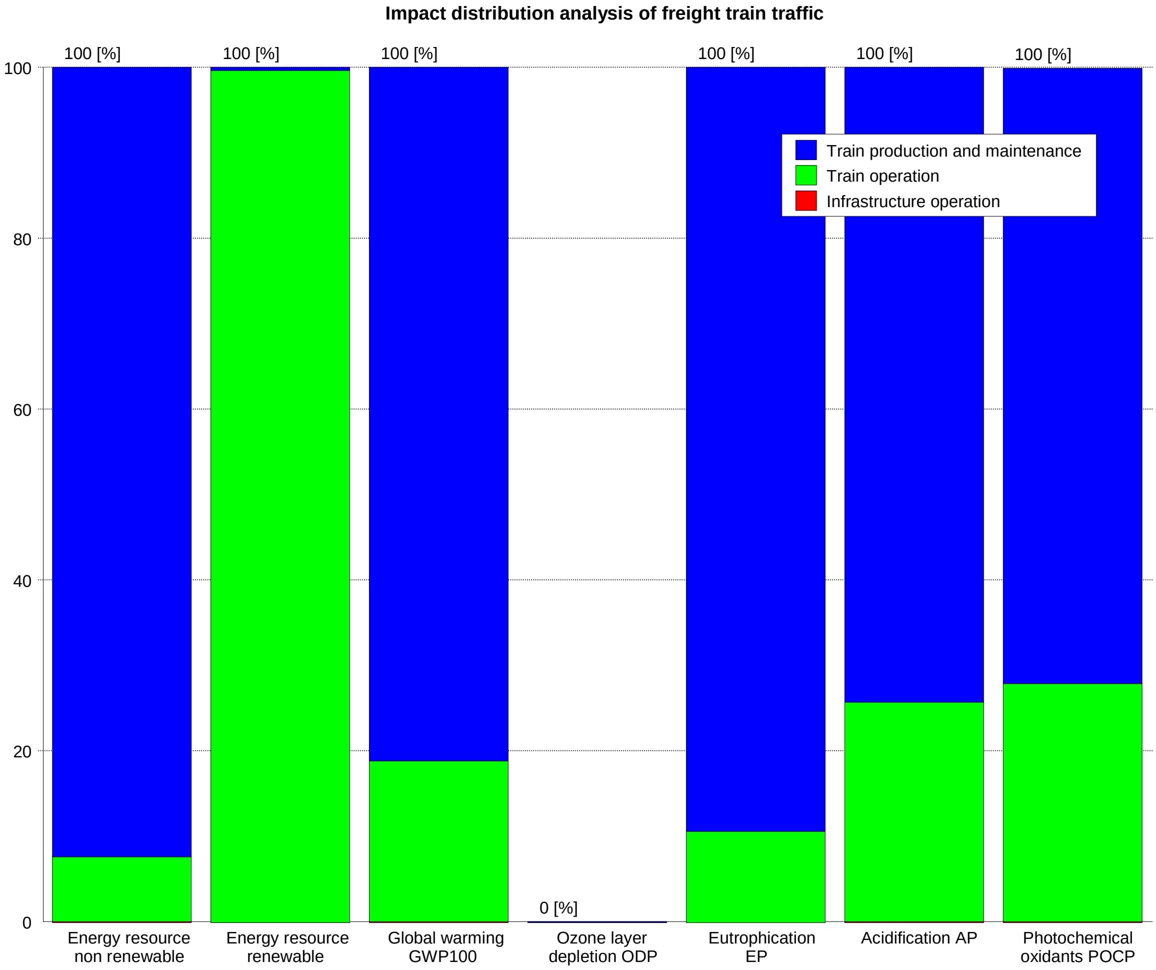

Figure 71 Impact distribution analysis of freight train traffic at the Bothnia Line. Note that so-called Green electric power is used for the operation of the trains.

9.8 Railway infrastructure analysis

9.8.1 Analysis and scenario description

One of the main goals for this project has been to be able to calculate and analyse the infrastructure of an entire railway line with all its components (track, tunnels, bridges, power systems etc.). This is now possible with use of the models described above. Thus, in this chapter the different component models have been put together in a large model covering an entire railway infrastructure. In the model, the different components are described in terms of technical design and quantities (length of tracks, bridges, tunnels etc.). This also means that an analysis is always specific for a specific railway line. In this case, we have used the Bothnia Line to exemplify a modelling of an entire railway line. The component models have been adjusted to meet the technical design of the Bothnia Line and the used quantities are shown in Table 36 below.

Table 36 Specification of main quantities used in the model calculations of the railway infrastructure at the Bothnia Line. The data are specific for the Bothnia Line.

Railway component	Specification
Total railway track length (including side tracks)	209 000 m
Length of side tracks	26 000 m
Length of main railway	209 000 m-26 000 m=183 000 m
Number of railway tunnels	16
Length of main railway tunnels	24 538 m
Length of service tunnels	14 360 m
Length of access tunnels	2107 m
Railway bridge length	10 930 m
Track foundation length	209 000-10 930-24 538=173 532 m
Length of electric power and signal installations	209 000 m
Railway passenger stations	36 m^2 railway station per 1000 m main railway
Freight terminals	130 000 m^2 for the entire Bothnia Line corresponding to 130000/183=710 m^2/1000 m main railway

9.8.2 Results from the analysis

9.8.2.1 Energy results

The use of primary energy resources for the entire infrastructure at the Bothnia Line is shown in Figure 72. The results are calculated by combining the different railway component models. In this case, the results are shown for the entire infrastructure and divided into construction, maintenance and operation. The results are shown in total for the Bothnia Line and cover the entire calculation period of 60 years. As shown in the figure, construction stand for the larges part of the energy use but both maintenance and operation are major contributors. The main energy use for operation is heating of railway switch during wintertime (de-icing) which stand for 2050 TJ while illumination stands for a smaller energy use. The main part of that consists of hydropower due to the use of so-called green electric power. The energy use has also been divided in the different activity groups used in the project and the result is shown in Figure 73. As shown in the figure, production of the different materials used in the infrastructure stands for the largest part of the energy use. The actual infrastructure construction work (construction+maintenance) stands for a much smaller energy use (41 % of material production). The infrastructure operation is the same as in the previous figure.

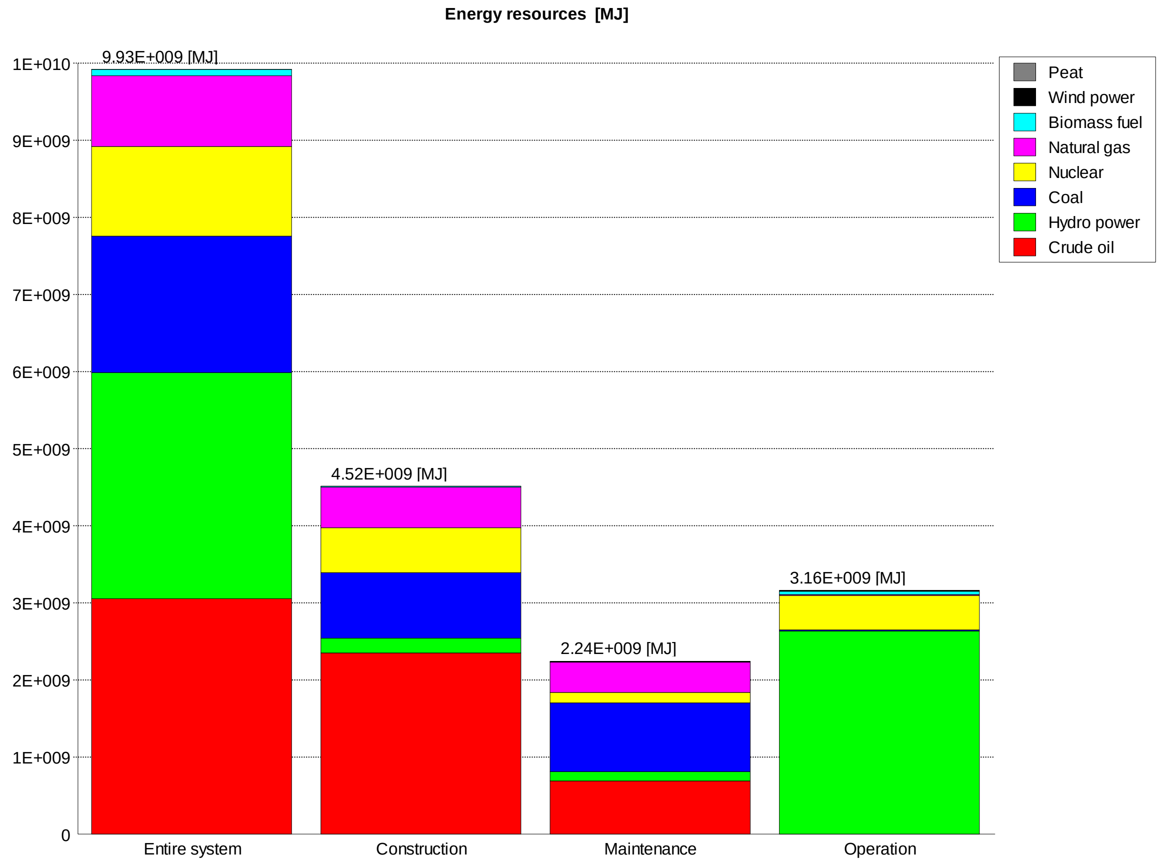

Figure 72 Use of primary energy resources for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The energy use is divided into construction, maintenance and operation and shows the results over a calculation period of 60 years. The figure does not include the train traffic.

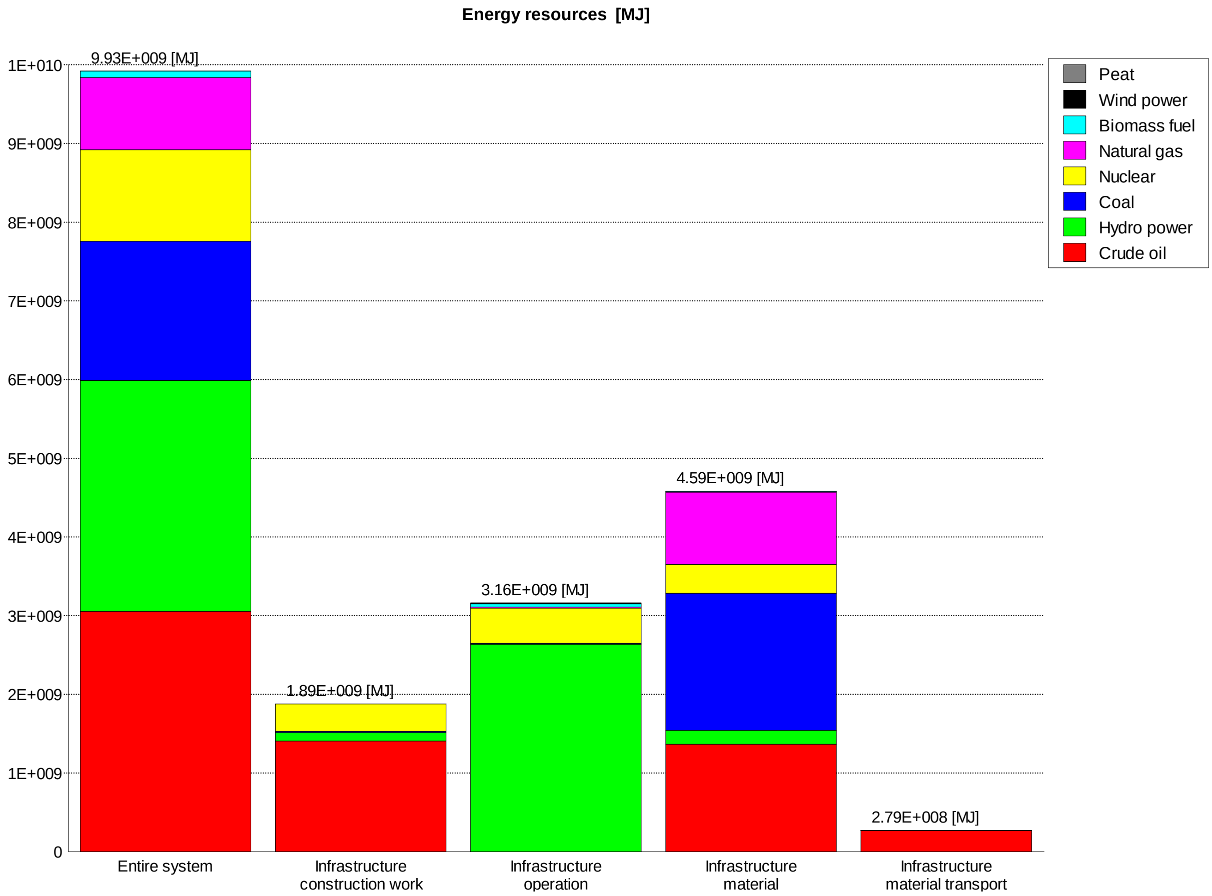

Figure 73 Use of primary energy resources for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The energy use is divided into activity groups including construction, maintenance and operation and shows the results over a calculation period of 60 years. The figure does not include the train traffic.

9.8.2.2 Emission results

The emission of greenhouse gases from the entire infrastructure of the Bothnia Line is shown in Figure 74 and Figure 75. The main greenhouse gas is fossil-based CO_2 while emissions of N_2O only give a minor contribution. The CO_2 emission due to deforestation also gives a large contribution to the greenhouse gas emissions but note that we have assumed that there originally was forest on more or less the entire railway line area (43 m width around the track). The construction phase stands for the main part of the greenhouse gas emissions while the emissions from maintenance are much smaller. Emissions from operation of the infrastructure are very small due to the use of green electric power (mainly hydropower). As shown in Figure 75, the main source of greenhouse gases is the production of the different materials used in the infrastructure while the actual construction work is smaller. The transport of the different infrastructure materials only gives a smaller contribution. Significant sources for fossil CO_2 are steel production (38.8 %), cement production (24.8 %), operation of vehicles and machines (15.5 %), production of buildings (8.4 %) and production of explosives (2.5 %).

The uptake of CO_2 in the concrete (carbonation) during product use (service life) is also shown in the figures as hatched negative values. The CO_2 uptake in concrete is relatively small compared to the emissions from the entire railway infrastructure. The reason for this is mainly that only a fraction of the infrastructure materials and work is related to concrete and that a large part of the concrete is used for sleepers with a low uptake of CO_2 (slow carbonation, high concrete quality). The secondary use of concrete for example crushed waste sleepers is not included in the railway model. In the secondary use stage of the concrete, a lot more CO_2 can be taken up by the concrete.

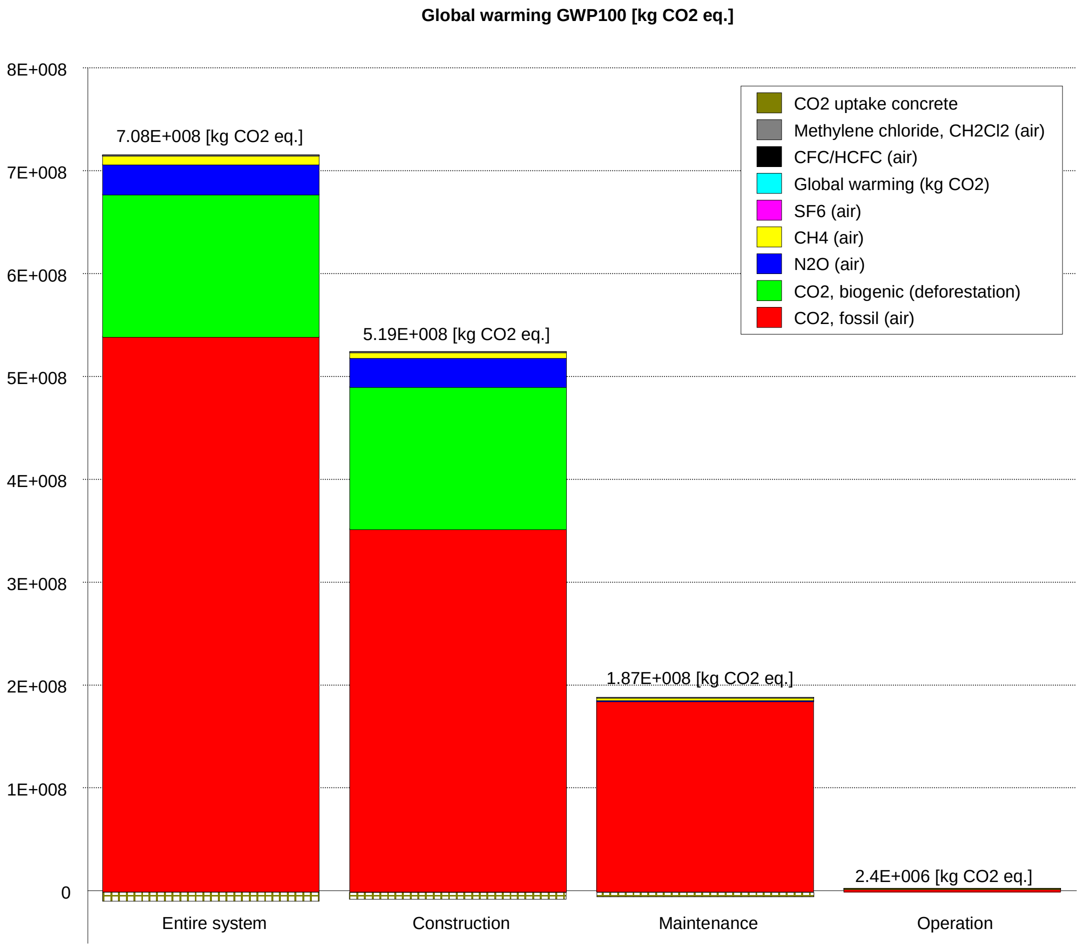

Figure 74 Emissions of greenhouse gases for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The emissions are divided into construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the train traffic. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

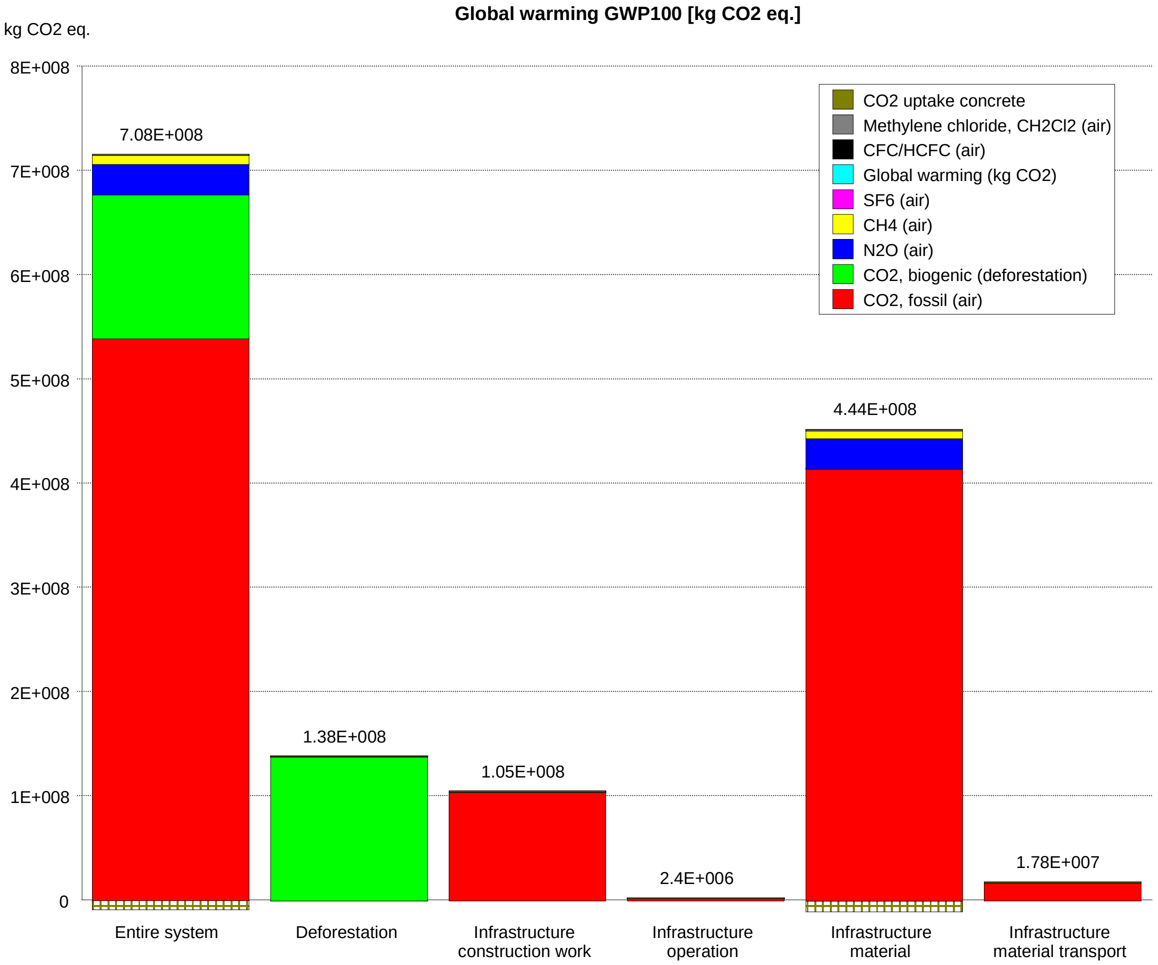

Figure 75 Emissions of greenhouse gases for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the train traffic. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted.

The emissions of acidifying and eutrophying pollutants are shown in Figure 76 and Figure 77. The emissions are shown in total and divided in the activity groups. As shown from the figures, the emissions show the same emission pattern as the CO_2 emissions except of course for the CO_2 uptake and the emissions from deforestation. The main sources of acidification are the emissions of NO_X and SO_2. Significant sources for NO_X are operation of vehicles and machines (31.7 %), cement production (10.4 %), production of buildings (8.8 %), steel production (6.7 %), production of explosives (3.8 %) and copper production (2.2 %). Significant sources for SO_2 are copper production (29.6 %), production of buildings (11.5 %), production of explosives (11.0 %) and cement production (10.2 %). The main source for eutrophication is the emission of NO_X.

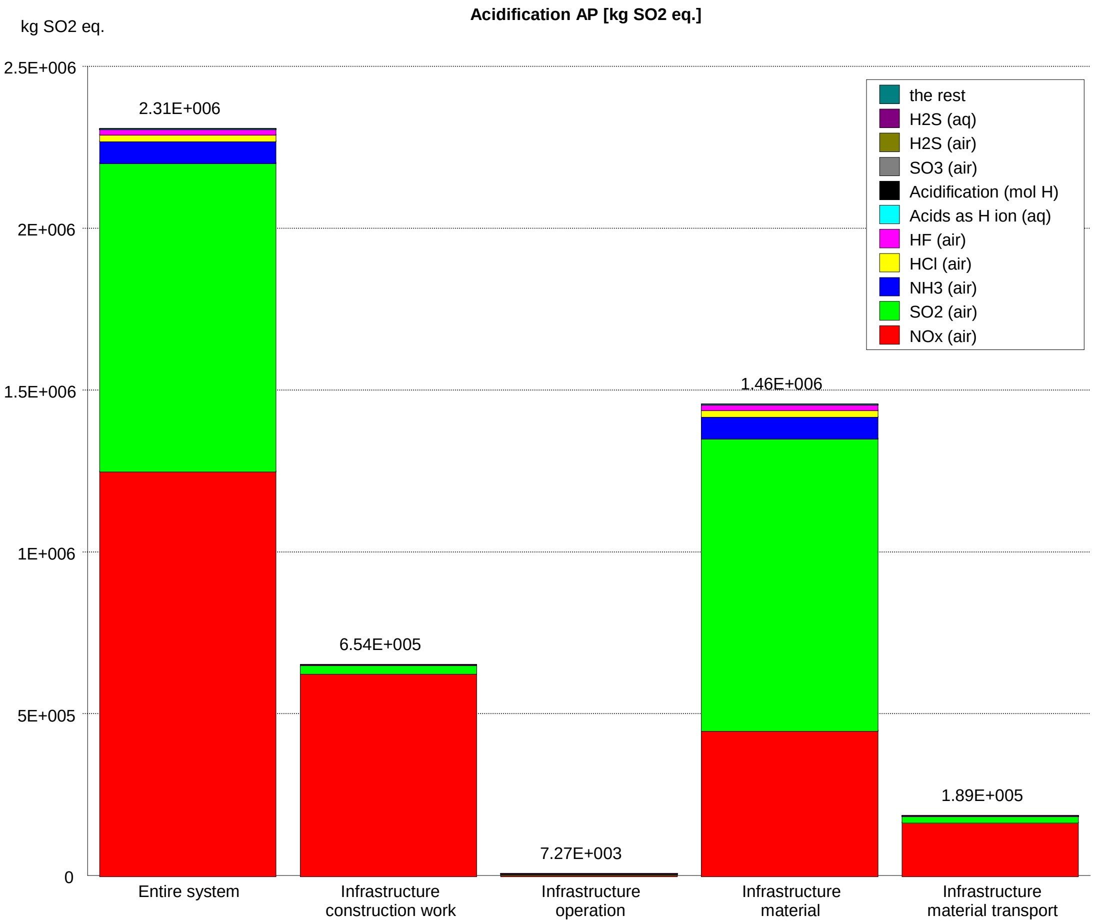

Figure 76 Emissions of acidifying pollutants for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the train traffic.

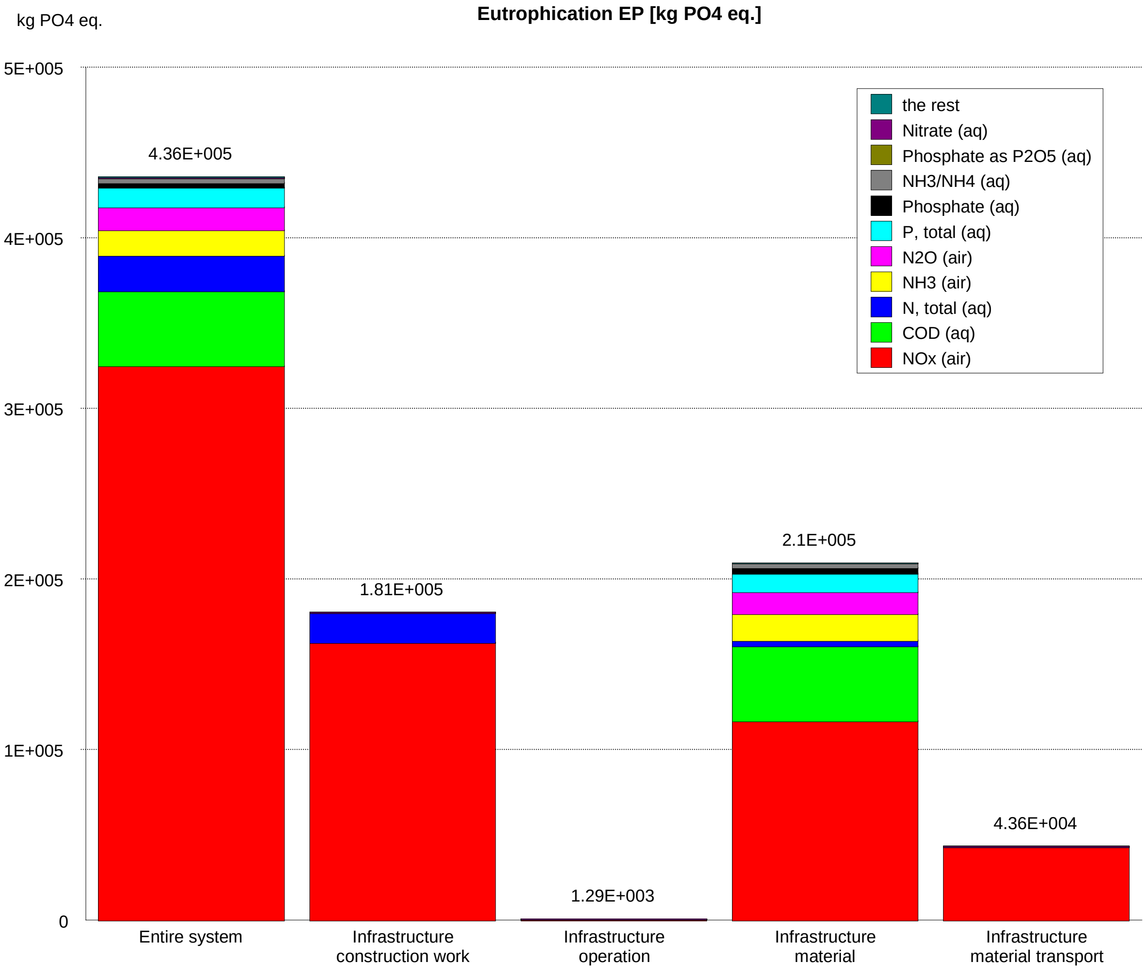

Figure 77 Emissions of eutrophying pollutants for the entire railway infrastructure at the Bothnia Line. The figure shows the total results including all parts of the infrastructure. The emissions are divided into activity groups including construction, maintenance and operation and show the results over a calculation period of 60 years. The figure does not include the train traffic.

9.8.3 Results from the Bothnia Line example

An EPD for the entire railway infrastructure of the Bothnia Line has been performed[18]. The total infrastructure model has been used with adapted data for the Bothnia Line. The results are presented for the entire infrastructure and are in this case shown per km main railway. The results include construction, maintenance and operation over a calculation period of 60 years. A full set of impact categories are calculated and the results are shown in Table 37.

In Table 38, the different resource uses have been broken down into single material uses. The largest contributors are presented in the tables. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources

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[18] EPD Railway infrastructure, Environmental Product Declaration for the railway infrastructure on the Bothnia Line., Reg. no. S-P-00196, UN CPC 53212, Date 2010-03-19.

of the emissions. The overview activity areas are explained in chapter 9.1.1. The distribution of the emission impact categories in the overview activity areas are shown in Table 39.

The graphic overview impact distribution analysis of the entire railway infrastructure is shown in Figure 78. Here, the contribution distribution of each overview activity areas is shown for the different impact categories.

Table 37 Environmental impact of the railway infrastructure (the traffic and the trains not included) for Bothnia Line calculated and presented per km of main railway line. All construction, operation and maintenance activities over 60 years are included for the infrastructure.

Impact category	Unit/km main railway	Construction	Operation	Maintenance	Total
Resource use					
Non-renewable materials	kg/km	123 509 793	2 581	7 480 894	130 993 268
Renewable materials	kg/km	35 459	0	29 628	65 088
Non-renewable energy	MJ/km	23 570 557	2 598 904	11 591 285	37 760 746
Renewable energy	MJ/km	1 158 948	14 686 092	708 136	16 553 175
Recycled resources	kg/km	256 519	0	85 762	342 281
Water	kg/km	9 385 278	0	6 204 482	15 589 760
Land use	m^2/km	53 159	30 376	3 374	86 909
Emissions					
Global warming	kg CO_2 eq./km	2 833 428	13 130	1 020 028	3 866 586
Acidification	kg SO_2 eq./km	8 717	39.8	3 866	12 623
Ozone depletion	kg CFC-11 eq./km	0	0	0	0
POCP (Photochemical oxidant formation)	kg ethene-eq./km	879	5.14	531	1 414
Eutrophication	kg PO_4^{2-}eq./km	1 894	7.05	481	2 382
Other					
Output of materials for recycling	kg/km	393	0	310 770	311 163
Waste, hazardous	kg/km	4 653	5 761	1 205	11 620
Waste, excess soil	kg/km	90 421 855	0	0	90 421 855
Waste, other	kg/km	4 087 273	4 672	2 011 413	6 103 358

Table 38 Specification of resources making the largest contributions to the different resource use categories for the railway infrastructure.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 96.5%, Sand and gravel: 1.7%, Limestone CaCO3: 1.3%, Fe (res): 0.4%
Renewable materials	kg	Wood: 100 %
Non-renewable energy	MJ	Crude oil: 44.2%, Coal: 25.6%, Nuclear: 16.8%, Natural gas: 13.4%
Renewable energy	MJ	Hydro power: 97.4%, Biomass fuel: 2.5%, Wind power: 0.1%
Recycled resources	kg	Ferrous scraps: 98.9%, Steel scrap: 0.6% , Copper scrap: 0.4%, Stainless steel scrap: 0.1%

Table 39 Main process contributors to the different impact categories for the railway infrastructure.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 63.0 % Infrastructure construction work: 14.8 % Infrastructure material transport: 2.3 % Infrastructure operation: 0.3 % Deforestation: 19.5 %
Acidification	kg SO_2-eq.	Infrastructure material: 63.8 % Infrastructure construction work: 28.3 % Infrastructure material transport: 7.6 % Infrastructure operation: 0.3 % Deforestation: 0.0 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 69.4 % Infrastructure construction work: 24.4 % Infrastructure material transport: 5.8 % Infrastructure operation: 0.4 % Deforestation: 0.0 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 48.9 % Infrastructure construction work: 41.6 % Infrastructure material transport: 9.2 % Infrastructure operation: 0.3 % Deforestation: 0.0 %

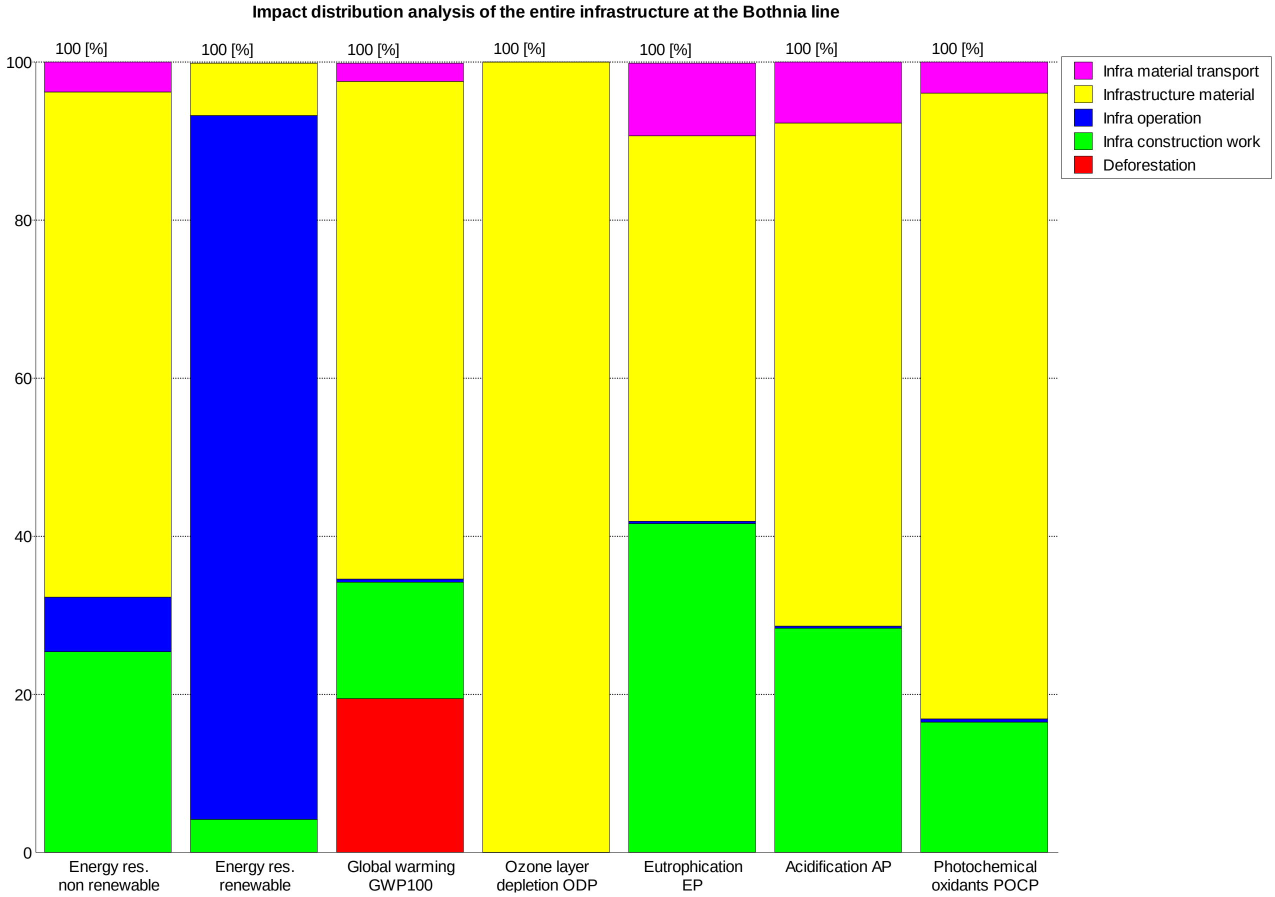

Figure 78 Impact distribution analysis of the entire infrastructure at the Bothnia Line.

9.9 Railway passenger and freight transport analysis

9.9.1 Analysis and scenario description

A final goal for environmental transport calculation is to be able to calculate the environmental performance for an entire passenger or freight transport. Such a calculation has to combine the entire railway infrastructure and the train transport activities. This can now easily be performed with the different models presented in the previous chapters. However, to be able to distinguish between freight and passenger transports, the infrastructure has to be allocated to freight and passenger transport respectively. In principle, the total freight and passenger transports work is calculated for the calculation period of 60 years. The infrastructure results over the same calculation period of 60 years are then allocated to the total freight and passenger transport work respectively according to the amount of transport work. The methodology is described in chapter 3.1 and the transport assumptions are presented in chapter 4. Since both the infrastructure and the transport assumptions are specific for each railway line, the transport profile will also be unique for a specific railway line.

Transport calculations have been performed for the Bothnia Line of both passenger and goods transports. In this case, with the used traffic assumptions, 31.5 % of the infrastructure has been allocated to the passenger transports and 68.5 % has been allocated to the transport of goods.

9.9.2 Results from the analysis

9.9.2.1 Energy results

The use of primary energy resources for both the entire infrastructure and the train transports at the Bothnia Line is shown in Figure 79. The results are calculated by combining the total infrastructure model with the train traffic model. In this case, the results are shown for the entire infrastructure with passenger and freight transports and divided into construction, maintenance and operation. The results are shown in total for the Bothnia Line and cover the entire calculation period of 60 years. As shown in the figure, the train traffic share stands for 56.7 % of the total primary energy use and thus the infrastructure stand for 43.3 %. We can also see that the operation of the trains stands for a large energy use (52.8 %). Hydropower is the main energy source and this is a result of the use of green electric power for the operation of the Swedish train system. The energy use has also been divided into the different activity groups used in the project and the result is shown in Figure 80.

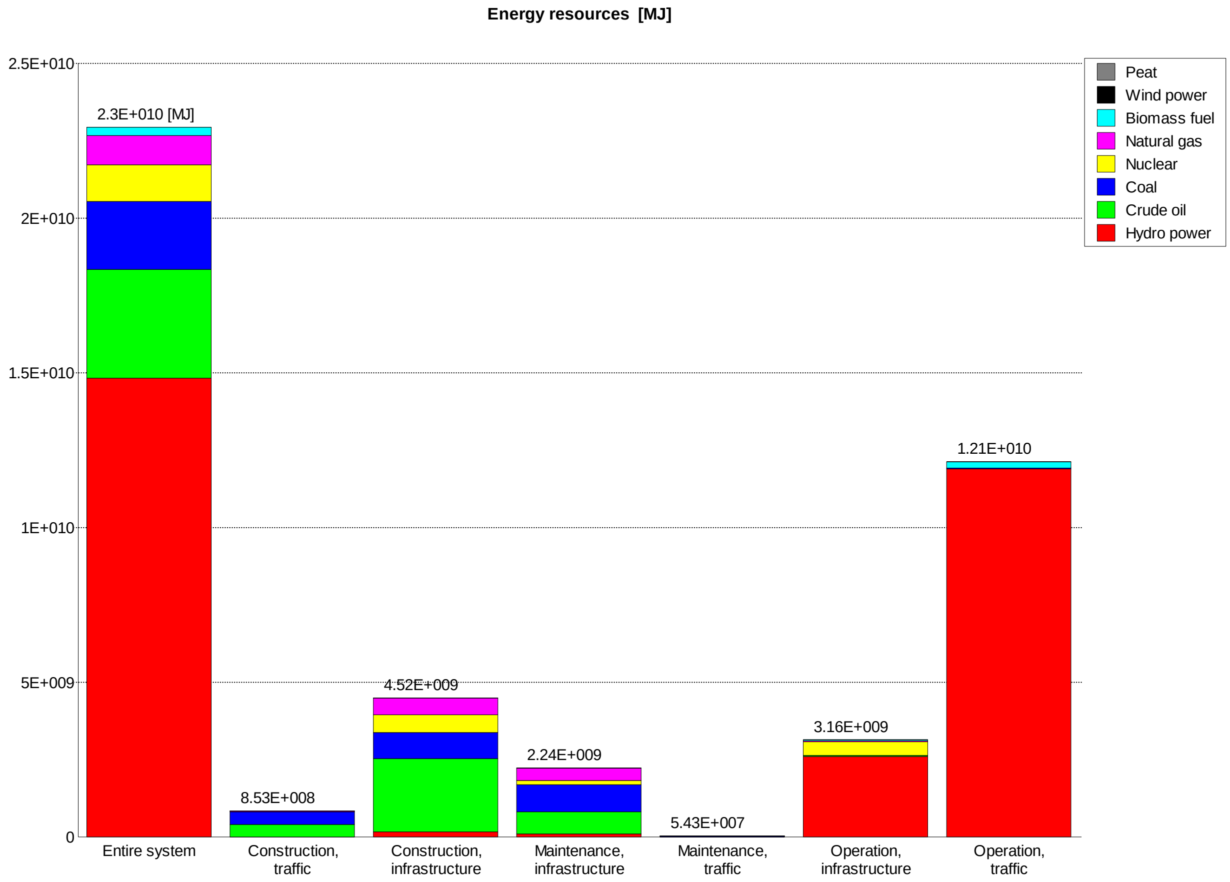

Figure 79 Use of primary energy resources for the Bothnia Line. The figure shows the total results including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The energy use covers construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the entire energy results over a calculation period of 60 years.

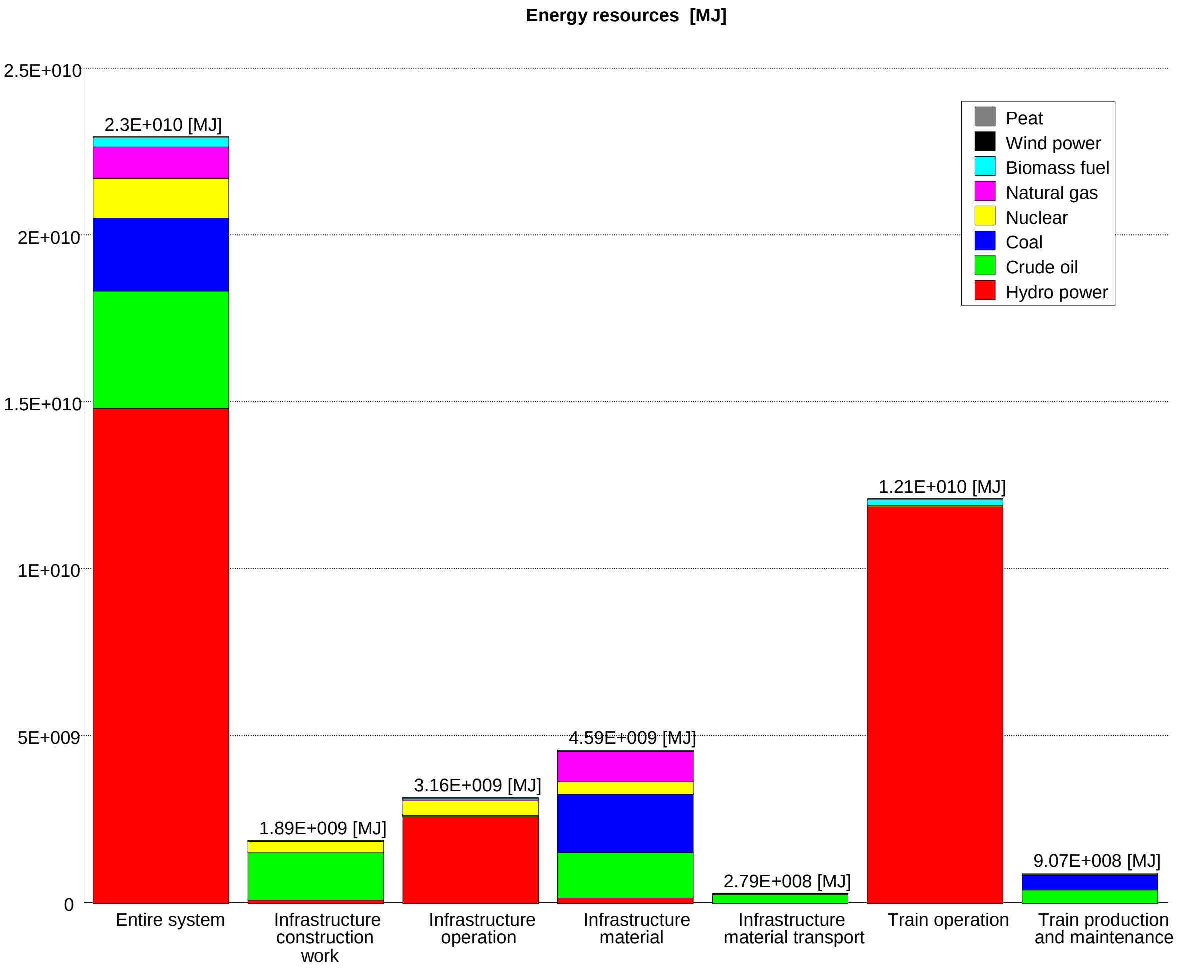

Figure 80 Use of primary energy resources for the Bothnia Line. The figure shows the total results including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The energy use covers construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the entire energy results over a calculation period of 60 years. The results are here divided into different activity groups.

9.9.2.2 Emission results

The emissions of greenhouse gases from the entire infrastructure and the total transport work (passenger and goods) of the Bothnia Line are shown in Figure 81 and Figure 82. Of the total global warming potential (GWP) from the entire transport system, the train traffic contribution is 6.7 % and the contribution from the railway infrastructure is 93.3 %. The main greenhouse gas is fossil-based CO_2 while emissions of N_2O only give a minor contribution. The CO_2 emission due to deforestation gives a large contribution to the greenhouse gas emissions also for this total system view, but note that we have assumed that there originally was forest on more or less the entire railway line area (43 m width around the track). The infrastructure construction phase stands for the main part of the greenhouse gas emissions while the emissions from infrastructure maintenance are much smaller. Emissions from operation of the trains and the infrastructure are very small due to the use of green electric power (mainly hydropower). The emissions from vehicle production is significant and depends mainly on the use of steel products, while the maintenance of the trains shows a low CO_2 emission due to a generally low energy use for that process. As shown in Figure 82, the main source of greenhouse gases is the production of the different materials used in the infrastructure while the actual construction work is smaller. The transport of the different infrastructure materials only gives a smaller contribution. The uptake of CO_2 in the concrete (carbonation) during product use (service life) is also shown in the figures as hatched negative values (see comments in chapter 9.8.2.2).

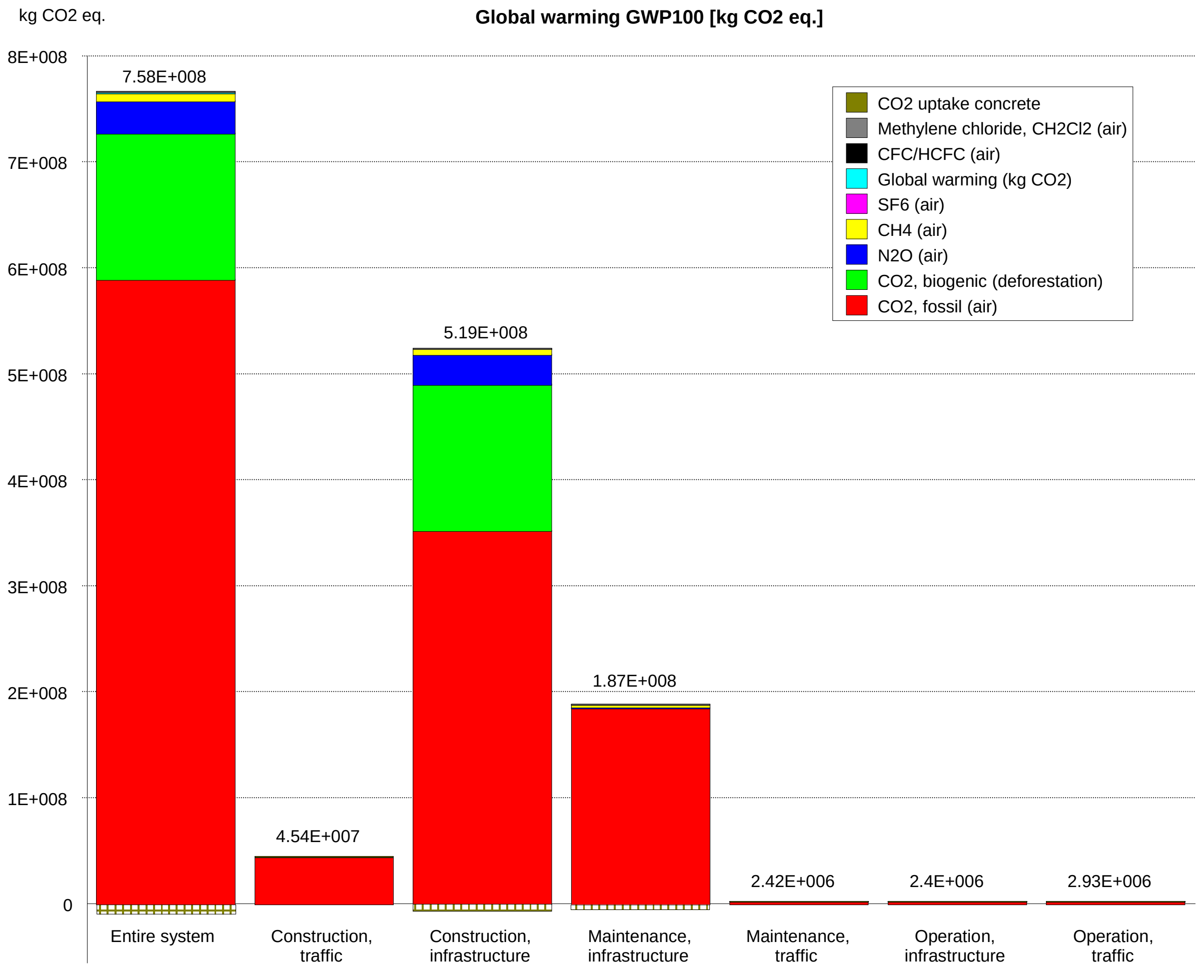

Figure 81 Emissions of greenhouse gases for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted. Note that so-called green electric power has been used for the train traffic calculations.

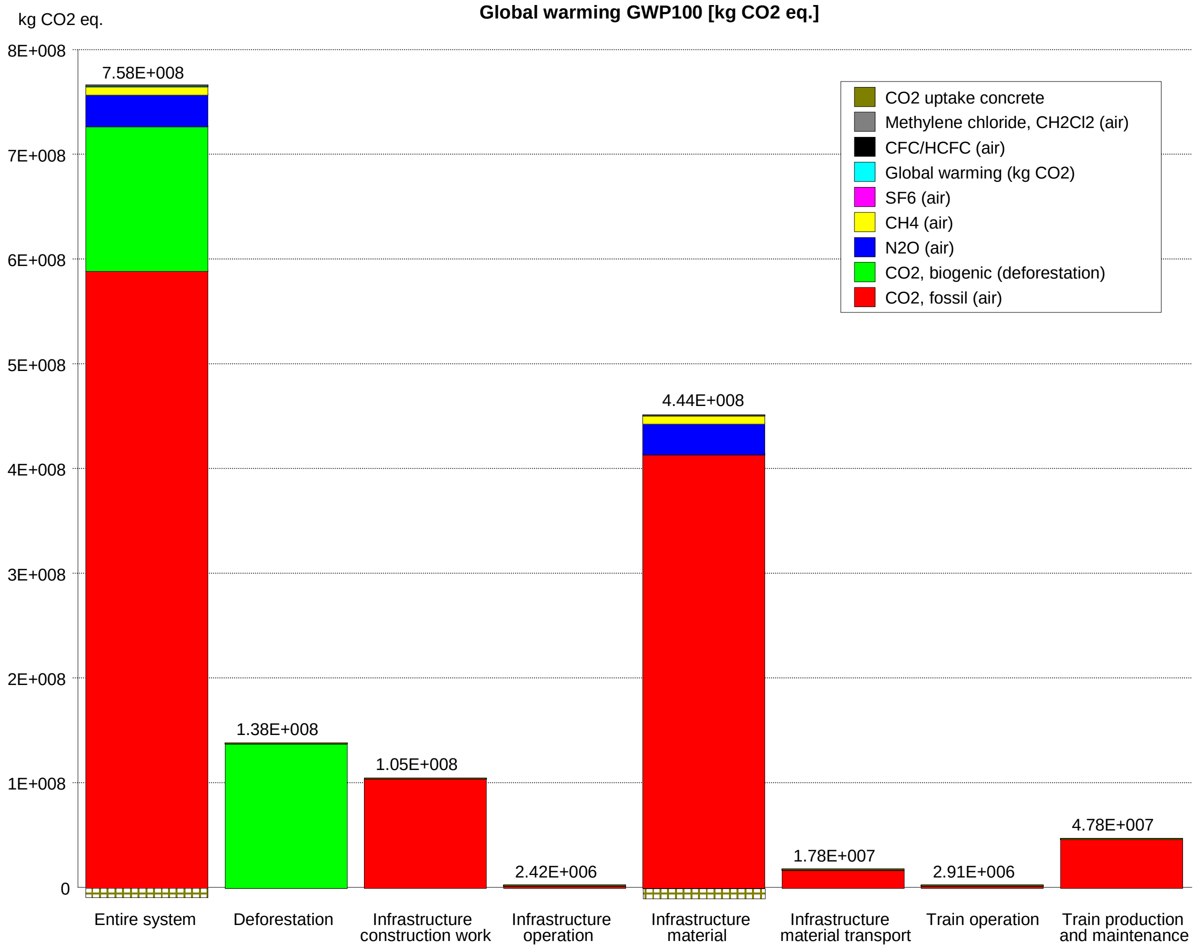

Figure 82 Emissions of greenhouse gases for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Uptake of CO_2 in concrete during product use is shown as hatched negative values. The total sum is the net value when the uptake is subtracted. The results are here divided into different activity groups. Note that so-called green electric power has been used for the train traffic calculations.

The emissions of acidifying pollutants are shown in Figure 83 (divided in construction, operation and maintenance) and Figure 84 (divided in the activity groups). Of the total acidifying pollutants from the entire transport system, the train traffic contribution is 9.8 % and the contribution from the railway infrastructure is 90.2 %. As shown from the figures, the emissions show the same emission pattern as the CO_2 emissions except of course for the CO_2 uptake and the emissions from deforestation. The main sources of acidification are the emissions of NO_X and SO_2.

The emissions of eutrophying pollutants are shown in Figure 85 (divided in construction, operation and maintenance) and Figure 86 (divided in the activity groups). Of the total eutrophying pollutants from the entire transport system, the train traffic contribution is 4.4 % and the contribution from the railway infrastructure is 95.6 %. As shown from the figures, the emissions show the same emission pattern as the CO_2 emissions except of course for the CO_2 uptake and the emissions from deforestation. The main source for eutrophication is the emission of NO_X.

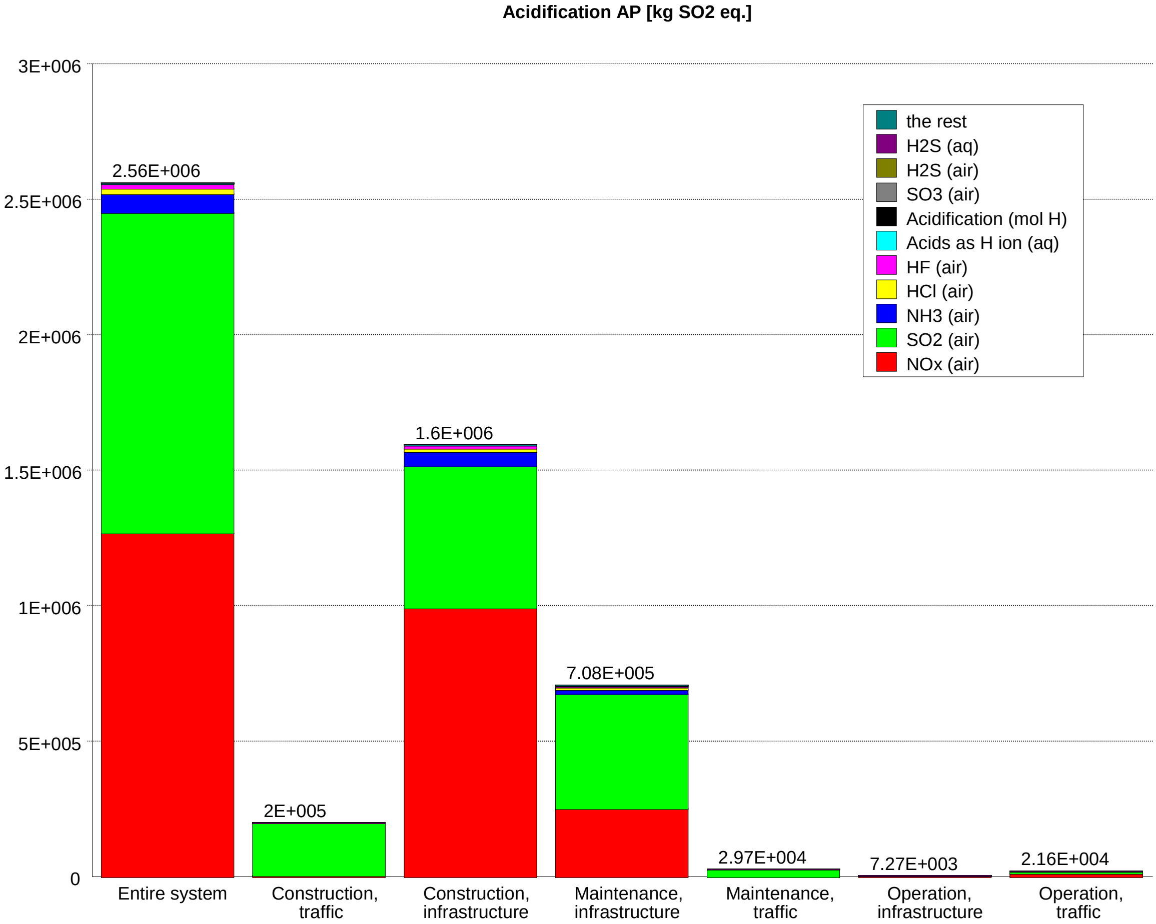

Figure 83 Emissions of acidifying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Note that so-called green electric power has been used for the train traffic calculations.

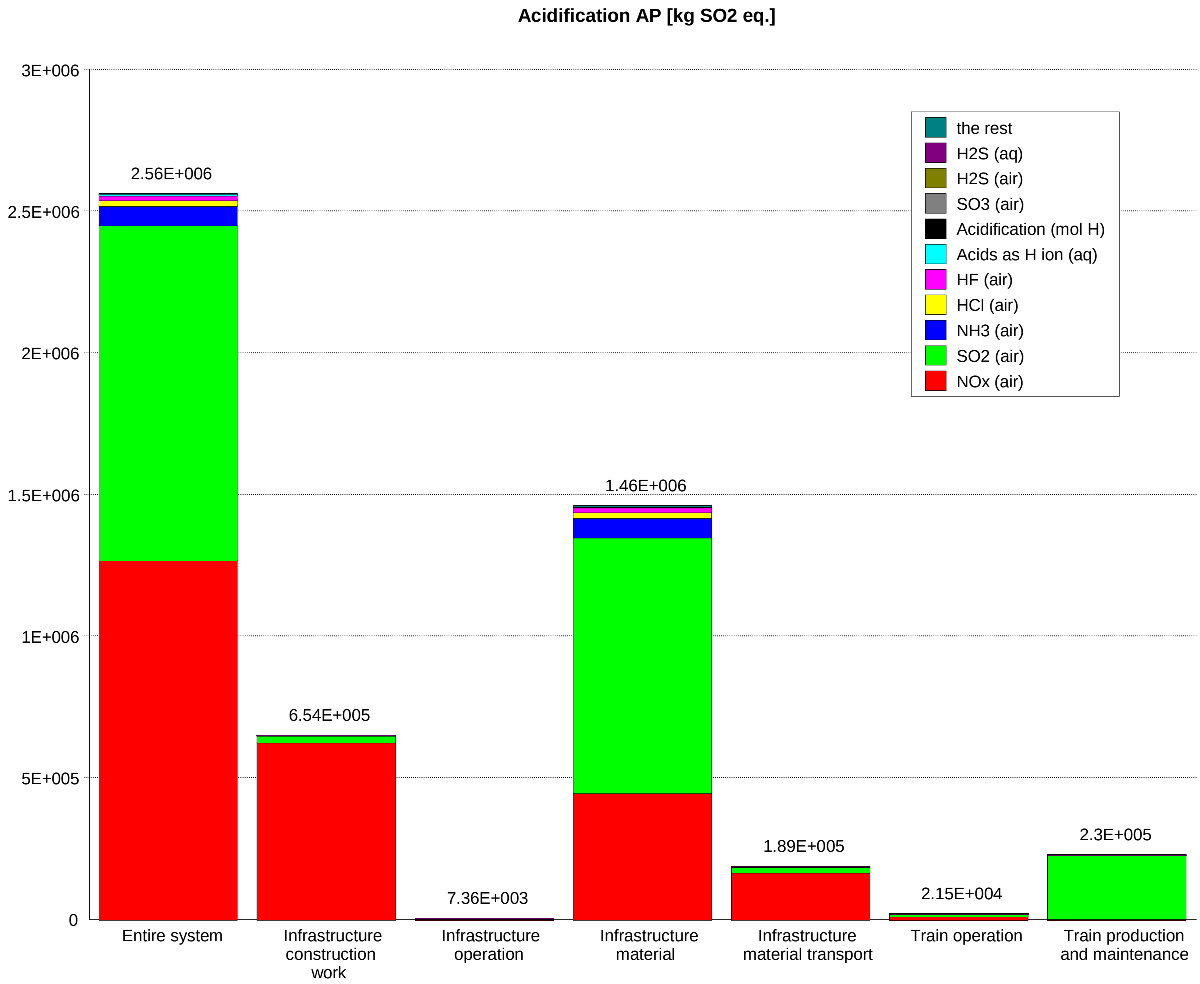

Figure 84 Emissions of acidifying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. The results are here divided into different activity groups. Note that so-called green electric power has been used for the train traffic calculations.

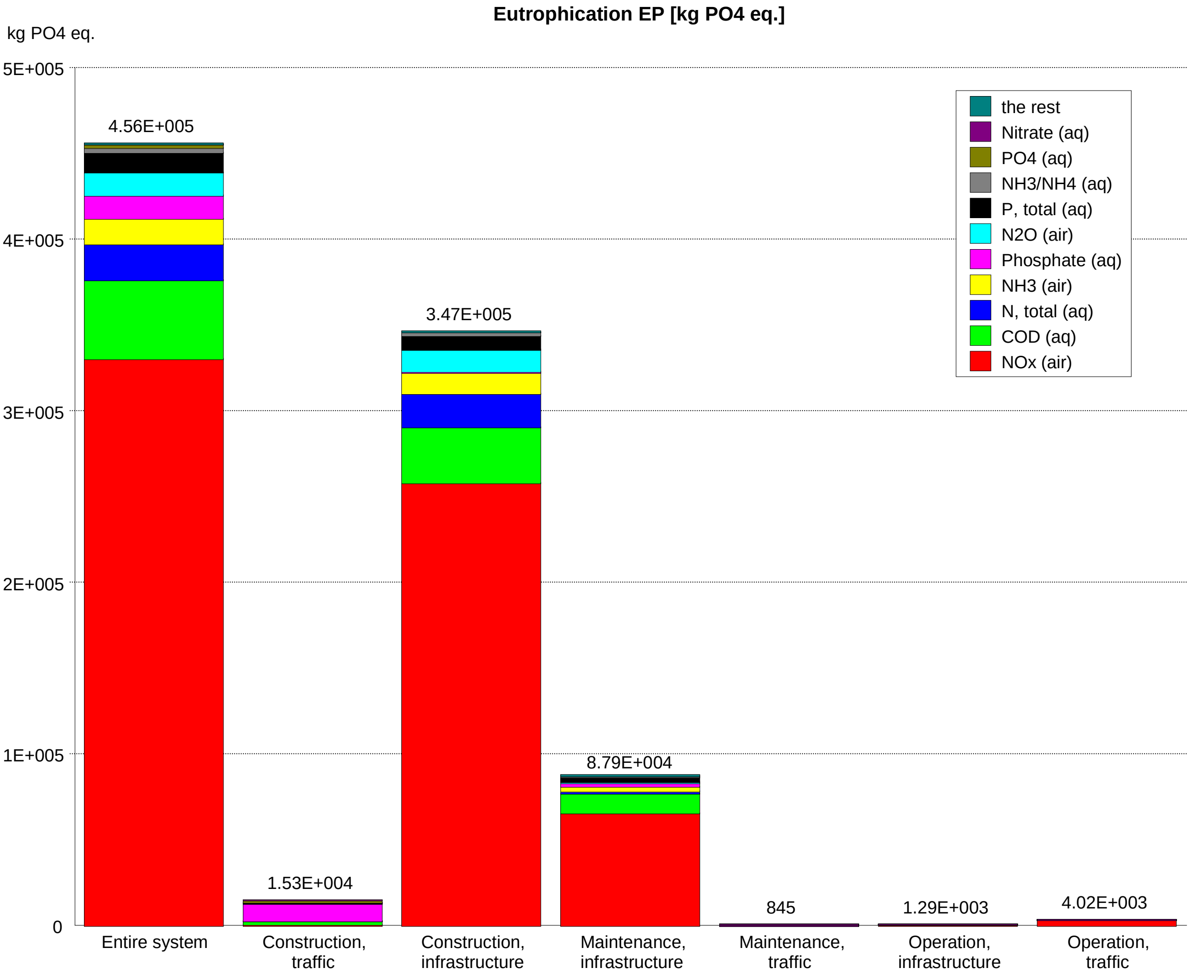

Figure 85 Emissions of eutrophying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. Note that so-called green electric power has been used for the train traffic calculations.

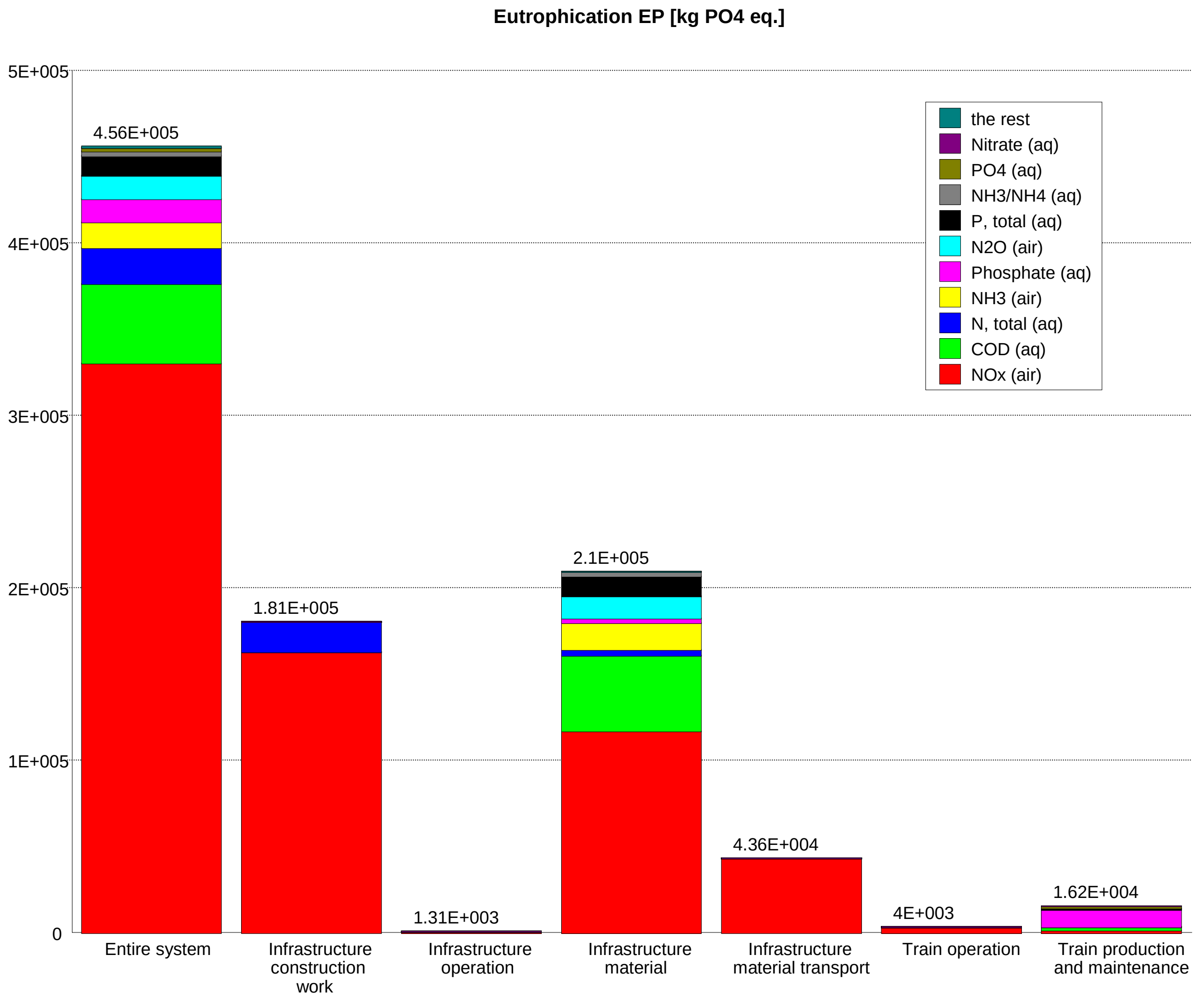

Figure 86 Emissions of eutrophying pollutants for the Bothnia Line. The figure shows the total emissions including all parts of the railway infrastructure and the transport work (the traffic, freight and passenger). The emissions cover construction, maintenance and operation for the railway infrastructure as well as for the train traffic activities. The figure shows the total emissions over a calculation period of 60 years. The results are here divided into different activity groups. Note that so-called green electric power has been used for the train traffic calculations.

9.9.3 Results from the Bothnia Line example

An important objective for environmental calculations of transport solutions is to be able to calculate the environmental performance of an entire transport of either passenger or goods. This can be achieved by an environmental product declaration (EPD) which can offer a standardised way for transport comparison. EPDs for both passenger[19] and freight[20] transports on the Bothnia Line, including railway infrastructure and the train transport, has been developed. The total railway transport model has been used with specific data for the Bothnia Line. The results are presented for a complete transport of passenger and goods and the results are presented per passenger-km and tonne-km respectively. The results include construction, maintenance and operation over a calculation period of 60 years. A full set of impact categories are calculated and the results are shown in Table 40 (passenger transport in passenger-km) and Table 43 (freight transport in tonne-km).

In Table 41 (passenger transport) and Table 44 (freight transport), the different resource uses have been broken down into single material uses. The largest contributors are presented in the tables. For the emission impact categories, the different categories have been broken down into overview activity areas in order to show the main sources of the emissions. The overview activity areas are explained in chapter 9.1.1. The distribution of the emission impact categories in the overview activity areas are shown in Table 42 (passenger transport) and Table 45 (freight transport).

The graphic overview impact distribution analysis of a complete train transport is shown in Figure 87 (passenger transport) and Figure 88 (freight transport). Here, the contribution distributions of each overview activity areas are shown for the different impact categories.

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[19] EPD Passenger Transport, Environmental Product Declaration for passenger transport on the Bothnia Line., Reg. no. S-P-00194, UN CPC 6421, Date 2010-03-19.

[20] EPD Freight Transport, Environmental Product Declaration for freight transport on the Bothnia Line., Reg. no. S-P-00195, UN CPC 6512, Date 2010-03-19.

Table 40 Environmental impact of a passenger transport including both the railway infrastructure and the train traffic at the Bothnia Line calculated and presented per passenger-km over 60 years. All construction, operation and maintenance activities over 60 years are included for the transport.

Impact category	**Unit/passenger-km**	**Infrastructure construction**	**Infrastructure operation**	**Infrastructure maintenance**	**Train (construction and maintenance)**	**Train (operation)**	**Total**
Resource use							
Non-renewable materials	kg/passenger-km	3.46E-01	7.22E-06	2.09E-02	1.72E-04	4.64E-05	3.67E-01
Renewable materials	kg/passenger-km	9.92E-05	0	8.29E-05	0	0	1.82E-04
Non-renewable energy	MJ/passenger-km	6.59E-02	7.27E-03	3.24E-02	3.77E-02	6.22E-04	1.44E-01
Renewable energy	MJ/passenger-km	3.24E-03	4.11E-02	1.98E-03	0	3.30E-01	3.76E-01
Recycled resources	kg/passenger-km	7.18E-04	0	2.40E-04	0	0	9.58E-04
Water	kg/passenger-km	2.63E-02	0	1.74E-02	0	0	4.36E-02
Land use	m^2/passenger-km	1.49E-04	8.50E-05	9.44E-06	0	5.14E-04	7.57E-04
Emissions							
Global warming	kg CO_2 eq./passenger-km	7.93E-03	3.67E-05	2.85E-03	2.05E-03	7.93E-05	1.29E-02
Acidification	kg SO_2 eq./passenger-km	2.44E-05	1.11E-07	1.08E-05	9.83E-06	5.86E-07	4.57E-05
Ozone depletion	kg CFC-11 eq./passenger-km	2.04E-12	0	2.20E-12	3.31E-12	0.00E+00	7.56E-12
POCP (Photochemical oxidant formation)	kg ethene eq./passenger-km	2.46E-06	1.44E-08	1.48E-06	1.73E-06	4.99E-08	5.73E-06
Eutrophication	kg PO_4^{2-}eq./passenger-km	5.30E-06	1.97E-08	1.34E-06	7.48E-08	1.09E-07	6.85E-06
Other							
Output of materials for recycling	kg/passenger-km	1.10E-06	0	8.69E-04	0	0	8.71E-04
Waste, hazardous	kg/passenger-km	1.30E-05	1.61E-05	3.37E-06	0	0	3.25E-05
Waste, excess soil	kg/passenger-km	2.53E-01	0	0	0	0	2.53E-01
Waste, other	kg/passenger-km	1.14E-02	1.31E-05	5.63E-03	0	4.85E-06	1.71E-02

Table 41 Specification of resources making the largest contributions to the different resource use categories for an entire passenger transport at the Bothnia Line.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 96.5%, Sand and gravel: 1.7%, Limestone $CaCO_3$: 1.3% , Fe (res): 0.5%
Renewable materials	kg	Wood: 100.0 %
Non-renewable energy	MJ	Crude oil: 45.7% , Coal: 32.0%, Nuclear: 12.4%, Natural gas: 9.8%
Renewable energy	MJ	Hydro power: 98.2%, Biomass fuel: 1.7%
Recycled resources	kg	Ferrous scraps: 98.9%, Steel scrap: 0.6% , Copper scrap: 0.4%, Stainless steel scrap: 0.1%

Table 42 Main process contributors to the different impact categories for an entire passenger transport at the Bothnia Line.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 52.7 % Infrastructure construction work: 12.4 % Infrastructure material transport: 1.9 % Infrastructure operation: 0.3 % Deforestation: 16.3 % Train production and maintenance: 15.8 % Train operation: 0.6 %
Acidification	kg SO_2 eq.	Infrastructure material: 49.3 % Infrastructure construction work: 21.8 % Infrastructure material transport: 5.8 % Infrastructure operation: 0.2 % Deforestation: 0.0 % Train production and maintenance: 21.5 % Train operation: 1.3 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 56.2 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 % Train production and maintenance: 43.8 % Train operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 42.5 % Infrastructure construction work: 14.9 % Infrastructure material transport: 3.5 % Infrastructure operation: 0.3 % Deforestation: 0.0 % Train production and maintenance: 37.7 % Train operation: 1.1 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 47.6 % Infrastructure construction work: 40.5 % Infrastructure material transport: 8.9 % Infrastructure operation: 0.3 % Deforestation: 0.0 % Train production and maintenance: 1.1 % Train operation: 1.6 %

Table 43 Environmental impact of a freight transport including both the railway infrastructure and the train traffic at the Bothnia Line calculated and presented per tonne-km over 60 years. All construction, operation and maintenance activities over 60 years are included for the transport.

Impact category	**Unit/tonne-km**	**Infrastructure construction**	**Infrastructure operation**	**Infrastructure maintenance**	**Train (construction and maintenance)**	**Train (operation)**	**Total**
Resource use							
Non-renewable materials	kg/tonne-km	5.09E-01	1.06E-05	3.09E-02	5.53E-05	2.44E-05	5.40E-01
Renewable materials	kg/tonne-km	1.46E-04	0	1.22E-04	1.28E-06	0	2.70E-04
Non-renewable energy	MJ/tonne-km	9.72E-02	1.07E-02	4.78E-02	3.96E-03	3.34E-04	1.60E-01
Renewable energy	MJ/tonne-km	4.78E-03	6.06E-02	2.92E-03	3.21E-04	1.73E-01	2.42E-01
Recycled resources	kg/tonne-km	1.06E-03	0	3.54E-04	7.59E-05	0	1.49E-03
Water	kg/tonne-km	3.87E-02	0	2.56E-02	2.93E-03	0	6.72E-02
Land use	m^2/tonne-km	2.19E-04	1.25E-04	1.39E-05	5.82E-06	2.70E-04	6.34E-04
Emissions							
Global warming	kg CO_2 eq./tonne-km	1.17E-02	5.41E-05	4.21E-03	1.80E-04	4.22E-05	1.62E-02
Acidification	kg SO_2 eq./tonne-km	3.59E-05	1.64E-07	1.59E-05	8.89E-07	3.11E-07	5.33E-05
Ozone depletion	kg CFC-11 eq./tonne-km	3.01E-12	0	3.25E-12	0	0	6.26E-12
POCP (Photochemical oxidant formation)	kg ethene-eq./tonne-km	3.62E-06	2.12E-08	2.19E-06	9.20E-08	3.59E-08	5.96E-06
Eutrophication	kg PO_4^{2-}eq./tonne-km	7.81E-06	2.91E-08	1.98E-06	4.83E-07	5.80E-08	1.04E-05
Other							
Output of materials for recycling	kg/tonne-km	1.62E-06	0	1.28E-03	5.71E-06	0	1.29E-03
Waste, hazardous	kg/tonne-km	1.92E-05	2.38E-05	4.97E-06	1.23E-06	0	4.91E-05
Waste, excess soil	kg/tonne-km	3.73E-01	0	0	0	0	3.73E-01
Waste, other	kg/tonne-km	1.69E-02	1.93E-05	8.30E-03	1.25E-05	2.55E-06	2.52E-02

Table 44 Specification of resources making the largest contributions to the different resource use categories for an entire freight transport at the Bothnia Line.

Resource category	Unit	Largest contributors
Non-renewable materials	kg	Solid rock: 96.5%, Sand and gravel: 1.7%, Limestone $CaCO_3$: 1.3%, Fe (res): 0.4%
Renewable materials	kg	Wood: 100.0 %
Non-renewable energy	MJ	Crude oil: 43.8%, Coal: 25.9%, Nuclear: 16.9%, Natural gas: 13.3%
Renewable energy	MJ	Hydro power: 98.1%, Biomass fuel: 1.9%
Recycled resources	kg	Ferrous scraps: 98.9% , Steel scrap: 0.6% , Copper scrap: 0.4%, Stainless steel scrap: 0.1%

Table 45 Main process contributors to the different impact categories for an entire freight transport at the Bothnia Line.

Impact category	Unit	Largest contributors
Global warming	kg CO_2 eq.	Infrastructure material: 62.1 % Infrastructure construction work: 14.6 % Infrastructure material transport: 2.3 % Infrastructure operation: 0.3 % Deforestation: 19.2 % Train production and maintenance: 1.1 % Train operation: 0.3 %
Acidification	kg SO_2-eq.	Infrastructure material: 62.3 % Infrastructure construction work: 27.7 % Infrastructure material transport: 7.4 % Infrastructure operation: 0.3 % Deforestation: 0.0 % Train production and maintenance: 1.7 % Train operation: 0.6 %
Ozone layer depletion	kg CFC-11 eq.	Infrastructure material: 100.0 % Infrastructure construction work: 0.0 % Infrastructure material transport: 0.0 % Infrastructure operation: 0.0 % Deforestation: 0.0 % Train production and maintenance: 0.0 % Train operation: 0.0 %
Photochemical Ozone Creation Potential	kg ethene-eq.	Infrastructure material: 77.7 % Infrastructure construction work: 16.3 % Infrastructure material transport: 3.8 % Infrastructure operation: 0.3 % Deforestation: 0.0 % Train production and maintenance: 0.8 % Train operation: 0.5 %
Eutrophication	kg PO_4^{2-}eq.	Infrastructure material: 46.2 % Infrastructure construction work: 39.5 % Infrastructure material transport: 8.7 % Infrastructure operation: 0.3 % Deforestation: 0.0 % Train production and maintenance: 4.7 % Train operation: 0.6 %

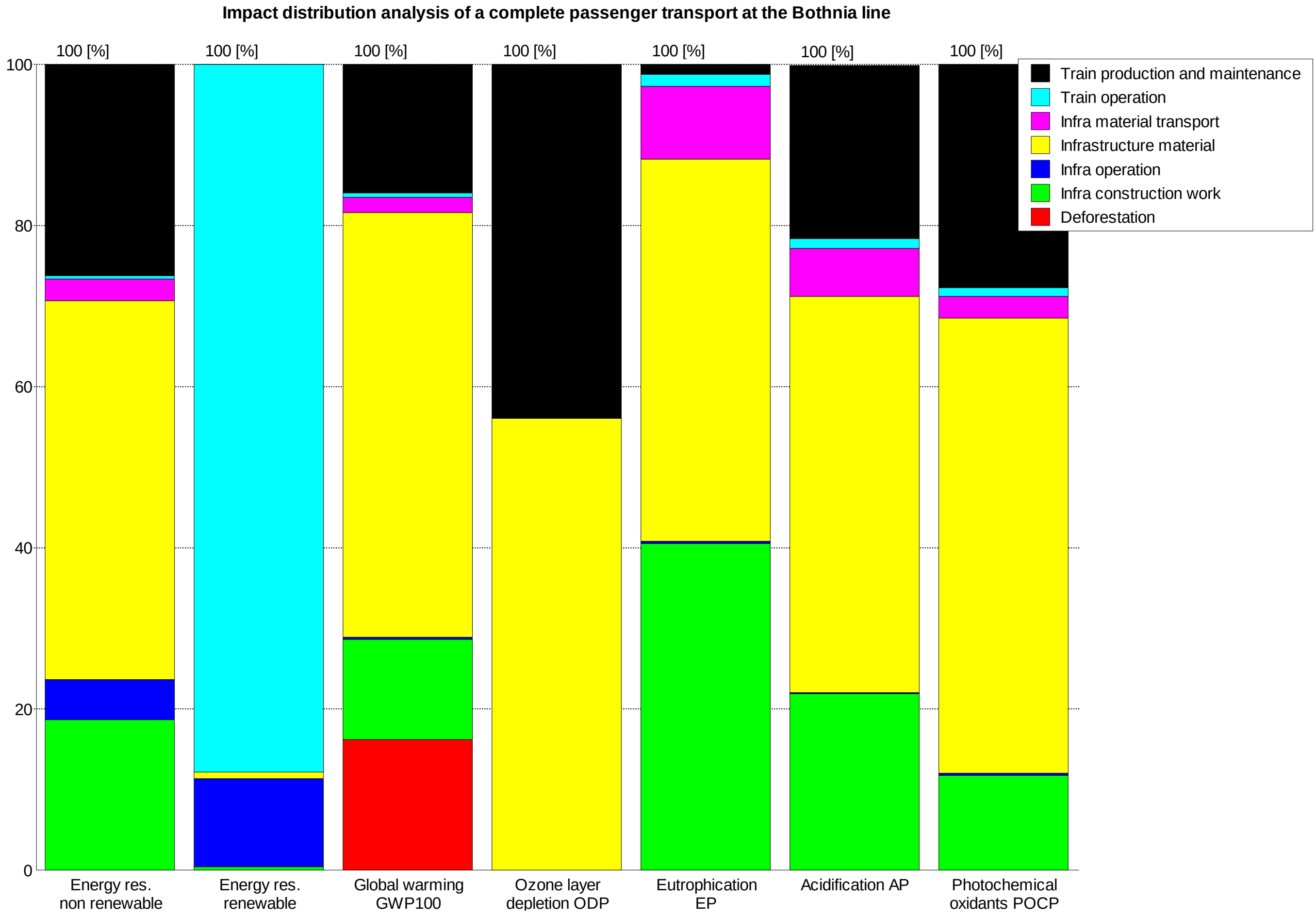

Figure 87 Impact distribution analysis of a complete passenger transport at the Bothnia Line.

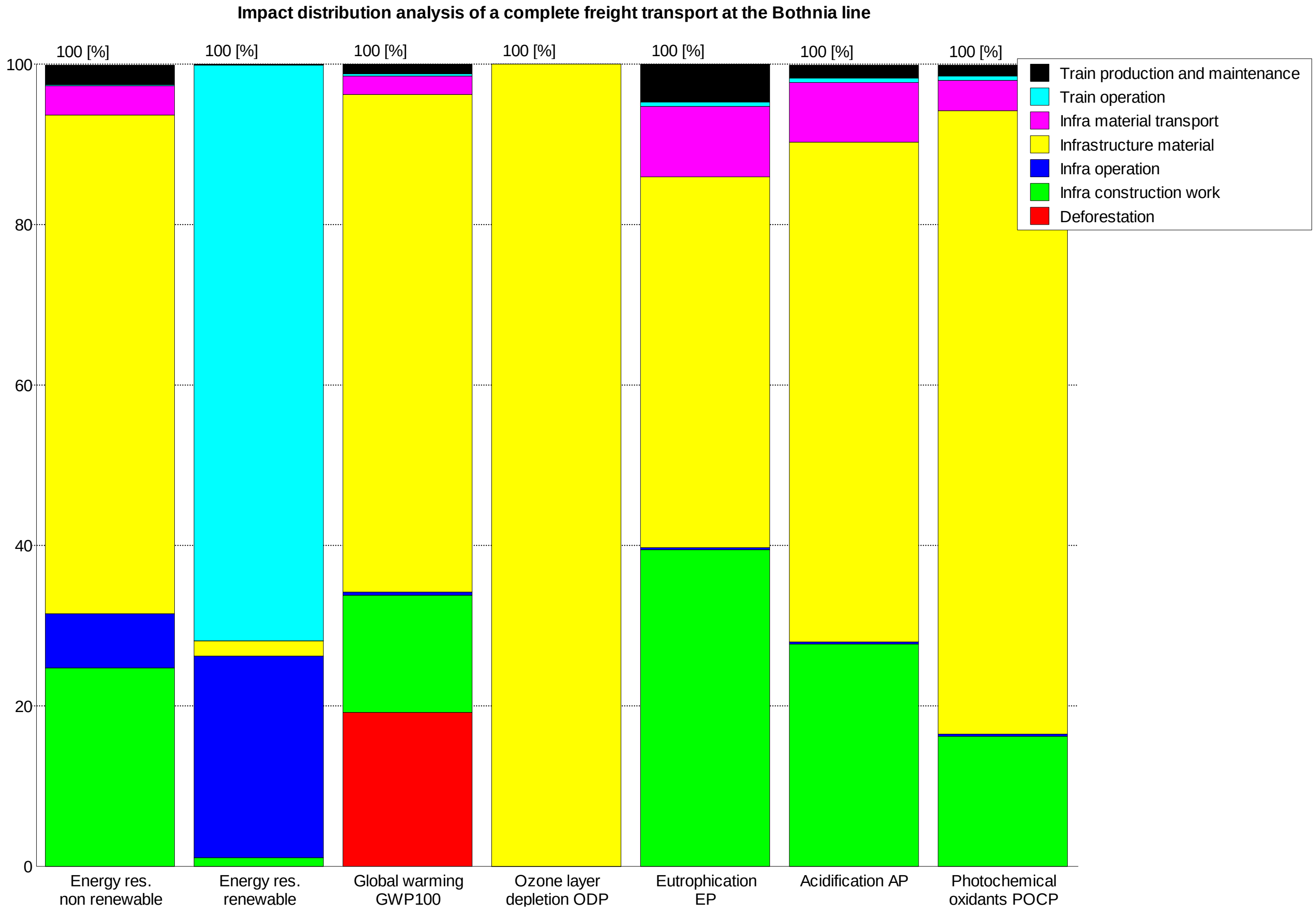

Figure 88 Impact distribution analysis of a complete freight transport at the Bothnia Line.

10 Environmental product declarations (EPD) for railway infrastructures and railway transports

The core of the EPDs developed for the infrastructure and the transports on the Bothnia Line is the environmental performance section that is based on the LCA described in this report.

Another important part of the EPD is the quantified description of how the infrastructure and the transports on the railway affect the landscape that it goes through. That environmental aspect is not mandatory to describe according to the International EPD system, but it was found a very important aspect for infrastructure and transports when developing the PCR and was therefore included in the PCR. The quantification of impact on the landscape was made both by applying the so called Biotope method, developed by Vattenfall, and by using new methodology for quantification of noise disturbance on people and birds.

In the beginning of the process of EPD development, the intention was to make just one EPD for the entire transport system of the Bothnia Line. However, it was quite early realised that it would be valuable for the future also to make separate EPDs for subsystems. It would then not only be possible to get information on the environmental impact from the subsystems themselves, e.g. the track foundation substructure, but also to put together different general subsystem information/EPDs to obtain estimated information on the environmental impact from other railway system configurations than the Bothnia Line. With that approach, it would for example be possible to add data from the EPDs for tunnel substructure, track system and power, signalling and telecom systems to produce generic data for a railway line that mostly goes through tunnels. However, all the EPDs are based on the Bothnia Line and are thus more or less general/specific for that application. It is thus important to keep that in mind when using the data in other applications. If a railway application differs significantly from the Bothnia Line, the railway models have to be used to calculate specific data for that application. The EPDs for the Bothnia Line and their structural interdependency are shown in Figure 89 below.

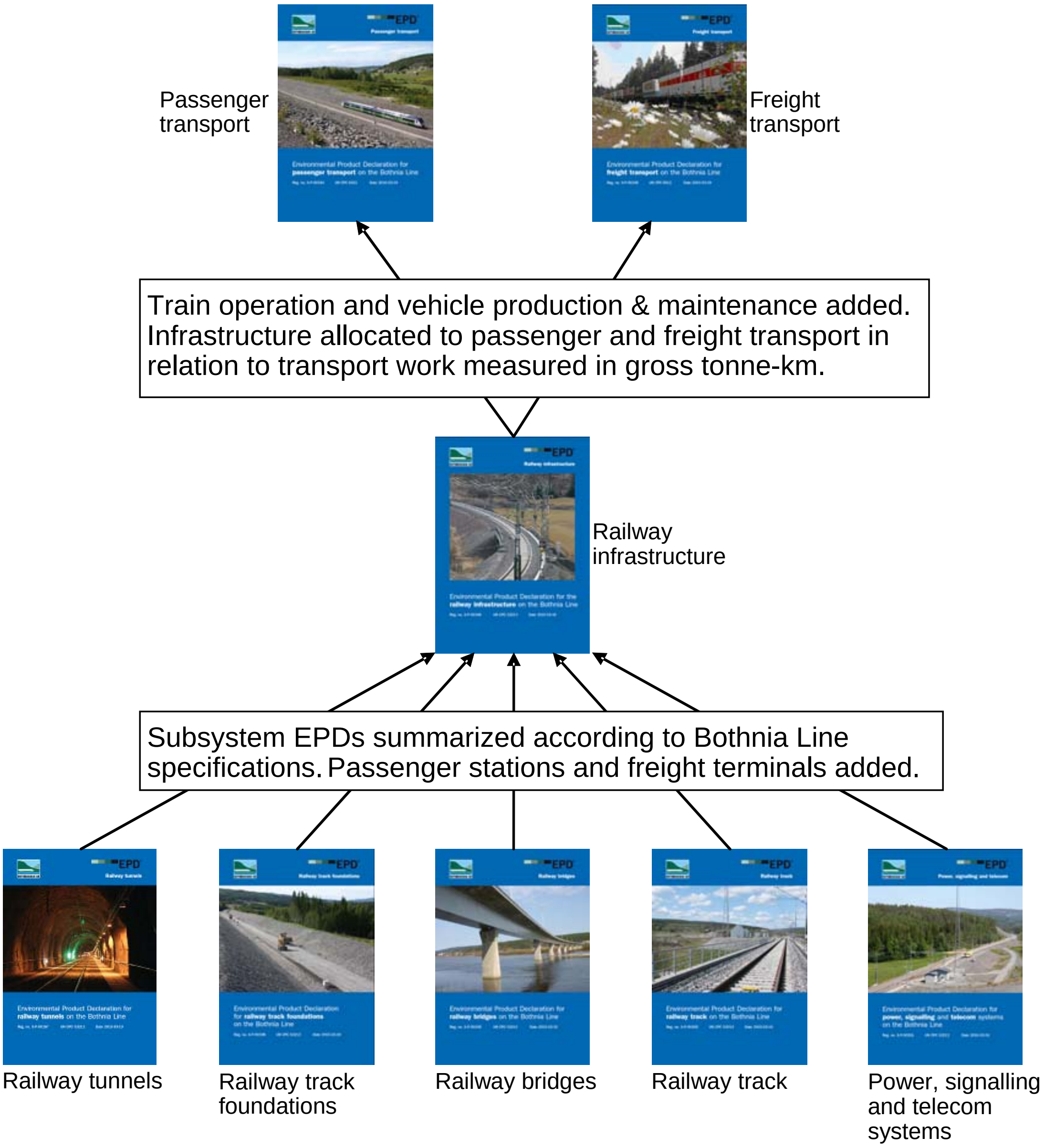

Figure 89 The hierarchic structure of the EPDs for the Bothnia Line. Added parts and allocations described for each level.

The development and content of the EPDs are described in the EPD report[21] available at www.botniabanan.se. Descriptions of how background material for the different sections in the EPDs has been developed can also be found in that report. All results and analyses are however not presented in detail there, but can be found in this background reports and in the EPDs. The LCA data used in the EPDs are entirely based on the LCA railway models presented in this report. Small differences between the results used in the EPDs and the results presented in this research study

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[21] Uppenberg, S., Aava-Olsson, B., Berglund, M., Environmental Product Declarations for the Bothnia Line - Final Report. Botniabanan AB, Örnsköldsvik. (2010).

can exist due to updated and different assumptions of some material use and some transport distances. The differences only reflect a further development of the models and the latest results are used in this research presentation.

11 Discussion and conclusions

11.1 Which parts of the system give the largest contribution to environmental impact?

The question of which processes within a product's/service's life cycle that gives the largest environmental impact is crucial and the basis for all effective improvement work. One way of identifying these processes is to perform a life cycle assessment (LCA) for the product or service in focus. The development of LCA-models for the Bothnia Line can therefore now also help us answering this question for rail transports.

If we start with looking at the dominance analyses for passenger and freight transport, Figure 87 and Figure 88 respectively, we can see some differences that have to be explained. A large share of the contribution to ozone layer depletion and POCP (potential for creation of ground-level ozone) comes from vehicle production & maintenance for passenger transport, but not for freight transport. The difference depends on that input data for production of Coradia Lirex passenger trains include emissions of ethene and CFCs, while the used input data for freight locomotives and wagons does not. The difference can be related to use of materials in the passenger trains that are not used in freight trains.

There is also a significantly larger share of the contribution to global warming and acidification from vehicle production & maintenance for the passenger transport than for freight transport. That is explained by the fact that a transported passenger needs a larger "share" of the vehicle than a transported tonne of goods if the ratio "tonne vehicle per passenger or tonne of goods" is calculated. In other words, the transport of goods is more vehicle efficient than the transport of passengers if compared per passenger and tonne of goods. The majority of the emissions from vehicle production & maintenance are related to the production of materials like steel, aluminium etc.

For both passenger and freight transport, there is a significant share of the contribution to global warming coming from deforestation. That is related to the permanent transition of forest land to railway land. Forest areas that are cut down and transformed to railway land will not be replanted, and the CO_2-emissions from the cut down biomass is therefore regarded as an emission of fossil CO_2 which contributes to global warming (see section 3.1 for more details). The contribution is quite large (ca 20 %) for the Bothnia Line, since the railway was built almost entirely on forest land.

Apart from the contributions from the processes mentioned above, we can also see that there are significant contributions from the emissions related to the infrastructure construction work (emissions from machines like excavators, dumpers etc.) and minor contributions from material transports, infrastructure operation and train operation. The emissions from train operation are very low because the electricity mix used for train operation consists almost entirely of hydropower (99.2 % in 2008) and the remaining electricity from biomass fuel (0.8 %). If we, on the other hand, study the use of energy resources, the train operation stands for the majority (52.6 %) of the energy use over the life cycle (see Figure 79).

The main part of the contributions to all environmental impact categories comes from raw material acquisition and production of materials used for the construction of the infrastructure, like steel, concrete etc. The contributions from different materials and subsystems to the environmental impact category global warming are described in Table 46 below. Note that the figures presents shares of the contribution to global warming just for infrastructure material, not for the entire systems described in the EPDs for passenger and freight transport.

Table 46 Detailed dominance analysis for the contribution of infrastructure material to the environmental impact category Global warming.

Material/subsystem	**Track**	**Tunnels**	**Bridges**	**Stations**	**Track Foundations**	**Power, signalling, telecom**	**Total**
Steel	29 %	4 %	5 %		3 %	3 %	**43 %**
Cement	6 %	10 %	11 %		5 %	0 %	**32 %**
Buildings				11 %			**11 %**
Aluminium						4 %	**4 %**
Explosives	0 %	2 %			1 %		**3 %**
Plastics	0 %	1 %			1 %	1 %	**2 %**
Copper						1 %	**1 %**
Total	**35 %**	**16 %**	**16 %**	**11 %**	**10 %**	**9 %**	**97 %**

As shown in Table 46 above, a few materials totally dominate the emissions of carbon dioxide related to production of infrastructure material. Steel and cement together stands for 75 % of the total CO_2 emissions related to infrastructure material. The data for buildings, that give a contribution of 11 % in table 3.4, are aggregated data for material related emissions and construction work related to the building of stations and freight terminals. The majority of these emissions come from the use of steel and concrete. Therefore, steel and cement can be said to stand for some 85 % of the total material related CO_2 emissions for the Bothnia Line's infrastructure.

11.1.1 Steel

Looking at the different subsystems, we can see that the track system is dominating the CO_2 emissions related to steel (29 %). Approximately 26 of these 29 % are related to the production of rails, and the rest is related to reinforcement steel in sleepers, and equipment for fastening of rail to sleeper.

The contribution from steel for the other subsystems, are related to reinforcement steel (e.g. in bridges and steel fibres in shotcrete), steel beams for bridges, cables etc.

11.1.2 Cement

For cement, there is not a dominance of climate impact from one single product as it is for steel. Tunnels and bridges are the infrastructure subsystems that contribute most to climate impact from cement production (10 % and 11 % respectively). The use of cement for tunnel construction is mainly related to shotcrete application (7.5 of the 10 %) on tunnel roof and walls. The rest is related mainly to injection of cement slurries and installation of concrete cable ducts. For bridges, cement is used in the concrete for bridge pier foundations, bridge piers and bridge superstructure, but also in concrete piles used for ground reinforcement.

Apart from tunnels and bridges, the subsystems track foundations and track also give a significant contribution to CO_2 emissions from cement production, 5 % and 6 % respectively. For track foundations, this is related to cable ducts and manholes, water culverts, and foundations for the catenary system. For the railway track, the emissions are entirely related to concrete sleepers.

11.2 Potential for reducing greenhouse gases from railway transports

The discussion above shows that the most important contributions to greenhouse gas emissions from transports on the Bothnia Line comes from infrastructure material, infrastructure construction work, deforestation and for passenger transports also from vehicle production. For vehicle production, the improvement potential lies in designing vehicles that can transport more passengers per tonne of vehicle, but also in using materials with lower emissions of CO_2 per mass unit. The energy use for the trains is a significant factor but in this case, when green electric power is used, the effect on greenhouse gas emissions is small. If diesel trains are used, the situation will be much different.

The emissions related to deforestation can be affected by choosing location of the railway so forest land is avoided. However, there are many other factors to take into account in the planning. It would have been difficult to reduce this component significantly for the building of the Bothnia Line since the region that it goes through consists mainly of forest land, and since the location to a great extent was determined by the topography, protected areas and location of cities and other inhabited areas.

The emissions of greenhouse gases from construction machines can probably to some extent be reduced by planning and management of vehicle usage but the main reduction potential lies in using more and more fuel efficient construction vehicles, and by switching over to vehicles that uses biofuels or electricity.

As said above, the largest contribution to greenhouse gas emissions comes from the production of the materials used in the construction of the infrastructure. Below follows a discussion on potentials for reducing greenhouse gas emissions from two important materials, steel and cement/concrete. The reduction potential is however very complex and the production is already today optimized as a result of many years development work both concerning the materials and the products. The discussion is thus very general and many aspects have to be considered when choosing materials.

The analysis shows that reducing the CO_2 emissions related to production of rails can be a possible way to take measures in order to reduce the total steel related CO_2 emissions for the railway infrastructure.

In principle, there are two ways of reducing the CO_2 emissions related to rails:

1. Reducing the amount of steel needed per km railway and time unit. This can be done either by using other rail profiles with lower steel content per meter, or by performing quality and maintenance in a way that the lifetime of the rail is maximized/optimized.

2. Reducing the emissions of CO_2 per tonne of rail steel. This must be done by the steel producers for example by using more renewable energy in their processes or by using more recycled steel, or both.

The achievement of the first alternative requires management of planning and maintenance. Guidelines for planning of track system and maintenance should highlight that the choice of rail profile and steel quality should be done in a way that minimizes the amount of rail steel per m railway over a time period of, say 60 years. In that calculation, it has also to be taken into account the maintenance (e.g. rail grinding or milling) that has to be performed in order to maximize the lifetime of the rail. It is of course also important to implement management routines that assure that the stipulated maintenance actually is performed according to the requirements.

Implementing procurement requirements is the way that an infrastructure manager can work for the achievement of alternative two. Environmental performance indicators (EPIs), like “amount of embedded CO_2 emissions per tonne of rail”, can be used to evaluate different suppliers. EPIs like “amount of recycled material per tonne of rail” can be another way of describing climate impact without specifying CO_2 emissions. If such procurement requirements shall be used, it is very important that the EPI values delivered from the suppliers are comparable and quality audited in some way. Using the international EPD system is one way of achieving that.

The conclusion of the dominance analysis for the Bothnia Line is that the main part of the embedded CO_2 emissions from the use of concrete products is related to use of different types of cement. This means that the cement or ready-made concrete is delivered to the construction site for use in e.g. shotcrete application in tunnels and for concretion of bridges. For the Bothnia Line, a smaller, but still significant, part is related to the use of precast concrete products like sleepers, ground reinforcement piles, cable ducts and manholes, water culverts and different types of foundations for the catenary system. Although there is a difference in the structure of the supply chain between bulk use and use of precast products, the actions that can be taken to reduce the embedded CO_2 emissions are much the same as described for steel above. Reduction of CO_2 emissions can be accomplished either by reducing the amount of material used or by reducing the embedded CO_2 emissions per tonne of cement/concrete, and this calls for management routines and procurement requirements.

There is also a connection between concrete use and steel use in the use of steel reinforcement for concrete. The steel reinforcement is usually made of recycled steel produced in an Electric Arc Furnace (EAF furnace). The energy for an EAF comes mainly from electric power and the production of that electric power is thus of great importance. In the study, world-wide industry average data[22] has been used for the EAF steel production. This data is heavily based on coal,

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[22] IISI (International Iron and Steel Institute) Life Cycle Inventory Study for Steel Industry Products (1999). (EAF route). World-wide LCI data.

natural gas and oil. If instead the electric power for the EAF production was based on low CO_2 production such as hydro power, biomass fuel power, wind power, or nuclear power, the overall CO_2 emissions from the concrete products can be significantly reduced.

Guidelines for planning and dimensioning of tunnels and bridges should emphasize the importance of optimizing the amounts of material needed for the constructions over the lifetime. It might e.g. be worth choosing a higher quality in order to extend the lifetime. For concrete constructions, there is not much maintenance during the lifetime, so the planning and dimensioning of the constructions is crucial for the resulting carbon footprint of the construction.

In procurement, EPI values like "amount of embedded CO_2 emissions per tonne of concrete" can be used to evaluate different suppliers also for concrete products. It might be necessary to formulate EPI values differently for bulk concrete and precast products. For e.g. sleepers, "amount of embedded CO_2 emissions per sleeper" might be a better EPI value to use, depending on the supplier's routines for emission calculations. If such procurement requirements shall be used, it is very important that the EPI values delivered from the suppliers are comparable and quality audited in some way. Using the international EPD system is one way of achieving that.

Product safety and reliability in operation is always important factors for railways. Different reduction measures shall therefore be put into a larger perspective where different aspects are valued.

11.3 Identification of data and knowledge gaps

In the LCA-study for the Bothnia Line, we have learnt that it is possible to collect data with quite good quality for all the major flows of material and energy resources. Although the accessibility and compilation of needed data could generally be improved greatly within civil engineering projects like the construction of the Bothnia Line.

Our experience is that the major gaps in data and knowledge lies within supplier's ability to present reliable and comparable data for the EPIs described in chapter 11.2 above. If management routines and procurement requirements are going to be used to reduce the environmental impact from infrastructure material, it is a challenge to get comparable data from different suppliers for e.g. "carbon footprint per tonne rail steel". Most suppliers of most products can today present a figure for such an EPI, but there are often great differences and uncertainties in what that figure describes. The value is entirely dependent on how system boundaries are drawn, what data has been used for energy processes etc. It is therefore important to find common ways of performing calculations within different product groups. That is also one of the major goals for the EPD-system. EPDs have to be based on product category rules (PCR) which are developed for different product groups. The same way of thinking will probably also be implemented in the ISO standard for carbon footprint of products that is under development.

The accuracy is also different for different substances. Energy flows and main resources and emission can usually be well covered. Unusual emissions, smaller resource uses and wastes can be a problem usually because of poor survey. These problems can be reduced by a structured survey during construction, maintenance and operation.

11.4 Environmental benefits from building the Bothnia Line

The EPDs presents figures on the environmental impact from transports on the Bothnia Line, but we must not forget that the motive for building the railway was of course to reduce the environmental impact from transports of passengers and goods in the region. The developed LCA-models can now help us calculating the "payback time" for such an extensive railway project. In the planning of the Bothnia Line it was calculated that the CO_2 forecast for transferring of freight transports from road to railway would give a reduction of CO_2-emissions of ca 54 000 ton per year. The LCA for railway infrastructure now tells us that the total CO_2-emission for 1 km of Bothnia Line over the entire lifecycle (60 years) is ca 3 900 ton, which gives an emission of 714 000 ton for the entire Bothnia Line (183 km main line). That results in a "payback time" of ca 13 years (714 000/54 000) for the CO_2-emissions. The payback time for other emissions can of course be calculated in the same way if there are forecasts for the reduction potentials.

11.5 Possibilities in use of developed LCA-models and EPDs

The developed LCA-models are built in a way that makes them very flexible and possible to use for all railway infrastructures. The LCA models are made with the LCA software, KCL-ECO. A primary objective of the project work was to make flexible models that can be used to calculate an energy and environmental profile for an entire railway transport, including both the railway infrastructure and the railway traffic. Other field of applications are e.g. in the analysis of the design of the railway infrastructure in order to improve the construction. To meet these requirements, the LCA model has been made in different model units. The units can then be put together to form an entire railway transport model. The LCA model units are:

- Railway track foundation model
- Railway track model
- Model of electric power and control systems for railways
- Railway tunnels model
- Railway bridges model
- Model of passenger stations and freight terminals
- Model of passenger and freight trains including train operation

All models are divided in construction, operation and maintenance. The construction part covers the initial construction of the new railway. The operation part includes the on-going operations during the lifetime of the railway such as electric power use for operation of the trains, for heating of railway switches or for operation of control electronics. The maintenance includes replacement of old railway components when the lifetime of the components has expired. The layout of the model structure has been chosen to reflect the order in which the railway is constructed.

All parameters in the models can be modified to make the models represent different system designs of railway infrastructure, e.g. different types of tunnels like single track or double track, with or without service tunnel etc. It is, however, necessary to have some knowledge about LCA in general and the specific LCA software and models to be able to perform new calculations based on the developed models. The LCA-models are not designed with an interface that makes it possible for anyone, regardless of knowledge, to adjust parameters and get new results for other system layouts.

The results presented in the EPDs can be used as generic data for other new railway lines in Sweden or other countries given that the requirements for representativeness are fulfilled, see chapter 10. The different subsystem EPDs can also, under the same prerequisite mentioned, be used to generate new data for a railway project. If, for example, a new railway tunnel of the same type as the Bothnia Line tunnels are going to be built, the EPDs for railway tunnel, railway track and power, signalling and telecom systems can be added and multiplied by the length of the new tunnel in kilometres to produce environmental data for the new railway tunnel infrastructure.

The EPD results can also be used to identify the order of magnitude for environmental impact of different processes in a railway project. For example, the climate gas emissions from machines used for the construction of the Bothnia Line can in the dominance analysis be identified to stand for ca 15 % of the total climate gas emissions presented in the EPD for railway infrastructure.

Appendix A

A LCA models of railway infrastructure and railway traffic

In this appendix, the model structure of the different model units is presented. Unfortunately, it is very difficult to show an entire model with a readable format in a report. Even the unit models are to complex to be readable in the report; they can easily be read as pdf-file on the computer screen using the zoom enlargement of the Acrobat Reader.

A.1 Railway track foundation model

In this chapter, the LCA model structure of the track foundation is shown. The track foundation includes all operations of the railway track except laying of rails. The layout of the model tries to follow a logic order of the construction work. The work starts with a geotechnical survey to investigate the ground. After that, an eventual forest is removed. The removed biomass is treated as deforestation. The forest felling is followed by different excavation works to remove soil and to make different earth and rock cuts. The ground is then stabilised by filling with blast stone or stabilised by concrete pile and cement/lime columns. The stabilised ground is refilled and the different base courses are formed to make the foundation for the railway track. In addition, different technical products are also installed such as foundations for contact line poles.

The model is divided in construction, maintenance and operation. The construction part is shown in Figure 90 and maintenance and operation is shown in Figure 91. No operation activities exist for the track foundation. In the figures, a list of codes is shown. This code list is used to code the modules to make it possible to identify the modules later on in the analysis.

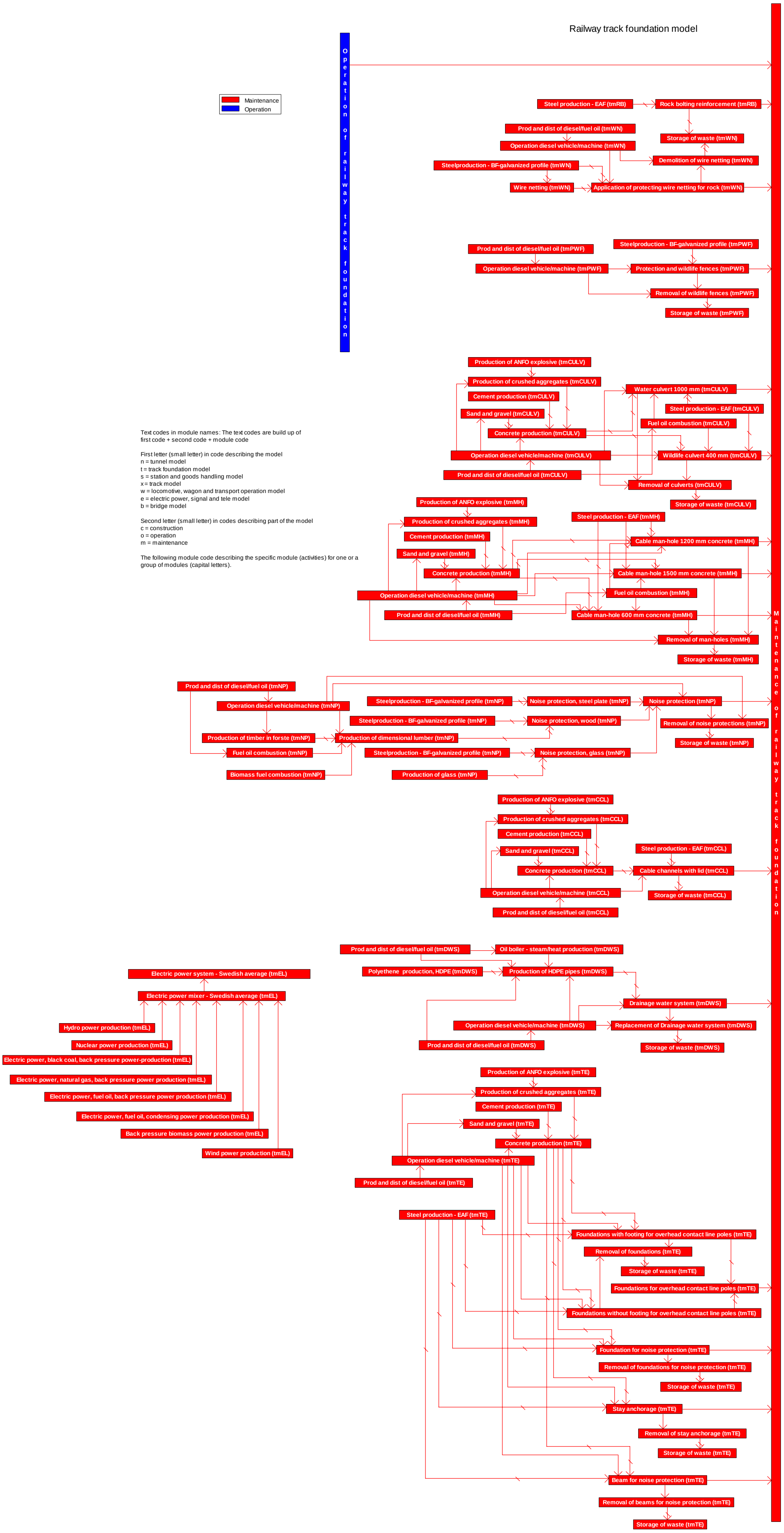
Text codes in module names: The text codes are build up of
first code + second code + module code

First letter (small letter) in code describing the model
n = tunnel model
t = track foundation model
s = station and goods handling model
x = track model
w = locomotive, wagon and transport operation model
e = electric power, signal and tele model
b = bridge model

Second letter (small letter) in codes describing part of the model
c = construction
o = operation
m = maintenance

The following module code describing the specific module (activities) for one or a group of modules (capital letters).

Figure 90 Railway track foundation model structure. Construction part. (Use pdf file and read figure from screen for improved readability).



Text codes in module names: The text codes are build up of first code + second code + module code

First letter (small letter) in code describing the model
n = tunnel model
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Second letter (small letter) in codes describing part of the model
c = construction
o = operation
m = maintenance

The following module code describing the specific module (activities) for one or a group of modules (capital letters).

Figure 91 Railway track foundation model structure. Operation and maintenance part. (Use pdf file and read figure from screen for improved readability).

A.2 Railway track model

Figure 92 and Figure 93 show the construction, maintenance and operation models of the actual railway track. This model includes the laying of the railway track with an automated diesel driven train. The train handles sleepers, rails and filling of track ballast. The model includes the production of sleepers and rails but not the production of the track application train. The operation of the track application train is however included. Bothnia Line specific production data for rails are used[23]. Data for wooden sleepers are included in the model as an option but not used in the Bothnia Line or in this study. The model also includes rail-milling operations. The track maintenance is performed by a similar train as for the construction phase and used for track replacement. Operation of tracks is mainly focused on the use of electric power for railway switches and illumination.

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[23] Rail production data from Voestalpine AG.

Text codes in module names: The text codes are build up of
first code + second code + module code

First letter (small letter) in code describing the model
n = tunnel model
t = track foundation model
s = station and goods handling model
x = track model
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e = electric power, signal and tele model
b = bridge model

Second letter (small letter) in codes describing part of the model
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m = maintenance

The following module code describing the specific module (activities) for one or a group of modules (capital letters).

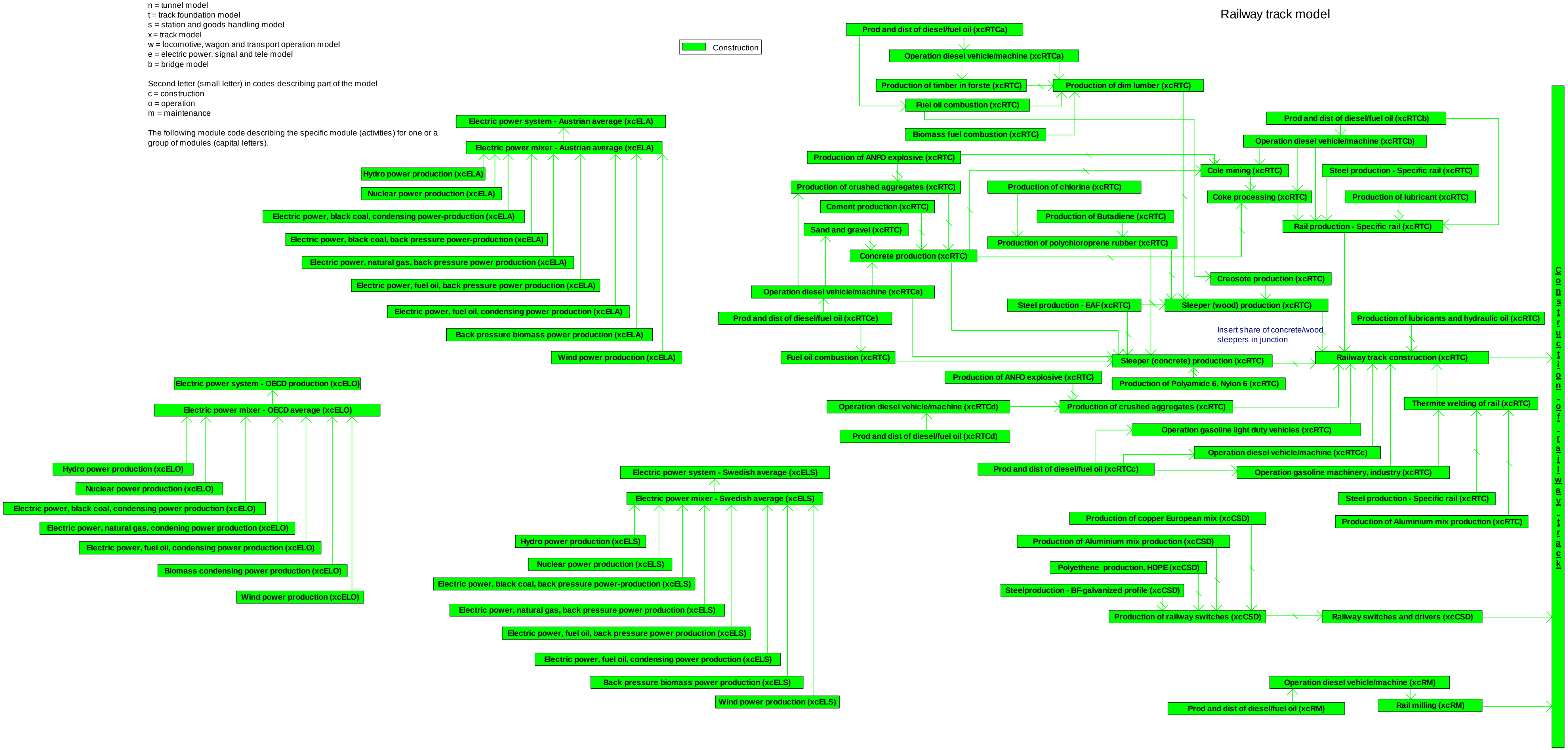
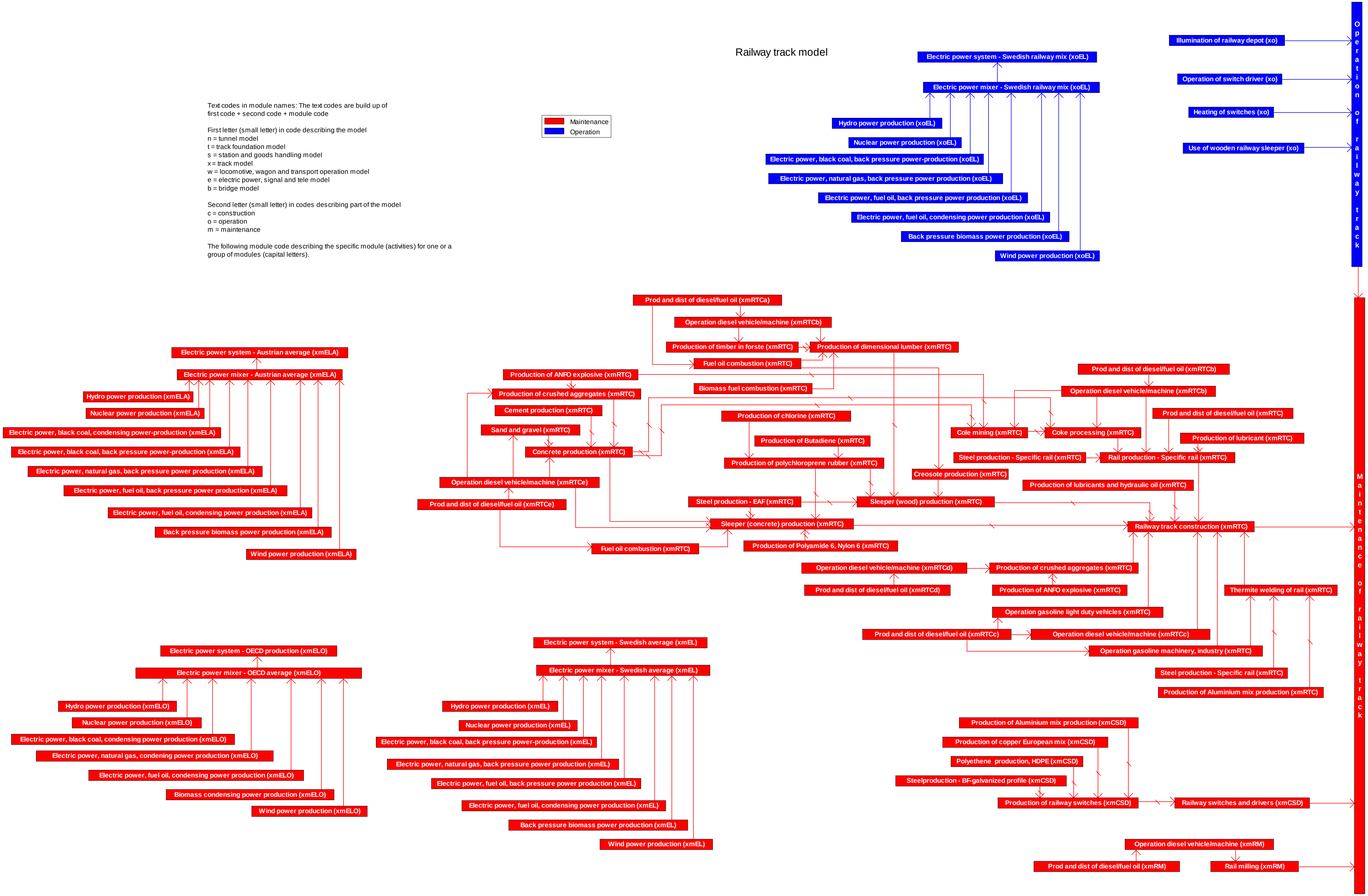


Figure 92 Railway track model structure. Construction part. (Use pdf file and read figure from screen for improved readability).



Text codes in module names: The text codes are build up of
first code + second code + module code

First letter (small letter) in code describing the model
n = tunnel model
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e = electric power, signal and tele model
b = bridge model

Second letter (small letter) in codes describing part of the model
c = construction
o = operation
m = maintenance

The following module code describing the specific module (activities) for one or a
group of modules (capital letters).

Figure 93 Railway track model structure. Operation and maintenance part. (Use pdf file and read figure from screen for improved readability).

A.3 Model of electric power and control systems for railways

Figure 94 and Figure 95 show the construction, maintenance and operation models of the electric power and control system. The electric and electronic systems have been divided into electric power supply, signal and communication and tele communication systems. In addition, there are also modules for different groundwork used e.g. for installation of power lines or houses for electronics. The electric power supply modules are used for electrified railways. These modules can be switched of when calculating a railway for e.g. diesel operation.

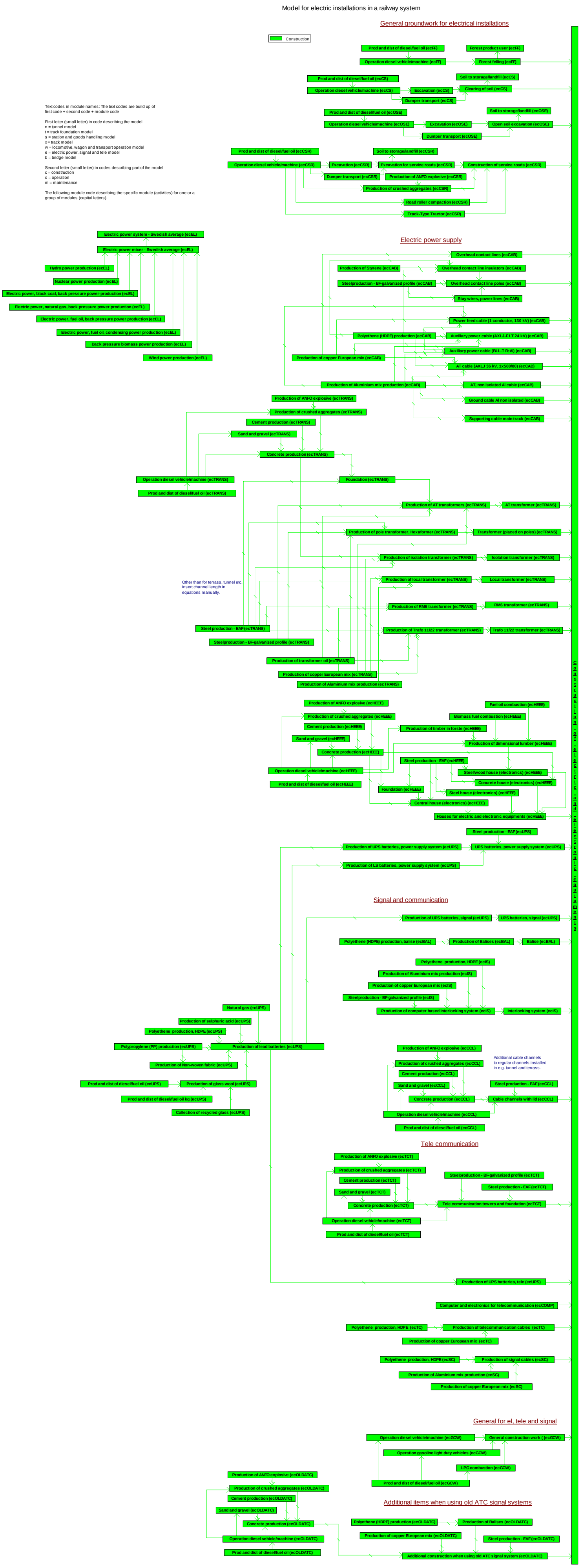

Figure 94 Power and control model structure. Construction part. (Use pdf file and read figure from screen for improved readability).

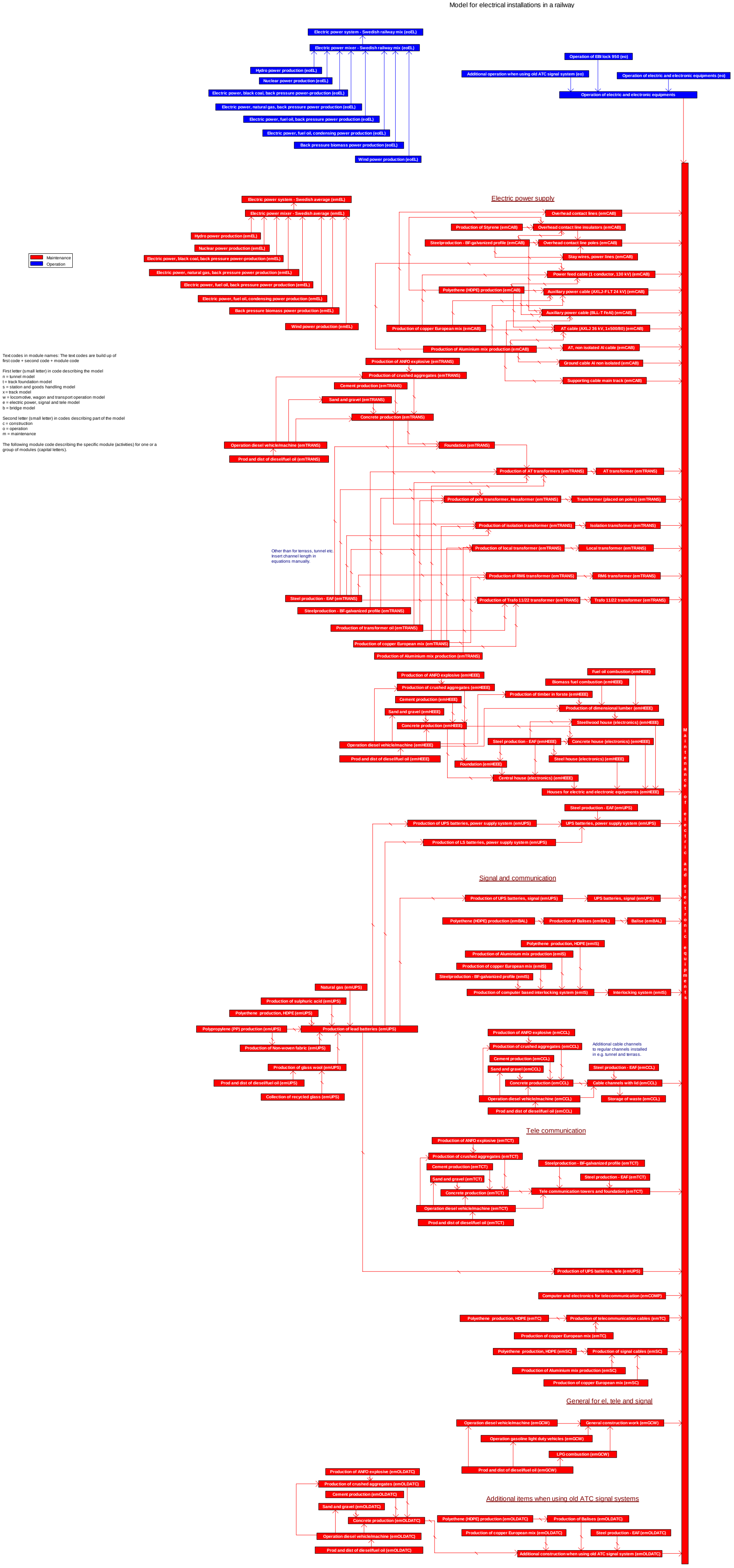

Figure 95 Power and control model structure. Operation and maintenance part. (Use pdf file and read figure from screen for improved readability).

A.4 Railway tunnel model

Figure 96 and Figure 97 show the construction, maintenance and operation models of railway tunnels. The models cover standard tunnel driving techniques including drilling, blasting and loading/transport of stone material. The model also covers shotcrete and drain application. Three independent tunnel tubes are used, main tunnel (train tunnel), service tunnel and access tunnel. The length of the different tunnel tubes can be chosen freely. Tunnel equipments are also included in the model.

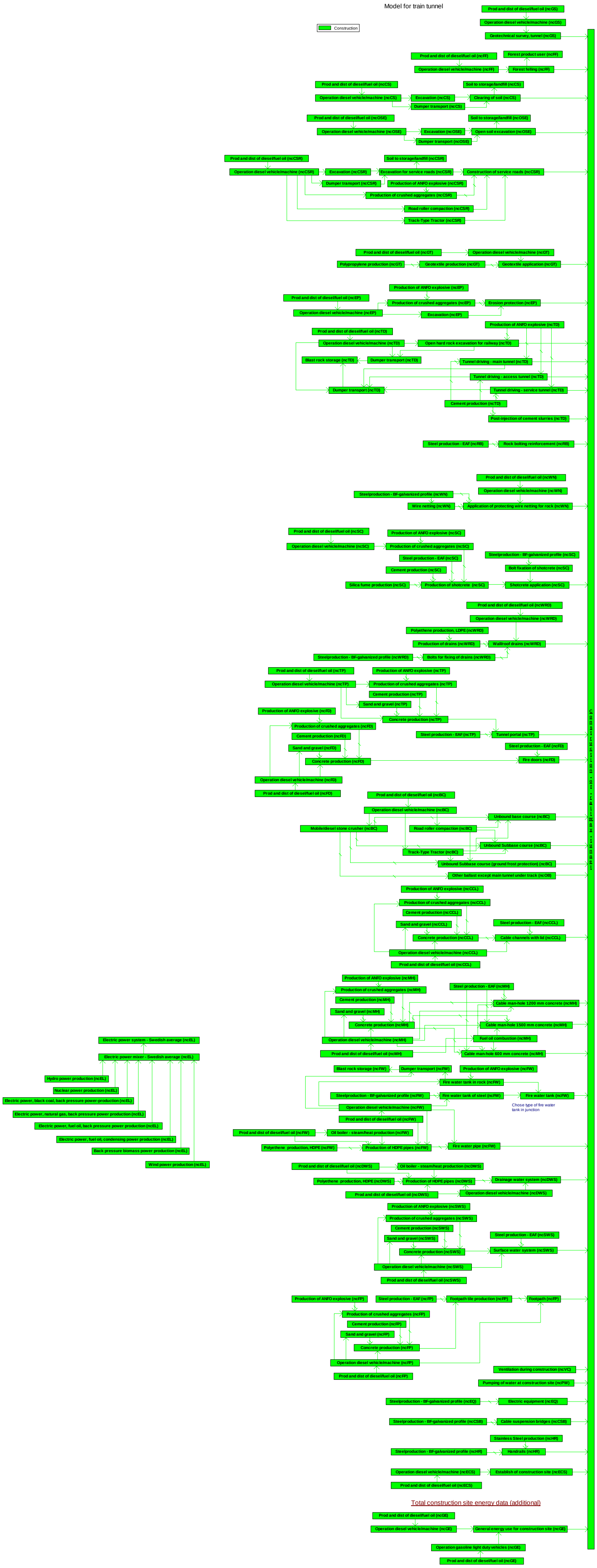

Figure 96 Railway tunnel model structure. Construction part. (Use pdf file and read figure from screen for improved readability).

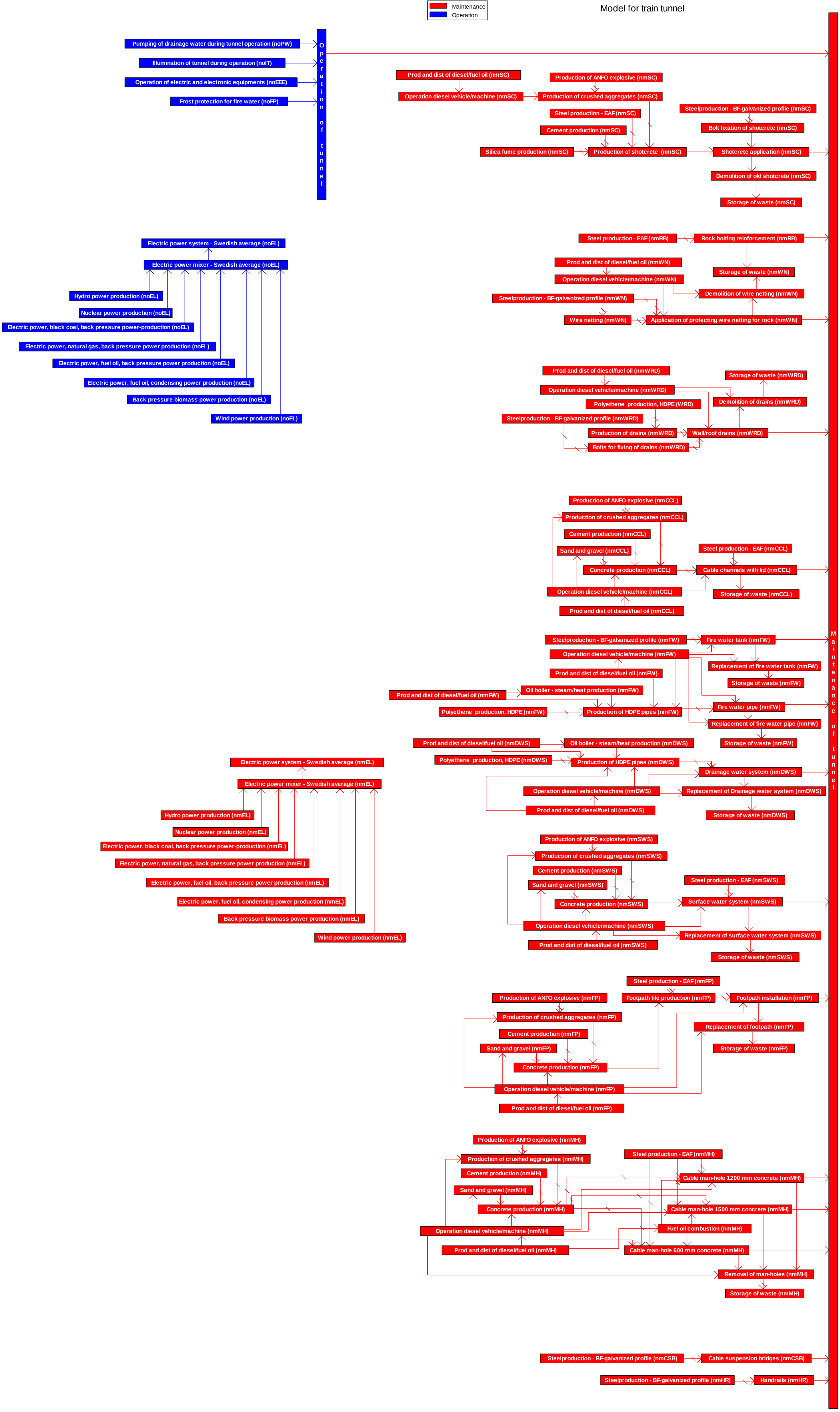

Figure 97 Railway tunnel model structure. Operation and maintenance part. (Use pdf file and read figure from screen for improved readability).

A.5 Railway bridge model

Figure 98 and Figure 99 show the construction, maintenance and operation models of railway bridges. The models are designed to handle different types of bridges but three types are mainly in focus; Concrete portal frame bridges, Steel girder bridges and Concrete beam bridges. In the model, the bridge piers and the bridge superstructures are defined in terms of material and quantity. The bridge foundation works and other excavation works are specified as well as technical equipments on the bridge. For the on-site concreting process, empirical data from different bridge construction projects are used (use of electric power, diesel etc.).

Railway bridge model

Text codes in module names: The text codes are build up of
first code + second code + module code

First letter (small letter) in code describing the model
n = tunnel model
t = track foundation model
s = station and goods handling model
x = track model
w = locomotive, wagon and transport operation model
e = electric power, signal and tele model
b = bridge model

Second letter (small letter) in codes describing part of the model
c = construction
o = operation
m = maintenance

The following module code describing the specific module (activities) for one or a group of modules (capital letters).

Figure 98 Railway bridge model structure. Construction part. (Use pdf file and read figure from screen for improved readability).

Figure 99 Railway bridge model structure. Operation and maintenance part.

A.6 Model of passenger stations and freight terminals

In a railway system, different types of stations are needed for loading, unloading and transfer of goods and passenger. Figure 100 shows the construction, maintenance and operation models of railway passenger stations and freight terminals. The model includes modules for felling of eventual trees, excavation works, production of the station buildings and heating of the station building during operation. Three different heating systems are included in the model; electric power, fuel oil and biomass fuel (wood). In addition, electric power is also used in the stations for general power supply. For the maintenance of the stations, a reconstruction module is used after the lifetime of the station is expired.

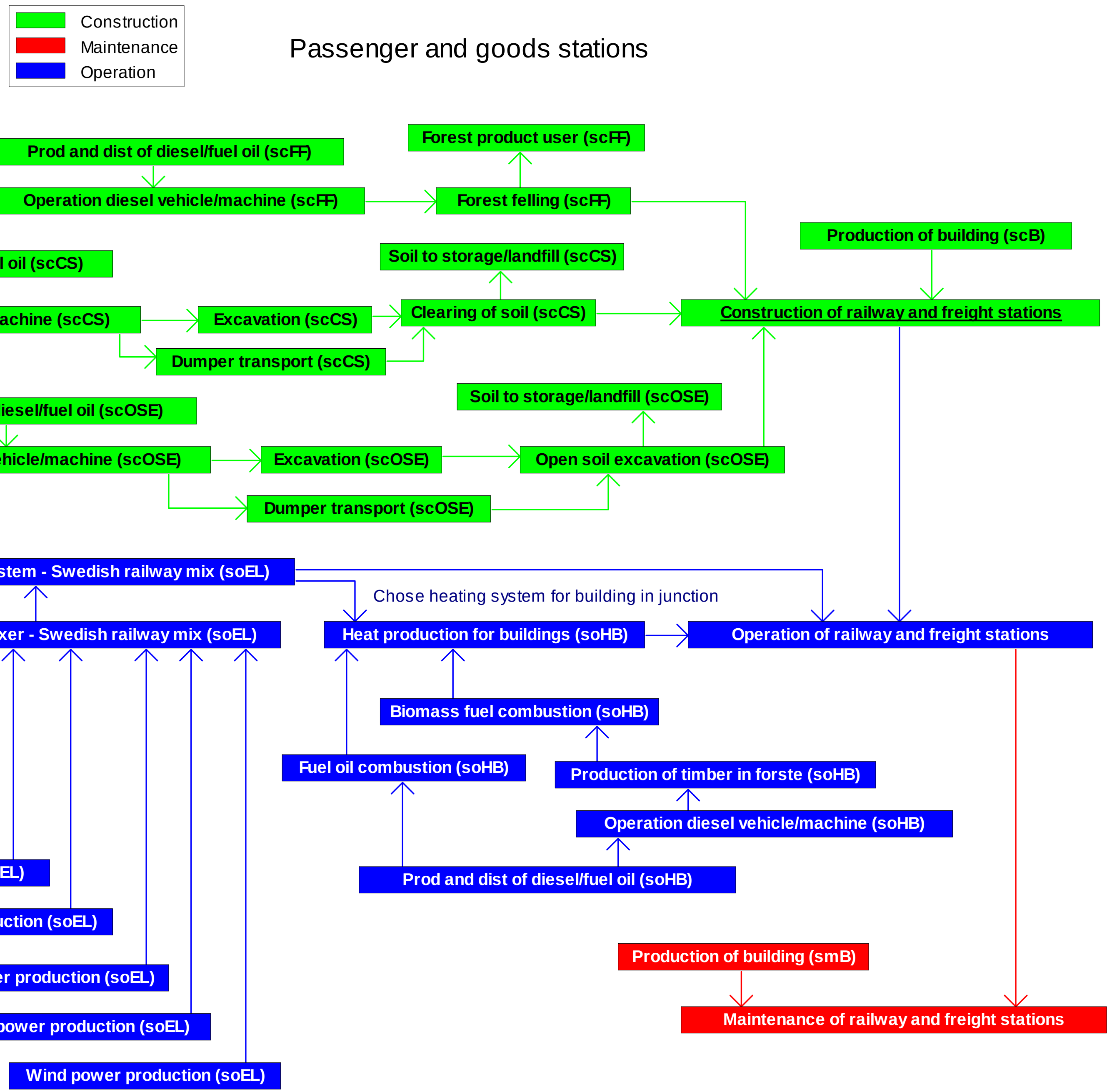

Figure 100 Model structure for railway passenger stations and freight terminals including construction, maintenance and operation.

A.7 Model of passenger and freight trains

In a complete railway transport model, the railway traffic also has to be included in addition to the railway infrastructure. Thus, the railway traffic model has to include both passenger and freight trains and cover a full LCA of the trains including construction of the trains, operations of the trains and maintenance of the trains. Figure 101 shows the construction, maintenance and operation models of passenger and freight trains. An important aspect of train operation and train traffic is the type of energy used for the train operation. In general, two types of energy supply exist; diesel oil and electric power. The model includes for the moment only electric power operation because that is the main energy source in the Swedish railway system. Specific data for the production of the electric power used at the Bothnia Line is used (Green electric power).

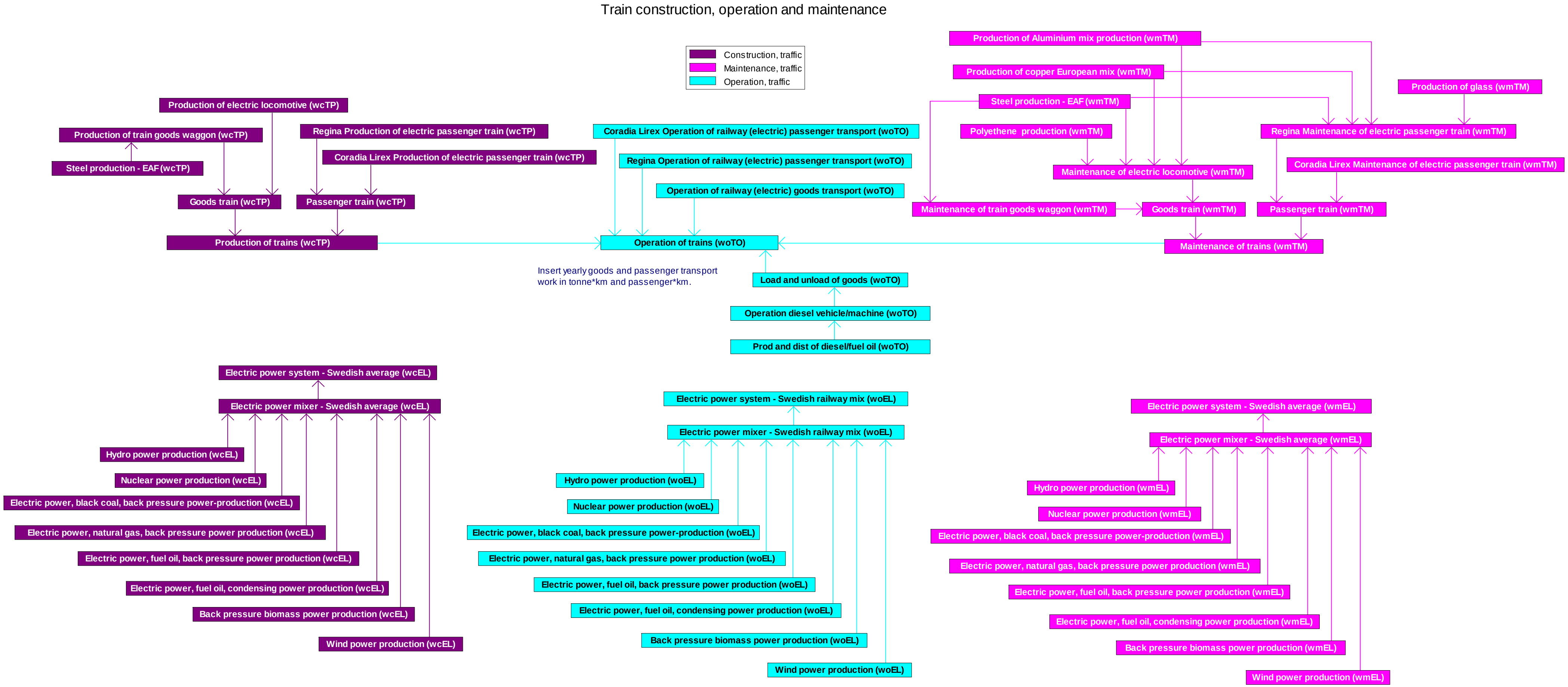

Figure 101 Model structure for passenger and freight trains including construction, maintenance and operation. (Use pdf file and read figure from screen for improved readability).