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Life-Cycle assessment of Future High-speed Rail in Norway

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Acknowledgements

I wrote my master's thesis partly at the university and partly in close connection with the industry sector. It was interesting, motivating and challenging to deal with these two different and complementary perspectives at the same time. I would definitely recommend this bilateral approach, especially in the field of industrial ecology, which is grounded in the industry sector.

I would like to express my gratitude to all the persons who participated, directly or indirectly in the writing of my master's thesis. I would like to thank my supervisor, Professor Edgar Hertwich at NTNU as well as all the staff at MiSA, especially my co-supervisor Johan Pettersen. Then, I would like to thank my family and my friends who were with me in the good but also in the more difficult moments of my studies that started in Switzerland and ended in Norway. Last but not least, this master's thesis is more readable thanks to Moïra who helped me improve the language.

Abstract

The aim of this study is to provide an overview of the core factors for the environmental performance of future Norwegian high-speed rail (HSR) and to study their likely development up to 2050 in a life-cycle assessment (LCA) perspective. The analysis included the infrastructure, rolling stock and operations.

This work was conducted with MiSA, an environmental consulting company based in Trondheim, Norway. MiSA recently completed a life-cycle inventory (LCI) for HSR in Norway. To start with, core factors were chosen through a literature review. The corridor Oslo-Trondheim was then modeled using the new LCI in order to establish a set of the core factors to analyze. The LCA was performed with SimaPro. LCA literature is the preferred source for emissions data. First because results show that emissions must cover life-cycle emissions from fuel, electricity, materials and processing (source-to-wheel). Second, LCA provides guidelines for good practice for environmental accounting and benchmarking of transport alternatives.

Chapter 4 is an investigation of the core factors. Through the study of technical writings for current and future use of HSR in Norway, as well as sensitivity analyses, certain core factors were earmarked to produce detailed scenarios for future use up to 2050.

Cement, steel, XPS, infrastructure, deforestation and the number of passengers per day are core factors. Cement, steel and XPS are the materials that have the most impact. The impact of the infrastructure of future Norwegian HSR is high because the number of passengers and the carbon footprint (CF) of the electricity mix used for operation are low. Norwegian HSR is lacking passengers. A high number of passengers in the Norwegian context constitutes a low number of passengers in other European countries. A high potential for change is to abstract passengers from air travel, which is the most used mode of transport in Norway in 2010. The energy used for operation and the energy per seat-km are not core factors because the electricity mix used for operation has a low CF (166 g CO_2/kWh).

The impact of HSR is reduced on average by 17% by updating the database (scenario updated 2010). The impact is reduced by 50% in a likely future (scenario 2050) by improving the production technology of the materials for the infrastructure and by having more passengers. Finally, the impact is reduced by 60% by, in addition to changes from scenario 2050, setting specific requirement to the suppliers and by having an active yield management (scenario 2050+).

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Masters Thesis

for

Carine Grossrieder
Spring 2011

Life-cycle assessment of future high-speed rail in Norway

Livssyklusvurdering av høyhastighetstog i Norge

Background and objective

Studies that have investigated the environmental performance of regular and high-speed rail have concluded that the treatment of temporal considerations is important for many of the controlling factors, including energy efficiency of whole trains, seat capacity per train and seat utilization. Prospective studies for railway need also consider scenarios for the development of energy supply for rail operation. Most high-speed trains are electric, and the future electricity system therefore becomes a particularly sensitive model decision.

The aim of this project is to provide an overview of important factors that are sensitive to changes over time, and to investigate their importance to life-cycle assessment of high-speed rail in Norway. The work will be conducted at the environmental consulting company MiSA. MiSA is currently establishing a life-cycle inventory for high-speed rail in Norway, as well as the competing long-distance transport alternatives. MiSA's work will be finished by February 1st 2011 and inventories will be made available to the student.

The following questions should be considered in the project work:

1. What are the core factors for the environmental performance of high-speed rail in Norway
2. What is the likely development scenarios for these factors up to 2070
3. Implement the scenarios in a life-cycle assessment of high-speed rail in Norway

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

<u>One – 1</u> complete original of the thesis shall be submitted to the authority that handed out the set subject. (A short summary including the author’s name and the title of the thesis should also be submitted, for use as reference in journals (max. 1 page with double spacing)).
Two – 2 – copies of the thesis shall be submitted to the Department. Upon request, additional copies shall be submitted directly to research advisors/companies. A CD-ROM (Word format or corresponding) containing the thesis, and including the short summary, must also be submitted to the Department of Energy and Process Engineering

Department for Energy and Process Engineering, 11 January 2011

Olav Bolland	Edgar Hertwich
Department Head	Supervisor

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1 INTRODUCTION

Background

Norway is assessing the feasibility – financial costs, social and environmental impacts - of future high-speed rail (HSR). The size of potential market for HSR in Norway is assessed as much smaller than HSR markets already established in other countries such as France and Germany, but similar to that of Sweden (Atkins Ltd 2011). VWI (2006) conducted a feasibility study that shows several advantages for Norwegian HSR. HSR reduces travel times, greenhouse gases (GHG) and exhaust emissions. The accessibility between major cities and regions will increase. HSR transport reduces air transport considerably and will resolve airport capacity problems in the future.

Experiences from other European countries show that the Norwegian context presupposes the following three conditions to achieve a positive result. Firstly, main markets should be concentrated on the major points off demand. In addition, only a few numbers of intermediate stops should be taken in greater communities with sufficient traffic demand. Secondly, planning of infrastructure should aim for single track, where technically possible, for cost optimization. Thirdly, additional regional services should play a feeder role for the high-speed network (VWI 2006).

HSR means running 200 km/h or faster. Infrastructure, rolling stock and operation are part of an integrated concept. Rail has comparable travel times with air traffic and shorter travel times than car traffic in such an integrated system (VWI 2006). New lines need to be built. Their maximum speeds depend on topography and on the settlement structure. For instance in Norway, for an average running speed of about 150 km/h or more to be reached, it would not be possible to have many stops between the major cities. Additionally, new train technology with high power is required for fast acceleration. Usually, the new HSR infrastructure consists of a combination of existing and upgraded infrastructure (VWI 2006). This would be the case in Norway as well (Metier AS 2007).

The figure below shows an estimate of the average number of passengers per day for Norwegian HSR on the left and the expected travel times on the right. The lines Oslo-Bergen and Oslo-Trondheim are the most important connections in Norway for HSR (VWI 2006). This finding is shared by (Atkins Ltd 2011) and supported by international studies that show that high volumes of travel generally produce the best economic / financial case for HSR routes. These two lines are considered to be worth realizing.

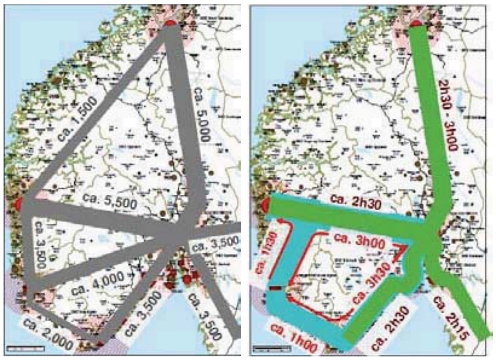

Figure 1-1: Basic network for Norwegian HSR, copied from VWI (2006)

Aim and scope

Previous studies that have investigated the environmental performance of conventional rail and HSR have concluded that the treatment of temporal considerations is important for many of the controlling factors such as the energy efficiency of whole trains, seat capacity per train and seat utilization (Korsmo and Bergsdal 2010; UIC 2009; Network Rail 2010). Infrastructure as well plays a key role. Especially when the electricity mix used for operation has a low carbon footprint (CF) (Stripple and Uppenberg 2010; UIC 2009), which is the case in Norway. The materials used for the construction phase are worth a deeper study (Korsmo and Bergsdal 2010).

The development of the energy supply for rail operation should also be included. Most HSR are operated with electricity. The future electrical system therefore becomes a particularly sensitive model decision.

This work is conducted with MiSA[1], an environmental consulting company. MiSA has recently completed a life-cycle inventory (LCI) for HSR in Norway, as well as the competing long-distance transport alternatives. This LCI for HSR is used in this project. The life-cycle assessment (LCA) is performed with SimaPro[2]. LCA literature is the preferred source for emissions data. First because results show that emissions must cover life-cycle emissions (source-to-wheel) from fuel, electricity, material and processing. Second, LCA provides guidelines for good practice for environmental accounting and benchmarking of transport alternatives (Svåna 2011). This LCA study will give a comprehensive picture of the reality, even if reality is simplified and distorted to a certain extent.

The aim of this study is not to compare HSR with other means of transportation, but rather to find out core factors for Norwegian HSR and to draw their likely development in a 60 years perspective in an LCA point of view. To do so, the corridor investigated in this study is Oslo-Trondheim. HSR will improve journey times from 6h45 currently to 2h45. If a new separate HSR line is built, this line is expected to attract around 4920 passengers per day in 2025 (Atkins Ltd 2011).

Research questions

The following questions are answered in this project:

1. What are the core factors for the environmental performance of HSR in Norway?
2. What are the likely development scenarios for these factors up to 2070?
3. What are the results of the implementation of the scenarios in an LCA of HSR in Norway?

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[1] www.misa.no

[2] SimaPro is the most widely used LCA software.

Outline

1. *What are the core factors for the environmental performance of HSR in Norway?*

Core factors for the environmental performance of HSR in Norway are found out of the literature in chapter 2, and out of an LCA model called HSR-LCA model in a chapter 3. Chapter 2 consists of a literature review. In chapter 3, HSR-LCA, the model developed in this project is explained. HSR-LCA consists of three main parts: infrastructure, rolling stock and operation. Infrastructure and rolling stock are further divided into construction, maintenance and waste/end-of-life. Operation consists of two parts: operation of rolling stock and operation of infrastructure.

In chapter 4, some of the core factors found in chapter 2 and 3 are investigated. In section 4.1, focus is put on elements from the background system (cement, steel and XPS). In section 4.2, elements from the foreground system are examined (electricity mixes, electricity required to run a train, number of passengers per day, seat capacity per train, load factor. Chapter 4 is organized in such a way that first, theory on the element is given. Additionally, for some elements, a sensitivity analysis is conducted. To make it clearer for the readers, sensitivity analysis are put in blue boxes. Sensitivity analyses are conducted on:

Table 1-1: List of the sensitivity analyses conducted

Cement	Use of secondary material for clinker production
	Use of secondary fuel for clinker production
Steel	Energy efficiency
	Use of scrap
	Use of common steel for rails
XPS	Blowing agent
Energy	Energy per pkm
	Electricity mix used for operation

The sensitivity analyses conducted were time-consuming. For instance, for steel production, to change the energy efficiency, a coefficient has been introduced to reduce all the energy sources. In SimaPro, steel production is organized in such a way that each process consists of a single box. Original processes from the database cannot be modified. They have to be copied and linked together again. The same has been done for cement production. Direct emissions have also been adjusted by introducing parameters. Please see appendix 2: “List of the parameters” for more details.

Note: At the beginning of chapter 2, 3 and 4 a short summary of the chapter is given. The sensitivity analyses are in blue boxes.

2. *What are the likely development scenarios for these factors up to 2070?*

The likely development scenarios for these factors are drawn up to 2050 and not 2070. This change of 20 years is due to the literature that mainly covers the time span up to 2050. The likely development of these factors is based on chapter 4.

3. *What are the results of the implementation of the scenarios in an LCA of HSR in Norway?*

The scenarios are implemented and the results are given in chapter 5.

1.1 LIFE-CYCLE ASSESSMENT

The ISO14040:2006 (ISO 2006a) standard on LCA gives the framework and principles on what LCA is and why it should be applied. Details on the techniques, requirements and guidelines on LCA are found in the ISO14044:2006 (ISO 2006b).

According to ISO14040:2006 life cycle is the *"consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal"* and Life cycle assessment (LCA) the *"compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle".* LCA consists of four steps (ISO 2006a, 2006b):

1. Definition of goal, scope and functional unit
   "The goal and scope of an LCA shall be clearly defined and shall be consistent with the intended application. Due to the iterative nature of LCA, the scope may have to be refined during the study." "The functional unit is the quantified performance of a product system for use as a reference unit." *(ISO 2006b)*

2. Life cycle inventory (LCI)
   "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" *(ISO 2006a)*

3. Life cycle impact assessment (LCIA)
   "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 produce " *(ISO 2006a)*

4. Interpretation of the study
   "phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" *(ISO 2006a)*

LCI is the most demanding task in performing LCAs. Data is collected for the background and foreground system. Background data is data for generic materials, energy, materials and waste management system. Usually, 80% of data is readily available in databases. Foreground data refers to specific data such as a particular product system or a particular specialized production system. In many cases, it has to be collected from companies. In the LCIA, the environmental relevance of all inputs and outputs is assessed. Usually, inventory results of an LCA contain hundreds of different emissions that have to be assigned to impact categories. For instance, CO_2 and CH_4 are both assigned to the impact category "Global Warming". SO_2 and NH_3 are assigned to "Acidification". Emissions are weighted through the use of characterization factors. For example, in a 100 years perspective, 1 kg

CH_4 contributes 25 times more to global warming than 1 kg CO_2. The impact category “Global Warming” being expressed in CO_2 equivalents, the characterization factor is 1 for CO_2 and 25 for CH_4. A final and optional step consists of the normalization[3] of the results in order to show to what extent an impact category has a significant contribution to the overall environmental problem. The functional unit or unit of comparison makes it possible to compare products with different performance characteristics. For instance, A is a milk carton to be used only once and B a returnable milk bottle that can be used ten or more times. If the goal is the study of milk packaging systems, A and B cannot be compared directly. A more appropriate approach would be to compare ways of packaging in order to deliver 1000 liters of milk (Pré Consultants 2008).

Important fields of applications of LCA are packaging and packaging materials, energy, building materials, detergent and other cleaning systems, TVs and computer systems or food (from traditional and organic culture) (Heijungs 2007).

For more details on LCA mathematics, please see Appendix 1: “LCA Mathematics”.

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[3] Normalization is done by dividing the impact category by a normal value. The most common procedure to determine the normal value is the determination of the impact category indicators for a region during one year. If desired, the results can be divided further up by the number of inhabitants of a region.

2 CORE FACTORS FOR THE ENVIRONMENTAL PERFORMANCE OF HSR IN THE LITERATURE

Core factors for the environmental performance of HSR are found in the literature. A total of seven studies are investigated. The first three are directly related to Norwegian HSR (Svånå 2011, Korsmo and Bergsdal 2010, Schlaupitz 2008), the fourth one to Swedish HSR (Stripple and Uppenberg 2010), the fifth one to European HSR (UIC 2009) and the sixth one to German HSR (Rozycki et al. 2003). The last one compares conventional rail with HSR (Network Rail 2010).

The core factors for the environmental performance of future Norwegian HSR are first presented in the table below. The studies investigated are presented into more detail after the summarizing table.

Table 2-1: Core factors in the literature

Background system	References
Share of infrastructure on a system level	Svånå (2011), Korsmo and Bergsdal (2010), Schlaupitz (2008), Stripple and Uppenberg (2010), UIC (2009), Rozycki et al. (2003), Network Rail (2010)
Construction phase of infrastructure	Svånå (2011), Korsmo and Bergsdal (2010), Stripple and Uppenberg (2010)
Production of rails	Stripple and Uppenberg (2010)
Steel	Korsmo and Bergsdal (2010), Schlaupitz (2008), Stripple and Uppenberg (2010), Rozycki et al. (2003), Network Rail (2010),
Cement	Korsmo and Bergsdal (2010), Schlaupitz (2008), Stripple and Uppenberg (2010), Rozycki et al. (2003), Network Rail (2010)
XPS	Korsmo and Bergsdal (2010)
Use of more renewable energy in the steel/cement production process	Stripple and Uppenberg (2010)
Use of more recycled steel/cement	Stripple and Uppenberg (2010)
Deforestation	Svånå (2011), Schlaupitz (2008), Stripple and Uppenberg (2010)
Foreground system	**References**
Component based model	Svånå (2011), Korsmo and Bergsdal (2010), UIC (2009)
Electricity mixes	Svånå (2011), Schlaupitz (2008), Stripple and Uppenberg (2010), UIC (2009), Rozycki et al. (2003), Network Rail (2010)
Passengers per train	Svånå (2011), Schlaupitz (2008), UIC (2009), Network Rail (2010)
Traction energy	Rozycki et al. (2003)
Seat occupancy	Svånå (2011), Schlaupitz (2008), UIC (2009); Network Rail 2010
Improving maintenance to increase lifetime of components and thus, decrease emissions	Stripple and Uppenberg (2010)
Freight transport	Schlaupitz (2008)

1. **A Methodology for Environmental Assessment - Norwegian High Speed Railway Project Phase 2. 2011. Asplan Viak, MiSA, VWI, and Brekke Strand.**
   Norway

The Norwegian Rail Administration hired Asplan Viak AS to conduct the project "Environmental analyses", as part of Phase 2 of the assessment of future Norwegian HSR. Asplan Viak took as partners MiSA, Verkehrswissenschaftliches Institut Stuttgart GmbH (VWI Stuttgart) and Brekke & Strand Akustikk AS. This project was supervised by Siv. ing Randi Birgitte Svånå.

The report is divided into four subjects:

- Subject 1 – Landscape analyses (Asplan Viak)
- Subject 2 – Environmental intervention effects (Asplan Viak)
- Subject 3 – Effects on noise (Brekke & Strand Akustikk AS, VWI)
- Subject 4 – Assessment of climate related environmental effects (MiSA)

Subject 4 only is of interest for this master thesis. The aim of subject 4 is *"to describe the approach to calculate the temporal distribution of emissions of carbon dioxide equivalents (CO2e), as resulting from development or non-development of high speed rail (HSR) concepts for passenger and freight transport in Norway."*

To do so, a component based inventory was developed by MiSA. This modular approach provides the flexibility for later adjustments and refinements for implementation in Phase 3. The composition of the corridors and the technologies for railway infrastructure and rolling stock can be adjusted as well. Modules are developed for all modes of transportation; rail, road and air. The goal is to compare HSR with alternative mode of transport. Final calculation for the corridor alternatives will be carried out in phase 3.

This master thesis is based on the component model developed by MiSA.

2. **Miljøbudsjett for Follobanen. 2010. Jernbaneverket Utbygging**
   Norway

Korsmo and Bergsdal (2010) conduct an LCA on the new double-track line, Follobanen, from Oslo to Ski. The performed LCA includes the compilation and quantification of input factors and emissions. It includes the construction, operation/maintenance and waste/disposal for a computation period of 60 years. The LCA of infrastructure represents a complex model with many input factors and processes. The LCA has been computed with SimaPro. The data for the background system comes from the Ecoinvent-database while the data for the foreground are compiled by the authors.

This HSR line, Follobanen, has three specificities. Firstly, 95% of the line will consist of a deep tunnel. Secondly, the tunnel will have a high proportion of shotcrete (betonginjisering) concrete in the mountains. Finally, the open tracks have extensive structures concentrated on short stretches.

According to the Product Category Rules (PCR), the lifetime of Follobanen and all of its components is set to 60 years. This leads to overestimations of the components that have longer lifetime, such as bridges and tunnels. On the other hand, the impacts of components with shorter lifetimes are underestimated.

The data for the foreground used for this master project are taken from Follobanen. Additionally, scaling coefficient to switch from double-tracks tunnels and bridges to one-track tunnels and bridges were used. No scaling coefficient for open sections was used, since double-track open section is used as well in this master thesis.

The LCA is structured as followed:

Level 1: Track options
- Alternative 1: 1-tube tunnel (1-løpstunnel) , with double track
- Alternative 2: 2-tubes tunnel (2-løpstunnel), with 1 track each

Level 2: Life cycle phase
- Construction
- Maintenance
- Waste from maintenance
- Disposal after end-of-life

Level 3: Track stretches
- Tunnel stretches
- Arrival to Ski

Level 4: Components
- Open track
- Structures
- Components of the tunnel
- Railway techniques (incl. technique installations)

The results for level 1 show that the tunnel option with two tubes has the highest impact. Most emissions are related to their construction. For level 2, it is the construction and the maintenance which are allocated 90% of the emissions in all impact categories.

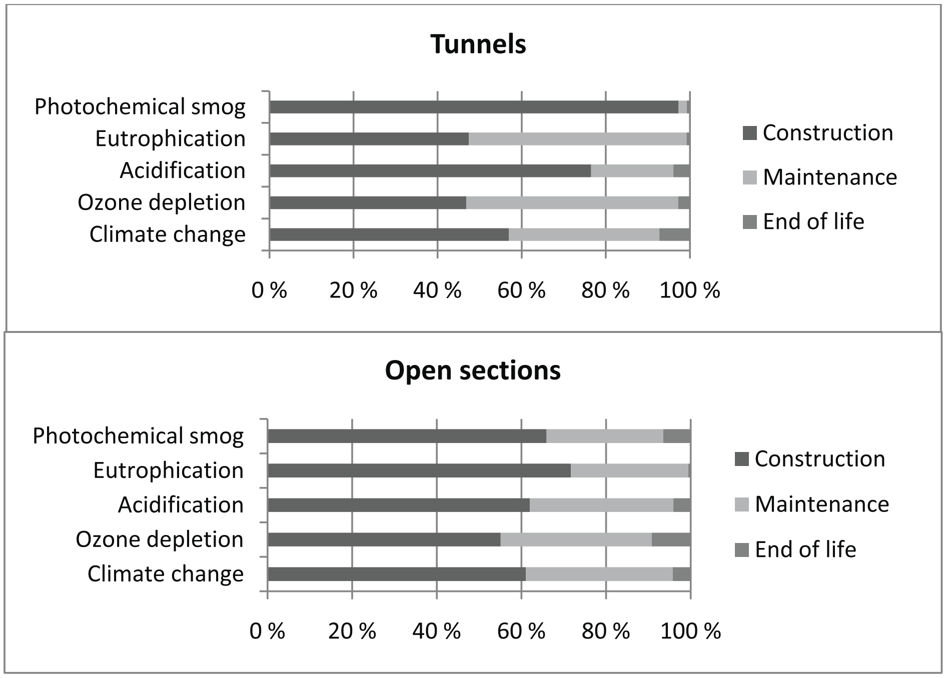

Figure 2-1: Follobanen - Life-cycle phase

On level 3, it is the tunnel stretches that clearly dominate. On a component level (level 4), it is the components of the tunnel that dominates. Steel, cement and concrete represent 75% of the climate gas emissions. Steel stands for 85% of the emissions for eutrophication. Extruded polystyrene foam (XPS) is allocated 80% of the emissions of ozone depletion. The production and combustion of diesel is accounted for 12% of the emissions of photochemical smog.

The table below shows the results for infrastructure construction.

Table 2-2: Follobanen - Infrastructure construction (kg CO_2 eq per m*year)

Lifetime = 60 years		
Open section (double track)	**Tunnel (double track)**	
	1 tube	2 tubes
134	210	265

3. **Energi- og klimakonsekvenser av moderne transportsystemer-Effekter ved bygging av høyhastighetsbaner i Norge. 2008. Norges Naturvernforbund**
   Norway

Schlaupitz (2008) completed a study for GHG and energy for Norwegian HSR. The study does certainly present one of the technically most comprehensive inventories for infrastructure of Norwegian HSR, based on international studies. The lifetime is set to 100 years. This is to take into account the changes in electricity mixes and changes in technology. He assumes a decrease in energy consumption up to 2020 and 2030 due to an improvement in energy efficiency. He also addresses the issue of deforestation in terms of carbon release from trees and from the soil. Finally, he compares infrastructures of other modes of transports such as roads and airports with the infrastructure of HSR.

He found that the construction of a double track line would not increase the GHG emission by more than 25%. He thus recommends the building of a double track line so as to make the most profit from the infrastructure. This conclusion is quite surprising and does not match the findings of HSR-LCA, where emissions increase by 70% from single to double track. Nevertheless, there are uncertainties related to the scaling of the single track to double tracks when it comes to the use of inputs (innsatsfaktorer) for construction and the maintenance (Korsmo and Bergsdal 2010). In this project, I also used scaling factors that give higher differences from one-track to double-track.

The table below shows the results for infrastructure construction.

Table 2-3: Schlaupitz - Infrastructure construction (kg CO_2 eq per m*year)

Lifetime = 100 years					
Open section		**Tunnel**		**Bridge**	
single	double	single	double	single	double
18	22	59	72	90	125

4. **Life cycle assessment of railways and rail transports. 2010. Swedish Environmental Research Institute (IVL)**
   Sweden

Stripple and Uppenberg (2010) have used an LCA model to address the environmental performance of the Botnia Line, in the north of Sweden. This line is one-track. The results have then been used to develop Environmental Product Declarations (EPDs). For passengers transport, deforestation, infrastructure construction work and infrastructure material contribute most significantly to climate impact. The calculation period is set to 60 years. The LCA software used is KCL-ECO

The entire railway system has been divided up into 7 general railway component models:

1. Railway track foundation model
2. Railway track model
3. Railway electric power and control system model
4. Railway tunnel model
5. Railway bridge model
6. Railway passenger station and freight station and freight terminal model
7. Passenger and freight train model including train operation

In HSR-LCA, the five first general railway component models are grouped into 3 entities: track, tunnel and bridge. Track consist of 1, 2 and 3; tunnel of 2, 3 and 4; bridge of 2 and 5. Stations (6) are not included in HSR-LCA. Train and operation are each one entity in HSR-LCA. Train includes the construction, maintenance and end-of-life of rolling stock. Operation includes operation of train and infrastructure.

The table below shows the results for infrastructure construction.

Table 2-4: Botnia Line - Infrastructure construction (kg CO_2 eq per m*year)

<table>
<tr><td colspan="8">Lifetime = 100 years</td></tr>
<tr><td rowspan="3">Botnia Line</td><td rowspan="2">Track foundation (1)</td><td rowspan="2">Track (2)</td><td rowspan="2">Electric power and control system (3)</td><td colspan="2">Tunnel (4)</td><td rowspan="2">Bridge (5)</td><td rowspan="2">Station (6)</td></tr>
<tr><td>short <1000m</td><td>long >1000m</td></tr>
<tr><td>15</td><td>6</td><td>17</td><td>25</td><td>166</td><td>45</td><td>4</td></tr>
<tr><td rowspan="3">HSR-LCA</td><td colspan="3" rowspan="2">Open section (1+2+3)</td><td colspan="2">Tunnel (2+3+4)</td><td colspan="2" rowspan="2">Bridge (2+5)</td></tr>
<tr><td>short <1000m</td><td>long >1000m</td></tr>
<tr><td colspan="3">38</td><td>48</td><td>189</td><td colspan="2">51</td></tr>
</table>

LCI data has been obtained from different sources (literature, from single plants and processes in operation, from equipment supplier, from legislation and directives). As long as possible, specific electric power was used for the different processes. For instance, a Swedish electric power production mix has been used for general use. For operation (train and infrastructure), a “green” electric power production mix has been used because the Swedish Rail Administration buys that type of electric power in accordance to its environmental strategy. In 2008, “green” meant 99,2% hydropower and 0,8% biomass fuel based.

Deforestation contributes to up to 20% of climate change. The Botnia Line has almost entirely been built on forest land. These forest areas have been cut down and transformed into railway areas. These changes are univocal and trees will not be replanted. Therefore, CO_2 emissions arising from the cut down of biomass are accounted for as emissions of fossil CO_2 which contribute to climate change. In Norway, forest area consists of almost 40% of the national landscape. Furthermore, mountainous areas consist of 44% of the territory, and wetlands, lakes and glaciers of 13% (SSB Statistisk sentralbyrå 2009). There is therefore high probability that trees will be cut. Deforestation should thus be addressed for Norwegian HSR also, in a way or another.

Infrastructure construction work has significant contributions (emissions from machines like excavators, trucks, etc) and limited contributions (material transport, infrastructure and train operations). Raw material acquisition and production of materials used for construction of infrastructure are crucial contributors to environmental impact categories. Steel accounts for 43% of the total emissions and cement for 32%.

Potentials for reducing climate impacts: For vehicle production, improvement potentials are found in designing vehicles in a way to transport more per ton and in the use of materials with lower emissions of CO_2 per mass unit. For deforestation, locations out of forest areas could be chosen. However, given the Norwegian topology, the potential here is not very high. Protected areas have also to be considered in the balance. For construction machines, there is a minor potential in the planning and the management of vehicle usage and a major one in the use of more fuel efficient vehicles, and the shift to renewable energy such as biofuels or electricity.

Potentials to reduce CO_2 emissions embedded in steel and cement:

- To reduce the amount of steel/cement needed per km railway/tunnel/bridge and time unit. This can be achieved by the use of rail profiles with lower steel content per meter, and/or by maximizing the lifetime by improving the maintenance strategy.
- To reduce the emissions of CO_2 per tonne of steel/cement. This could be done by using more renewable energy in the steel/cement production process and/or by using more recycled steel/cement. These measures call for management routines and procurements requirements.

5. **Carbon Footprint of HSR infrastructure (Pre-Study) - Methodology and application of HSR operation of European Railways. 2009. UIC International Union of Railways**
   Europe

UIC (2009) developed a methodology to account for the infrastructure of high-speed passenger traffic. The transport system is modeled according to the components of operation, rolling stock and track system. They developed a calculator with individual accessible options such as electricity mix, share of bridges/tunnels, average numbers trains running one single track a day and load factor. They drew several conclusions:

- The track system mainly determines the carbon footprint (CF) of the infrastructure. That is, the higher the share of tunnels/bridges, the higher the CF.
- The share of infrastructure is not negligible. It ranges from 31% to 85%, depending on the electricity mix used for operation, the traffic on the rail network and the share of tunnels and bridges.
- The CF of the transport system depends on the number of trains per day per track. For instance, the CF of an infrastructure is of 10.87 g CO_2 per m with 25 trains per day on a single track while it is of 3.1 g CO_2 per m with 90 trains per day on single track.
- The share of infrastructure increases with a decrease in the CF of the electricity mix.

The table below shows the results for infrastructure construction.

Table 2-5: UIC (2009) - Infrastructure construction (kg CO_2 eq per m*year)

<table>
<tr><td colspan="8">Lifetime = 100 years</td></tr>
<tr><td rowspan="2">UIC</td><td>Earth works for common track (1)</td><td>Double railway track (2)</td><td>Railway track, switch (3)</td><td>Telecommunications and signalization equipments (4)</td><td>Energy requirements (5)</td><td>Tunnel (6)</td><td>Bridge (7)</td></tr>
<tr><td>9</td><td>22</td><td>20</td><td>1</td><td>2</td><td>79</td><td>186</td></tr>
<tr><td rowspan="2">HSR-LCA</td><td colspan="2">Open section (1+2+3+4+5)</td><td colspan="2">Tunnel (2+4+5+6)</td><td colspan="3">Bridge (2+5+7)</td></tr>
<tr><td colspan="2">53</td><td colspan="2">104</td><td colspan="3">210</td></tr>
</table>

6. Ecology Profile of the German HSR Passenger Transport System, ICE. 2003. Rozycki, Koeser and Schwarz

Germany

CO_2 emissions for the ICE transport system are equivalent to 69.4 kg per ICE km. This amount is dominated by the energy used for operation (rail electricity). For passenger rail transport, rail infrastructure is not allocated more than 15% of the overall CO_2 emissions. The construction phase dominates the life cycle of most rail infrastructure components. The electricity mix consists of 63% fossil fuels (pit coal, lignite), 30% nuclear and 7% renewable (hydro, wind, photovoltaic). This underlines the findings by UIC (2009), that conclude that the share of infrastructure decreases with a increase in the CF of the electricity mix.

From their sensitivity analysis, the following factors become evident to play a key role for the ecological footprint on the transport system:

- Train capacity utilization (passenger per train)
- Traction energy (consumption, diesel or electricity drive)
- Train load (e.g. trains per day) on the track
- The share of tunnels

7. Comparing environmental impact of conventional and high speed rail. 2010. Network Rail

United Kingdoms

Performances of conventional rail are compared with HSR rolling stock likely to be put into services in the 2025-2030 timeframe. Nowadays, the energy for train in England is based on diesel. The following factors affecting comparisons of energy consumption and GHG emissions are highlighted:

- **Direct performance (energy consumption) of rail rolling stock**: weight reduction, aerodynamic improvements, improvements in the overall electrical efficiency (including regenerative braking systems)
- **Seating occupancy levels and service frequency**: HSR has higher energy uses than conventional rail. This additional energy use is counter-balanced by their higher occupancy level.
- **Direct and indirect GHG emissions from electricity production:** In the timeframe the new rolling stock will be in use, significant decarbonisation of electricity in the UK is expected
- **Indirect emissions resulting from the construction, maintenance and decommissioning of rolling stock:** The significance of this parameter will increase in the future as electricity generation decarbonizes.
- **Energy consumption/emission resulting from construction and use of new rail:** The experts have not identified differences concerning the infrastructure of the conventional rail and HSR. Because the emissions will be spread over a higher number of passengers for similar routes, the embedded infrastructure emissions will be lower per passenger km.

3 CORE FACTORS FOR THE ENVIRONMENTAL PERFORMANCE OF HSR OUT OF THE MODEL

Core factors for the environmental performance of HSR were found in the literature in chapter 2. In this chapter, core factors are found out of a LCA model. The data for the background system comes from the Ecoinvent-database version 2.2 while the data for the foreground is based on the LCI currently being established by MiSA for HSR in Norway. The LCA has been computed with SimaPro.

In section 3.1, the general framework for LCA of HSR is described. In section 3.2, the model is applied to a specific case, the corridor Oslo-Trondheim, also called HSR-LCA. The Oslo-Trondheim HSR corridor consists of 83% open sections, 15% tunnels and 2% bridges (Metier AS 2007). Six categories are investigated: climate change, ozone depletion, human toxicity, terrestrial acidification, freshwater eutrophication and water depletion.

The table below summarizes the results found in this chapter.

Table 3-1: Core factors from the model

		Impact categories					
		Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
Background system	Steel	x	x	x	x	x	x
	Cement	x					
	Diesel	x	x		x		
	XPS		x				
	Copper			x		x	
	Blasting				x		
	Gravel						x
Foreground system	Share of infrastructure on a system level						
	Construction phase of infrastructure						
	Open sections						
	Passengers per train						

3.1 DESCRIPTION OF HIGH-SPEED RAIL MODELS

This section gives a brief description of HSR models. For more details, please see “*A Methodology for Environmental Assessment - Norwegian High Speed Railway Project Phase 2*” by Asplan Viak, MiSA, VWI, and Brekke Strand (2011) and ”*Miljøbudsjett for Follobanen” by* Korsmo, A.-R. and H. Bergsdal. (2010).

HSR models consist of three main parts: infrastructure, rolling stock and operation.

- **Infrastructure**: A complete assessment of the climate-related emissions for HSR must include the construction of infrastructure components. This calls for a component-based emissions model that distinguishes between tunnels, bridges and open sections since they have different carbon footprints. In this type of model, core parameters may be possible to change to fit corridor settings. Sensitivity analysis for controlling parameter is possible. Furthermore, stakeholders can investigate several assumptions for market, infrastructure use and future electricity supply (Svåvå 2011).
- **Rolling stock:** Life-cycle of rolling stock is treated in a simple manner because infrastructure construction is much more important in a term of GHG emissions (ibid).
- **Operation:** Energy use to run the trains in terms of per seat or per passenger transport is modeled in accordance with the scope of this study, in line with specific train system properties regarding train system, topography and temporal issues (Svåvå 2011).

Functional unit

The generic functional unit for HSR assessment is *a transport service to meet the total transport demand*. In the case of this project, the FU is *a transport service to meet the total transport demand from Oslo to Trondheim*.

Background and foreground systems

Background data is used for generic materials (e.g. cement or steel), energy, transport and waste management systems. Typically, it can be found in databases and literature. The background systems comprises of all inputs of energy, fuel, services and materials. All the inputs are modeled using the Ecoinvent[4] LCA database version 2.2, with the latest updates in May 2010.

Foreground data refers to specific data needed to model the system. It is typically data that describes a specific product system or a specific specialized production system (Pré Consultants 2008).The foreground system of HSR models consists of (Svånå 2011):

- Energy use for operation
- Corridor-specific factors for occupancy and load factors
- Composition of infrastructure from major components

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[4] Ecoinvent is one of the most comprehensive international LCI databases with more than 4’000 LCI datasets in the areas of agriculture, energy supply, transport, biofuels and biomaterials, bulk and speciality chemicals, construction materials, packaging materials, basic and precious metals, metals processing, ICT and electronics as well as waste treatment.

Land use and land use changes (LULUC)

LULUC generate gas emissions that are not covered in this report. These emissions are generated through deforestation and release of soil carbon from the clearing of land required for new HSR corridors. Indirect LULUC emissions may also be caused by drainage of wetlands through change of water ways or other. Two previous studies have estimated GHG emissions from clearing vegetation on the track line. Stripple and Uppenberg (2010) estimate the GHG emissions from deforestation to be 20% of the total emissions, soil carbon not included. Schlaupitz (2008) finds a much lower contributions of GHG emissions from deforestation and soil carbon release resulting from a simpler estimation. Soil carbon and standing forest are both sources for climate change potentials from biogenic materials (Svånå 2011). One way to evaluate emissions from LULUC could be to use generic factors, separating between forest, grasslands, croplands and wetlands developed by (Müller-Wenk and Brandão 2010). Another way would be to systematically implement the vegetation and soil carbon in a geographic information system (GIS) model (Svånå 2011).

Service inputs

Service inputs such as insurance, banking and others may be significant for the environmental footprint of other transportations systems such as private cars or airplanes that are compared to HSR (Chester and Horvath 2010). Nevertheless, they are generally left out of most transport studies. Service inputs could be systematically implemented through the use of input-output methodologies.

3.2 CASE STUDY: OSLO-TRONDHEIM

LCA model for HSR has been applied to the corridor Oslo-Trondheim. The case study is called HSR-LCA. HSR-LCA consists of three main parts: infrastructure, rolling stock and operation. The lifetime of HSR-LCA is set to 60 years.

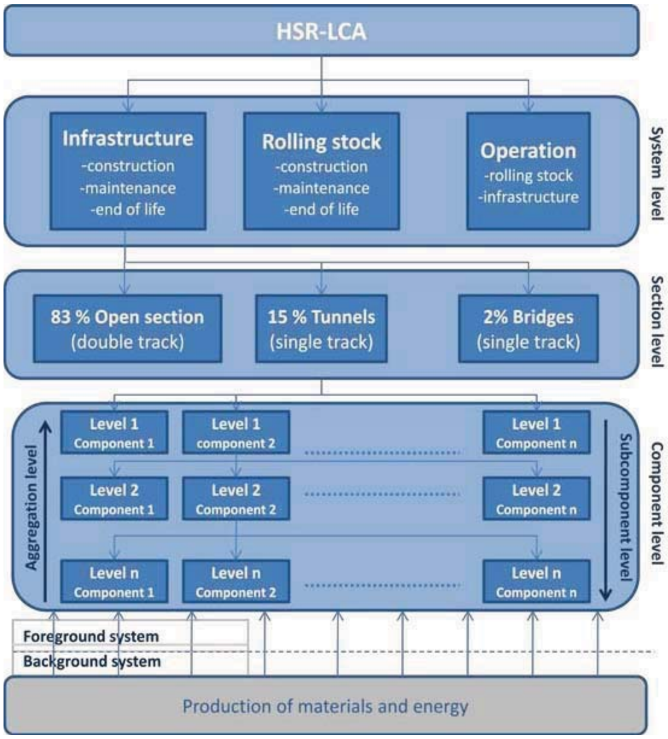

Figure 3-1: HSR-LCA - Overview

Infrastructure

Numbers for the amount of open sections, tunnels and bridges are based on the report by Metier AS (2007). Oslo-Trondheim has the highest number of open section and the lowest number of tunnels and bridges. The total amount of km is equal to 486 (403 km of open section, 72 km of tunnels and 11 km of bridges).

Processes from the foreground system are modeled using the LCI compiled by MiSA. More precisely, open sections and tunnels are based on the LCI for Follobanen developed by Korsmo and Bergsdal (2010) while bridges are based on the new LCI developed by MiSA. Coefficients to switch from double-track tunnels and bridges to single-track tunnels and bridges were used. A coefficient of 0,8 was used to switch from double track tunnel (2 tubes with 1 track in each). A coefficient of 0,6 was used to switch from double track bridge to single track bridge. I have set these two coefficients based on my observations of the current Norwegian railway network. Open sections were not modified since they already had a double-track. I have also added maintenance for bridges. I added 40% of the materials used for construction. The 40% is based on Korsmo and Bergsdal (2010) who found numbers for maintenance of tunnels and open section in this range. The maintenance of bridge requires further investigation. However, bridges consisting of 2% of the line HSR-LCA, this point was not given the most attention.

Processes from the background system (materials used for the infrastructure) are modeled using the Ecoinvent database which refers to European conditions, and thus to European electricity mixes. The CF is of 531 g CO_2 eq per kWh.

Rolling stock

To determine the amount of train required for the calculation period of 60 years, I have assumed the following schedule: one train is running every hour from 6am to 12pm, from Oslo to Trondheim and from Trondheim to Oslo. This means a total of 38 journeys per day. The distance of the journey is 486 km (Metier AS 2007). The lifetime of a train (15’000’000 km) is used as denominator to find the final number of train required to carry all the passengers for the period of time of 60 years.

$$\frac{38\frac{journeys}{day}*486\frac{km}{journey}*365\frac{day}{year}*60year}{15'000'000\frac{km}{train}} = 27\ trains \tag{1}$$

Two trains are added extra for any cases of reparation or emergency leading to a total of 29 trains.

The train used from the database is the ICE from Ecoinvent version 2.2. The technology used is a mix of the ICE 1 (40%) and the ICE 2 (60%). I modified it to match the technology used for the ICE 3. That is, I switched aluminium used for ICE production from primary to secondary and I increased the number of seats from 309 (Spielmann et al. 2007) to 650 to match the weight per seat of the ICE 3 (Svånå 2011). With all these modifications, the CF per passenger due to production decreases from 7,83 ton CO_2 eq. per seat to 2,94 ton CO_2 eq. per seat. I modified as well consequently the maintenance.

Operation

A consumption mix based on NORDEL consumption 2006-2008 (166 g CO2 eq/kWh) is used for the foreground system. The mix consists of 61% renewable, 21% nuclear and 18% fossil sources. It is developed by MiSA based on the most recent statistics[5]. The CF is of 166 g CO_2 eq per kWh. This electricity mix used is very close to the one used for Europabanan – a proposed high-speed rail track in Sweden –which is equal to 160 g CO2 eq/kWh (Åkerman).

I assume trains with 250 seats and a load factor of 55% (source). This gives a number of 5225 passengers per day (pday) to be carried.

$$250\ \frac{seat}{train} * 0{,}55\ \frac{passenger}{seat} * 38\frac{train}{day} = 5225\, pday \tag{2}$$

This number is very close from the 4920 pday (scenario D: building of new separate HSR line) expected by Atkins Ltd (2010) for 2024.

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[5] https://www.entsoe.eu/index.php?id=65

3.2.1 IMPACTS OF HSR-LCA

The results for HSR-LCA are presented to consider all spheres of the earth: atmosphere, biosphere, lithosphere and hydrosphere. Six impacts categories are investigated to represent them:

1. Climate change (CO_2 eq), atmosphere
2. Ozone depletion (CFC-11 eq), atmosphere
3. Human toxicity (1,4-DB eq), biosphere
4. Terrestrial acidification (SO_2 eq), lithosphere
5. Freshwater eutrophication (P eq), hydrosphere
6. Water depletion (m^3), hydrosphere

Results are presented on a system level, on a section level, on a component level and finally per pkm.

3.2.1.1 SYSTEM LEVEL

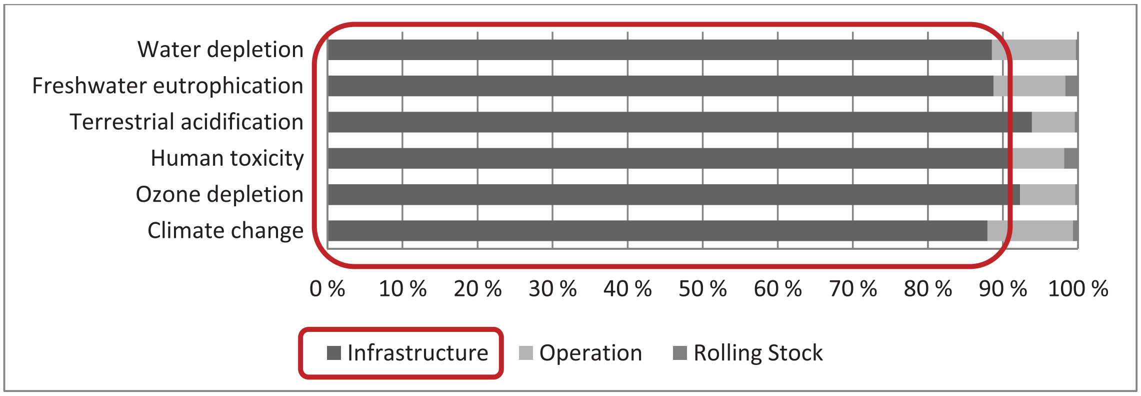

Figure 3-2: HSR-LCA - Life-cycle

Infrastructure accounts for a large share of the emissions; from 88% for climate change to 94% for terrestrial acidification. It is not surprising to find a large amount for infrastructure since the electricity mix used for operation has a low CF (166 g CO2 eq per kWh). This corresponds with the findings by UIC (2009), Network Rail (2010 and Rozycki (2003) that emphasize the larger share of infrastructure with a electricity mix with low CF for operation and the lower share of infrastructure with an electricity mix with high CF. For instance, UIC (2009) found shares for infrastructure ranging from 9% with an electricity mix with high CF for operation to 31-85% for electricity mix with low CF. The 88% of HSR-LCA are a bit upper this scale. Amongst others factors, this could be due to the small numbers of trains running on the infrastructure, leading to a low use of electricity for operation, a small total of emissions for operation and thus a larger share for infrastructure.

Table 3-2: HSR-LCA - Life-cycle

	Infrastructure	Operation	Rolling Stock
Climate change (ton CO2 eq)	5,82E+06	7,69E+05	4,49E+04
Ozone depletion (ton CFC-11 eq)	7,16E-01	5,75E-02	2,91E-03
Human toxicity (ton 1,4-DB eq)	3,28E+06	2,96E+05	6,79E+04
Terrestrial acidification (ton SO2 eq)	3,14E+04	1,97E+03	1,46E+02
Freshwater eutrophication (ton P eq)	2,50E+03	2,87E+02	4,77E+01
Water depletion (km3)	7,93E+04	1,01E+04	2,71E+02

Focus is put on infrastructure, since it represents 88 to 94% of the total impact of HSR-LCA.

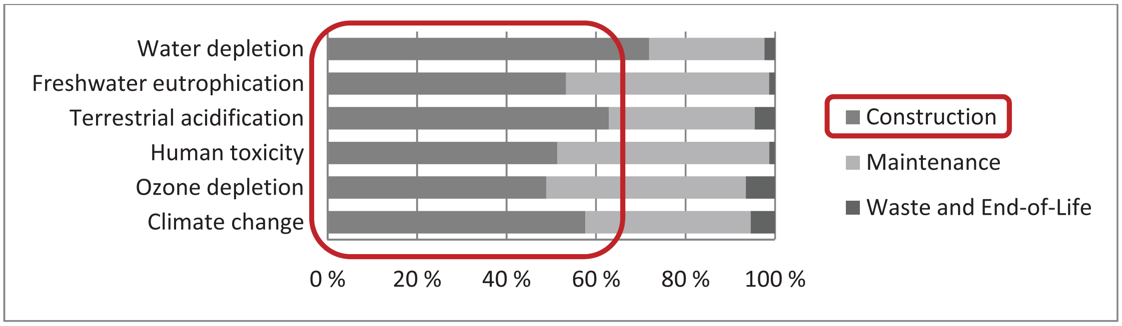

Figure 3-3: HSR-LCA - Life-cycle phases of the infrastructure

As found for Follobanen (Korsmo and Bergsdal 2010) and for the Botnia Line (Stripple and Uppenberg 2010), construction is the life-cycle phase which is allocated most of the emissions.

3.2.1.2 SECTION LEVEL

The figure below shows the impacts of the construction phase only. The first raw represents the share of km between open section (403 km), tunnel (72 km) and bridge (11 km). The open section has double tracks while tunnels and bridges have single track.

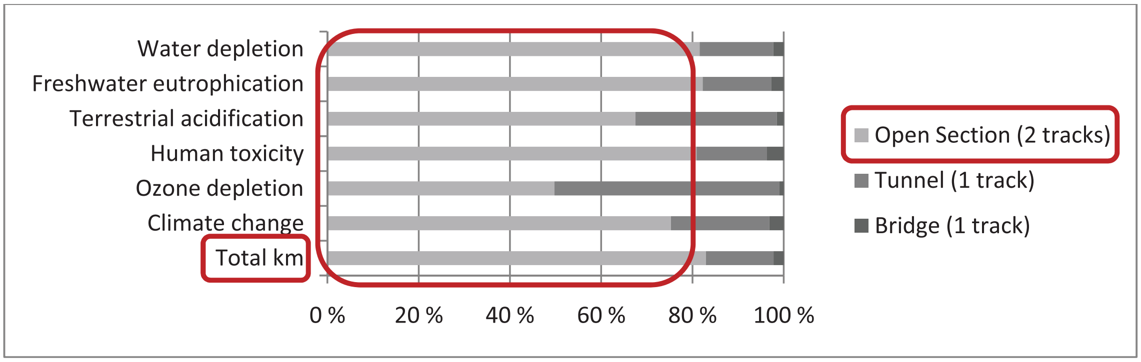

Figure 3-4: HSR-LCA - Impacts of the construction of the sections

The open section has the highest share for all impact categories. Nevertheless, for ozone depletion, tunnel and open section have very close shares (50% for open section and 49% for tunnels). This might be due to the XPS used in tunnels. For Follobanen -which consists of 95% tunnels- XPS accounts for 80% of the emissions for ozone depletion.

Only the construction phase of each section is considered. It eases the scaling to adjust the lifetimes. For instance HSR-LCA, the Follobanen and the Botnia Line have a lifetime of 60 years. Schlaupitz (2008) and the UIC (2009) used a lifetime of 100 years.

Table 3-3: HSR-LCA - Impacts of the construction of the sections

		Bridge (1 track)	Open Section (2 tracks)	Tunnel (1 track)
Climate change	kg CO2 eq/m*y	146	131	167
Ozone depletion	kg CFC-11 eq/m*y	0,000006	0,000009	0,000040
Human toxicity	kg 1,4-DB eq/m*y	85	71	60
Terrestrial acidification	kg SO2 eq/m*y	0,40	0,69	1,41
Freshwater eutrophication	kg P eq/m*y	0,049	0,057	0,046
Water depletion	m3/m*y	1,99	2,40	2,12

The construction of 1 m of tunnels with single track is the most intensive section in half of the impact categories. Nevertheless, the construction of 1 m of bridge is the most intensive process for human toxicity. This high result is due to the steel used for a steel bridge and to the steel used as reinforcement for a concrete bridge. The higher results for open sections are due to the use of steel of low quality and copper for freshwater eutrophication and to the use of gravel used for the ballast for water depletion.

The results found for the construction of the infrastructure of HSR-LCA are now compared with other studies: Stripple and Uppenberg (2010) for the Botnia Line in Sweden, Korsmo and Bergsdal (2010) for the Follobanen in Norway, Schlaupitz (2008) for future Norwegian HSR and UIC (2009) for the European context. In order to do so, scaling coefficients were used. The table below shows the coefficients used.

Table 3-4: Coefficients to scale the sections from double to single track

	HSR-LCA (Grossrieder 2011)	Schlaupitz (2008)
Tunnel (1 tube)	0,8	0,82
Tunnel (2 tubes)	0,6	-
Bridge	0,7	0,72
Open section	0,6	0,81

Coefficients for HSR-LCA are based on my observations of the current Norwegian railway network. Coefficients from Schlaupitz (2008) are obtained by dividing results for single track by results for double track. My coefficients are smaller, leading to higher differences from double to single track. This is especially true for open sections. Åkerman (2011) uses coefficients of 1,8 for tunnels, 1,6 for bridges and 1,7[6] for open sections to scale the Botnia Line from single to double track. By inversing

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[6] The coefficient of 1,9 is the average of the three coefficients used for open sections : 1,9 for railway track, 1,25 for railway track foundations and 2 for power, signaling and telecom systems (Åkerman 2011)

the coefficients to find the coefficients to scale from double to single, we find coefficients of 0,56 for tunnels, 0,63 for bridges and 0,58 for open sections. The coefficients that I used for HSR-LCA are close to the coefficients used by Åkerman (2011) for the Botnia Line for all the sections.

Table 3-5: Comparison of the impacts of the construction of the sections (kg CO_2 eq per m*y)

		HSR-LCA		**Botnia Line**		**Follobanen**		**Norwegian context**	**EU context**
		Grossrieder (2011)		Stripple and Uppenberg (2010)		Korsmo and Bergsdal (2010)		Schlaupitz (2008)	UIC (2009)
Lifetime		*60*	*100*	*60*	*100*	*60*	*100*	*100*	*100*
Open section	single track	79	47	38	23	80	48	18	32
	double track	131	**79**	63	**38**	134	**80**	**22**	**54**
Tunnel	single track	167	**100**	189	**151**	159	**100**	**59**	**83**
	double track	278	167	315	189	210	126	72	104
Bridge	single track	161	**97**	51	**30**	-	-	**90**	**147**
	double track	230	138	72	43	-	-	125	210

adjusted number of track | adjusted lifetime

Results for HSR-LCA are found in the middle of the scale tunnels and bridges. For open sections, they are found on the top of the scale. They are closest to Follobanen results, which is not surprising since the data for the materials used are the same.

Open section (double track, lifetime=100 years)

22 (Schlaupitz) < 38 (Botnia Line) < 54 (EU) < 79 (HSR-LCA) < 80 (Follobanen)

80 (Follobanen) = 22 (Schlaupitz)***3,6**

Schlaupitz and Botnia Line have similar results. EU is in the middle. HSR-LCA and Follobanen have similar and higher results.

Tunnel (single track, lifetime=100 years)

59 (Schlaupitz) < 83 (EU) < 96 (Follobanen) < 100 (HSR-LCA) < 113 (Botnia Line)

113 (Botnia Line) = 59 (Schlaupitz**)*1,9**

The difference between the lowest and the highest results is not as significant as for tunnels.

Bridge (single track, lifetime = 100 years)

30 (Botnia Line) < 90 (Schlaupitz) < 97 (HSR-LCA) < 147 (EU)

175 (EU) = 30 (Botnia Line)***4,9**

The largest differences are found for bridges. This is, the EU bridge has 4,9 times as much impact as the bridge from the Botnia Line. Railway bridges can be designed in several different ways[7], which might be one of the reasons for the difference. Also, the amount of material is quite high for bridges, which might lead to even larger differences, depending on the database used.

3.2.2 COMPONENT LEVEL

Table 3-6: Results - Core infrastructure components

	Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
Steel (low quality)	***39 %***	***18 %***	***52 %***	***21 %***	***58 %***	***32 %***
Steel (high quality)	***14 %***	*6 %*	***15 %***	***11 %***	***17 %***	*6 %*
Steel (total)	53 %	24 %	67 %	32 %	75 %	38 %
Cement	***21 %***	6 %	3 %	5 %	2 %	4 %
Diesel	10 %	***24 %***	-	12 %	-	-
XPS	-	***36 %***	-	-	-	-
Copper	-	-	***18 %***	2 %	14 %	-
Blasting	2 %	-	-	***41 %***	-	-
Gravel	2 %	-	2 %	2 %	2 %	***37 %***

Steel and cement are the components emitting the most in terms of climate change. This is in line with findings from previous studies. Steel is responsible for the majority of the emissions for climate change, human toxicity and freshwater eutrophication. For ozone depletion, diesel is the leader. For terrestrial acidification, blasting is on top. For water depletion, gravel used as ballast-material is the major culprit.

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[7] The three commonly types of bridges used in Sweden are: “concrete portal frame bridge” (small bridges with two piers), “steel girder bridge” (large bridges with several concrete piers and a superstructure made of steel girder with an overlay structure of concrete), “concrete beam bridge” (large bridges with several concrete piers and a superstructure made of concrete) (Stripple and Uppenberg 2010)

3.2.3 RESULTS PER PKM

The different compartments of the model (infrastructure, rolling stock and operation) are standardized into vehicle-kilometer (vkm) and further down to person-kilometer (pkm). In accordance with Anderson and Lukaszewicz (2006), the weight of passenger is neglected for energy consumption. See section "4.2.1: Energy required to run a train" for more details.

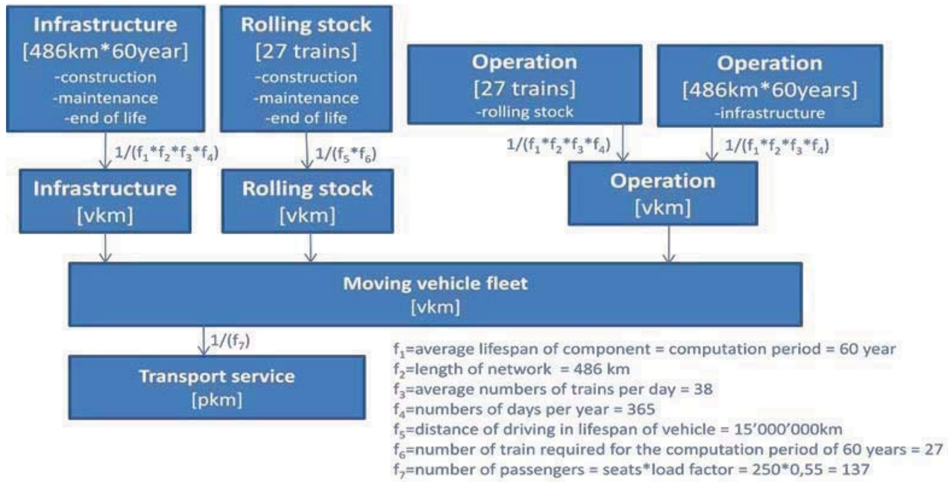

Figure 3-5: Calculation of demand factors for transport service, developed from UIC (2009)

Below are results for:

- **Infrastructure**: 14'400 g CO_2 eq per vkm, 105 g CO_2 eq per pkm
- **Operation**: 1900 g CO_2 eq per vkm, 14 g CO_2 eq per pkm
- **Rolling stock**: 111 g CO_2 eq per vkm, 0,81 g CO_2 eq per pkm
- **TOTAL**: 16'411 g CO_2 eq per vkm, 120 g CO_2 eq per pkm

These results fit well with the results found by UIC (2009). Before starting discussing, it is important to note that Norwegian conditions are very specific. A low Norwegian share of tunnels and bridges corresponds to an average European share of tunnels and bridges. Furthermore, a high Norwegian number of pday per line correspond to a low European numbers pday per line.

For the specific case of HSR-LCA, the conditions are as following, for an *European scale*: electricity mix with low CF, low traffic and low load factor, average share of tunnels and bridges.

Infrastructure

UIC (2009) found numbers ranging from 2 g CO_2 eq per pkm (average share of tunnels and bridges, high traffic and high load factor) to 67 g CO_2 eq per pkm (high share of tunnels and bridges, low traffic and low load factor). The 105 g CO_2 eq per pkm found in this study are above these numbers. It is not possible to scale the results directly here because not only the construction phase is included, but also the maintenance and end of life. The impact of the construction phase could be decreased by a longer lifetime. However, this is not the case for maintenance and end of life. A longer lifetime results in an increase of maintenance, which results in an increase of materials used and an increase of the impact of end of life.

An approach that could sound more correct is to assume that the maintenance of the infrastructure of HSR-LCA is quite high, compared to others study and thus, reduce a little bit the 105 g CO2. Nevertheless, even the 105 g CO2 found for HSR-LCA are overestimated due to shorter lifetime and high maintenance, it is likely that they will still be on the top of the UIC's scale, even after scaling.

Operation

UIC (2009) found numbers ranging from 4 g CO_2 eq per pkm (electricity with low CF[8], high traffic and high load factor), 11 g CO_2 eq per pkm (electricity with low CF, low traffic and low load factor), to 20 g CO_2 eq per pkm (electricity with high CF[9], high traffic and high load factor). The 14 g CO_2 eq per pkm found in this study are close of the case of the 11 g CO_2 eq per pkm found by UIC(2009). They correspond to electricity with low CF, low traffic and low load factor. These are the typical conditions for HSR-LCA.

Rolling stock

UIC (2009) found numbers ranging from 0,49 g CO_2 eq per pkm (high traffic of 90 trains per day and high load factor of 80%) to 1,47 g CO_2 eq per pkm (low traffic of 25 trains per day and low load factor of 25%). One may have thought to find results at the top of the scale. However, this is not the case. This is due to the fact that the technology used by UIC (2009) is based on calculations by who use a combination of 40% ICE1 and 60% ICE2. In this project, the combination used by Rozyki el al. (2003) has been modified to correspond with ICE3 production technology. Thus, even if the traffic is low (38 trains per day) and the load factor on average (55%), result for rolling stock are low due to cleaner production technology.

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[8] UIC (2009) el mix with low CF = 50% nuclear, 10% fossil fuel (natural gas, coal), 40% renewable (hydro, wind)

[9] UIC (2009) el mix with high CF = 27% nuclear, 56% fossil fuel (natural gas, coal), 17% renewable (hydro, wind)

4 CORE FACTORS INVESTIGATED

Core factors for future Norwegian HSR have been discussed in the two previous chapters, first from the literature in chapter 2 and then from the model in chapter 3. It is not possible to investigate all the core factors for the environmental performance of HSR in Norway. Nevertheless, many of them are investigated in this chapter. In the background system, cement, steel and XPS are examined. In the foreground system, electricity mixes, electricity requirements to run a train, number of passengers per day, seat capacity per train, load factor, lifetimes of components, and recycling and reuse are addressed.

This chapter is organized in such a way that first, theory on the core factor is given. The theory first refers to the production technology of today. Then, the time horizon is widened to 2050. This is in order to build up scenarios up to 2050 presented in chapter 5. Additionally, for some elements, a sensitivity analysis is conducted. To make it clearer for the readers, sensitivity analyses are put in blue boxes. The table below summarizes the findings of the sensitivity analyses. An x indicates where the potential is relevant. No x was marked for energy per pkm because with an electricity mix use for operation with a low CF, the energy per pkm only influences to a less extent the overall performance of HSR-LCA. Note that it is not the electricity mix used for operation that is a core factor but the choice of the electricity mix used for operation.

Table 4-1: Sensitivity analyses – Summary of the findings

		Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
Cement	Use of secondary materials for clinker production	x					
	Use of secondary fuel for clinker production	x	x			x	
Steel of low quality	Energy efficiency	x	x	x	x	x	
	Use of scrap	x			x	x	x
Steel of high quality	Energy efficiency	x	x	x	x	x	
	Use of scrap	x			x	x	
	Use of common steel for rails	x	x	x	x	x	
XPS	Blowing agent		x				
Energy	Energy per pkm						
	Choice of electricity mix used for operation	x	x	x	x	x	x
	Electricity mix used for operation						

The sensitivity analyses conducted were time consuming. In SimaPro, production systems are organized in such a way that each process consists of a single box. Original processes from the database cannot be modified. They have to be copied, modified and linked together again. Please see appendix 2: "Details on model changes" to see the list of the parameters used.

4.1 BACKGROUND SYSTEM

Background data is data for generic materials, energy, materials and waste management system. Usually, 80% of data is readily available in databases.

4.1.1 CEMENT

The cement industry is energy intensive. It consumes 9% of the overall energy consumption by industries and is allocated 25% of the global direct CO_2 emissions by industries (Rubel et al. 2009). On a global level, the cement industry is responsible for approximately 5% of global anthropogenic CO_2 emissions. On a process level, 0.9 tonne of CO_2 are emitted for 1 tonne of cement produced. The production of clinker is the most energy intensive process. Regular fuels oil, petcokes and coal are usually used as energy source (Vos et al. 2007).The figure below shows the stages in the manufacture and use of cement.

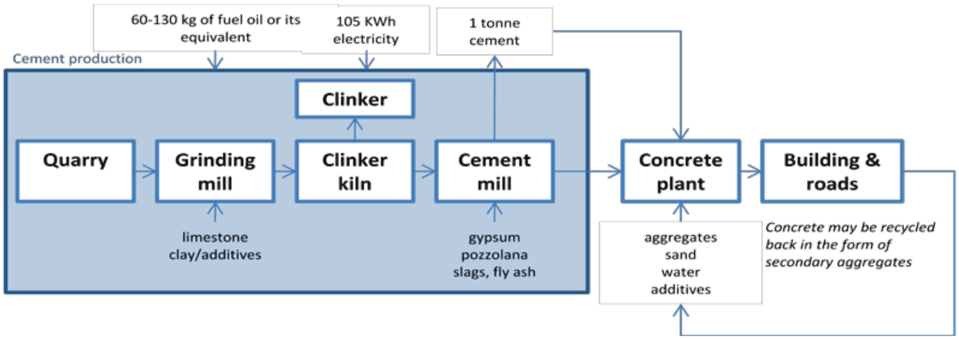

Figure 4-1: Stages in the manufacture and use of cement, developed from Kellenberger et al. (2007

Emissions

The primary emissions for the manufacture of Portland cement are particulate matter (PM and PM-10), NOx, SO_2, CO and CO_2. NOx are emitted during the fuel combustion by oxidation of chemically-bound nitrogen in the fuel and by thermal fixation of nitrogen in the combustion air. The quantity and type of NOx generated is affected by the type of fuel used. SO_2 are generated from both the sulfur compounds in the raw materials and from sulfur in fuel. CO_2 emissions from Portland cement manufacturing are generated by two mechanisms: 1. combustion of fuel at high-temperatures and 2. calcining of limestone or other calcareous material (Vos et al. 2007).

Co-processing (use of secondary material and secondary fuel)

CEMBUREAU (2009) states co-processing as the optimum way to recover energy and material from waste. It will both reduce the dependency to fossil fuels and contribute to lower the environmental footprint of cement production. Alternative fuels must have a significant calorific value and mineral components of alternative raw materials must be suitable for the production of clinker or cement. Some materials provide both a calorific value and mineral components. For instance, the Austrian cement industry started to co-process tyres in 1980 already. The clinker burning process of tyres offers the simultaneous recovery of energy and material. The high calorific value of rubber is used to substitute fossil fuels and the inert components, mainly iron and alumina, to substitute raw materials.

The shares for secondary fuels are subject to strong fluctuations, depending on the offer and demand and the political situations. For instance, meat-and-bone meal and animal fat has been more easily available after the bovine spongiform encephalopathy (BSE) crisis (Kellenberger et al. 2007). In 2006, the European cement industry used 18% of alternative fuels, saving about 5Mt of coal and resulting in a reduction of 8Mt of CO_2 emissions. For this same year, alternative materials consisted of about 5% of the raw materials used in the production of clinker, accounting for 14.5 Mt/year (CEMBUREAU 2009).

Typical alternative fuels used by the cement industry consist of domestic waste, discarded tyres, waste oil and solvents, plastics, textiles and paper residues. Typical biomass consist of animal meal, logs, wood chips and residues, recycled wood and paper, agricultural residues like rice husk, sawdust, sewage sludge and biomass crops (WBSCD 2010). The table below shows the different possible sources to substitute clinker.

Table 4-2: Sources to substitute clinker (WBSCD and IEA 2009)

Clinker substitute	Source	Availability
Ground blast furnace slag	Iron or steel production	Future iron and steel production volumes are very difficult to predict
Fly ash	Flue gases from coal-fired furnaces	Future number and capacity of coal-fired power plants is very difficult to predict
Natural pozzolanas	Volcanoes, some sedimentary rocks, other industries	Depends on local situation
Artificial pozzolanas	Specific manufacture	Very limited due to economic constraints
Limestone	Quarries	Readily available

Carbon capture and storage (CCS), thermal and electric efficiency

CCS is a new technology that has not yet been proven on an industrial scale for cement production yet that is potentially promising. As estimated, 80% of all new cement capacity until 2050 will be located in developing countries. Therefore, prospective studies on CO_2 storage must be expanded and cover these countries. The original design of an installation largely defines its thermal efficiency. The savings on a per unit basis range from 0.2 to 3.5 GJ/t clinker. In 1990, the weighted average thermal energy consumption for a current state of the art dry manufacturing clinker kiln was 3.605 MJ/t clinker. In 2006, it reduces by 6% to 3.382MJ/t clinker (WBSCD and IEA 2009).

Low and carbon-negative cements

Pilot projects on low-carbon or carbon-negative cements have been developed by start-up companies. These new processes are still in the developmental stage and pilot plants are expected to be built in 2010/11. These cements appear to have similar mechanical properties than Portland cement. Currently, they have not been tested as being economically viable or tested for their long-term suitability and none have been accepted in the construction industry where strong material and buildings standards exist. For all of these reasons is it unknown whether or not they can have an impact on the future of the cement industry. Nevertheless, they are presented below (WBSCD and IEA 2009):

- **Novacem**: Based on magnesium silicates rather than limestone as used in Ordinary Portland Cement. Magnesium silicates are converted to magnesium oxide using a low-carbon and low-temperature process, adding minerals additives that accelerate strength development and CO_2 absorption, offering a prospect of carbon-negative cement.
- **Calera**: mixture of calcium and magnesium carbonates
- **Calix's**: includes capture of CO_2 emissions
- **Geopolymer cement**: makes use of waste materials from the power industry (fly ash, bottom ash), the steel industry (slag), and from concrete waste to produce alkali-activated cement.

Roadmap indicators up to 2050

Table 4-3: : Cement roadmap indicators 2012-2050 (WBSCD and IEA 2009)

	2012	**2015**	**2020**	**2025**	**2030**	**2050**
Thermal energy consumption per tonne clinker [GJ/tonne]	3.9	3.8	3.5-3.7	3.4-3.6	3.3-3.4	3.2
Share of alternative fuel and biomass use	5-10%	10-12%	12-15%	15-20%	23-24%	37%
CCS						
no of pilots plants	2	3				
no of demo plants operating		2	6			
no of commercial plants operating				10-15	50-70	200-400
Mt stored	0.1	0.4	5-10	20-35	100-160	490-920
Tonne CO_2 emission per tonne cement	0.75	0.66	0.62	0.59	0.56	0.42

Sensitivity analysis (secondary material and secondary fuel)[10]

The impact of cement for the construction of the infrastructure is given one more time in the table below to remind which impact categories are more sensitive to changes.

Table 4-4: HSR-LCA - Construction of infrastructure - impact of cement

	Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
Cement	***21 %***	6 %	3 %	5 %	2 %	4 %

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[10] It is assumed that clinker consists of 0% secondary material and 0% secondary fuel in the base case. However, this is not exact. Clinker consists of 7% secondary materials and 4% secondary fuels.

In Ecoinvent, all secondary raw materials enter the system without burdens as they are declared waste. The product or process from which from the secondary materials are by-products are allocated 100% of the burdens (Kellenberger et al. 2007). In other words, it is “free” to use secondary materials. Only direct emissions are accounted for. Direct emissions are accounted for in CO_2 emissions[11]. This is why only CO_2 eq emissions decrease in the figure below. Please see Appendix 3 for more details on emissions of secondary material.

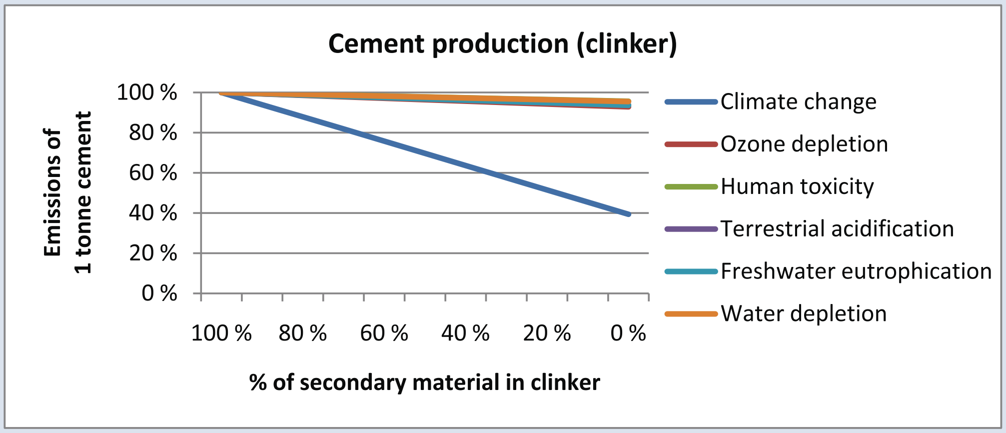

Figure 4-2: Cement – Sensitivity of secondary material in clinker production

To introduce secondary fuel, heating values are used as converting factor. An average heating value of 22.4 MJ is used per kg secondary fuel and of 32.5 MJ per kg primary fuel (Künniger et al. 2001). The figure below shows a sensitivity analysis of the introduction of secondary fuel for clinker production.

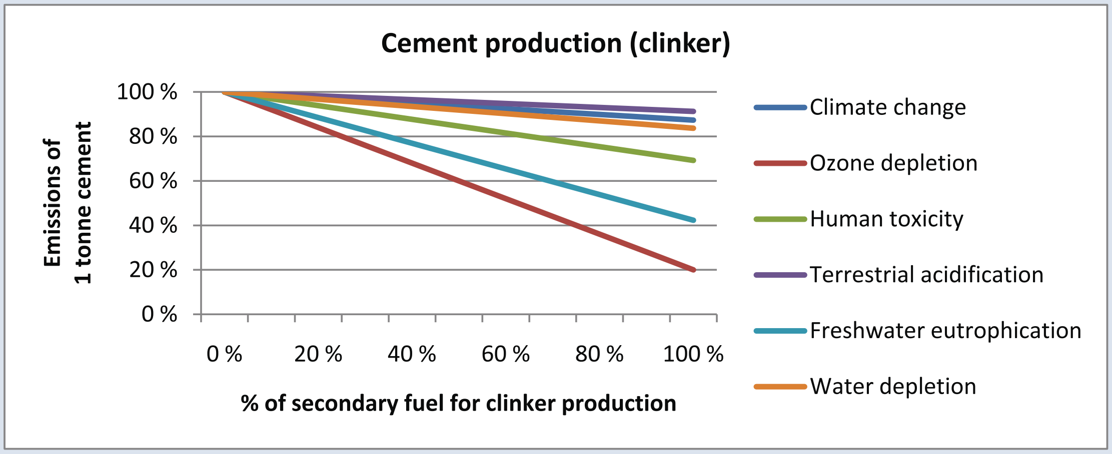

Figure 4-3: Cement - Sensitivity of secondary fuel in clinker production

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[11] Around 75% of the original waste mass is transferred to gaseous compounds such as CO_2, N_2, H_20 and minor trace gases. Out of these elements, only CO_2 has an environmental relevance and thus poses the majority of the emissions from the municipal solid waste incinerators site. On the other hand, the practically unavoidable emission of CO_2 reflects the achievement of the last decades to make waste incineration cleaner by the installation of flue gas purification systems which mainly prevent emissions to air. Emissions of CO_2 are discerned according to the fossil or biogenic origin of the carbon in the incinerated waste (Doka 2003).

4.1.2 STEEL

Steel has become essential to modern society. It is fundamental in a greener world. For instance for lighter more efficient vehicles, the construction of smart electrical grids, transport infrastructure, development or high energy efficient residential housing and commercial buildings. Over 1.3 billion tons of steel are manufactured and put to use every year. At present, close to 50% of steel is produced and used in China. The volume of steel produced will continue to grow, in particular in developing areas like Latin America, Asia, Africa and the Indian sub-continent. In these regions more than 60% of steel consumption will be used for the creation of new infrastructure (World Steel Association 2010). Steel is an energy and emissions-intensive industry, relying strongly on fossil fuels. Iron and steel industries represent 21% of the global energy consumption by industries and account for around 4-5% of total world CO_2 emissions. On average, the production of every tonne of steel is allocated 1.9 tonnes of CO_2. Figure below shows the basic flows of steel production as it is modeled in Ecoinvent (Classen et al. 2009)

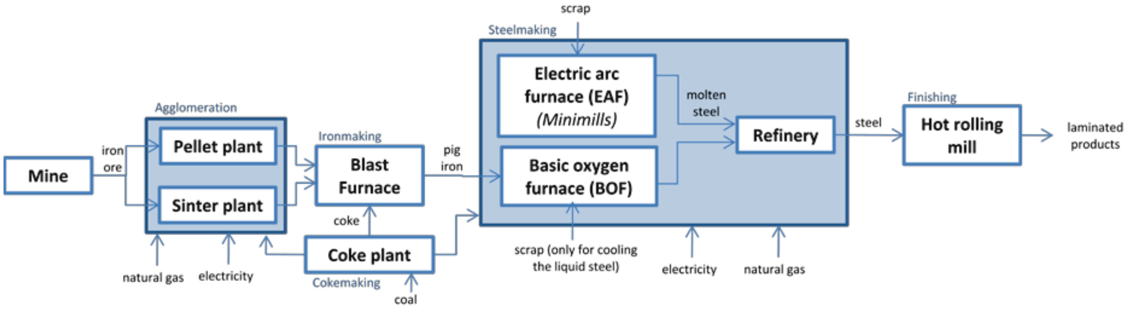

Figure 4-4: Steel production, developed from Classen et al. (2009)

- **Mining**: Iron ore is extracted.
- **Agglomeration:** The iron ore agglomeration process improves the iron content and/or physical properties of ore.
- **Cokemaking:** Coke is an essential part of integrated steelmaking. It provides the carbon to remove the oxygen from iron ore and the heat to produce molten iron in the blast furnace
- **Ironmaking**: Iron ore is reduced to metallic iron through the removal of the oxygen. This conversion is the most energy-intensive stage of the steel process and has the potential to emit the largest CO_2 emissions. The most common way –and only way described in Ecoinvent- to produce iron involves the blast furnace. It accounts for 90% of world iron production (Asia Pacific Partnership for Clean Development and Climate 2007). Two other possible and proven routes are the Direct Reduction (DR) process e.g. MIDREX or the Smelting Reduction (SR) process e.g. COREX. These two routes may prevent the necessity for coking plants and sinter machines (European Commission 2001).
- **Steelmaking**: Basic oxygen furnace (BOF) is the traditional way for steelmaking. Coal is used as the energy source in BOF. Electric arc furnace (EAF) are used to produce secondary steel. Scrap can be inserted into electric arc furnace (EAF) or BOF.

Energy efficiency

The steel industry has reduced its energy consumption per tonne of steel produced by 50% in the last 50 years. Due to this dramatic improvement in energy efficiency, it is estimated to have only a marginal further improvement on the basis of existing technology (World Steel Association 2010). A highly promising way to reduce energy consumption is the higher use of scrap. Minimills (EAF), which base their steel production mainly on scrap, consume about half as much energy as integrated steel works. By changing from open blast-furnaces to electric arc furnaces, the steel industry could also reduce its use of energy by 50% (Kram et al. 2001).

Recycling

Steel products can be easily recycled through smelting. Steel that is finally melted from waste can be recycled by being added to new product. Proportions vary from 10 to 100%, depending upon the end product and its quality requirements. In the long term, all steel should be used in closed cycles in order to maximize recycling (Berge 2009). The limiting factor is scrap availability. This factor is not likely to increase significantly for the years to come. Global scrap availability is today about 0.4 ton of scrap per ton of crude steel produced. If by 2050 today's level of crude steel production were to double, scrap availability is estimated to amount to about 0.6 ton per ton of crude steel (Rubel et al. 2009)

Sensitivity analysis (energy efficiency +recycling rate+ quality)

The impact of steel for the construction of the infrastructure is given one more time in the table below to remind which impact categories are more sensitive to changes.

Table 4-5: HSR-LCA - Construction of infrastructure - impact of steel

	Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
Steel (low quality)	**39 %**	**18 %**	**52 %**	**21 %**	**58 %**	**32 %**
Steel (high quality)	**14 %**	6 %	**15 %**	**11 %**	**17 %**	6 %

The figure below shows the potential for energy efficiency for steel of high and low quality.

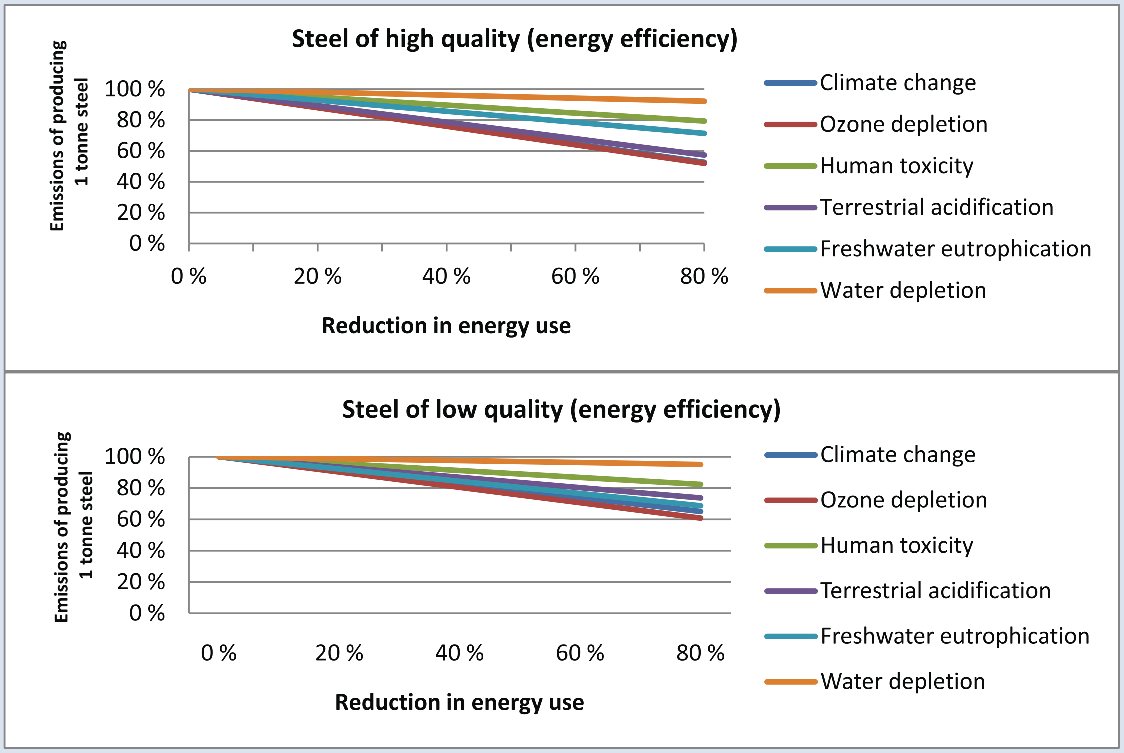

Figure 4-5: Steel – Sensitivity analysis of energy efficiency

The figure below shows the potential for the use of scrap for steel of high and low quality. The major feedstock for the production of recycled steel is ferrous scrap. Scrap can consist of scrap from inside the steel-works, cuts-offs from steel product manufacturers (e.g. vehicle builders) and capital or post consumer scrap (e.g. end of life products) (Classen et al. 2009). Emissions of heavy metals depend largely on the scrap quality. Cadmium is one of the main contributors to human toxicity. This heavy metal is principally used for the production of rechargeable nickel cadmium , for other end uses such as pigments, coatings and plating and as a stabilizer for plastics (USGS 2011). For instance, if end of life products are used as scrap source, unavoidably an amount of cadmium will enter the secondary steel production system due to, for example, coatings. Because cadmium being one of the main contributor to human toxicity, human toxicity increases with the increase of the use of scrap.

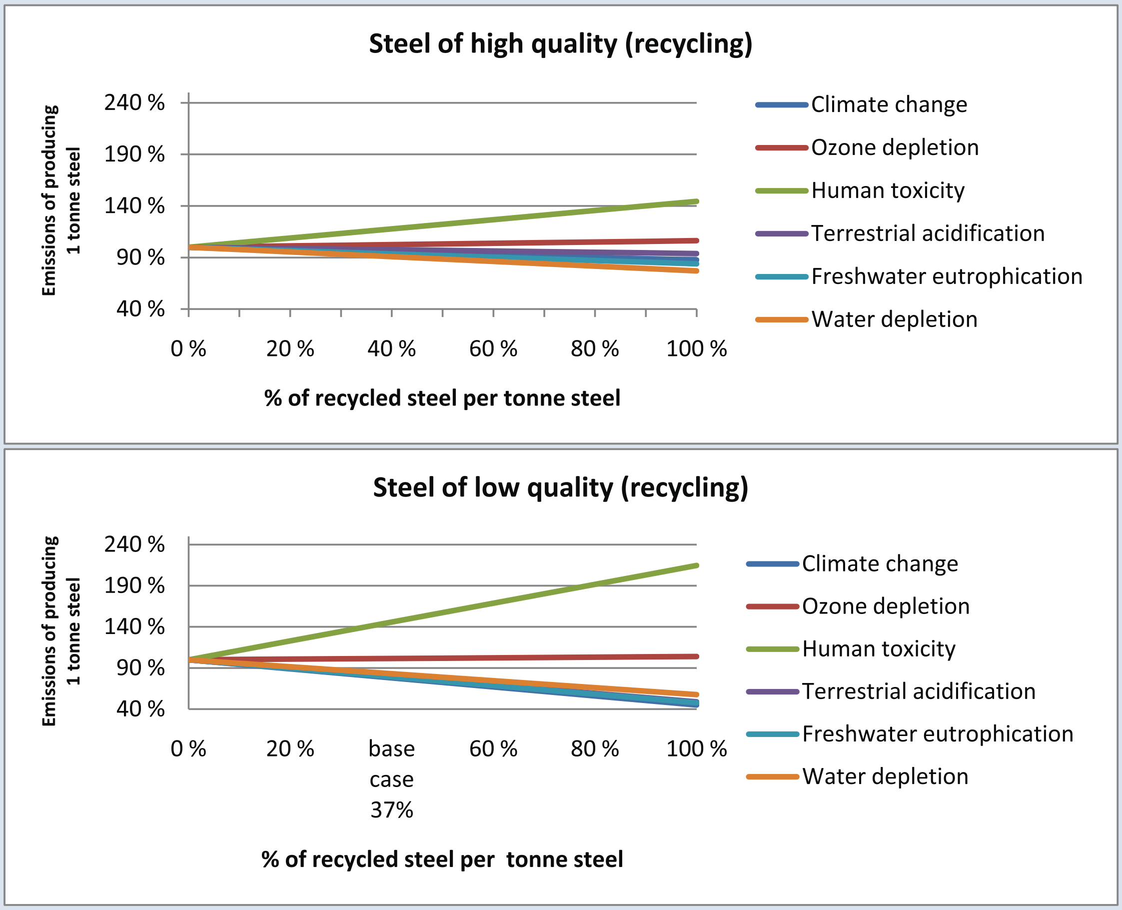

Figure 4-6: Steel - Sensitivity analysis of recycling rate

The figure below shows the potential for the decrease of the use of chromium steel.

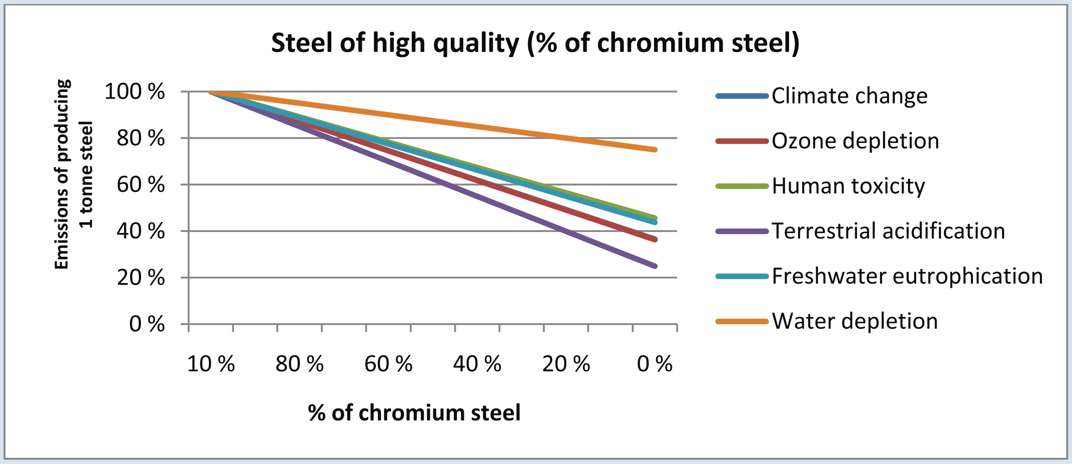

Figure 4-7: Steel of high quality - Sensitivity analysis of quality

4.1.3 EXTRUDED POLYSTYRENE (XPS)

XPS foam, technically referred to as extruded polystyrene has many attributes such as stable R-value[12] (thermal resistance), moisture resistance and high compressive strength which renders it an outstanding building material. Furthermore, because it is a plastic material, it does not corrode, rot or support the growth of mold or mildew. It is resistant to soil microorganisms and does not provide nutrient value to vermin. All these durable qualities makes XPS in many applications such as cold storage, frost protected shallow foundations or protected roof membrane assemblies the only recommended or approved material (Fabian et al. 2004).

Figure below shows the basic flows of XPS production as it is modeled in Ecoinvent (Kellenberger et al. 2007). XPS is made by melting polystyrene granulate. A blowing agent is injected into the mixture to form gas bubble. The blowing agent can be CO2, HFC-134 or HFC-152a.

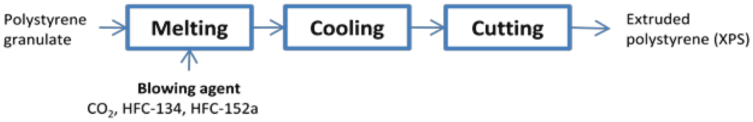

Figure 4-8: XPS production, developed from Kellenberger et al. (2007)

Recycling and reuse

There is both an environmental as well as an economic benefit from the reuse or recycling of XPS. Nevertheless, there are still enormous challenges to overcome concerning the easy removal or collection, current conservative building facilities practices and the low potential of XPS being removed from existing buildings (Fabian et al. 2004).

Other insulation materials

Vacuum insulation panels (VIP) could be used instead of XPS as insulation material. It is considered one of today's most promising high performance thermal insulation material on the market. The downsides are their fragility and the fact that they cannot be cut on site (Baetens et al. 2010). Glass wool might be an option as well. However, as XPS is being used amongst other factors for its high compressive strength, it is not certain that VIP and glass wool have such a property. Schonhardt (2003) computed impacts for XPS, VIP and glass wool using the eco-indicator 99 (H) methods. The figure below shows the total impact in milli-points per m^2.

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[12] "Thermal resistance is a measure of the resistance (opposition) of heat flows as a result of suppressing conduction, convection and radiation. It is a function of material thermal conductivity, thickness and density. Thermal resistance, R-value is expressed in m^2-K/W."(Al-Homoud 2005)

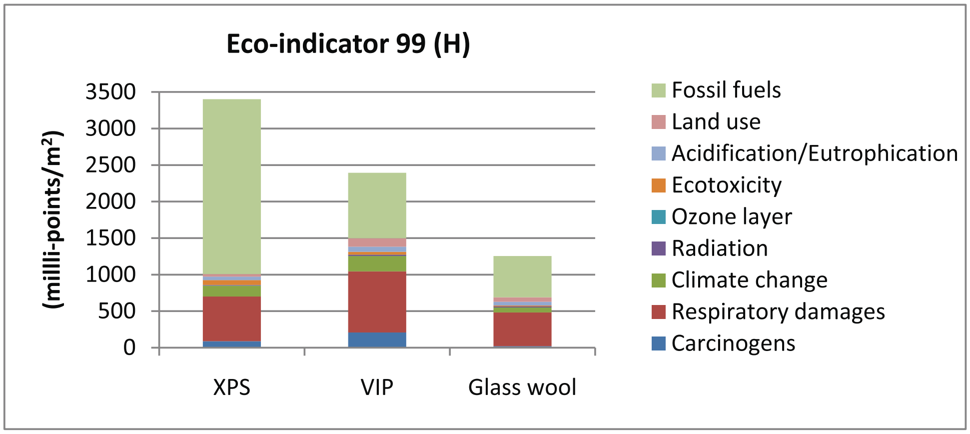

Figure 4-9: Comparison of glass wool, XPS and VIP with the method Eco-indicator 99 (Schonhardt et al. 2003)

Sensitivity analysis (production technology for XPS)

The impact of XPS for the construction of the infrastructure is given one more time in the table below to remind which impact categories are more sensitive to changes.

Table 4-6: HSR-LCA - Construction of infrastructure - impact of XPS

	Climate change	Ozone depletion	Human toxicity	Terrestrial acidification	Freshwater eutrophication	Water depletion
XPS	-	***36 %***	-	-	-	-

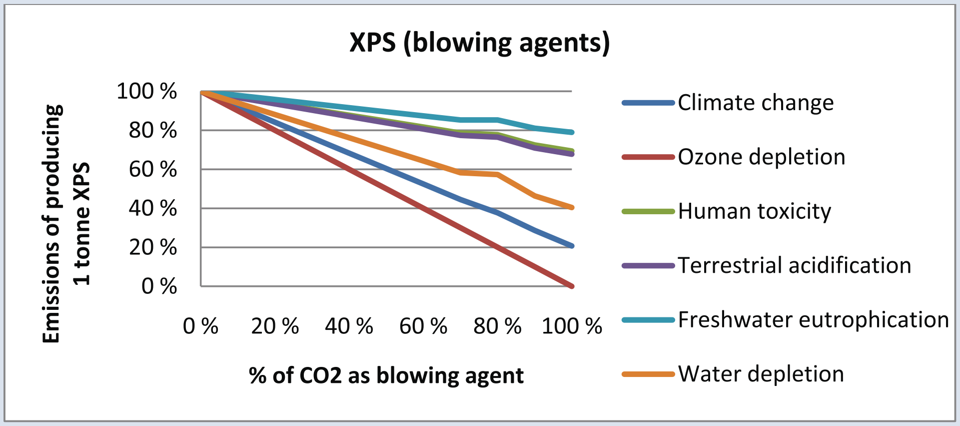

Figure 4-10: XPS - Sensitivity analysis of blowing agent

4.2 FOREGROUND SYSTEM

Foreground data refers to specific data such as a particular product system or a particular specialized production system. In many cases, it has to be collected from companies. The foreground of HSR-LCA consists of the energy required to run a train, the electricity mix used for operation, market considerations such as the number of passengers per day, the lifetime of main components and the recycling and reuse of elements.

4.2.1 ENERGY REQUIRED TO RUN A TRAIN

The energy consumption of trains has been reduced by 25-30% per seat-km or per passenger-km from 1994 to 2002-2005, for comparable operations. The reasons for this improvement in the energy performance are due to (Anderson and Lukaszewicz 2006):

1. Improved aerodynamics that reduces air drag
2. Regenerative braking
3. Lower train mass per seat
4. Improved energy efficiency in power supply

Energy per seat-km or passenger-km

All other factors being equal, the higher speed of modern trains would have increased the energy consumption by 63%. Nevertheless, energy consumption per seat-km or passenger-km is reduced by 25-30%. This is made possible by wide bodies that increase the seating capacity by 25% compared to a carbody with normal width. Some new cars are also longer. This results in less train mass and lower aerodynamic drag (Anderson and Lukaszewicz 2006).

Aerodynamic considerations

Modern trains, designed to run at high speed, have a better aerodynamic performance than older trains. They have longer and more streamlined noses in the front and rear and are smoother along the roof and walls. This reduces the energy consumption by 22% (Anderson and Lukaszewicz 2006).

Energy recovery

A train consumes energy when it is accelerating, running uphill, but also due to air drag, mechanical (rolling) resistance and comfort needs. The electric energy consumed to accelerate is converted into kinetic energy and into potential energy for running uphill (with exception for losses). These kinetic and potential energies can be converted back to electric energy if the electric motors are switched over to electrical generators. The newly generated electric energy can be fed back to the train. Despite the losses of this reverse process, if the braking is made totally by the electric regenerative brakes[13] (except at very low speeds) a modern electric train can regenerate and recover as much as

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[13] Motors are working as generators in regenerative braking mode and electric energy is fed back via the pantograph of the catenary. This energy can usually be used by other trains on the line. If other trains are not able to make use of this regenerated amount of energy, the energy may be fed back to the public network if converter stations are consequently technically equipped. If the total amount of regenerated energy cannot be absorbed, the voltage of the catenary will rise. If

60-70% of the energy inputs to accelerate and to run uphill. On the other hand, the energy needed to surmount the air drag and the mechanical resistance is dissipative and cannot be recovered at all. The energy to provide a comfortable environment in the train cannot be recovered either. Thus, the total percentage amount of energy recovery is usually 17% of the input into the pantograph (Anderson and Lukaszewicz 2006).

Seasonal variations

More energy is required to run a train in winter. On the one hand, the amount of comfort energy is increased due to heating. On the other hand, air density is higher at low temperature, leading to higher amount of air drag, proportional to air density. Seasonal variations are especially important, for high speed trains running at speeds of around 200 km/h or more, since these type of trains usually have 50% of their energy consumption due to air drag (Anderson and Lukaszewicz 2006).

Impacts of tunnels

The aerodynamic resistance of a train is higher when passing through tunnels than on open track. The main factors are (VWI 2006):

1. Cross-sectional area of tunnel and train
2. Length of tunnel and train
3. Frictional drag of tunnel and train surface

When entering a tunnel, a train can be compared to a piston entering a cylinder. The larger the cross section, the less aerodynamic resistance and lower energy consumption. From this, f_{tunnel} can be derived:

$$F_{tunnel} = aerodynamic\ resistance\ ratio = \frac{train's\ cross\ section}{tunnel's\ cross\ section}$$

The longer the tunnel, the higher the amount of energy required to push the air towards the end of the tunnel. Two near-linear function can be assumed: one for tunnels shorter than 1km and one for tunnels longer than 1km (Gackenholz 1974).

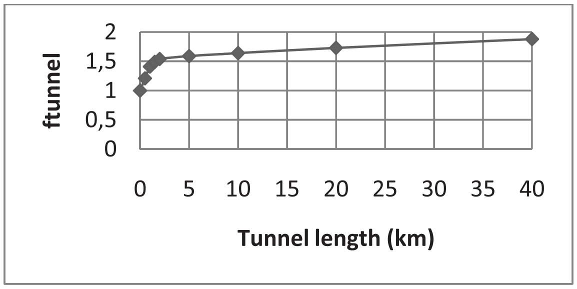

Figure 4-11: Tunnel impact on specific energy consumption, adapted from Svånå (2011)

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the voltage is rising too high, the regeneration is stopped automatically and the braking is made by mechanical or magnetic brakes.

Impacts of the number of stops

For lower speeds, the specific energy consumption rises with stop quantity. However, the opposite occurs for high speed; with a rising number of stops, specific energy consumption tends to decline. This non intuitive founding is explained further with the table below.

Table 4-7: Effects of stop quantity for the ICE3 at a permitted track speed of 330 km/h (Svånå 2011)

	1 stop	**2 stops**	**3 stops**	**6 stops**	**11 stops**
$E_{el,acc}$	1'030	2'060	3'090	6'181	11'331
$E_{el,const}$	8'926	8'208	7'458	5'206	1'454
$E_{el,aux}$	844	868	901	999	1'162
$E_{el,dec}$	-384	-784	-1'176	-2'351	-4'311
$E_{\_el}$	**10'416**	**10'353**	**10'0273**	**10'034**	**9'636**

$E_{\_el}$ is made up of four components: Energy to accelerate $E_{el,acc}$ to run at constant speed $E_{el,const}$, auxiliary energy $E_{el,aux}$ and energy recovered with regenerative braking $E_{el,dec}$. If braking energy is not recovered, energy consumption rises with stop quantity. In contrast, the energy consumed to accelerate rises more than the energy consumed to run at constant speed, as the number of stops increases. If energy is recovered, the amount of energy recovered from braking is enough to compensate for the rising energy consumption to accelerate more (Svånå 2011).

Sensitivity analysis (energy per pass-km)

The figure below shows the influence of the energy used per pkm[14] on the overall emissions of HSR-LCA. For the same amount of energy used per pkm, the impact is minor with an electricity mix with low CF (166 g CO_2 eq per kWh) and is notable for an electricity mix with a high CF (531 g CO_2 eq per kWh).

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[14] 0,075 kWh per pkm (0,0425 kWh seat-km, 55% load factor, X2000 in 2004) corresponds to HSR-LCA, 0,085 kWh per pkm to ICE 1 and 2 (Spielmann et al. 2007), 0,06 kWh per pass-km (0,0425 kWh per seat-km, 70% load factor) to X2000 in 2007 and 0,05 kWh per pkm the energy use expected for Europabanan, a proposed high-speed rail track in Sweden (Lukaszewicz and Anderson 2009).

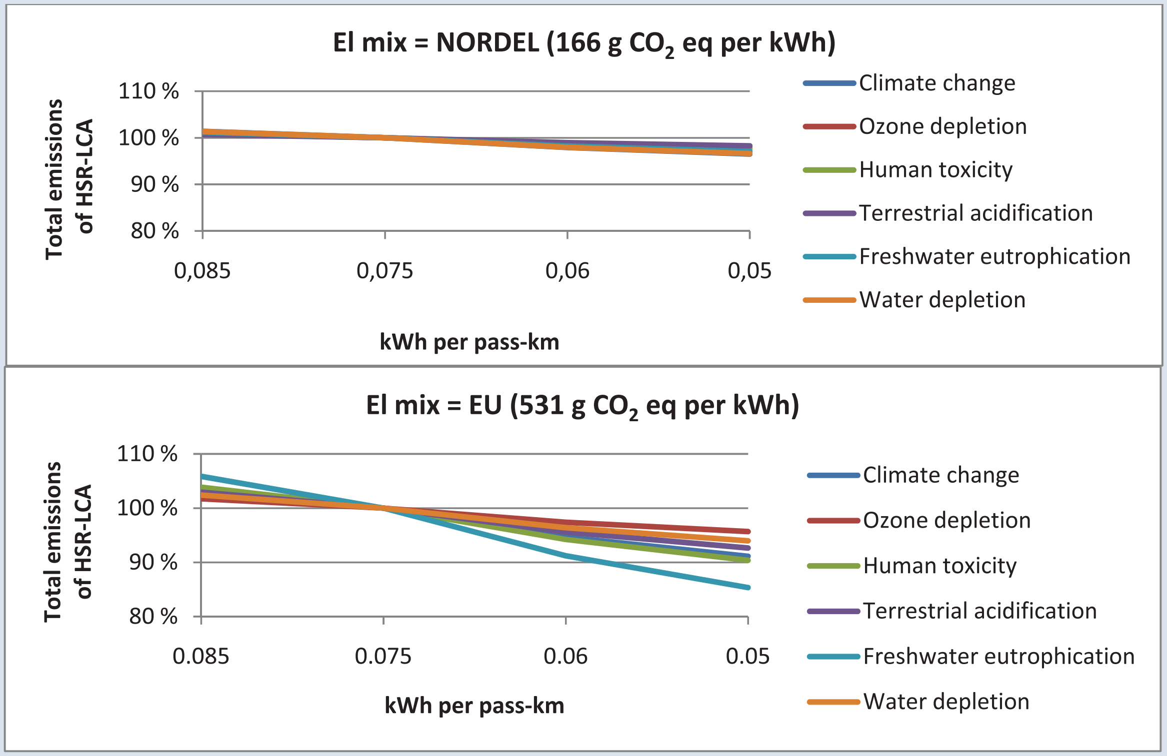

Figure 4-12: Energy - Sensitivity analysis of kWh per pass-km

4.2.2 ELECTRICITY MIXES

Electricity mix is a core factor for the environmental performance, especially when the electricity mix used for operation has a low CF, which is the case in Norway (UIC 2009; Network Rail 2010; Rozycki et al. 2003; Schlaupitz 2008).

Sensitivity analysis (el mix for operation)

Six electricity mixes (medium voltage) for operation are tested below to investigate the fluctuation of the share of infrastructure, operation and rolling stock. Transmission and losses are included in the electricity mixes. The figure below show the results for electricity mixes ranging from a CF of 7 g CO2 eq/kWh for hydropower to 976 g CO2 eq/kWh for coal. The general framework, where the share of infrastructure increases/decreases with a decrease/increase of the CF of the electricity mix is verified here. The results are given in %. The purpose is to show the share of infrastructure, operation and rolling stock. The share of operation would never be counterbalanced by the share of infrastructure, even with an el mix with very high CF. In order to do so, more trains should run on the infrastructure.

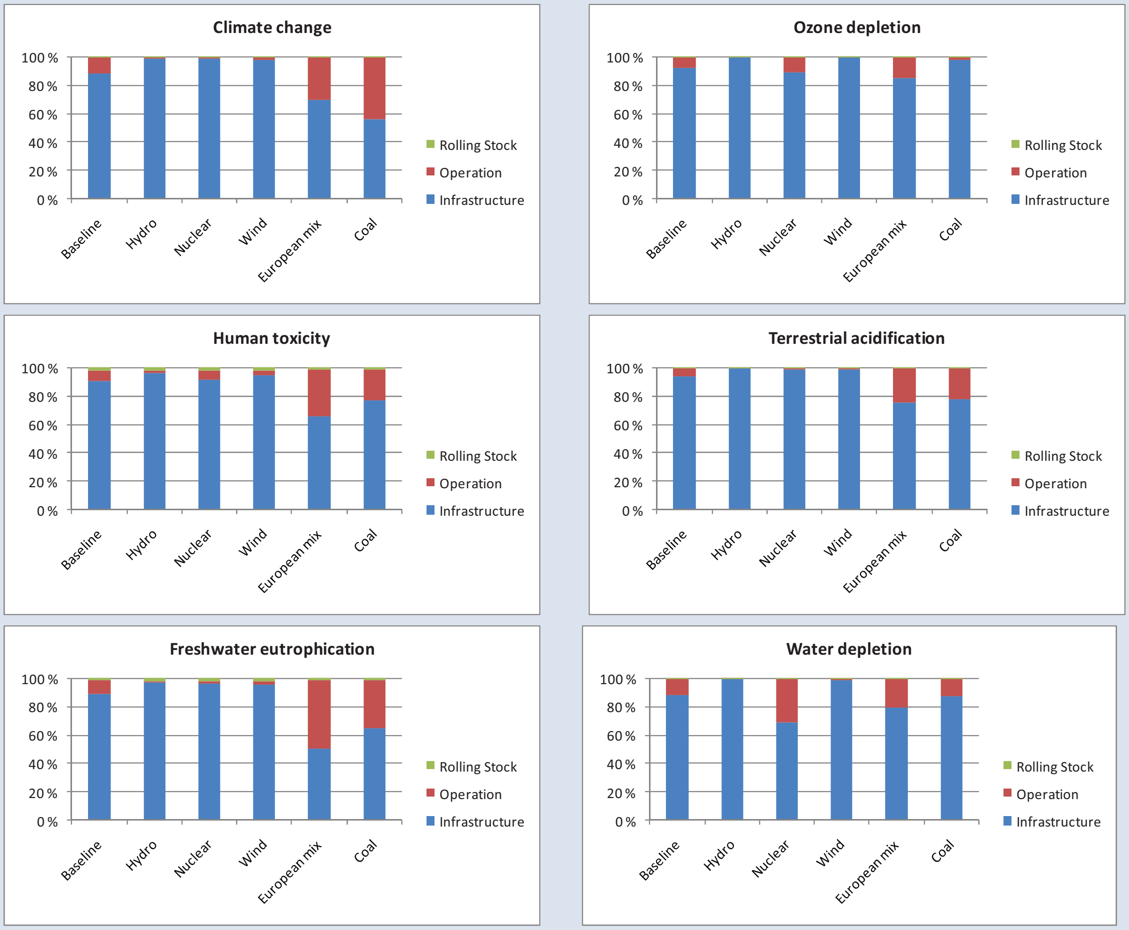

Figure 4-13: Sensitivity analysis - Electricity mix for operation

4.2.3 MARKET CONSIDERATIONS

After all the technical aspect of HSR considered until now the focus is put on market considerations such as the number of passengers per day, the seat capacity per train and the seat occupancy or load factor.

Passengers per day (pday)

It is difficult to find out numbers for total passengers per day for all means of transportation for the corridor Oslo-Trondheim for a given year. The following system was used as starting point. Firstly, the number of passengers from Oslo airports to Trondheim airport and back have been taken from Norwegian statistics for 2010 (SSB 2011). Secondly, other means of transport (classic rail, car and coach) have been scaled up by using the percentages from Atkins Ltd (2011).

Table 4-8: Number of passengers for Oslo-Trondheim (2010)

	share (Atkins Ltd 2011)	per year	per day
Air	47 %	1,59 millions (SSB 2011)	4354
Car	31 %	1,05 millions	2872
Rail	17 %	575'000	1575
Coach	4 %	48'900	134
Total		**3,26 millions**	**8935**

Air is the mode of transport that clearly dominates the corridor Oslo-Trondheim. The Table below distinguishes between business and leisure.

Table 4-9: Share of business and leisure travels for Oslo-Trondheim (2010) (Atkins Ltd 2011)

	Air	Classic rail	Car	Coach
Business demand	**57 %**	18 %	8 %	8 %
Leisure demand	43 %	82 %	92 %	6 %

Air is dominated by business travels. Passengers with high value of time usually take flight. Journey times and frequency of services are core factors. In 2010, classic rail only provided 5 services a day, buses 2 while 28 flights were offered per day for Oslo-Trondheim. On the other hand, leisure travel is more uniformly shared between car, air and rail. This is due to the importance put by leisure travelers on minimizing travel costs and the ability to travel as a group. Also, traveling by car is very convenient for tourism trips or for making visits of extended duration, such as out-of-town sightseeing for instance (ibid).

The key market potential for HSR in Norway is air travel, which is currently dominated by business travel. This finding is shared by Schlaupitz (2008). International studies have shown that after introducing HSR, some air corridors have been canceled. Nevertheless, HSR has the potential to attract leisure travelers from long-distance routes, partly because HSR may allow the possibility of out-and-back travel within a day, avoiding the hotel costs associated with car use. To compete with air travel, HSR will need to provide a competitive service, in terms of frequency, journey times, fares, accessibility and comfort (ibid).

Norsk Bane (2009) is expecting around 8’800 pday in 2025 between Oslo and Trondheim for rail. On the other hand, Atkins Ltd (2010) is expecting 4920[15] pday (scenario D: building of new separate HSR line). The baseline-case of this project has been modeled with 5225[16] pday. Thus, the baseline case is between the findings from Norsk Bane (2009) and Atkins Ltd (2010). 8’800 pday (Norsk Bane 2009)

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[15] The numbers from Atkins Ltd have been computed by using the Norwegian Long Distance Transport Model (NMT5). For more information on the NTM5 model, please see the “Evaluation of the Norwegian long distance transport model (NTM5) by (Rekdal 2006)

[16] 38 journeys per day, train with 250 seats, load factor of 55%

seem to be quite high. It corresponds to the total passengers traveling today from Oslo to Trondheim with all modes of transport in 2011.

Seat capacity per train

Seat capacities per train are ranging from 140 to 360. Note that the first four numbers for HSL, AGV and "California HSR project" are projected numbers. The average seat capacity of trains in use today is ranging from 200 for X-2000 to 300 for AVE in Spain.

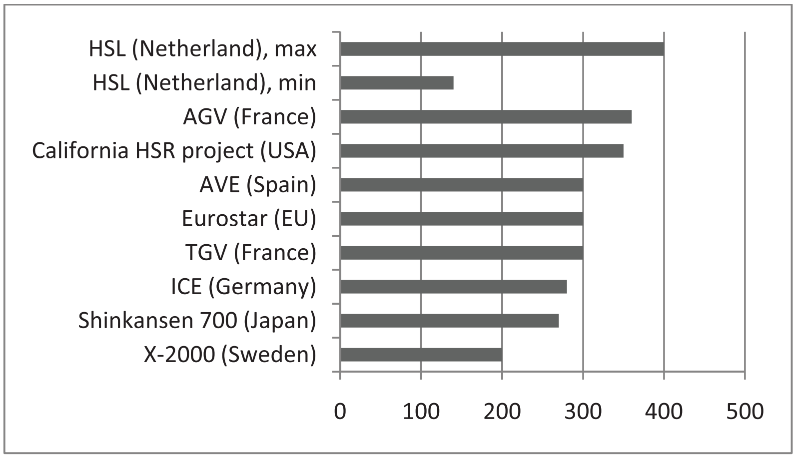

Figure 4-14: Seat capacity per train, international review

Seat occupancy or load factor

Local or regional trains usually need to have large seat capacity or standing areas for peaks in rush hours. These capacities are not used most of the day or year leading to low load factors, ranging from 20-40%. In contrast, modern high-speed trains with competitive travel time and ticket pricing usually have high load factors ranging from 50-75% and that is comparable to most domestic air lines. For instance, in 2004, the load factor for X 2000, a Swedish high speed train was of 55% (Anderson and Lukaszewicz 2006).

The load factor ($\frac{number\ of\ passenger-km}{offered\ number\ of\ seat-km}$) is the main determinant of energy consumption per passenger-km. In Scandinavia, load factors for fast regional services with electric trains vary from 20 to about 40% and the energy consumption ranges from 0.07 kWh/ pass-km for the highest load factor to 0.18kWh/pass-km. In contrast, for long-distance operations, load factors are quite high typically 55-60% and energy consumption is around 0.08kWh/pass-km. However, X 2000[17] trains nowadays transport more passenger than assumed previously. This is partly due to longer train and partly to higher load factors than anticipated in 1994. In 2004, the load factor was in the order of 55% instead of 44%, resulting in specific energy consumption of 0.075kWh/passenger-km (Anderson and Lukaszewicz 2006). Anderson and Lukaszewicz (2009) show in a recent study a further increase of the load factor for X200 to 60%, resulting mainly from a more active yield management.

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[17] Swedish high speed train with maximum speed in service of 200 km/h and a mass of 366 tonnes

Furthermore, they note that the average load factor for future high-speed trains might even be higher.

4.3 LIFETIME OF MAIN COMPONENTS

The figure below presents technical lifetimes used in previous environmental assessment for high-speed. They range from 10 to 100 years. The first three are used in Norwegian (N) studies, the next two for Swedish (S) studies and the last three for European studies (D=Germany, F=France, EU=Europe).

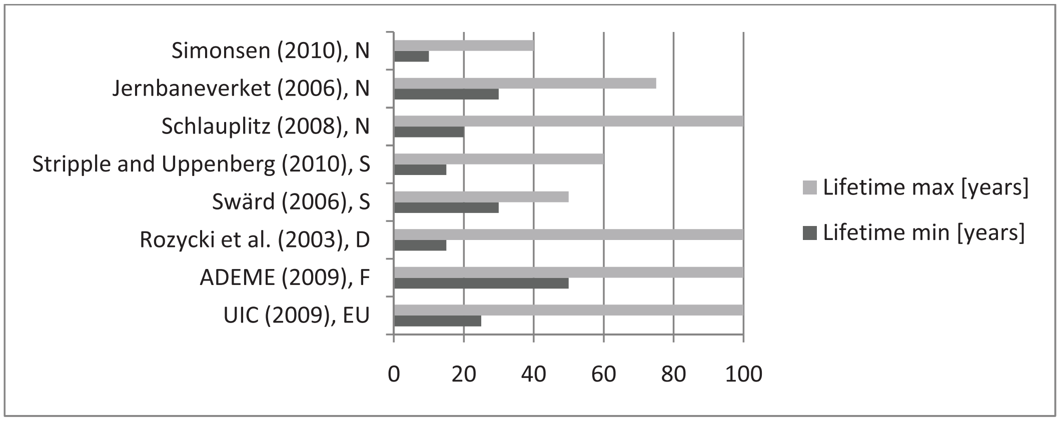

Figure 4-15: Lifetime min and max from previous environmental assessment

Swård (2006), through an empirical study, highlighted the extension of lifetimes thanks to good maintenance and, hence, the reduction of wearing. For instance, this can be achieved by grinding and lubricating the rails. On the other hand, the lifetimes might be reduced by more reusable designs that might reduce the weight of the components and thereby their lifetime.

4.4 RECYCLING AND REUSE

4.4.1 COMPONENT LEVEL

For Swedish railways, ballast-material, cables, rails and railway ties are reused. Ballast-material if sorted out in the cleaning process, can be mixed with others materials, and used further down in an embankment. It can also be used at marshalling yards or as filling material when constructing roads. A market is starting to develop in this last area. However, materials are often polluted, and might not be used for environmental reasons. Cables are not reused but can be recycled material. Rails taken away from the track go through a quality control before they can be reused. X-rays are used to find tendencies to fracture. Nevertheless, it is not possible for rails to go back to their original condition and standards exist on how much the head of the rail is allowed to be worn down. Railway ties are reused when possible. The major quantity is usually worn out when exchanged. Reuse of railway ties have good potential to increase in the future, as the new railway ties with the pandrol attachment appliances are more durable. On the other hand contact wire systems are not reused nor recycled. Components of contact wire systems get too worn out and therefore cannot be reused. They are often alloyed, making them more difficult to recycle (Swärd 2006).

4.4.2 MATERIAL LEVEL

Network Rail (2010) conducted a sensitivity analysis on embedded GHG emissions. A very significant impact on the final results is caused by the percentage of recycling of materials at the end of life of infrastructure and trains, to a much lesser degree. Because the effect of embedded infrastructure emissions dominates the overall assessment, the importance of designing easily recyclable infrastructure is highlighted.

Steel

Steel structures are usually easy to disassemble. They are most often produced in standardized dimensions and quite easy to re-use. On the other hand, steel used in reinforced concrete is not possible to reuse and must be recycled. Steel content can be up to 20% in reinforcement and the extracting process is relatively expensive and complex. Machines are used for crushing the concrete, electromagnets for separating, etc Steel in electric cables is nearly impossible to recycle due to copper. Another issue for steel of high quality – or chromium steel – is the surface treatment that can lead to complications when recycling (Berge 2009).

Cement

Cement is used to make concrete that is used in construction. Basically, cement is mixed with chemical admixtures and water to make concrete. Therefore, it is difficult to recycle cement per se but it is possible to recycle concrete that is made out of cement (Collins 2010).

5 SCENARIOS UP TO 2050

The first question in this project "What are the core factors for the environmental performance of HSR in Norway?" was answered in chapters 2 and 3. Some core factors found in chapters 2 and 3 were investigated further in chapter 4. In chapter 5, the last questions: "What are the likely development scenarios for these factors up to 2070?" and "What are the results of the implementation of the scenarios in an LCA of HSR in Norway?" are answered.

5.1 SCENARIOS DEVELOPMENT

"2010" consists of HSR-LCA without any updates in the database. Additionally, three scenarios have been developed:

1. **Updated 2010:** Only the background system has been adjusted. This is to account for the time span between the modeling of the LCA data from the database for the background and their use in HSR-LCA.

2. **2050:** The background and foreground system have been changed. The numbers for the background system are based on literature studies for 2050. This means that this scenario is feasible based on production technique and material available.

3. **2050+:** The background and foreground system have been modified. The numbers are based on scenario 2050. However, scenario 2050+ is beyond the average production techniques and quantity of materials available at that time. To reach the goals set in 2050+, the organization running the train and the infrastructure will have to dress a list of specific requirements to its suppliers in order to "deliver the transport service to meet the total transport demand" (functional unit). The requirements concern the materials and energy used in the production process. For instance, one could require from cement producers cement with 60% secondary materials and secondary fuel. Concerning operation the objective could be to drive the trains with a "clean electricity mix".

Table 5-1: Values for the parameters used in the scenarios

				Units	2010	Updated 2010	2050	2050+
Background	**Cement**	secondary material		% of secondary material	7 %	5 %	37 %	60 %
		secondary fuel		% of secondary fuel	4 %	18 %	37 %	60 %
	Steel	energy		% of decrease in energy use	-	10 %	20 %	40 %
		quality		% of chromium steel in rails	100 %	10 %	10 %	10 %
		Use of recycled steel	high quality	%	-	37 %	60 %	80 %
			low quality	%	37 %	37 %	60 %	80 %
			rails	%	-	37 %	60 %	80 %
	XPS	blowing agent	CO_2	%	50 %	70 %	90 %	100 %
			HFC-134a		25 %	10 %	-	-
			HFC-152a		25 %	20 %	10 %	-
Foreground	**El mixes for operation**			CF (g CO_2 per kWh)	166	166	130	100
	Energy per seat-km			kWh per seat-km	0,041	0,041	0,035	0,035
	Load factor			%	55 %	55 %	70 %	80 %
	Energy per pass-km			kWh per pkm	0,075	0,075	0,050	0,044
	Passenger per day			person (share of HSR)	5223 (43%)	5223 (43%)	8685 (72%)	9899 (82%)
	Trains per day			train	38	38	49	49
	Reuse	rails		% being reused further	-	-	-	18 %

Notes

1. Please see again figure 3: "Overview of HSR-LCA". The parameters used for the scenarios are "jumping" directly from the background system to the system level. Because the parameters are taken from the core factors investigated in chapter 4. No parameters is inserted into either the section level or the component level. For instance, on a section level, there is no variable to address the fluctuation of the overall impact of HSR-LCA if it were built not only with double track but a mix of double and single track. On a component level, a parameter could have been used to account for the reduction of the amount of steel/cement needed per component, as proposed by Stripple and Uppenberg (2010) as potentials to reduce CO_2 emissions embedded in steel and cement.

2. CCS is chosen as a solution to get a cleaner cement in the 2050 horizon (WBSCD and IEA 2009). Because the majority of the emissions for the production are occurring in CO_2 eq, it was tempting to use CCS to get rid of the CO_2 eq emissions. However, in an LCA perspective, the emissions are assessed from "source-to-wheel". Therefore, the impact of a CCS plant should also be included. Also, no CCS technology is modeled in the Ecoinvent database, making it difficult to use in this LCA study.

Cement

The base case consists of 7% of secondary materials and 4% secondary fuel. Both numbers have been changed to correspond with the European industry that used about 5% of secondary material and 18% secondary fuel in 2006 (CEMBUREAU 2009). WBSCD and IEA (2009) predict a use rate of 37% for both secondary materials and secondary fuel in 2050. The share of 60% for secondary materials for in scenario 2050+ is based based on Geopolymer cement (WBSCD and IEA 2009) that make use of waste material from the power industry (fly ash, bottom ash) and the steel industry (slag). The share of 60% for secondary fuel in scenario 2050+ is to reflect the share of secondary material.

Steel

The update of 10% in energy efficiency is based on my estimations. This number might be too high for the overall steel production modeled in the foreground system. A more appropriate approach would have been to apply this increase in energy efficiency to the oldest process of the database only. The 20% is based on the International Energy Agency that set the energy efficiency potential, based on today's best available technologies (IEA 2009). Nevertheless, by changing from open blast-furnaces to electric arc furnaces, the steel industry could also reduce its use of energy by 50% (Kram et al. 2001), leading to the number of 40% energy saving.

The quantity of chromium steel used in rails has been decreased due to an overestimation in "2010".

The share of recycled steel has been increased to 37% for the three different steels in "updated 2010"to match with the steel of low quality of "2010". Global scrap availability is today about 0.4 ton of scrap per ton of crude steel produced. If by 2050 today's level of crude steel production were to double, scrap availability is estimated to amount to about 0.6 ton per ton of crude steel (Rubel et al. 2009). "2050" has 60% recycled steel, based on scrap available in 2050. "2050+" has 80% recycled steel, implying that a commitment has to be taken to buy "steel that is made out of 80% of scrap".

XPS

The use of CO_2 as blowing agent is increased. CO_2 is more environmentally than HFC-134 and HFC152a as blowing agents.

Electricity mix for operation

The mix for scenario 2050 consists of 70% renewable (hydro), 16% fossils (8% coal, 8% natural gas) and 10% nuclear. The mix for scenario 2050+ consists of 80% renewable (hydro), 12% fossils (6% coal, 6% natural gas) and 10% nuclear. I have developed these new electricity mixes using the

Ecoinvent data version 2.2. It is difficult to know what electricity mixes will be representative of the average electricity mix offered on the market in 2050. For instance, Graabak and Feilberg (2011) quantify the emissions of CO_2 from the power system in Europe in a time perspective up to 2050. They created scenarios on variations in demand. The specific emissions from the electricity mixes are ranging from 361 g CO_2 /kWh to 31 g CO_2 /kWh.

Energy per seat-km

The numbers are based on the report by Lukaszewicz and Anderson (2009) who estimate green train energy consumption for high-speed rail operations.

Load factor

In 2004, the load factor was in the order of 55% for the X2000 (Anderson and Lukaszewicz 2006). Anderson and Lukaszewicz (2009) show in a recent study a further increase of the load factor for the X2000 to 60%, resulting mainly from a more active yield management. Furthermore, they note that the average load factor for future high-speed trains might even be higher. The 70% for scenario 2050 are is an increase based on the estimation of the author from the load factor of 55% in 2010. To reach the 80% of scenario “2050+”, an active yield management will be required.

Energy per pass-km

The energy per pass-km is obtained by dividing the energy per seat-km by the load factor.

Passengers per day

The original number of 12147[18] pday for all mode of transportat is kept and developed further in scenario 2050 and 2050+. In scenario 2050, HSR gains benefit from all mode of transport that loose 50% of their passengers. Additionally, in scenario 2050+, the airline Oslo-Trondheim is deleted.

Trains per day

Trains per day are increased by 30% (38 to 49) to satisfy the demand of the increased number of pday from scenario 2010 to scenario 2050+. Note that the number of seats of 250 seats per train remains constant.

Reuse

The reuse of rail is estimated at 18%. This number is taken from Swärd (2006) who allocates 38 GJ/year to rails used on main line tracks and 7 GJ/year to rails used in regional tracks.

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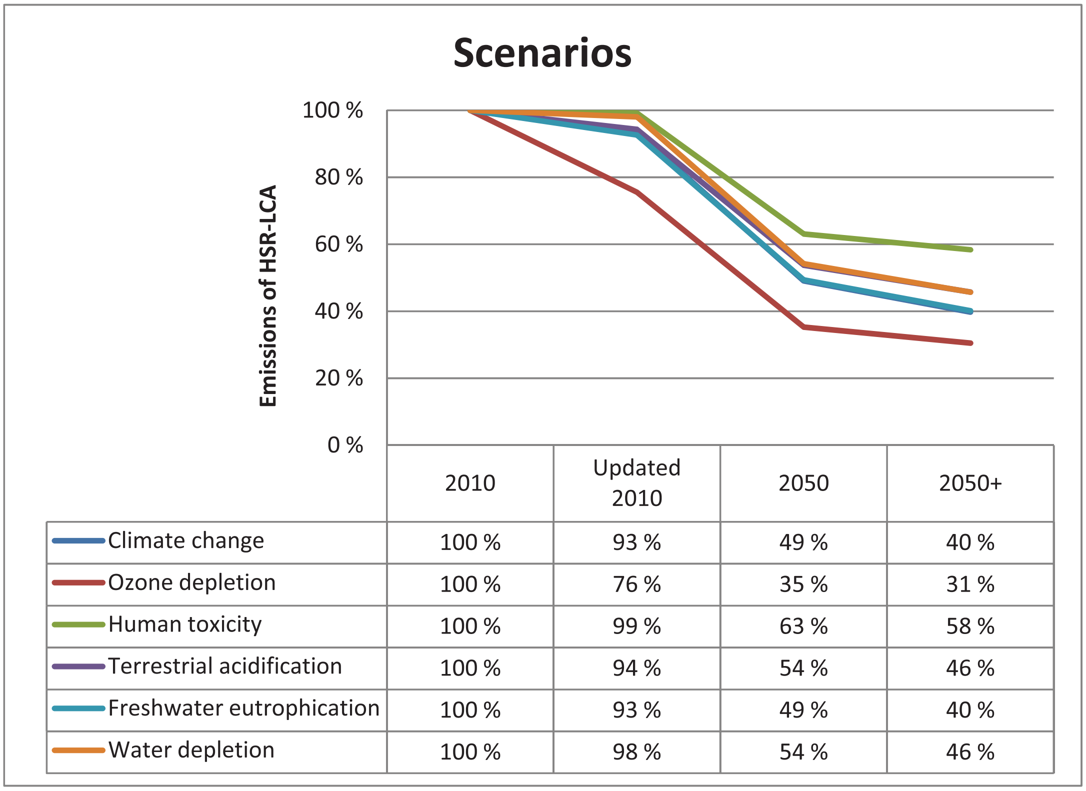
[18] 5223pdy/43%, 43%= share of HSR

5.2 PRESENTATION OF THE RESULTS

The figure below shows the results for the three scenarios for the six impact categories. Emissions are on average of 83% of the total for scenario Updated 2010, of 57% of the total for scenario 2050 and of 48% of the total for 2050+[19]. Emissions could be reduced by almost 20% by adjusting the database, by 50% in a likely future and by 60% by setting specific objectives to have a "green HSR". It appears as though the potential for reducing emissions for HSR transport service is huge. For all scenarios, human toxicity consists of the upper limit and ozone depletion of the lower limit.



	2010	Updated 2010	2050	2050+
Climate change	100 %	93 %	49 %	40 %
Ozone depletion	100 %	76 %	35 %	31 %
Human toxicity	100 %	99 %	63 %	58 %
Terrestrial acidification	100 %	94 %	54 %	46 %
Freshwater eutrophication	100 %	93 %	49 %	40 %
Water depletion	100 %	98 %	54 %	46 %

Figure 5-1: Results of the scenarios

- **Climate change:** The decrease comes to a large extent from the use of secondary materials in the clinker production for cement, to the higher use of recycled steel for steel of low quality. To a lesser extent, it comes from the increase in energy efficiency for steel of high and low quality, from the use of recycled steel for steel of high quality and from the decrease of use of chromium steel for rails
- **Ozone depletion**: All the impact categories are following a general trend. Nevertheless, the slope for ozone depletion is sharper from 2010 to "updated 2010". This is due to the shift in

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[19] Each impact category is given the same weight. How correct it is to allocate the same weight to all the impacts could be discussed further. For example, the 83% would go up quickly if less weight would be given to ozone depletion. Nevertheless, the idea here is to give an indication of the overall impact of each scenario.

blowing agent in XPS production to a large extend and to the use of secondary fuel in clinker production and the increase in energy efficiency for steel of high and low quality to a minor extend.

- **Human toxicity:** The curve follows the general trend. The decrease comes from the increase in energy efficiency for production of steel of low quality to a large extent and from the increase in energy efficiency for production of steel of high quality to a lesser extent. Nevertheless, the reason why the slope of the curve is less sharp is due to the increase use of recycled steel.

  The major feedstock for the production of recycled steel is ferrous scrap. Scrap can consist of scrap from inside the steel-works, cuts-offs from steel product manufacturers (e.g. vehicle builders) and capital or post consumer scrap (e.g. end of life products) (Classen et al. 2009). Emissions of heavy metals depend largely on the scrap quality. Cadmium is one of the main contributors to human toxicity. This heavy metal is principally consumed for the production of rechargeable nickel cadmium , for other end uses such as pigments, coatings and plating and as stabilizers for plastics (USGS 2011). If end of life products are used as scrap source, an unavoidable amount of cadmium will enter the secondary steel production system due to for example coatings. Cadmium being one of the main contributor of human toxicity, this is one of the reason of why human toxicity increases with the increase of the use of scrap.
- **Terrestrial acidification:** The decrease comes mainly from the increase in energy efficiency for both steel of high and low quality and the increase rate of recycled steel for steel of low quality.
- **Freshwater eutrophication:** The decrease comes mainly from the increase in energy efficiency and the increase rate of recycled steel for steel of low quality.
- **Water depletion:** The decrease is mainly due to the increase use of recycled steel for steel of high and low quality

System level

The table below shows the results on a system level for climate change only.

Table 5-2: Scenarios results - System level - climate change

		2010	Updated 2010	2050	2050+
Infrastructure	g CO2 eq per pkm	104,74	96,69	52,38	40,73
Operation	g CO2 eq per pkm	13,75	13,75	5,08	5,79
Rolling stock	g CO2 eq per pkm	0,81	0,81	1,07	0,94
HSR-LCA	**g CO2 eq per pkm**	**119,29**	**111,25**	**58,52**	**47,45**

- The results for infrastructure decrease. From “2010” to “updated 2010”, the decrease is due to changes of technology in material production in the background system. For “2050” and “2050+”, the decrease is due to changes of technology in material production in the background system and in increased numbers of passengers per day in the foreground system.
- On the one hand, the results remain constant from “2010” to “updated 2010” for operation. This is not uprising since no changes are made in the foreground system. On the other hand, it is interesting to note that even if the number of passengers increases, the overall emissions for operation per pkm decrease from “2050” to “2050+”. This is due to cleaner electricity mixes used, higher load factor and lower energy per seat.
- The results for rolling stock first remain constant and then increase. As for operation, no change is made in the foreground system from “2010” to “updated 2010”, leading to a satus quo for rolling stock as well. The increase from “updated 2010” to “2050” is due to the higher number of trains used. The results decrease from “2050” to “2050+” because even if the number of trains remains constant, the load factor is higher, leading to a lower impact per passenger.

6 DISCUSSION

6.1 METHODS AND SOURCES

The six impact categories chosen gave a larger perspective than previous studies. For instance, Stripple and Uppenberg (2010) addressed climate change only. For the construction of the infrastructure of the Botnia Line, they found an impact of 1% for copper and 3% for explosives. For the construction of the infrastructure of HSR-LCA, I found an impact of 18% for copper for human toxicity and an impact of 41% for explosives for terrestrial acidification.

Nevertheless, there are many sources of railway traffic pollutants and not all of them were addressed. For instance, the emissions of particle were not addressed. Particles have several sources such as the dust created by the excavation and construction work, the emissions arising due to the maintenance of the rails and the railway wear particles. Gustafsson et al. (2007) underline the importance of the inhalable fraction of railway wear particles. Even if the magnitude of the different sources is not clear, wear of rails, wheels and brakes have been pointed out. The composition of the railway wear particles consists mainly of iron. Other metals such as zinc, manganese, copper, chromium and nickel are found in lower concentration. Submicron particles, which are considerably smaller than railway wear particles, are emitted from traffic. Their origin is unknown.

6.2 ASSESSMENT AND APPLICATION OF THE RESULTS

To reassess the results, it would be interesting to apply the updates of scenario “updated 2010” on the model and to apply the updated model on another corridor with a higher number of tunnels and bridges, for example the corridor Oslo-Bergen (Metier 2007).

6.3 ALLOCATIONS ISSUES

The use of secondary materials for cement production has been pointed out as one of the main potential to reduce the impact of climate change. However, an allocation issue remains. The case of metallurgical slags from steel production is described below to explain this issue:

The production of steel generates by-products. The most significant by-product is metallurgical slags. They can either be used as civil works aggregates or as substitute for clinker in cement production. The cement industry, by adopting extensive use of such slags could play a key role in reducing the CO_2 emissions from both industries. The remaining question is: how will both industries share the benefits of this emission reduction in their overall carbon footprint? Clinker production for use in cement consumes by far the largest percentage of energy and is allocated most of the industry’s emissions. By using blast furnace slag, the clinker content in typical Portland cement could be reduced from 90% down to about 30%, or even below that level (Rubel et al. 2009). According to the International Energy Agency, this substitution will lead to reductions in annual energy consumption up to 0.5 exajoule and up to 200 million tons of CO_2 emissions, annually.

6.4 USE OF HIGH-SPEED TRAIN FOR PASSENGER AND/OR FREIGHT

On the one hand, future Norwegian HSR will only carry passengers (Pettersen 2011). On the other hand, the impact of the infrastructure of future Norwegian HSR is high, mainly because it is lacking passengers.

Nowadays, Norwegian freight transport is dominated by road (47%) and sea transport (46%). Rail transport only accounts for 7% (Monsrud, 2009). There is a huge potential to transfer freight to rail. If tripling the capacity for rail freight transport by 2030, Statens vegvesen (2010) expects a reduction of 165’000 tonnes of GHG emissions.

If HSRs infrastructure was not only used for passenger transport but also for freight, the environmental impacts of constructing and maintaining it would not only be divided up by passengers, but by passengers and freight. Simonsen (2010) proposed a method to give different weights to passengers and freight for the construction, operation and maintenance of road infrastructure. These numbers could be used as basis to find out specific numbers to rail.

Schlaupitz (2008) underlines the importance of including freight already in the construction phase in order to find out solutions for the use of infrastructure.

6.5 FUTURE WORK

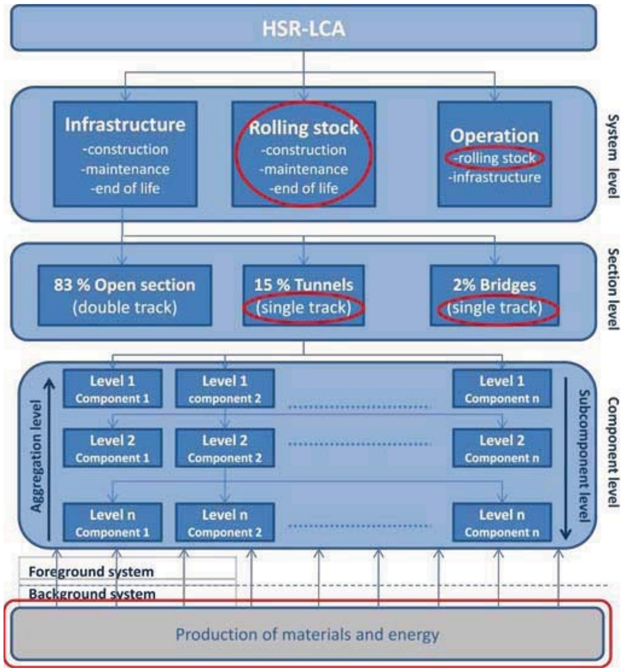

Figure 6-1: HSR-LCA – Overview of the parts investigated

The parts of the model that were investigated in this project are circled in red.

- **Background system**: The production of materials was investigated carefully. An additional step could be to analyze specific electrical power for the different processes, as did Stripple and Uppenberg (2010) for the Botnia Line.

- **Component level**: The effect of a change of choice, amount or design of material for a component could be investigated. For instance, steel has a very long lifetime. Steel's strength and durability allow for long product life cycles. For instance, buildings and bridges made with steel last from 40 to 100 years, or longer with proper maintenance (World Steel Association 2008). Therefore, not only the emission due to the initial production should be considered but a key contribution from the steel industry is to work closely with its customers to optimize the design and use of steel in steel-using products in order to reduce the overall footprint (World Steel Association 2010).

- **Section level**: The results found for HSR-LCA indicated that open sections have a high impact. When comparing open sections of HSR-LCA with other studies, they are found at the top of the scale of the results of the different open-sections. The open sections of HSR-LCA are based directly on the open section developed by Korsmo and Bergsdal (2010) for the Follobanen. The Follobanen has the specificity of having extensive structures concentrated on short stretches. This could be one of the reasons for this high result. Future work should reconsider the open sections and base them on other existing HSR lines. Also, Oslo-Trondheim consists of the line with the lower share of tunnels and bridges. It would be interesting to see results for the line Oslo-Bergen, which has a high share of tunnels and bridges (Metier 2007).

- **System level**: The construction and maintenance phases of infrastructure are heavy. The maintenance will be done in the future, while the construction will be done "today". New technologies that might be found in the near future should definitely be considered for maintenance.

7 CONCLUSION

The conclusion is presented by answering the three research questions.

What are the core factors for the environmental performance of HSR in Norway?

- Cement
- Steel
- XPS
- Infrastructure
- Deforestation
- Passengers per day

Cement, steel and XPS are the materials that have the most impact. The share of the infrastructure of future Norwegian HSR is high because of the impacts of the materials used but also because of the low number of passengers and the low CF of the electricity mix used for operation. A high Norwegian number of passengers consists of a low European number of passengers (UIC 2009). Norwegian HSR is lacking passengers. A high potential to have more passengers on HSR is to abstract passenger from air, which is the most used mode of transport in Norway at this time (Atkins 2011).

The energy used for operation and the energy per seat-km are not core factors because the electricity mix used for operation has a low CF (166 g CO_2/kWh). Deforestation has been identified as a core factor. Nevertheless, it has not been modeled.

What are the likely development scenarios for these factors up to 2050?

- Cement: Decrease of the impact due to an increase of the use of secondary materials and secondary fuel for the production of clinker.
- Steel: Increase in energy efficiency by 20% and use of scrap up to 60%
- XPS: Use of CO2 as blowing agent only
- Infrastructure: Decrease of impact due to changes of technology in material production in and to increased numbers of passengers per day
- Passengers per day: Increase due to the transfer of passengers from other mode of transport to HSR

What are the results of the implementation of the scenarios in an LCA of HSR in Norway?

The impact of future Norwegian HSR is reduced on average by 17% by updating the database, by 50% in a likely future and by 60% in a scenario where more resources than available are used. For instance, for steel, more than the scrap amount available by 2050 is used. If more scrap than available is used for HSR in Norway, it means that less will be available elsewhere. The impact of HSR will decrease while the global emissions will still increase as the emissions will emitted elsewhere. Furthermore, in HSR-LCA, no distinction is made between local and global emissions. Are the heavy emissions from the production of steel allocated to Norway, even if no steel is produced in Norway or to the country that is producing the steel that Norway buys for its HSR infrastructure?

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9 APPENDICES

9.1 APPENDIX 1: LCA MATHEMATICS

LCA mathematics are the same as input-output analysis (IOA) mathematics which are based on flows between economic agents. As a rule, physical flows (products, materials, energy and waste) between economic agents are accompanied by monetary flows. Usually, physical and monetary flows go in opposite directions. For instance an electric power plant sends electricity to a steel factory. In return, the steel factory sends some money back to the power plant. In some cases, physical and monetary flows can have the same direction. A factory which sends chemical waste to a waste incinerator has to send money in that direction as well (Suh 2007).

While LCA flows are usually accounted for in physical flows, IOA flows are usually physical. LCA are conducted to assess the impacts of a given product or production system. IOAs are generally conducted for macroeconomic assessments. For instance, an IOA can be used to assess the production of average primary aluminium while an LCA can distinguish further between different aluminium alloys. Both LCAs and IOAs describe inter-process relations. On the one hand, an LCA gives a better level of details than an IOA. On the other hand, IOAs are generally more complete at the national level (Strømman and Suh 2007).

IOA and LCA mathematics

After World War II, Wassily Leontief (1905-1999) was concerned with the conversion of the US economy (Polenske 2004). In the late 1930s, he devised the revolutionary IO method that can depict the inter-industry relation of an economy by showing how the output of an industry is the input of another industry. He could then predict the effect of the changes of an industry on another and analyze the interdependence of industries in an economy. Today, input-output analysis had become one of the most widely applied methods in economics (Miller and Blair 1985).

The following methodology is taken from the handbook of input-output table compilation and analyses (United Nations 1999):

1. **Goods flows between industries**

Consider three producers and their transactions. F_{ij} are the flow of goods from industry *i* to *j*.

Table 9-1: IO flow table and accounts

	Industry 1	Industry 2	Industry 3	Final demand	Total output
Industry 1	F_{11}	F_{12}	F_{13}	y_1	x_1
Industry 2	F_{21}	F_{22}	F_{23}	y_2	x_2
Industry 3	F_{31}	F_{32}	F_{33}	y_3	x_3
Total input	x_1	x_2	x_3		

2. Technical relationships between industries

A fundamental assumption is that for a given time period the interindustry flow F_{ij} depends entirely and exclusively on the total output x_j of sector j for that same time period. Input and output relationships are transformed into technical relationships by using technical coefficients a_{ij}:

$$a_{ij} = \frac{F_{ij}}{x_j} \tag{3}$$

All the coefficients a_{ij} can be grouped in an A matrix:

$$\begin{bmatrix} a_{11} & \cdots & a_{1j} \\ \vdots & \ddots & \vdots \\ a_{i1} & \cdots & a_{ij} \end{bmatrix} \tag{4}$$

3. Effects along the value chain

With the input structure represented by the A matrix, it is possible to obtain the amount of all the inputs each industry requires in order to produce one unit of its output. However, this does not tell us anything about the inputs required before, all along the value chain. The production of a product generates a long chain of interaction in the production processes. Each product can be used as inputs for other products but also as input for itself. This creates a chain of requirement that goes to infinity:

$$\lim_{n\to\infty} \sum_{i=0}^{i=n} A^i = I + A + A^2 + \ldots + A^n = (I - A)^{-1} = L \tag{5}$$

L is the Leontief inverse matrix that depicts the full impact of an increase of final demand y on all industries. The total output is obtained by multiplying the Leontief inverse matrix L by the vector of final demand y.

$$x = (I - A)^{-1} y = Ly \tag{6}$$

Note that even if the mathematics of input-output economics are not too complicate, especially now with powerful computers available to compile and inverse the matrices, the data requirements are enormous because the expenditures and revenues of each branch of economic activity have to be represented.

4. Computations of the emissions

The total output x of the system above is multiplied by a stressor matrix S in order to have the total emissions for a given demand y. S gives the emissions emitted by each process.

$$Total\ emissions = SLy \tag{7}$$

9.2 APPENDIX 2: LIST OF THE PARAMETERS

The table below gives the list of the parameters used in HSR-LCA, their value in the base case (scenario 2010), the process(es) where they are used.

Table 9-2: List of the parameters used in HSR-LCA

	Parameters	Base case	Processes	Remarks
Basis steps	A	0	Cement, at plant/CH U_PARAMETER	
			Betongstøp	
			Sement	
			Sikringsstøp	
			Betong, elementer	
			Stål (lavkvalitet)	
	B	1	Cement, at plant/CH U_PARAMETER	
			Betong, elementer	
			Betongstøp	
			Sikringsstøp	
			Sement	
			Stål (lavkvalitet)	
Cement	clinker_1mat	1	Clinker, at plant/CH U_PARAMETER	*7% sec material*
	clinker_1fuel	1	Clinker, at plant/CH U_PARAMETER	*take specific MJ/kg into account to change it*
	clinker_2fuel	1	Clinker, at plant/CH U_PARAMETER	*take specific MJ/kg into account to change it*
Energy efficiency	steel_coke	1	Steel, converter, chromium steel 18/8, at plant/RER U_PARAMETER	*can vary from 1 to 0*
			Pig iron, at plant/GLO U_PARAMETER	
			Steel, converter, unalloyed, at plant/RER U_PARAMETER	
			Sinter, iron, at plant/GLO U_PARAMETER	
			Ferronickel, 25% Ni, at plant/GLO U_PARAMETER	
	steel_ng	1	Steel, converter, chromium steel 18/8, at plant/RER U_PARAMETER	*can vary from 1 to 0*
			Pig iron, at plant/GLO U_PARAMETER	
			Steel, converter, unalloyed, at plant/RER U_PARAMETER	
			Steel, electric, chromium steel 18/8, at plant/RER U_PARAMETER	
			Steel, electric, un- and low-alloyed, at plant/RER U_PARAMETER	
			Sinter, iron, at plant/GLO U_PARAMETER	
			Pellets, iron, at plant/GLO U_PARAMETER	
			Ferronickel, 25% Ni, at plant/GLO U_PARAMETER	
	steel_coalmix	1	Pig iron, at plant/GLO U_PARAMETER	*can vary from 1 to 0*
			Steel, electric, chromium steel 18/8, at plant/RER U_PARAMETER	

			Steel, electric, un- and low-alloyed, at plant/RER U_PARAMETER	
			Pellets, iron, at plant/GLO U_PARAMETER	
	steel_diesel	1	Ferronickel, 25% Ni, at plant/GLO U_PARAMETER	*can vary from 1 to 0*
Decrease in direct emissions due to increase in energy efficiency	direct_coal	1	Steel, converter, chromium steel 18/8, at plant/RER U_PARAMETER	*= steel_coalmix*
			Pig iron, at plant/GLO U_PARAMETER	
			Steel, electric, chromium steel 18/8, at plant/RER U_PARAMETER	
			Steel, electric, un- and low-alloyed, at plant/RER U_PARAMETER	
			Pellets, iron, at plant/GLO U_PARAMETER	
			Ferronickel, 25% Ni, at plant/GLO U_PARAMETER	
	direct_ng	1	Steel, converter, chromium steel 18/8, at plant/RER U_PARAMETER	*= steel_ng*
			Pig iron, at plant/GLO U_PARAMETER	
			Steel, converter, unalloyed, at plant/RER U_PARAMETER	
			Steel, electric, chromium steel 18/8, at plant/RER U_PARAMETER	
			Steel, electric, un- and low-alloyed, at plant/RER U_PARAMETER	
			Sinter, iron, at plant/GLO U_PARAMETER	
			Pellets, iron, at plant/GLO U_PARAMETER	
			Ferronickel, 25% Ni, at plant/GLO U_PARAMETER	
	direct_coke	1	Pig iron, at plant/GLO U_PARAMETER	*= steel_coke*
			Steel, converter, unalloyed, at plant/RER U_PARAMETER	
			Sinter, iron, at plant/GLO U_PARAMETER	
Recycling	steel_high_chrom	1	Stål (høykvalitet)_rails	*% of chromium steel for steel of high quality, can vary from 1 to 0*
	steel_high_2ndqual	0	Stål (høykvalitet)_rails	*1-steel_high_chrom*
	steel_rec_high	0	Stål (høykvalitet)	*% of recycling of steel of high quality, can vary from 0 to 1*
	steel_primary_high	1	Stål (høykvalitet)	*1-steel_rec_high*
	steel_rec	0,37	Reinforcing steel, at plant/RER U_PARAMETER	*% of recycling of steel of low quality, can vary from 0 to 1*
	steel_primary	0,63	Reinforcing steel, at plant/RER U_PARAMETER	*1-steel_rec*
	steel_rec_rails	0	Stål (høykvalitet)_rails	*% of recycling of steel for rails, can vary from 0 to 1*
	steel_primary_rails	1	Stål (høykvalitet)_rails	*1-steel_rec_rails*

Blowing agents	XPS_CO2	0,5	Polystyrene, extruded (XPS), at plant/RER U_PARAMETER	*can vary from 0 to 1, XPS_CO2+XPS_134+XPS_152=1*
	XPS_134	0,25	Polystyrene, extruded (XPS), at plant/RER U_PARAMETER	
	XPS_152	0,25	Polystyrene, extruded (XPS), at plant/RER U_PARAMETER	*= 1-XPS_CO2-XPS_134*
Electricity mix for operation	el_op_baseline	1	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	CF_130	0	Operation (kWh), Tot_strekning_60years	*Electricity mixes used for the scenarios*
			Operation vkm	
	CF_100	0	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	el_op_coal	0	Operation (kWh), Tot_strekning_60years	*Electricity mixes used for the sensitivity analysis*
			Operation vkm	
	el_op_wind	0	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	el_op_nuclear	0	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	el_op_hydro	0	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	el_op_europe	0	Operation (kWh), Tot_strekning_60years	
			Operation vkm	
Energy required	e_skm	0,041		*only for calculations*
	load_factor	0,55	Infrastructure_pkm	*can vary from 0 to 1*
			Operation (kWh), Tot_strekning_60years	
			Operation vkm	
			Operation_pkm	
			Oslo-Trondheim_pkm	
			Rolling stock_pkm	
	e_pkm	0,0745	Operation (kWh), Tot_strekning_60years	*= e_skm/load_factor*
			Operation vkm	
Trains	train_day	38	Infrastructure_vkm	
			Operation (kWh), Tot_strekning_60years	
			Operation vkm	
	increase_trains	1	Rolling Stock_60years_livsløp	
			Rolling stock_vkm	
Reuse	rails_reuse	1	Strekning3_Jernbaneteknikk	*1= no reuse, 0=100% reused*
			Strekning2_1løp_Jernbaneteknikk	
			Strekning2_2løp_Jernbaneteknikk	

Coefficients to switch from 1 to 2 tracks	bridge2_1		ConcreteBridge_1track_construction	*Coefficient to switch from double to single track for bridges*
			ConcreteBridge_1track_EndofLife	
			ConcreteBridge_1track_EndofLife	
			ConcreteBridge_1track_Waste	
			ConcreteBridge_1track_Waste_EndofLife	
			SteelBridge_1track_Construction	
			SteelBridge_1track_Maintenance	
			SteelBridge_1track_Waste_EndofLife	
	tunnel2_1		Tunnel_1track_Construction	*Coefficient to switch from double to single track for tunnels*
			Tunnel_1track_EndofLife	
			Tunnel_1track_Maintenance	
			Tunnel_1track_Waste	
			Tunnel_1track_Waste_EndofLife	