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Early-phase Life Cycle Assessment of New Concepts for Fjord Crossings Along Coastal Highway Route E39

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MASTER THESIS

for

Student Ole Magnus Iversen

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Early-phase life cycle assessment of new concepts for fjord crossings along Coastal Highway Route E39

Tidligfase livsløpsvurdering av nye konsepter for fjordkryssinger ved Ferjefri E39

Background and objective

The background of this master thesis is current political and technological debates concerning possible developments of a ferry-free road connection along the western coast of Norway, from Kristiansand to Trondheim. Due to the region's challenging topography with deep and wide fjords, new and innovative solutions for fjord crossings will need to be developed, and the Norwegian Road Administration has already started this work.

Challenging fjord crossings require novel solutions and new technology in combination with existing technology. Some early concepts indicate that the structures that will require large material quantities and have a significantly higher environmental footprint than traditional crossings. There are also large uncertainties concerning the construction, installation and maintenance of these new and unconventional structures, and the potential environmental impact from this.

The objective of this master thesis is to contribute to the understanding of environmental impacts from new concepts for fjord crossings, and their contribution to the environmental performance of new transport solutions, by performing an LCA of a selection of proposed concepts for fjord crossings for the planned Coastal Highway Route E39. The work should build on the student's previous work with establishing a life cycle inventory based on "prosesskoder", and evaluate how suitable this system is for unconventional structures, and whether new adaptations or modules would be recommended. Attention should be devoted to unknown factors in the construction phase, i.e. any special requirements related to construction of components, transport to construction site, anchoring and mooring etc.

Results from the LCA should be compared to LCA results for conventional road infrastructure and if appropriate to emissions from traffic. Crossing concepts should be evaluated as part of a transport system in a life cycle perspective to assess the environmental trade-offs between infrastructure investments and operation.

The following tasks are to be considered:

1. Carry out a literature study on concepts and technologies that are relevant for the work. Identify knowledge gaps and parts of the system that are insufficiently understood.
2. Provide a systems definition, including description of goal and scope, system boundaries, data inputs and assumptions.
3. Develop a life cycle inventory for the construction, maintenance and operation of the selected crossing concepts.
4. Develop a model in SimaPro based on the existing model for "prosesskoder", evaluate the suitability of the existing model, and develop new modules or extensions where needed.
5. Report results from the LCA and identify and assess uncertainties and sensitivities for key parameters.
6. Compare your results with existing LCA knowledge of conventional road infrastructure. Evaluate proposed crossings as part of a transport system and compare this with alternative scenarios for some selected examples.
7. Develop a written report according to scientific criteria, with discussion of findings, agreement with literature, strengths and weaknesses of your methods, and possible practical and/or methodological implications and recommendations of your work.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his/her 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 analysed 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.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 14th January 2014

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Preface

This work concludes my education at the Norwegian University of Science and Technology (NTNU), within the International Master's programme of Industrial Ecology. The master's thesis was conducted in collaboration with the environmental systems analysis consultancy MiSA AS a subsidiary of Asplan Viak AS, and with support and data material from the Norwegian Public Road Administration (Statens vegvesen). To be able to work with inputs from academia at NTNU, experienced environmental analysts at MiSA, and road infrastructure specialists from Statens vegvesen has been very helpful. I would strongly recommend future students in Industrial Ecology to establish the same type of contact with the industry or sector they are analyzing.

The attached work description was used as a basis for the scope of this thesis, with one exception. The SimaPro-model created prior to this thesis based on process codes (prosesskoder) from Statens vegvesen was not developed further. The main reason for this is that the material quantities from the proposed concepts for crossing the Sognefjord are not described within the process code framework.

I want to thank my supervisors Professor Helge Brattebø from NTNU, and Håvard Bergsdal at MiSA for their good advice and support throughout this process. Their insight has been very important for choosing, and also limiting the scope of this thesis to achieve a reasonable and presentable result. I did the majority of my work at the office of MiSA, and want to thank everyone there for including me in their work environment. I also want to thank Mohammed Hoseini from Statens vegvesen for his support, and for putting me in contact with the Coastal Highway Route E39 (Ferjefri E39) project. My gratitude goes out to all the people in Statens vegvesen who took their time to answer my phone calls and emails. They are too many to be listed here, but their contributions have been highly important.

Lastly I want to thank my friends, family and loved ones for supporting me throughout this process.

Ole Magnus Kålås Iversen
June 2014

Abstract

The goal of this thesis was to analyze the potential indirect environmental impacts, mainly greenhouse gas (GHG) emissions associated with the construction of novel fjord crossings along Coastal Highway Route E39 in Norway. This was done by conducting an early-phase Life Cycle Assessment (LCA) of the concepts claimed technically feasible for crossing the Sognefjord. The contribution of GHG-emissions from fjord crossing infrastructure compared to traffic related emissions was investigated in detail. The GHG-emissions related to the Sognefjord crossing were applied in a fictional fjord crossing scenario to calculate potential payback periods for the infrastructure investment. In addition, a simplified analysis was conducted based on the two (previous) route choice alternatives of Hafast and Fefast along route E39.

The literature review showed that there are significant differences between the GHG-emissions associated with road infrastructure. For bridges, the material production phase is identified as the main source of emissions. The construction, operation and maintenance related activities are of less importance. However in most studies the construction phase seems to be roughly estimated, or based on a scarce amount of data. When traffic is included, it is the main contributor to GHG-emissions per kilometer of road in a life cycle perspective.

The GHG-emissions associated with of each of the three Sognefjord crossing concepts were calculated to be around 100 times higher than traditional road infrastructure per kilometer. Life cycle phases considered were material production, construction, operation and maintenance over 100 years. The Submerged Floating Tunnel (SFT) was found to have the highest total emissions, with about 605 900 tonnes of CO_2-equivalents. The Suspension Bridge (SB) had emissions of 493 200 tonnes, and the Floating Bridge (FB) approximately 380 800 tonnes of CO_2-eq in the conducted analysis. The material production phase was responsible for more than 94 % of the emissions in all three cases. The production of concrete, construction and reinforcement steel was the major contributor in this phase.

On a per kilometer basis the SFT emitted approximately 148 400 tonnes, the SB 133 300 tonnes, and the FB 86 500 tonnes of CO_2-eq. Comparing the three fjord crossing concepts by their effective roadway area used directly for vehicle operation offers another picture. The SB is the highest emitting structure per m^2 of effective roadway area, with about 1 160 kg of CO_2-eq. The SFT and FB had emissions of respectively 1 060 and 910 kg of CO_2-eq per m^2. The SFT had the highest total energy consumption and the highest impact in the majority of the other environmental impacts considered in the analysis. In a 40 year time horizon, traffic related emissions were responsible for less than 21 % of the total GHG-emissions when included for the Sognefjord crossing concepts. This result differs from the literature, where the traffic related emissions mostly are the dominant source compared to the infrastructure.

Several of the calculations from the fictive fjord crossing scenario indicated GHG-emission payback periods of more than 100 years for technologically advanced fjord crossings. This occurred when the AADT was lower than 2000 or the replaced road shorter than 8 km. A future reduction of CO_2-emissions from fuel combustion due to improved vehicle technology was also associated with payback periods longer than 100 years. The GHG-emissions related to the Hafast and Fefast route alternatives were almost equal in a 40 year time perspective. This was due to the Fefast alternative including more emission intensive infrastructure than the 13 km longer Hafast route.

The results from the LCA conducted in this thesis gave considerably higher GHG-emissions related to road infrastructure than previous studies. This was mainly due to the high material consumption of the fjord crossing concepts. The emissions associated with the infrastructure were still significant even when traffic related emissions were included in different scenarios. If Norway is to reach its emission reduction targets, road infrastructure related GHG-emissions of this scale should be taken into account when planning road corridors and designing fjord crossing concepts.

Sammendrag

Hovedmålet med denne oppgaven var å evaluere indirekte klimagassutslipp knyttet til utbygging av moderne fjordkryssingsløsninger for en fremtidig Ferjefri E39. En tidligfase livsløpsvudering (LCA) ble gjennomført for fjordkryssingsløsningene som er blitt fastslått teknisk gjennomførbare for en permanent kryssing av Sognefjorden. Klimagassutslippene knyttet til fjordkryssingsløsninger sammenlignet med utslipp fra vegtrafikk ble undersøkt i detalj. Undersøkelsen ble gjennomført ved å benytte klimagassutslippene fra kryssingsløsning for Sognefjorden i et fiktivt fjordkryssingscenario. I tillegg ble en analyse uført basert på de to (tidligere) vegtrasealternativene Hafast og Fefast langs E39.

Litteraturstudiet viste at det er signifikante forskjeller mellom størrelsen på klimagassutslipp forbundet med etablering a veginfrastruktur. For bruer er produksjonen av materialer identifisert som hovedkilden til utslipp. Aktiviteter knyttet til utbyggingsprosessen og drift og vedlikehold er mindre viktig. Til tross for dette er ofte utbyggingsfasen grovt beregnet eller basert på for få data. Når utslipp fra vegtrafikken er inkludert, er det hovedkilden til klimagassutslipp per km veg i et livsløpsperspektiv.

Klimagassutslippene fra hver av kryssingsløsningene for Sognefjorden ble beregnet til være rundt 100 ganger høyere enn for tradisjonell veginfrastruktur per kilometer. Livsløpsfasene som ble vurdert var materialproduksjon, utbygging, og drift og vedlikehold gjennom 100 år. Rørtunnelen hadde det høyeste totale utslippet av klimagasser, med omtrent 605 900 tonn CO_2-ekvivalenter. Hengebrua hadde utslipp på ca. 493 200 tonn, og flytebrua 380 800 tonn CO_2-ekv i den utførte analysen. Produksjonsfasen var ansvarlig for over 94 % av utslippene for alle de tre kryssingsløsningene. Produksjonen av betong, konstruksjonsstål og armering stod bak majoriteten av bidraget i denne fasen.

Per kilometer hadde rørtunnelen utslipp på ca. 148 400 tonn, hengebrua 133 300 tonn, og flytebrua 86 500 tonn CO_2-ekv. En sammenligning av fjordkryssingsløsningene basert på effektivt brubaneareal ga et annet bilde. Hengebrua hadde høyest utslipp per m^2 effektivt brubaneareal med ca. 1 160 kg CO_2-ekv. Rørtunnelen og flytebrua hadde utslipp på henholdsvis 1 160 og 910 kg CO_2-ekv. Effektivt brubaneareal var definet som bredden på kjørebanene ganget med den totale lengden til konstruksjonene. Rørtunnelen hadde det

høyeste energiforbruket og den høyeste miljøpåvirkningen innen majoriteten av de andre miljøpåvirkningskategoriene som er vurdert i denne analysen. Over en tidshorisont på 40 år var vegtrafikkrelaterte utslipp fra en framtidig Sognefjordkryssing ansvarlig for mindre enn 21 % av det totale klimagassutslippet forbundet med kryssingsløsningene. Dette resultatet avviker fra litteraturen, hvor vegtrafikkrelaterte utslipp for det meste er den dominerende kilden til klimagassutslipp sammenlignet med infrastrukturen.

Beregningene fra det fiktive fjordkryssingscenarioet indikerte en tilbakebetalingstid for klimagassutslipp på mer enn 100 år for krysningsløsninger tilvarende en Sognfjordkryssing. Dette inntraff når ÅDT var lavere enn 2000 kjøretøy per døgn, eller den erstattede vegkorridoren var kortere enn 8 km. En framtidig reduksjon i CO_2-utslipp fra forbrenning av drivstoff på grunn av ny kjøretøyteknologi var også forbundet med tilbakebetalingstider på mer enn 100 år. Klimagassutslippet knyttet til trasévalget mellom Hafast og Fefast var relativt likt over en tidshorisont på 40 år. Grunnen til dette var at traseen for Fefast inkluderte mer utslippsintensiv infrastruktur enn den 13 km lengre Hafast traseen.

Resultatene fra livsløpsvurderingen utført i denne oppgaven ga betraktelig høyere utslipp av klimagasser sammenlignet med veginfrastruktur i tidligere studier. Dette var hovedsakelig på grunn av det høye materialforbruket til fjordkryssingsløsningene. Klimagassutslippet knyttet til infrastrukturen var fortsatt signifikant selv ved en inkludering av vegtrafikkrelaterte utslipp i ulike scenarier. Hvis Norge ønsker å nå målene satt for en reduksjon av klimagassutslipp bør utslipp relatert til veginfrastruktur av en slik skala tas i betraktning ved planlegging av vegkorridorer og utforming av fjordkryssingsløsninger.

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Terms and abbreviations

AADT	Annual Average Daily Traffic
CED	Cumulative Energy Demand
EFFEKT	*A tool used by Statens vegvesen in road infrastructure planning*
EPD	Environmental Product Declaration
FB	Floating Bridge
GHG	Greenhouse Gas
GWP	Global Warming Potential
HSR	High-Speed Rail
ISO	International Organization for Standardization
JBV	Jernbaneverket (The Norwegian National Rail Administration)
LCA	Life Cycle Assessment
LICCER	Life Cycle Considerations in EIA of Road infrastructure
LWA	Lightweight aggregate
MiSA	MiljøSystemAnalyse (Environmental Systems Analysis)
NTNU	Norwegian University of Science and Technology
NTP	National Transport Plan
PBE	Personbilenhet (Passenger Car Equivalent)
PCR	Product Category Rules
ReCiPe	*Life cycle environmental impact assessment method*
SB	Suspension Bridge
SETAC	Society of Environmental Toxicology And Chemistry
SFT	Submerged Floating Tunnel
SimaPro	*Computer program for conducting Life Cycle Assessments*
SVV	Statens vegvesen (The Norwegian Public Road Administration)
TBP	Tonnes Bollard Pull

1 Introduction

Reducing emissions of greenhouse gases (GHGs) that contribute to global warming and climate change is becoming increasingly important both nationally and globally (IPCC,2013). In Norway, the transportation sector is responsible for about 32 % of the nation's annual emissions (Ministry of the Environment, 2012). The sector consists of all the common modes of transport; air, road, rail and water. Fuel combustion is the main source of GHG-emissions and from road traffic alone approximately 10 million tonnes of CO_2-equivalents are emitted annually (Statistics Norway, 2014). This share is nearly one fifth of Norway's total annual emissions, and represents more than half of the emissions from the transportation sector. GHG-emissions related to road transportation are therefore highly important to address. Particularly in order for Norway to be able to meet its obligations in the Kyoto protocol, with emission reductions of 30 % relative to 1990 within the year of 2020 (Ministry of the Environment, 2012).

1.1 Background

Even though road traffic is a major source of GHG-emissions, several studies are highlighting the importance of also assessing the emissions from establishing the transportation infrastructure system (Chester & Horvath 2009; Carlson 2011; Du & Karoumi 2014). In most of the studies done for road bridges the material production is responsible for the highest share of GHG-emissions during its lifetime (Du & Karoumi, 2014). However when GHG-emissions from traffic are included in the usage phase of the bridge, the infrastructure related emissions become less significant (Hammervold, et al., 2013). Even with a 50 % reduction of traffic related emissions, traffic will still dominate over emissions from traditional road infrastructure in a life cycle perspective Bergsdal, et al. (2013).

The application of Life Cycle Assessment (LCA) or similar methodology is mutual for the mentioned studies. LCA is a standardized method for quantifying potential environmental impacts associated with a product or service. The life cycle of a product usually covers extraction of raw material, processing, production, usage and disposal (European Commission, 2010). The method can be used to compare the environmental impact associated with two products during their life cycle. The use phase of road infrastructure is considerably longer than for many products, due to a technical life time up to 100 years (Schlaupitz, 2008). It is therefore important to take the whole life cycle of the structure into account when comparing different types of road infrastructure.

Norway is famous for its high mountains and deep fjords, but the topography also gives rise to major challenges when establishing a road infrastructure system. Due to this many roads include several ferry connections, resulting in increased travel time and lost productivity (Statens vegvesen, 2012a). In 2013 the Norwegian government announced their support of constructing a future Coastal Highway Route E39 without any ferry connections within the next 20 years (NTB, 2013).The route currently runs along the western coast of the country from Kristiansand in the south, to Trondheim in Central Norway. It is in total approximately 1100 kilometers long, and includes 7-8 ferry connections (Statens vegvesen, 2012a).

Constructing a permanent crossing of the Sognefjord is considered one of the biggest technological challenges for realizing a future Coastal Highway Route E39. At the desired crossing site, the fjord is about 3700 meters wide and 1250 meters deep (Statens vegvesen, 2012b). A permanent crossing here will require new technological solutions going beyond the state of the art of bridges. The Norwegian Public Roads Administration (Statens vegvesen) has conducted a feasibility study to assess the technological possibilities for crossing the Sognefjord (Statens vegvesen, 2012b). The main concepts investigated were a floating bridge, a suspension bridge, a submerged floating tunnel, and a combined solution. Along Route E39 several future route alternatives for road corridors are being evaluated (Statens vegvesen, 2011a). From a climate mitigation perspective it is important to assess the GHG-emissions related to these different route alternatives, especially if they involve a fjord crossing. The chosen route should in total give lower emissions during its life cycle.

Norway's National Transport Plan (NTP) for the period 2014-2023 has estimated the CO_2-emissions from constructing all the road projects within that time frame of 10 years to be about 700 000 tonnes of CO_2 (Ministry of Transport and Communications, 2013). This number may no longer be representative due to the political decision of constructing a future Route E39 without ferry connections. An early-phase LCA presented in a conference paper by Bergsdal, et al. (2013) indicated that constructing a submerged floating tunnel concept across the Sognefjord would give total emissions of at least 432 000 tonnes of CO_2-equivalents. This value gives basis for questioning the estimated emissions from the NTP, and the lower importance of infrastructure compared to traffic in a climate mitigation perspective. The mentioned paper also included a generic route planning scenario to compare the GHG-emissions from different fjord crossing concepts and an open section road around the fjord. Their findings have been a starting point for this thesis, and similar methods will be applied to further investigate this context.

1.2 Purpose

The purpose of this master's thesis is to evaluate and quantify the greenhouse gas emissions and potential environmental impacts of some of the proposed concepts for crossing the Sognefjord. This is done by performing an early-phase LCA based on their main material inputs and described construction activities. Additional focus will be put on emissions of GHGs, which will be evaluated in a broader perspective. The results will be compared to the GHG-emissions associated with traditional road infrastructure provided in literature. The infrastructure investment will also be compared to traffic related emissions. The result is expected to provide valuable information for decision makers regarding the climate and environmental impacts of large-scale road infrastructure projects such as Coastal Highway Route E39.

The following research questions will be addressed as part of the study:

- What is the size of the GHG-emissions associated with constructing and operating a permanent crossing of the Sognefjord, and how does it differ between the possible crossing solutions?
- How do the emissions from establishing the fjord crossing infrastructure compare to the emissions related to the traffic on the actual structures, and to the traffic emissions from alternative routes?
- Will the importance of assessing GHG-emissions from the road infrastructure increase when the structures reach a certain level of complexity similar to the proposed Sognefjord crossings?

1.3 Scope

The starting point of the LCA in this thesis will be the structures claimed technologically feasible to cross the Sognefjord described in Jakobsen (2013), Statens vegvesen (2014a) and Fjeld (2012). The life cycle phases of production, construction, operation and maintenance, and usage (traffic) will be covered. Demolition and disposal as an End Of Life (EOL) treatment will not be included. Hence a fully standardized LCA after the ISO 14040 series (ISO, 2006a) will not be conducted. The results will be presented for the environmental impact categories included in the ReCiPe method (Goedkoop, et al., 2013) and for energy consumption. Emissions of greenhouse gases will be the main focus and assessed in detail. The GHG-emissions will be elaborated further with a fictional fjord crossing scenario and a route choice analysis including emissions from vehicles.

This thesis will not be aimed at providing a basis for future developments of standardized models for LCA or road infrastructure. The methodological choices will however be consistent with literature to a reasonable extent. It is emphasized that this is an early-phase LCA. This indicates that the purpose of the analysis is to make an estimate of the environmental impact, and not to conduct a full scale LCA. This analysis will only cover the potential indirect environmental impact, and not the environmental impact on site or the disturbance of the landscape. The environmental aspects not covered by the scope of this thesis will be assessed qualitatively and discussed in the concluding chapters.

1.4 Outline

The thesis is divided in 7 chapters. The following chapter includes a literature review, ending with a summary of the most important discoveries. Then the scientific background and framework for LCA will be covered. The fourth chapter is the most extensive one. It includes a description of the case study with the fjord crossing concepts, followed by the methodological choices taken in this study. The additional route choice analysis is also included in the chapter. The results are presented in chapter five, and are discussed in detail in the following chapter. The final chapter provides a conclusion based on the outcome of the analysis, and ends with propositions for future research.

2 Literature

The literature was mainly collected through online search engines BIBSYS Ask and Google Scholar. Most of the non-scientific journal studies were collected via referral from other studies or through contact with academic supervisors and Statens vegvesen. The literature review presented here will cover a broader range of studies, rather than exclusively going through studies published about LCA of bridges and road infrastructure. For this reason most of the studies on LCA of bridges are covered through other literature reviews. Analyses conducted for tunnels, roads and railway will also be included. The aim is then to highlight the variations in application and methodology of environmental assessments and carbon footprint estimations of transportation infrastructure based on LCA methodology. This will be done by identifying knowledge gaps, critical parameters, and the main contributing factors to GHG-emissions.

2.1 Environmental assessments of fjord crossing alternatives.

There have not been conducted many studies for the environmental impact of different fjord crossing alternatives. In addition to the work conducted in Iversen (2013), only two studies were identified as environmental assessments using LCA methodology. They will be reviewed in this subchapter, and are both studies from Norway. The two studies were also an important source of inspiration for the topic of this thesis.

An "early-phase LCA" similar to this thesis was undertaken by ***Bergsdal, et al. (2013)*** as a contribution to the 2013 edition of the conference Strait Crossings. Their paper ***Environmental Footprint in Early Planning of Coastal Road Sections*** aimed to give an indication of the potential GHG-emissions associated with new fjord crossing technologies. The emissions associated with route choices at an early stage of infrastructure planning were also investigated. Generic values presented in the paper show that the construction of tunnels have 8 times higher GHG-emissions than open section roads when compared per km. Bridges have GHG-emissions 37 times higher than open sections. It's emphasized that emissions in general seem to increase with complexity and material consumption. The authors stress the importance of including traffic emissions if one is conducting an LCA of road infrastructure. A simple calculation showed that even with a 50 % reduction of traffic related emissions, traffic will still dominate over the emissions from infrastructure per km in a life cycle perspective. An early-phase LCA was conducted for the same Submerged Floating Tunnel (SFT) as the one analysed in this thesis. Their analysis estimated total emissions of 432 000 tonnes of CO_2-eq, related to its construction alone. This is about 16 times higher than the generic value for constructing a bridge on a per km basis, and 575 times higher than for constructing an open road section. The result was investigated further by a fictional fjord crossing scenario with different route alternatives as illustrated in Figure 1.

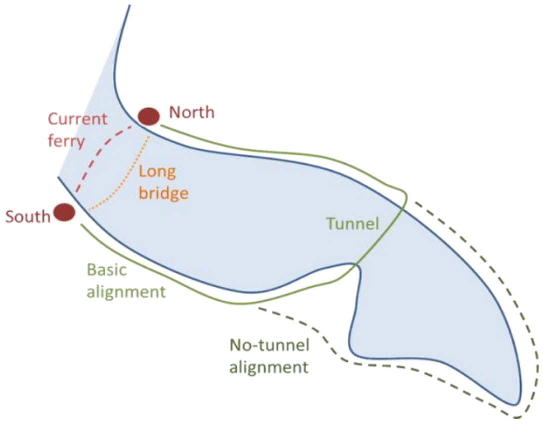


Figure 1 Fjord crossing alternatives represented by a ferry connection, a long bridge, an undersea tunnel connected to open sections, and a open section road around the fjord. Copied from Bergsdal, et al. (2013).

The ferry connection in their scenario was found to be the most emission intensive per km over a time horizon of 100 years. The emissions originated mainly from the combustion of marine diesel. Crossing a fjord with a bridge, tunnel or even a SFT *could* give lower emissions than an open section road in a 100 year time horizon. This however is highly depended on the length of the open section road, and the traffic intensity. It is noted that the availability of relevant data will be limited in a planning phase, and the life cycle inventory will need to be compiled on a higher amount of generic data.

A similar survey of fjord crossing alternatives was done in a study for **Statens vegvesen (2000)**. The title of the report can be translated to English as: ***Environmental comparison of a bridge, tunnel, and ferry – Life cycle assessment as a basis for comparing fjord crossing alternatives.*** The purpose of the study was to provide the road administration with extended knowledge of the environmental impact of different fjord crossing alternatives. The included environmental aspects were emissions of CO_2, CO, C_xH_y, NO_x, SO_x, particulate matter, and the consumption of electricity and fossil fuel. The analysis was conducted after ISO standards. A traditional environmental impact assessment that considers local aspects was not part of the study. The analysis was done for a crossing of a 1000 meter wide fictional fjord, with an assumed depth of 50 meter. The crossing alternatives were a concrete bridge, an undersea tunnel, a ferry connection and an open section road around the fjord with different lengths. A functional unit of "a fjord crossing solution for an average traffic intensity of 3000 vehicles per day over 25 year" was chosen. The concrete bridge alternative had the overall lowest impact within the environmental aspects considered in the study. The result indicated that emissions associated with undersea tunnels increases with the depth of the construction. This is mainly due to increased tunnel length, which is necessary for avoiding a steep gradient. The electricity consumption of the undersea tunnel was considerably higher than for the other alternatives. The ferry connection and the longest open section road around the fjord gave the highest CO_2 emissions. A concluding remark states that it is not possible to draw a general conclusion regarding which fjord crossing alternative is the most "environmentally friendly". When emissions from traffic were included, they dominated over infrastructure related emissions for all the alternatives.

2.2 LCA of Bridges

According to other literature reviews LCA methodology applied on bridges seem to date back to around 1998. There is however only a limited amount of studies available for LCA of road bridges (Du & Karoumi, 2014). The most relevant studies identified by a thorough literature search have already been covered in previous literature reviews by Hammervold, et al. (2013), Dequidt (2012), and Du & Karoumi (2014). A comparison of their coverage is included in Appendix A. All of the studies done on LCA of *road bridges* reviewed in Hammervold, et al. (2013) are also covered by Du & Karoumi (2014). Both Dequidt (2012) and Du & Karoumi (2014) covered 14 studies on LCA of road bridges, where 8 out of 14 studies overlap. In addition 3 more studies overlap by author, where different publications are referred to but cover the same topic or related studies. The most recent and comprehensive literature review was done by Du & Karoumi (2014). Their findings will be covered separately in this subchapter and serve as a bridge LCA state of the art for this thesis. The *case study* results of Hammervold, et al. (2013) and (Dequidt, 2012) will be assessed in detail afterwards. They are chosen because they represent two different analysis goals; comparison of bridge designs (Hammervold, et al., 2013), and an overall assessment of a single bridge (Dequidt, 2012). In addition the analyses are both done on bridges in Norway, which makes them particularly relevant for this thesis.

Life cycle assessment framework for railway bridges: literature survey and critical issues.

By Du & Karoumi, 2014.

This recently published paper covers both railway and roadway bridges. The lack of proper life cycle inventory data is identified as an important obstacle when performing LCAs for bridges. General assumptions, choice of scope and system boundaries, use of impact assessment methods, lifetime and other factors vary significantly between the reviewed studies. This leads to most studies *not being directly comparable*. The main environmental impacts considered, are emissions of CO_2 and energy consumption. In the majority of the studies the *production phase* with material manufacturing is the biggest contributor to these impacts. The emissions associated with material transportation and the construction processes at site seem to be less significant. This may however be influenced by the construction activities being estimated with rough numbers, or even not taken into account. The authors raise the question of whether material transportation from the supplier to the construction site, belongs to the material production phase or the construction phase.

Some of the reviewed studies look at different design options and material choices. The use of recycled or alternative materials in order to reduce emissions is then taken into account and evaluated. It is highlighted however that these kinds of design approaches and material choices should not compromise the durability of the bridge. This is mainly because a reduction in service life can be associated with increased emissions in a life cycle perspective. A general message from the paper is that there is a need for a consistent set of rules for conducting LCAs apart from the existing ISO standards. There is currently insufficient inventory data available for LCA of road infrastructure, and a standard set of guidelines is lacking. The main source of CO_2 emissions seems to be the production process of steel and the production of cement for concrete.

Environmental Life Cycle Assessments of Bridges

By Hammervold, Reenaas, and Brattebø, 2013

During the ETSI-project on bridge life cycle optimization a tool named *BridgeLCA* (Brattebø, et al., 2009) was developed. As part of the project, the tool was used for a case study on three road bridges in Norway. This journal article from 2013 includes the findings from this project and the results from the case study. The case study aimed to provide a more systematic and detailed approach than earlier studies, by analysing existing bridges. The analysis covered a steel box girder bridge with a span of 42,8 meter, a 37,9 meter wooden arch bridge and a 39,3 meter concrete box girder bridge. Thus the chosen bridges represents the three main construction materials for bridges; concrete, steel and wood. A functional unit of "1 m^2 of effective deck area through a lifetime of 100 years" was used, and also proposed for LCA of bridges.

The following environmental impacts were considered: Global warming, eutrophication, acid rain, ozone-layer depletion, human and eco-toxicity, and depletion of abiotic resources. The analysis included the end of life phase, but only considered the treatment of the main materials concrete, steel and wood

The concrete box girder bridge was found to have the lowest overall environmental impact, and the wooden bridge the lowest GHG-emissions. It is stated however that *the results should not be generalized*. The majority of the environmental impacts were related to the material production. The construction activities at site and material transportation were of minor importance. Certain materials were identified as being of minor importance, like formwork, mastic (adhesive) and explosives. The authors propose that these kinds of material can potentially be omitted from early-stage LCAs of bridges. The paper was concluded by emphasizing the importance of including many environmental impact categories when conducting LCAs, in order to avoid problem-shifting.

Life Cycle Assessment of a Norwegian Bridge

By Dequidt, 2012.

In this master's thesis an LCA was performed on Tverlandsbrua, a bridge that was under construction in the northern part of Norway. The bridge is 670 meters long, and has an effective bridge deck area of 15711,5 m^2. The goal of the thesis was to assess the overall environmental performance of one type of bridge. The analysis took the whole life cycle of the bridge into account, but assessed only the environmental performance in terms of GHG-emissions and energy consumption. The literature review identified cable-stayed bridges, arch bridges and other more architectural bridges, to be associated with higher emissions due to complex design methods and materials. Also previous LCAs on bridges have all been done on relatively *small bridges* with an estimated average effective deck area of 2 495 m^2.

The analysis in the thesis estimated GHG-emissions of 6 665 kg CO_2-eq per m^2 effective bridge area for Tverlandsbrua over a 100 year life cycle. The future traffic on the bridge was found to be responsible for close to 80 % of the total emissions. Excluding traffic, the analysis estimated emissions of 1 358 kg of CO_2-eq per m^2 effective bridge area. This gives total emissions of 21 335 tonnes of CO_2-eq for every process related to the *bridge infrastructure* during its life cycle. Disregarding that the bridge is 670 meter long, extrapolating the total emissions to a per 1 kilometre basis would give 31 845 tonnes of CO_2-eq.

When emissions from traffic are excluded the production phase is clearly the dominating phase, responsible for more than 60 % of the GHG-emissions. Maintenance and repair activities contribute to about 20 % and the construction phase contributes to less than 10 % of the total emissions. The main contributing materials were found to be concrete, construction steel, and reinforcement steel. Material production was also the main source of emissions in the maintenance and repair phase, where renewal of the wearing layer (asphalt) contributed to 99 %. This indicates that the production of materials actually was responsible for more than 80 % of the infrastructure related life cycle GHG-emissions in this study. In the construction phase only two processes were responsible for close to 100 % of the emissions. Transportation for 76,6 %, and diesel burnt in heavy equipment for 22,5 % of the emissions. The end of life phase had the lowest contribution during the whole life cycle with about 6 %, mainly associated with the treatment of reinforced concrete.

2.3 LCA and carbon footprint of road infrastructure

LCAs seem have been performed on traditional open section roads, to a higher extent than for bridges. LCAs have also been conducted for road pavements, material choices and recycling alternatives. Only a few LCAs have been performed on tunnels, as identified in Iversen (2013). A broad literature review for LCA of roads is given in the report ***Life cycle assessment of roads and pavements – Studies made in Europe*** by ***Carlson (2011)***. Most of the studies covered conclude that the energy use due to traffic overshadows the energy use for production, construction, operation and management of roads. It is highlighted that every road is unique, constructed with different dimensions, materials, purposes and in a large variety of landscapes. This makes a comparison between studies difficult, and not necessarily justified without a cautious approach. The availability of good data is identified to be low, which makes it difficult to establish a representative life cycle inventory. High energy use related to infrastructure can be regained during the life cycle if the infrastructure investment results in lower energy use from traffic.

Miliutenko (2010) provided the literature review ***Life Cycle Impacts of Road Infrastructure - Assessment of energy use and greenhouse gas emissions*** as part of her doctoral thesis. The review covered multiple articles from scientific journals and several other relevant studies. Some key factors are highlighted in the review: Environmental assessments seem to be focused on tailpipe emissions, and seldom on the indirect emissions from infrastructure, vehicle and fuel production. The studies undertaken for energy consumption of roads vary in methodological approaches and system boundaries. Generally they are conducted over a time horizon of 40-100 years. It is therefore important to take factors like lifetime choice, landscape variations, and level of detail into account when comparing results between different studies

Studies and work done by ***Statens vegvesen*** include the climate module in the tool ***EFFEKT*** (Straume, 2011) and some case studies for road projects. The empirical data for the climate impact calculation module in EFFEKT is documented in Statens vegvesen (2009a). The tool was developed to compare the GHG-emissions for different road corridor alternatives. Open section roads, tunnels, bridges and ferries are included in the module. The tool can potentially also be used to quantify the socio economic cost of the GHG-emissions

Several case studies are documented in a series of reports by the **University of Agder** for Statens vegvesen. One of them written by ***Phan (2012),*** can be translated to Energy ***consumption and greenhouse gas emissions related to constructing, operating and maintaining road infrastructure.*** The report is a summary and quality assurance of three bachelor theses from the University of Agder. The calculations were based on energy accounts provided by the main contractors from specific road projects in Norway. The report looked at a 1,8 km open section road with shares of both 2 and 4-lanes. To simplify the analysis the road was normalized to represent a 1,34 km 4-lane road.

The results gave GHG-emissions of 3 269 tonnes of CO_2-eq per kilometre. Lost carbon storage in the soil was included in this estimate, and without it the GHG-emissions would be 2 700 tonnes of CO_2-eq per kilometre. In the initial value diesel consumption of heavy machinery was responsible for about 52 % of the emissions, asphalt for 31 %, and lost carbon storage for 23 %. The share of the total GHG-emissions from the diesel consumption of the heavy machinery at the construction site was significantly higher in this study compared to others. The diesel consumption in this study is provided via energy reports from the contractors, which should make the estimated value more accurate. However the system boundaries and assumptions are not that clearly stated in the report, and it does not follow LCA methodology. The result may therefore not be directly comparable to other studies. Earthworks seem to be the main source of diesel consumption, but it is not stated explicitly.

A tool similar to EFFEKT was developed as part of **Life Cycle Considerations in EIA of Road infrastructure (LICCER) project** initiated by ERA-NET ROAD. The main goal of the project was to develop a user friendly model for conducting LCAs of the infrastructure and traffic related emissions from different road corridor alternatives during their life cycles (Brattebø, et al., 2013). Included environmental impact categories are emissions of GHGs and energy consumption. The model was tested on two case studies. One case study looked at crossing alternatives for the Oslo fjord in Norway, and is documented in ***O'Born, et al., (2013)*** and in ***Iversen (2013).*** Two different crossing alternatives were considered in the study: A new undersea tunnel parallel to the existing one and a new crossing solution with two bridges and about 10 kilometres of additional open section road. The analysis showed that a bridge alternative would give considerably higher infrastructure related GHG-emissions than the undersea tunnel. This was mainly due to the production of steel and concrete. However, when traffic was included in a 40 year time horizon the bridge alternative gave lower emissions. The main reason for this was that the bridge corridor alternative was 6,4 km shorter between the chosen start and end points.

The other case study is documented in the master's thesis ***Life Cycle Assessment in Early Planning of Road Infrastructure - Application of The LICCER-model*** by ***Liljenström (2013)***. The study looked at a 7 km long road section in Sweden with a need for improvement. The analysis done with the LICCER-model considered four alternatives for a future road section. One was keeping the current road, another was improving it, and the last two were alternative corridor solutions. The case study identified asphalt composition and related emissions factors together with earthwork volumes, as the most important and sensitive emissions sources. In addition the thesis included a thorough evaluation and comparison of different tools for conducting LCAs of road infrastructure. The author made a useful table that illustrates differences and similarities between the respective tools. This table is recreated and presented in Appendix A. The LICCER-model was concluded to be advantageous over some of the other models considered in the study. This was mainly due to possibility of comparing the emissions from different road corridors.

Fuglseth (2013) applied a methodology established by the Norwegian National Rail Administration (Jernbaneverket, JBV) for conducting an LCA a of road improvement in the master's thesis ***Life Cycle Impacts of Upgrading a 2-lane Highway to a 4-lane Modern Highway.*** Upgrading a 2-lane road to a highway was estimated to generate 3 175 tonnes of CO_2-eq per kilometre during a 60 year lifetime. The construction process *including* the production of materials had about equal environmental impact to the operation and maintenance phase. The production of asphalt with the paving process was the main contributor in both cases, and in total responsible for 47 % of life cycle GHG-emissions. The study was an important contribution for creating a shared methodology for LCA of transportation systems. The thesis also compared the JBV methodology with the methodology behind the EFFEKT model used by Statens vegvesen (2009a) The EFFEKT model gave lower results than the JBV methodology. This indicated that some processes may be underestimated, or measured differently in the current model.

A conference paper entitled ***Life Cycle Assessment of Norwegian Standard Road Tunnel.*** by ***Huang et, al., (2013)*** looked at the GHG-emissions and energy use related to the construction and operation of road tunnels. Their analysis applied a functional unit of "the construction and maintenance of 1 meter of road tunnel over a lifetime of 100 years". The result indicated emissions of 13 tonnes of CO_2-eq per meter tunnel. The biggest contributor with 42 % of the emissions was the production of concrete. Transportation of materials was responsible for 15 %, and fuel and electricity consumption for 17 % of the emissions. The contribution from the production and usage of explosives was found to be less than 5 %. Without the operation phase, the material production and construction of the tunnel emitted 6,5 tonnes of CO_2-eq per meter.

2.4 LCA and carbon footprint of transportation infrastructure

A detailed estimation of greenhouse gas projections for the national High-Speed Rail (HSR) assessment was conducted for the Norwegian National Rail Administration by Bergsdal et al (2012). In the final report **Environmental analysis – Climate, Norwegian High Speed Railway Project Phase 3** several interesting approaches are done. One of them is a calculation of a "payback period" for the infrastructure investment. A calculation of how long it will take for infrastructure investment in the proposed HSR corridors to become positive in a climate mitigation perspective. Payback periods are in the range of 35 to more than 60 years. A high share of tunnels is found to be a main factor for limiting the potential reduction in GHG-emissions. This is due to tunnels having significantly higher emissions per km HSR line compared to open sections. The result is calculated on a GHG-emission per passenger kilometre basis. This approach gives corridors with a low market potential higher associated GHG-emissions due to fewer passengers sharing the emissions.

Schlaupitz (2008) made a report that can be translated to ***Energy and environmental consequences of modern transportation systems - The effects of constructing High-speed rails in Norway.*** The study looked at the energy consumption and GHG-emissions during the life cycle of different transportation systems. The transportation modes considered were HSR, passenger car transportation, express busses, and airplanes. The highest GHG reduction potential identified for a future HSR-system were for a substitution from air traffic to railway. The increase in emissions from constructing a double track compared to a single track railway was lower than the identified increase for building a 4-lane compared to 2-lane road.

2.5 Summary of literature review

The majority of the environmental impacts associated with bridges and other types of road infrastructure seem to come from the material production phase. Most studies claimed that their results should not be generalized and compared. Regardless of this, a comparison of some of the identified GHG-emission values are presented in Table 1. This is done to illustrate the relative differences in the size of the GHG-emissions per kilometre. There are several methodological differences between the studies, but they will not be discussed further in this chapter.

Table 1: GHG-emissions per km of road infrastructure identified in the literature review. The lifetimes of the different structures is included along with a description of the type if study and its reference.

Road infrastructure type	tonnes CO_2-eq per km	Lifetimes	Study type	Reference
Open section road	1 020	100 years	Generic	Bergsdal et al (2013)
Tunnel section	2 230	100 years	Generic	Bergsdal et al (2013)
Open section 4-lane road	2700 (3260*)	0 years**	Case study	Phan (2012)
Upgrading a 2-lane road to 4-lanes	3 175	60 years	Case study	Fuglseth (2013)
Undersea tunnel (shotcrete)	3 958	0 years**	Case study	Iversen (2013)
Undersea tunnel (concrete elements)	5 274	0 years**	Case study	Iversen (2013)
Bridge section	7 360	100 years	Generic	Bergsdal et al (2013)
A standard Norwegian road tunnel	13 000	100 years	Generic	Huang et al. (2013)
Long bridge	31 845***	100 years	Case study	Dequidt (2012)
Submerged Floating Tunnel	118 000	100 years	Case study	Bergsdal et al (2013)

*includes possible lost carbon storage in soil

** 0 years imply that the analysis did not cover operation & maintenance

***the value is estimated from the actual result

The table above indicates that GHG-emissions increases significantly with more complex and longer road infrastructure types. Including the whole life cycle of the infrastructure seem to increase emissions. The inclusion of lost carbon storage in soil for LCAs of roads can give significantly higher emissions. The emission per km of submerged floating tunnel is more than 100 times higher than the emission for the generic open section road.

The GHG-emissions from establishing *traditional* road infrastructure is much lower per km than for traffic. Regardless of the traffic emissions being dominant, there are still significant differences between open sections, tunnels, bridges, ferry connections and new technologies like a SFT. It is therefore important from a climate mitigation perspective to consider GHG-emissions related to infrastructure in a road planning process.

3 Method

In this chapter the theory and framework behind Life Cycle Assessments will be covered shortly. For a more comprehensive description the reader is referred to the online version of the ILCD Handbook (European Commission, 2010). The methodological choices for this thesis will be explained the following chapter, together with the data collection and modeling process.

3.1 An introduction to Life Cycle Assessment (LCA)

LCA was born from the idea that an analysis aiming to evaluate the environmental impact or "footprint" of a product needs to assess all the phases of that product's life cycle. A product's life cycle will normally consist of extraction of raw material, processing, production, usage and disposal (European Commission, 2010). An LCA covers the whole life cycle of a product or service, and is often associated with the term «cradle-to-grave». A holistic analysis like this will contribute to the understating of unforeseen, underestimated or neglected environmental impacts along the value chain. The goal is then to avoid problem shifting, a term that refers to new environmental problems arising when others are solved. The framework for conducting an LCA is standardised by the International Organization for Standardization (ISO), and is covered in the ISO 14000 family on environmental management (ISO, 2006a,b).

A standardized LCA consists of four consecutive phases:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Life cycle interpretation

The standardization was mainly done to establish a common terminology and framework, while the method for conducting an LCA varies (Guinée, et al., 2010). Hence the scope and level of detail varies with each analysis.

3.1.1 The 1st phase - Defining the goal and scope

Before conducting an analysis it's important to evaluate the intention behind the it, and what it is trying to cover. The goal of an LCA could be to identify the biggest contributors to environmental impacts along the value chain of a product. It could also be to compare the environmental performance of two products, for instance whether to favor plastic or a paper bags.

The phase must contain a description of the system that will be analyzed, together with its boundaries. Setting the system boundaries is necessary to make scope of the analysis clear. There is a substantial difference between looking only at the energy consumption at a construction site or a factory, compared to looking at the whole value chain all the way up to the extraction of raw material. The consequences of the chosen system boundaries should always be evaluated and discussed as part of an analysis.

A functional unit needs to be determined in the goal and scope phase. This is a quantitative unit used as a reference to communicate and compare results from LCAs. Examples of functional units are producing 1 kg of beef, 1 kWh of electricity, 1 m^3 of concrete, or the production, construction, and operation of 1 kilometer of road for 60 years. It should also be addressed what type of environmental impact categories will be covered. Some assessments may only look at CO_2-emissions, while others include energy consumption, the potential impact on human health, eco-toxicological effects or resource depletion. The first phase is primarily about setting a goal with a measureable outcome, and choosing the means to reach this goal with the aid of existing guidelines, frameworks, methods and tools.

3.1.2 The 2nd phase - Establishing an inventory for analysis

This phase consists of data collection and organization. The purpose is to establish an inventory of material and energy consumption associated with the product or service being analyzed. Examples of inventory data is the amount of concrete used to build a bridge, the amount of steel need to construct a windmill, or the amount of animal feed needed to produce 1 kg of beef. The resource consumption is then connected to per unit emission data. For instance kilograms of CO_2-emmisions or joules of energy consumption, associated with producing 1 m^3 of concrete.

In general the analyst needs to collect data on all the inputs and outputs from the system. To do this for every single flow would be a time consuming process. As a reason for this, several databases have been established to cover the background processes. Background processes can be viewed as average descriptions of material or energy flows that are used in several analyses. A database can contain background processes with parameters for emissions per unit of commonly used materials like a 1 m^3 concrete, and 1kg of steel. The most extensive and widely used database today is the Swiss database Ecoinvent (2013).

3.1.3 The 3rd phase - Assessing the environmental impact

Environmental impact assessment in LCAs consists of multiple steps, where the goal is to quantify the potential environmental impact of a product or service throughout its life cycle. This is done by converting the vast amount of emissions and resource consumption data from the previous phase into more comprehensible results.

To assess the environmental impact a ***classification*** is done firstly to separate the data in the life cycle inventory. The inventory data is then divided into categories based on the type of environmental impact it contributes to. CO_2 for instance is classified as a contributor to climate change, while NO_2 can be classified both as a contributor to acid rain and also to photochemical oxidant formation.

When the classification is done the substances are ***characterized*** within their environmental impact category, giving them a shared unit. The characterization can either be done at a midpoint level or an endpoint level, depending on the goal of the analysis. Global Warming is a typical midpoint level impact category. Global warming, acid rain and water depletion are unique environmental problems, but they also contribute to endpoint level impacts like human health and ecosystem damage. A commonly used method for quantifying environmental impacts in LCA is known as ReCiPe (Goedkoop et al, 2013). The method consists of 18 midpoint and 3 endpoint level categories, and can be viewed in Appendix A. The method assesses a wide range of environmental problems from climate change and acid rain to human toxicity and water depletion.

The actual characterization step in the impact assessment phase involves a conversion of the emission values within an impact category to a shared unit. For instance gases that contribute to global warming consist of more than CO_2. A molecule of methane (CH_4) contributes roughly 25 times more to global warming than a molecule of CO_2. Greenhouse gases are therefore characterized within the environmental impact category Global Warming Potential (GWP), and expressed in CO_2-equivalents (Goedkoop et al, 2013). The same unit is used for estimating the *carbon footprint* of product or a service, and for quantifying GHG-emissions

In order to further evaluate the potential environmental impact, ***normalization*** and ***weighting*** can be done. Normalization is a procedure to compare the characterized impacts to national, regional or global averages within an impact category (ISO, 2006b). This procedure makes the impacts unit less, so they can be compared across categories. It is then possible to publish one single result where each category has a percentage share of the total environmental impact.

Issues then arise to whether one environmental problem can be considered a bigger problem than another. Weighting is a response to solve this issue, by giving each category a factor of importance. For instance by stating that global warming is twice as important to address as acid rain or ecotoxological effects. Choosing a weighting factor that quantifies the importance of one environmental impact category over another is quite difficult, and the processes of choosing these kinds of factors may be biased by the persons involved (Bare, 2010).

3.1.4 The 4th phase - Interpreting the results

In the final and concluding phase the result is interpreted, and all the uncertainties associated with the choices made in the previous phases are assessed. In order for a result to be used as a basis for decision making, the quality of the result should be evaluated along with its general applicability. Sensitivity analyses are usually performed to quantify the relative importance of the most emission-intensive processes. The interpretation phase may result in further investigations of critical parameters in the analysis. It may also be concluded that the result is of high quality and ready for implementation. The results can be evaluated further by a comparison with similar studies. However due to methodological differences, results may not always be directly comparable.

3.2 Conducting and communicating an LCA

An LCA can be done manually by hand, or in a spreadsheet like Excel. Due to the large amount of data, it is in general preferable to conduct the analysis with commercial or open software created for LCA. There are a number of computer programs available for conducting LCAs. The most commonly used are SimaPro (PRéConsultants, 2013), and GaBi (PE international, 2014). SimaPro includes the major databases and main characterization methods of interest. Another benefit of computer programs like SimaPro is that it can create a process network, along with diagrams and tables. The network shows where the emissions occur along a production process, making it easier to identify the source of the emissions (see Figure 2).

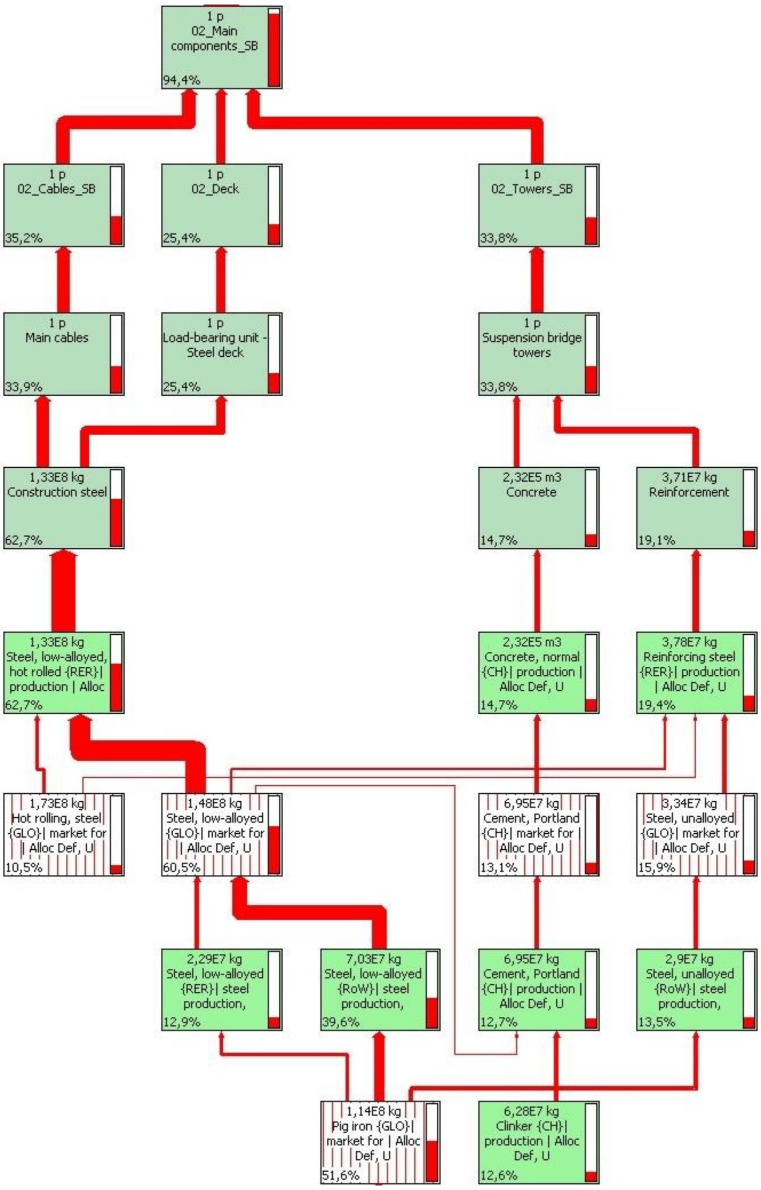


Figure 2: Illustration of the network function from SimaPro represented by the main components of the Suspension Bridge. Copied from SimaPro (PRéConsultants, 2013).

Conducting an LCA could potentially be a long and enduring process, but there are ways to make an analysis more efficient. In general you want to find data on the material consumption and energy consumption of products or services. Emissions data per unit of weight or volume of a material can be gathered the relevant industry, or from databases like the previously mentioned Ecoinvent.

3.2.1 Conducting LCAs of road infrastructure and transportation.

Historically LCA and similar forms of analysis haven be based on comparison of the environmental performance of products (Guinée et al, 2010). In the last decade the usage of LCA for evaluating the environmental footprint of infrastructure has increased. The number studies done for roadway bridges however are still limited (Du & Karoumi, 2014). In Norway a standard road mostly consists of open sections, but with a certain share of other infrastructure types. Road tunnels, undersea tunnels, bridges and ferries also make up the network of the road transportation infrastructure. It is therefore important to distinguish between the different types of infrastructure when conducting an analysis. A common unit for LCA of road infrastructure is the production, construction and operation of 1 kilometer of road over a specific life time.

Several tools and models have been developed specifically for LCA and environmental assessments of road infrastructure. A very useful table that illustrate and compare their abilities is given in the appendix of Liljenström (2013), and is recreated in Table B2 in Appendix A in this thesis. Most of the tools have been created for assessments of roads and pavements, with GHG-emissions as the only environmental impact considered. Only the previously mentioned *BridgeLCA* (Brattebø, et al., 2010) has been made exclusively for bridges. These kinds of tools eases the procedure of conducting environmental analysis of road infrastructure, but they also compromise the freedom that are given by complete LCA software's like SimaPro and GaBi.

3.2.2 Communicating the results from a LCA

LCAs can be conducted to create an Environmental Product Declaration (EPD) as a way of communicating the result. The goal with an environmental declaration is to encourage the demand and supply of products with a lower environmental impact (ISO, 2006c). In order for EDPs to be comparable, a set of common procedures needs to be followed. This is given by the Product Category Rules (PCR). A PCR document gives guidelines, requirements and a specific set of rules for creating EPDs (International EPD System, 2014). PCRs cover different product groups, communicated with a functional unit like 1 m^3 of concrete or 1 km of road infrastructure. A PCR document can be viewed as a recipe for making EPDs, where the importance lies in the comparability of the declarations.

3.3 Uncertainties

There are a number of uncertainties associated with conducting an LCA, and they can arise in every step of the analysis. By defining the system boundaries some processes will naturally be left out, which will impact the final result. Establishing the life cycle inventory based on background processes from databases also leads to uncertainties. The chosen background processes may have been modelled based on weak data, rough assumptions or extrapolation. It is in general desirable to collect project specific data, but that also has implications. Project specific data may be nonexistent, not available, or time consuming to gather, which favors the use of generic databases. There are also multiple uncertainties associated with the impact assessment phase. A general perception is that the closer one gets to a shared result and unit for all potential environmental impact categories, the more uncertain the value and method becomes (Bare, 2010). A single score environmental impact may be desired for decision making. The complexity of different environmental impacts however may not agree with having one single score. Most LCAs mainly cover emission data while site-specific problems like land use are not assessed properly (Bare, 2010). A full evaluation of the environmental impact of a product or service is therefore in general quite hard to achieve.

4 Case study - Coastal Highway Route E39

In 2010 the Norwegian Ministry of Transport and Communications commissioned Statens vegvesen to conduct a feasibility study for a future Coastal Highway Route E39 without any ferry connections. The current Route E39 runs along the western coast from Kristiansand in the south, to Trondheim in Central Norway, as illustrated in Figure 3.

There are currently 7 or 8 ferry connections depending on the inclusion of Voldafjorden crossing along the almost 1100 kilometers long route, (Statens vegvesen, 2012a). A full realization a Coastal Highway Route E39 without ferries may reduce the travel time from Kristiansand to Trondheim by approximately 7-9 hours.

Figure 3: Illustration of a future Costal Highway E39 along with the name of the major cities and fjords to be crossed.

The technological challenge with replacing the ferry connections is the extreme width and depth of some the fjords (see Figure 4). This requires the construction of entirely new fjord crossing concepts, different from what exists in the world today. (Statens vegvesen, 2012b)

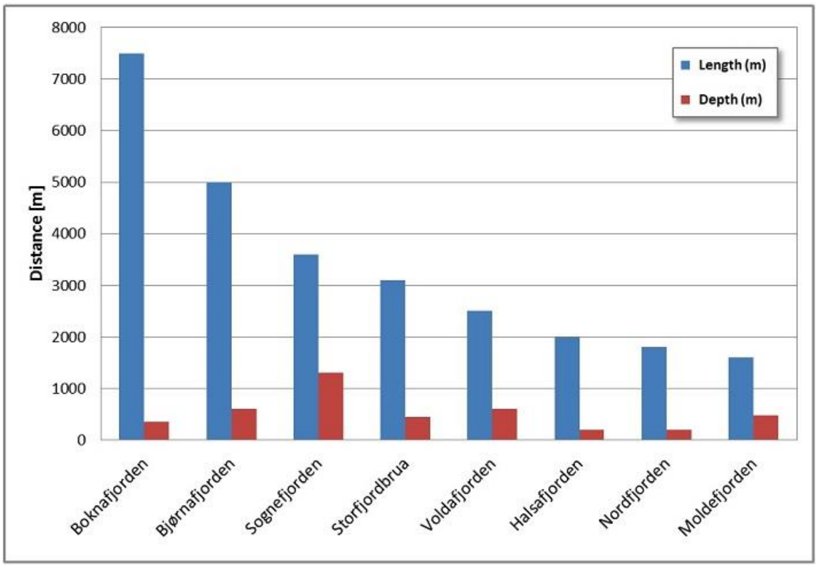


Figure 4: Fjord crossing lengths and depths along Route E39 , modified from Fjeld (2012).

4.1 Crossing the Sognefjord

Crossing the Sognefjord is considered one of the biggest challenges for realizing a future Coastal Highway Route E39 (Statens vegvesen, 2012b). The current ferry runs between Lavik and Oppedal, and is a proposed location for a permanent crossing (Figure 5). At this site the fjord is about 1250 meters deep and 3700 meters wide, which makes it extremely difficult to construct bridge supports. The main alternatives considered then are to construct a floating bridge, suspension bridge, submerged floating tunnel, or a combined solution (Statens vegvesen 2012b).

Figure 5: The current ferry connection and proposed site for crossing the Sognefjord modified from Fjeld (2012). ***The figure was made for illustration purposes, and exact bridge location may not be accurate.***

Due to level of difficulty of crossing the Sognefjord, it’s been undertaken a feasibility study to evaluate the technical possibilities (Statens vegvesen, 2012a). As a part this feasibility study, a competition were held where engineers and consultancies could propose ideas. Afterwards, the three winning concepts were asked to conduct feasibility studies of their own which are documented in Jakobsen (2013), Statens vegvesen (2014a) and Fjeld (2012). The reports have been the baseline for the LCA conducted in this thesis. A short description of design, materials and construction process of each concept is provided in this chapter. Additional details and technical specifications can be found in the relevant feasibility studies.

4.1.1 Floating Bridge

A group consisting of Aas-Jakobsen, and several other civil engineering and consultant companies suggested a floating suspension bridge with three spans for crossing the Sognefjord. Their concept is illustrated in Figure 6 below, and documented in the report "Sognefjorden Feasibility Study of Floating Bridge - Main report" (Jakobsen, 2013).

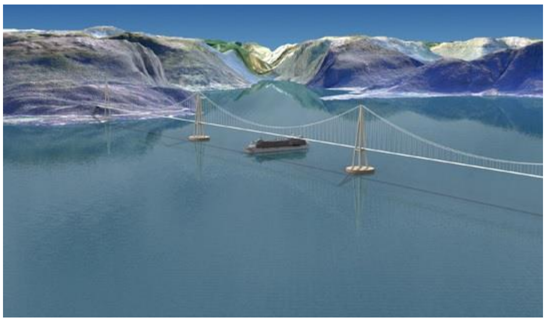


Figure 6: Overview of the three span floating suspension bridge concept described in Jakobsen (2013). Illustrations by Aas-Jakobsen.

A floating bridge, also known as a pontoon bridge is a floating structure or a part of a structure that is supported by pontoons or similar" (Jakobsen, 2013). Only two floating bridges have been built earlier in Norway. Nordhordlandsbrua is the longer of the two, with floating a section of 1246 meter, the other one is 931 meter. Evergreen Point Floating Bridge which crosses Lake Washington in the US is currently the world's longest, with a floating section of 2310 meter (Statens vegvesen, 2012b).

The Floating Bridge (abbreviated as "FB" in this thesis) proposed by Aas-Jakobsen and their collaborators for crossing the Sognefjord will have a total length of 4400 meter. Each span will be 1234 meters long, and the structure is connected to land by onshore viaducts at each end (see Figure 7). If realised, their concept will set a new standard for floating bridges.

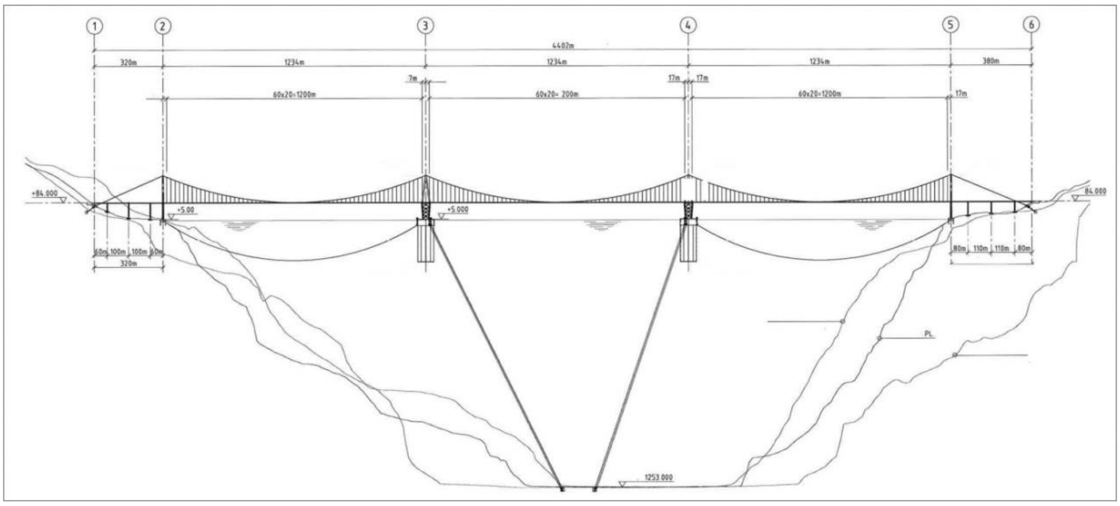


Figure 7: Side view of the Floating suspension bridge in three spans, copied from Jakobsen (2013).

Design and Materials

Two offshore towers constructed on the concrete pontoons, and two onshore viaducts make up the supporting structure of the bridge. The offshore towers are constructed mainly of steel. This is to reduce the weight and also to make the process of constructing at sea easier. The onshore towers are made of concrete. The pontoons are made out of concrete, lightweight aggregate concrete (LWA-concrete) and reinforcement. Olivine rock and additional concrete is used for ballast. The pontoons are anchored to the fjord bottom by suction anchors and offshore mooring chains. The anchoring system is mainly made of steel.

The bridge is designed with a 4,75 meter wide traffic lane in each direction, and a 3 meter wide walkway for cyclists and pedestrians (see Figure 8).

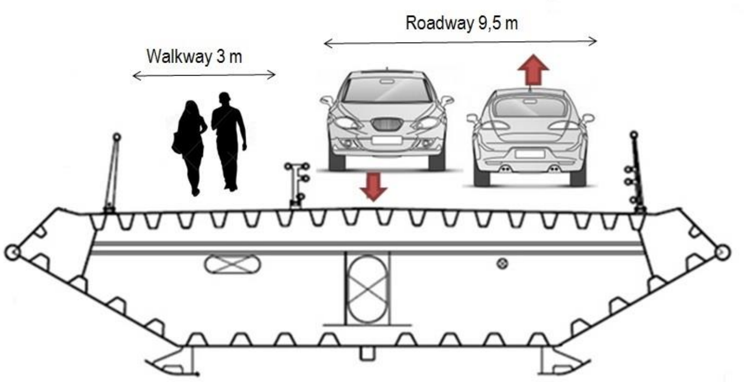


Figure 8: Cross section of the load-bearing unit with roadway and walkway widths.

Construction

The dry dock at Hanøytangen outside Bergen has been suggested for construction of the pontoons. The dock is situated about 150 kilometres from the crossing site in the Sognefjord. In the feasibility study the pontoons are assumed to be towed to the site by the aid of tugboats. The lower part of each of the offshore towers will be prefabricated in four parts and a lifted in place by a mobile offshore crane. The upper part of the tower will also be prefabricated, and is assumed to be lifted in place by a tower crane attached to the pontoons. The remaining construction processes are assumed to follow a traditional procedure for a suspension bride. This includes a climbing scaffolding process for erecting the concrete towers, and cable spinning with anchoring for the suspension system.

4.1.2 Suspension Bridge

The feasibility study for a suspension bridge was conducted by bridge engineers at Statens vegvesen. They proposed a 3700 meter single-span suspension bridge with a split box girder described in a conference paper by Isaksen, et al., (2013). The main material quantities necessary to construct a suspension bridge of this design is given in unpublished report by Statens vegvesen (2014a). An illustration of the proposed Suspension Bridge (abbreviated as "SB" in this thesis) for crossing the Sognefjord is given in Figure 9, and a side view the design is provided in Figure 10.

Figure 9: Overview of the 3700 meter single span suspension bridge
Illustration by Statens vegvesen

The current longest single bridge span constructed in the world is the Akashi-Kaikyō bridge in Japan, which has a main span of 1991 meter (Statens vegvesen, 2012b). The main challenge for constructing bridges of longer single spans is the impact of wind loads. To prevent aerodynamic instabilities, a split box girder is recommended by several bridge designers (Statens vegvesen, 2014a).

Figure 10: Side view of the Suspension bridge, copied from Isaksen, et al., (2013).

Design and Materials

The bridge is designed with load-bearing units made of steel. The two load-bearing units will be connected by cross beams, also made of steel. The bridge towers will be made of reinforced concrete. In order to sustain the weight of the bridge deck in such a long single-span, the towers need to be around 450 meters high. Each of the two load-bearing units will be designed with two narrow driving lanes and a walkway. The total width of the roadways will be 5,75 meters per section, and the walkways will be 3 meters wide. (see Figure 11).

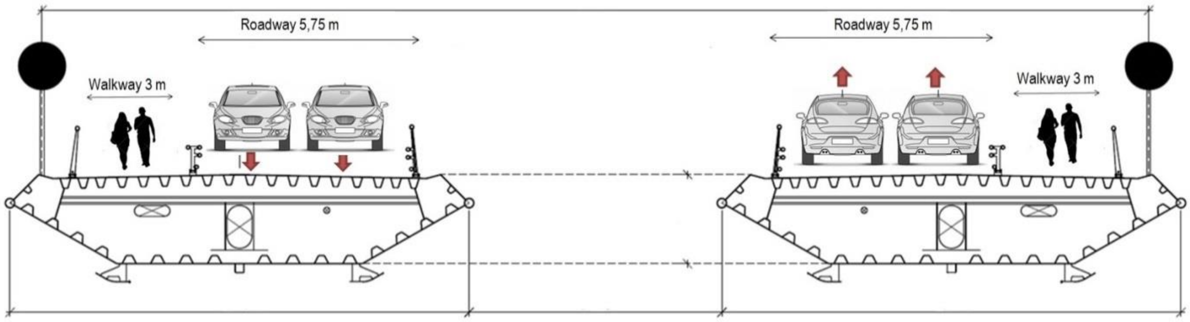


Figure 11: Cross section of the two load-bearings unit with roadway and walkway widths.

Construction

The construction process is not explicitly described in either of the mentioned papers. It is however assumed to be similar to other long suspension bridges like the Hardanger Bridge. The load-bearing unit is assumed to be prefabricated in sections and transported by an heavy duty vessel or ocean going freight ship. At site they are assumed to be lifted into place by an mobile offshore crane. The bridge towers are assumed to be constructed by climbing scaffolding, similar to the Floating bridge.

4.1.3 Submerged Floating Tunnel

The feasibility study for the Submerged Floating Tunnel (abbreviated as “SFT” in this thesis) was prepared by a design group under the name “Reinertsen Olav Olsen Group”. The study is documented in the report by Fjeld (2012), and the concept was declared technologically feasible. The main concept is illustrated in Figure 12 and 13, and it consists of two submerged arch shaped concrete tubes connected to pontoons.

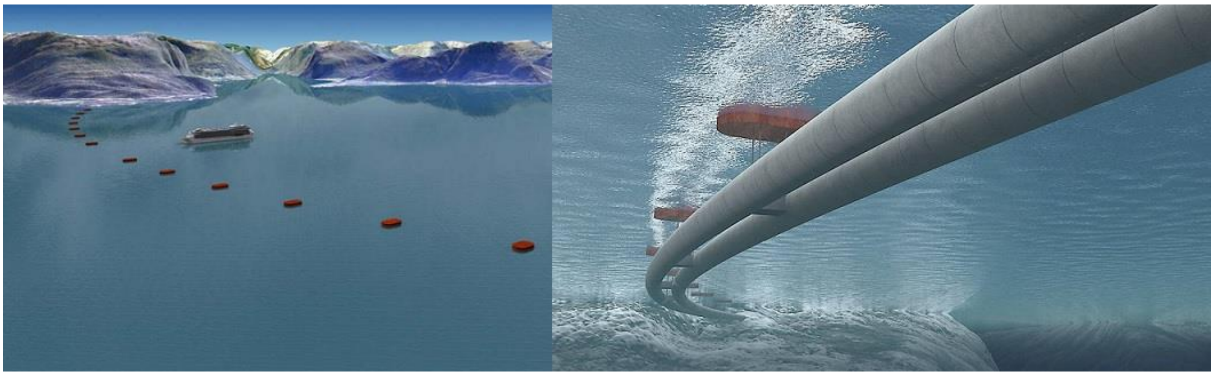


Figure 12: Overview and subsea view of the Submerged Floating Tunnel (SFT) concept described in Fjeld (2012). Illustrations by Statens vegvesen

A Submerged Floating Tunnel (SFT) like the one described in this feasibility study has never been built before. A similar concept was however evaluated in a previous assessment of possibilities from crossing Høgsfjorden in South Western Norway. The submerged floating considered in that assessment was approved as a technologically possible solution for the investigated fjord crossing (Statens vegvesen, 2012b).

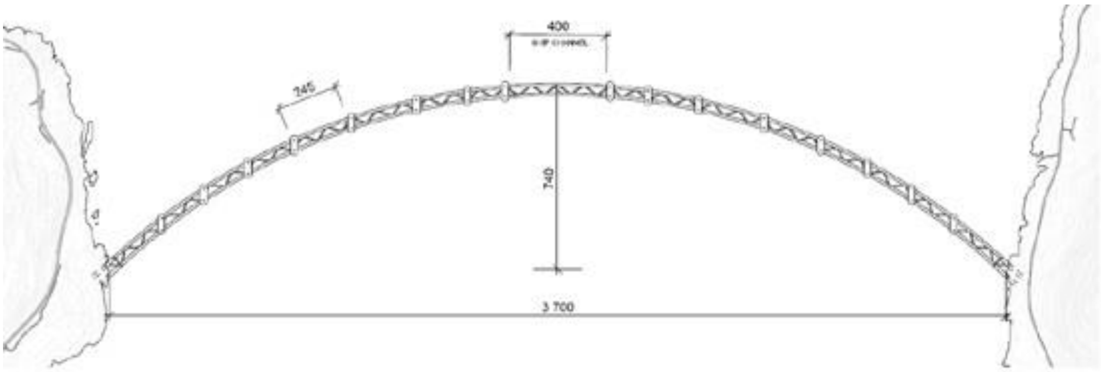


Figure 13: Over view sketch of the Submerged Floating Tunnel concept (copied from Statens vegvesen, (2012b)).

Design and Materials

The tubes will be made of concrete, supported by reinforcement and post-tensioning tendons. Pontoons made out of steel will be used to anchor the tubes to the sea surface, keeping the structure afloat. A cross section of the structure is illustrated in Figure 14. Each tube will be designed for two 3,5 meter wide traffic lanes and with a profile similar to a standard Norwegian T9,5 road tunnel. The feasibility study states that only one of the two lanes in will be used for traffic in the current concept. The other lane will be used for maintenance work, and for emergency stop possibilities. However in this analysis both lanes are assumed to be used for traffic. Each tube will then have a roadway width of 7 meters, as illustrated in Figure 15. The tubes are connected by diagonal bracings to keep the structure rigid, additional stabilization is provided by the pontoons. Landfall sections will connect the tubes on each side of the fjord.

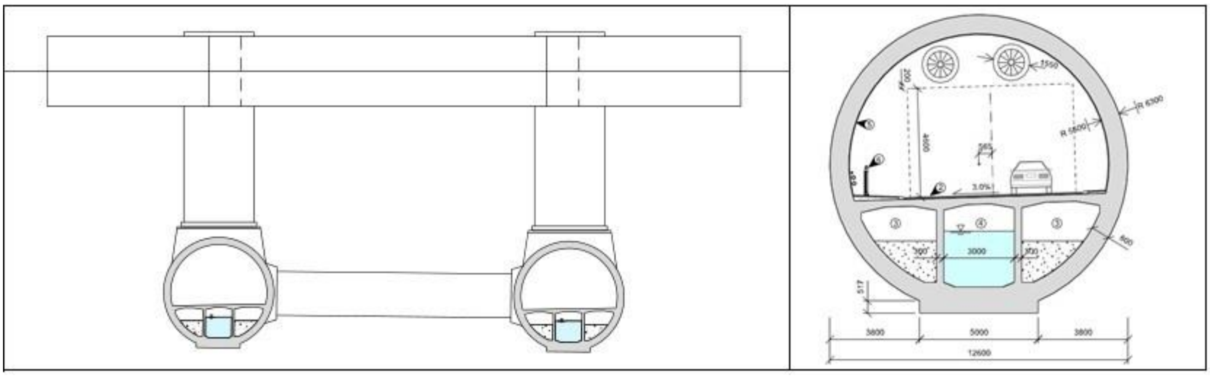


Figure 14: Cross section of the tube system illustrating the width of the construction, and design of the tubes with ballast chambers.

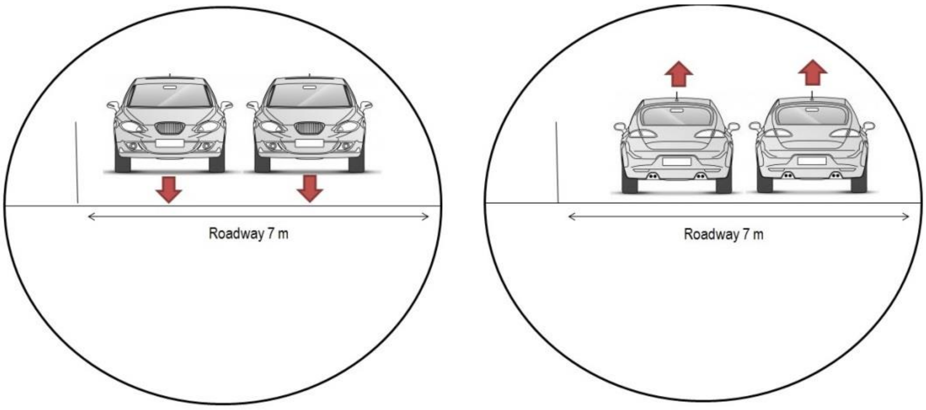


Figure 15: Cross section of the tube system illustrating the number of driving lanes and the width of roadways

Construction

Hanøytangen the same dry dock suggested for the construction of the Floating Bridge pontoons is proposed for constructing the SFT tube sections. The tubes will be constructed in 15 sections with lengths between 250-300 meters. A section like this is illustrated in Figure 16. The sections will be towed to the Sognefjord with the aid of 1 main and 4 assistant tugs, a distance of about 80 nautical miles. Remaining construction operations will be done at site, including the installation of the pontoons.

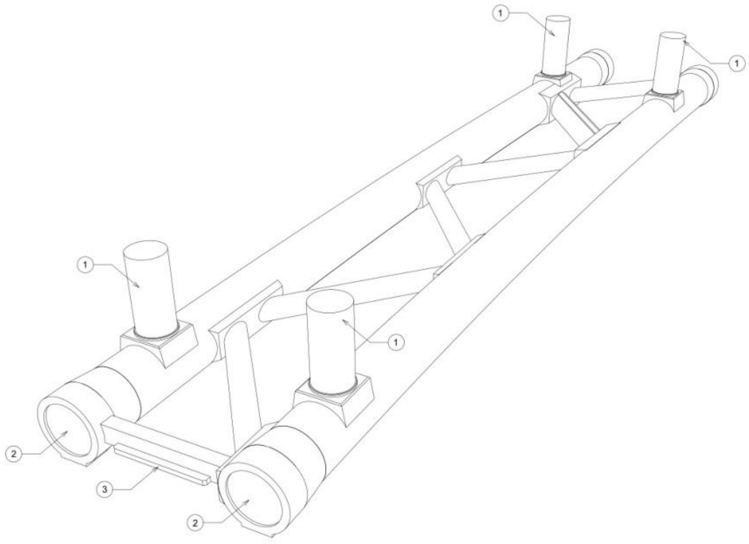


Figure 16: 3D sketch of a tube section, copied from Dr.Techn Olav Olsen (2012).

4.1.4 Comparison of the crossing concepts

The three crossing concepts have significant differences regarding the design. Their dimensions are compared and illustrated in Table 2. They are designed to serve the same main function of crossing the Sognefjord, but they have certain characteristics that will affect the interpretation of the final result. The impact on the analysis of GHG-emissions due to the variations in design will investigated based on additional functional units. This will be described in the following subchapter.

Table 2: Comparison of the dimensions of the three fjord crossing concepts

Crossing structure dimensions	Floating Bridge	Suspension Bridge	Submerged Floating Tunnel
Total bridge length (m)	4400	3700	4083
Construction width (m)	18,3	32,9	80
Number of traffic lanes	2	4	4
Number of pedestrian walkways	1	2	-
Total roadway width (m)	9,5	11,5	14
Roadway and walkways width (m)	12,5	17,5	20,5
Effective roadway area (m^2)	41 800	42550	57 162
Effective area (m^2)	55000	64750	83702
Bridge tower height	211	445	-

4.2 LCA methodology applied in the case study

In this subchapter the inventory and data collection will be described for the three concepts claimed technically feasible to cross the Sognefjord. Establishing the inventories on equal terms has been a main focus. The methodological choices for the analysis are presented and explained. The relative importance of the emission intensity of the fjord crossing structures compared to traffic-related emissions is evaluated by a fictional fjord crossing scenario. The details behind this additional analysis will be covered together with the traffic related emissions inventory.

The structure of this subchapter will follow the four phases of an LCA described earlier. Data collection and calculations will be explained, but the details are given in Appendix B. The analysis was conducted in the computer program SimaPro 8 (PRé Consultants, 2013). Background data have primarily been collected from the database Ecoinvent v3. Processes that have been modelled with other input data are described in Table B5-B10 in Appendix B. The configuration of the model set up in SimaPro has been based on recommendations from the literature review, the PCR document for roads.

4.2.1 Goal and Scope

The main goal is to compare and quantify the GHG-emissions associated with constructing the three concepts claimed technically feasible for crossing the Sognefjord. An additional goal is to compare the GHG-emissions associated with a Sognefjord crossing with traffic related emissions. This is done to elaborate the importance of considering the potential indirect GHG-emissions from constructing technologically advanced road infrastructure.

Functional Unit

The functional unit for this assessment will be:

- "**1 fjord crossing**"- *Defined as the production, construction, operation and maintenance of a permanent crossing of the Sognefjord between Lavik and Oppedal over a life time of 100 years.*

The results will be adjusted to the following more comparable functional units in accordance with literature:

- **1 km of road infrastructure**
- **1 m^2 effective area**

The definition of 1 km of road infrastructure in this assessment follows the PCR document for highways (except elevated highways), streets and roads (International EDP system, 2014). This is currently the closest alternative for a standardized “1 km fjord crossing” definition, since no PCR document have been established for road, tunnels, or bridges. Defining 1 m^2 of effective bridge area however has some implications. Dequidt (2012) applied this functional unit after the definition given in Hammervold, et al., (2013). In this thesis 1 m^2 has been defined based on two different approaches. One of the definitions applied is “1 m^2 of effective roadway area”. This definition covers only the area that serves a direct purpose for the movement of vehicles. The other definition follows Hammervold, et al., (2013) and includes walkways in an “effective bridge area”. The difference between the two can be seen from Figure 8, 11 and 15 in the case study chapter. Implications of the chosen definitions will be analyzed and discussed in detail.

System boundaries

All three crossing concepts were modelled after production, construction, operation and maintenance, and with the inclusion of traffic. The chosen system boundaries are illustrated in Figure 17. A life time of 100 year was assumed for all three crossing concepts. The production phase is defined here as the extraction of raw material, transportation and processing needed to create construction materials like concrete and steel. The construction phase is defined as the transportation of these materials to the relevant assembly or construction site, together with all the activities at the construction site. The operation and maintenance phase includes the infrastructure related activities after the opening of the fjord crossing. Traffic is treated separately. This definition of the respective life cycle phases is similar to the one used in Du & Karoumi (2014).

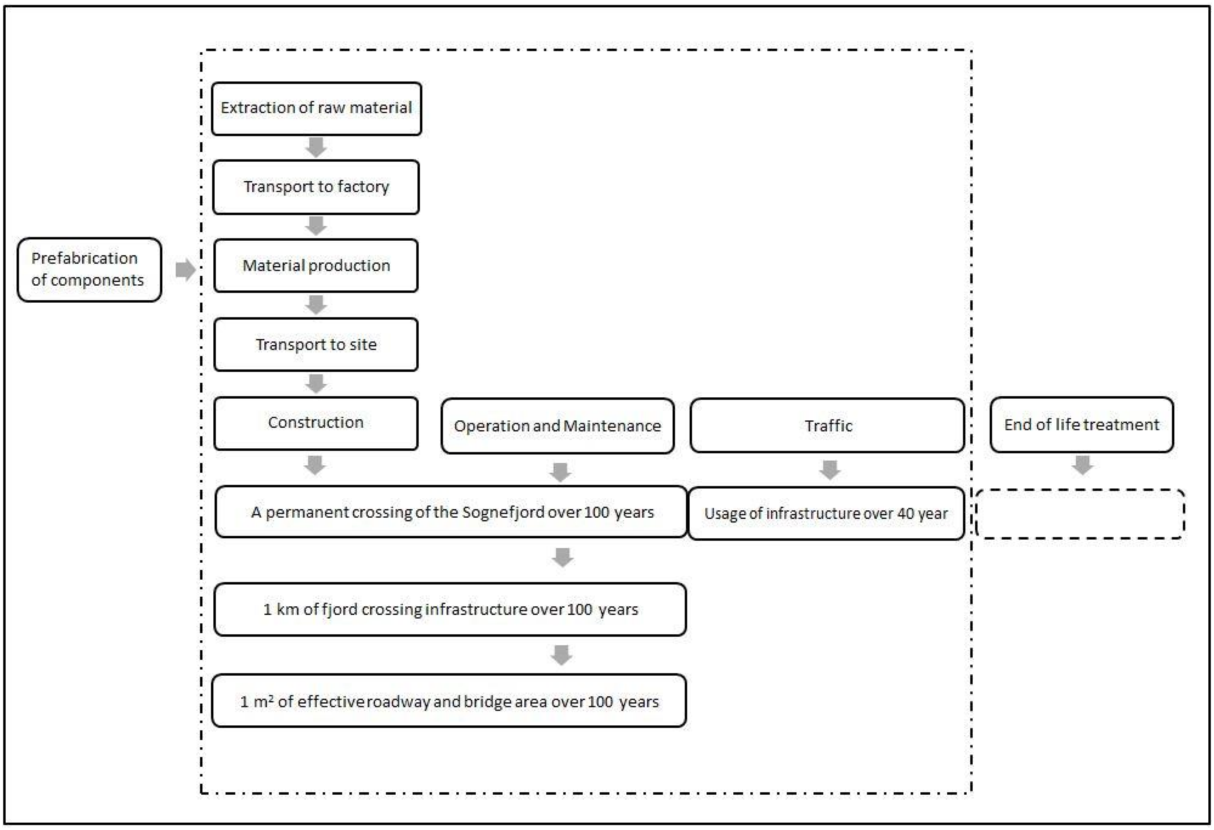


Figure 17: System boundaries applied in this analysis

4.2.2 Establishing the life cycle inventory

Collecting data for establishing a high quality life cycle inventory for something as complex as a fjord crossing structure imposes certain challenges. Covering every single process that may contribute to material consumption and emissions is quite challenging and time consuming. As a reason for this some choices have to be made. The guidelines given by SETAC (Society of Environmental Toxicology and Chemistry) states that" all components weighing less than 1 % of the total weight of a material or a process can be left out of a life cycle inventory (European Commission, 2010). Applying this approach to the total weight of the fjord crossing structures would most likely support an omission of all materials except the ones given in the feasibility studies. This approach will however not be followed explicitly in this study, but can be used as an argument for leaving some processes out of the system boundaries. Attempting to include and quantify unknown factors in the construction phase was an important part of this thesis. The procedure for this will be described later in this subchapter.

The Excel tool *BridgeLCA* described in Hammervold, et al., (2009) separates between material inputs with a "major and minor LCA impact". A similar approach has been taken in this analysis. Materials recognized with a minor LCA impact like paint, epoxy, formwork, mastic (adhesive) and explosives have not been quantified in the feasibility studies. As a reason for this, they have not been included within the scope of this analysis. Several other components have not been included either. They will be mentioned separately in their respective life cycle phases. The main reason for their omission is the difficulty of acquiring data, as emphasized by Du & Karoumi (2014) and Carlson (2011). Also the analysis conducted in this thesis is an early-phase LCA, aiming mainly at giving an indication of the size of the GHG-emissions. Performing a full scale detailed LCA will therefore not be attempted.

4.2.2.1 Production phase

Material quantities are often calculated at an early stage in road planning. This is done to assess the technological feasibility, and also to give a cost estimate of the infrastructure investment (Miliutenko, et al., 2011). A bill of quantities for the main construction materials was given in each of the feasibility studies. Table 3 provides a summary of theses quantities.

Table 3: Summary of the main material quantities given in the feasibility studies at an aggregated level

Material quantities	Floating Bridge	Suspension Bridge	Submerged Floating Tunnel
Concrete (m^3)	215 650	231 722*	424 671
Construction steel (tonnes)	56 109	128 125	61 488
Reinforcement steel (tonnes)	32 000	37 123*	113 922**
LWA-concrete (m^3)	77 000	-	-
Olivine (m^3)	310 000	-	-

*Estimated from the given reinforced concrete mass

**Includes post-tensioning cables

It should be taken into account that the material quantities given probably will be adjusted in a future construction process. In addition the structures may be oversized by the designers at this early stage in planning (Statens vegvesen, 2012b).The implication of this will be evaluated by a traditional sensitivity analysis similar to the one conducted in Hammervold (2009) and Fuglseth (2013). This will be done by increasing the main material inputs and processes with 10 % one at a time and comparing the new total GHG-emissions with the initial result. The result from this analysis will be presented in a bar chart, illustrating the percentage increase in total emissions due to a ten percent increase of each of the chosen inputs.

In all three feasibility studies, concrete with a compressive strength class of B45 or 55 are used. According to the Ecoinvent documentation given in Kellenberger et al (2007), the background process that represents this strength class is *Exacting concrete with de-icing agents.* Based on this documentation and geographical location of Norway , the Ecoinvent-process *Concrete, for de-icing salt contact {CH}| production | Alloc Def, U* is chosen. The abbreviation *CH* indicates that the background process represents average concrete production in Switzerland. Structural steel is assumed to be used for load-bearing portions, main cables, railings, and for the submerged floating tunnel pontoons. The steel process that best represents these types of applications is low-alloyed hot rolled steel (Classen et al, 2007). In this analysis the background process *Steel, low-alloyed, hot rolled {RER}| production | Alloc Def, U* has been chosen for all the structural steel components. The abbreviation RER indicates that the process represents average European production. Hot rolling and preparation of the product is included in the chosen Ecoinvent process. The Ecoinvent process *Reinforcing steel {RER}| production | Alloc Def, U* has been chosen for reinforcement steel and post-tensioning cables, and *Lightweight concrete block, expanded clay {CH}| production | Alloc Def, U* for LWA-concrete. Olivine production has been modelled similar to the extraction of gravel from a quarry, but the input of gravel was replaced by *olivine in ground* from nature.

The implication of the chosen background processes for construction steel, concrete and reinforcement will be evaluated by a sensitivity analysis. Each of highest contributing materials will be evaluated for each of the fjord crossing concepts. The analysis will cover alternative Ecoinvent background process representations impact on the final result. This implies that the total GHG-emissions from each of fjord crossing concepts will be recalculated with a different background process for concrete, steel and reinforcement. In addition EPDs from Norwegian suppliers of concrete and reinforcement are included in the sensitivity analysis. There are several EDPs available from the official Norwegian site for EDPs (EDP-Norge, 2014). The EPD from the concrete manufacturer Unicon (2012) was chosen for this analysis. The EDP for reinforcement steel from Celsa Steel Service (2012) was taken from the company’s homepage.

The model set up in SimaPro separates between main and minor components. The main components consist of the material quantities given in the feasibility studies. The minor components are defined as asphalt in the wearing layer, steel in the railings and technical installations like ventilators for the SFT. The estimation of the material input of asphalt and steel in the railings is based on the methodology behind the EFFEKT model (Statens vegvesen, 2009a). The number of ventilators in the SFT and their material input was estimated based on Iversen (2013). The parameters used for the calculations of the minor components are documented in Table B5 in Appendix B.

The additional processing of the materials apart from that included in the respective Ecoinvent processes will not be included within the scope of this analysis. This refers to processes like the casting of the concrete tubes and the forming of steel for structural components. The omission of this is also illustrated in Figure 17.

4.2.2.2 Construction phase

Building a data inventory for the construction phase is in general one of the main challenges with conducting a LCA for bridges and other road infrastructure types. The main reason for this is that information regarding machinery usage and specifications is often not available from the contractors (Du & Karoumi, 2014). It is therefore hard to make estimations before the project has been commissioned. In the three feasibility studies there are some descriptions of the construction phase that can be used as a basis for modelling energy and resource consumption. However since only potential fjord crossing concepts are being analyzed in this thesis, data from contractors cannot be collected. The best option is then to either collect data from tender documents and contractors from a completed project of similar size, or rely on data from literature. A SFT and a FB of the style proposed for crossing the Sognefjord has never been built before. A SB of the size needed to cross Sognefjorden at the described site has never been built either. Hence it’s not possible to find a directly comparable project.

The closest reference fjord crossing in Norway was found to be the Hardanger Bridge. The bridge is a 1380 meter long single span suspension bridge. Contact was made with the project managers from the bridge to gather experience. The mangers explained that amount of diesel or other liquid fuel consumed by machinery during a suspension bridge construction is not that high (Valen, 2014). The main construction machines like the tower crane, cable-spinning devices, and mobile concrete mixing plants all run on electricity. Assumptions of the number of hours each construction machine will be used were included in the tender document. However a follow-up of the actual amount of hours used per machine was not done. This is in general not common to do during bridge construction projects (Valen, 2014). Hence the assumed machine hours from the Hardanger Bridge are not necessarily applicable for estimations in this analysis. It was therefore decided that the data from the Hardanger Bridge were not directly applicable for this analysis. As a result of this reasoning, the inventory for the construction phase was mainly based on data from literature.

Construction site operations

In literature the construction phase is often quantified based on rough assumptions, weak data, or sometimes neglected entirely (Du & Karoumi, 2014). There were only two detailed studies done on Norwegian bridges identified in the literature review; the paper by Hammervold, et al., (2013) and the master's thesis of Dequidt (2012). An average diesel consumption of 2,41 per m^2 effective bridge area was estimated based on the input data and bridge dimensions given in Hammervold, et al., (2013) (see Appendix B for details). The bridges described an analysed in their paper are about a hundred times smaller than the bridges claimed technically feasible for a permanent crossing of the Sognefjord. Hence they are most likely not representative for a Sognefjord crossing. Dequidt (2012) however performed a LCA on the 670 meter long Tverlandsbrua. The bridge has four driving lanes and an effective bridge area of 15711,5 m^2. Based on this area and the input given in the thesis, energy consumption parameters were calculated and are presented in Table 3.

Table 4: Energy consumption parameters per m2 of effective bridge area estimated from Dequidt (2012). The details behind the calculations are given in Appendix B.

Energy type	Amount	Units
Marine diesel oil	1,83	liter/m^2
Diesel	9,87	liter/m^2
Electricity	28,64	kWh/m^2
Gasoline	1,53	liter/m^2

The main energy consuming processes for Tverlandsbrua were boat operations, crane lifts and excavations of masses on land and from the fjord bottom. The parameters given in Table 4 were used to calculate the energy consumption at the construction sites for the Sognefjord crossing concepts. The construction processes for each of the concepts were described in the previous subchapter, but it should be noted that these processes are not quantified accordingly in the analysis. The chosen approach is quite rough and has many associated uncertainties. A sensitivity analysis with an increase of 10 times higher energy consumption will be conducted to elaborate the impact of this approach. The outcome will be discussed in the concluding chapters

Transportation to site

Transportation of materials to site has been included in the construction phase in this study. The system boundaries for transportation have been set to Western Norway. Concrete is assumed to be supplied by a concrete producer in the Bergen Area like Ølen Betong or Unicon. The steel is assumed to be produced outside Norway and the system boundaries, but a transportation process on barges from the port of Bergen is included. Only the transportation of the main materials given in the feasibility studies is included. The following transportations schemes have been chosen:

- Transportation of materials to the Hanøytangen dry dock from Bergen by road.
- Transportation of olivine on a barge from Åheim to Hanøytangen. Åheim is the location of Sibelco, a major olivine producer in Norway.
- Transportation of materials from Bergen to the Sognefjord crossing site by truck or by sea.

The distances for the specific transportation routes are given in Table 5. They have been estimated with the aid of Google Maps and the online distances and transit time calculator from Searates LP (2014). Towing of the fabricated elements from Hanøytangen to the Sognefjord crossing site is described separately.

Table 5: Material transportation distances applied in this study

Transportation route	Distance	Unit
Bergen to Hanøytangen by road	25	km
Bergen to the Sognefjorden site by road	120	km
Hanøytangen to the Sognefjorden site by sea	150	km
Bergen to the Sognefjorden site by sea	160	km
Åheim to Hanøytangen by sea	250	km

A sensitivity analysis with global system boundaries will be conducted for the transportation processes to evaluate its importance. The transportation of the main steel components of the Suspension Bridge is included in this analysis. This includes the load-bearing unit and the suspension and main cables. The components are assumed to be transported from the same locations as for the Hardanger Bridge. The details behind these assumptions are given in Appendix B.

Towing to site

The pontoons for the Floating Bridge and the tube sections for the Submerged Floating Tunnel are designed to be towed from Hanøytangen dry dock to the Sognefjord crossing site. The towing operations are described in more detail in the feasibility studies by Jakobsen (2013) and Fjeld (2012). Tractor tugs with a 50 TBP (Tonnes Bollard Pull) and lead tugs with a 150-200 TBP are assumed to be used. The emissions from these vessels were modelled for specifically for this thesis due to the absence of a relevant background processes in Ecoinvent. This procedure is described in Appendix B.

Omissions

The following processes have not been included in the life cycle inventory for the construction phase: Abrasion of machinery at construction site, subsea operations related to the installation of the crossing structure, transportation of the workforce and electricity consumption in the barracks. Traffic disruptions during the construction phase are not included either. This omission is based on an assumption that the ferry will continue to run normally until the crossing structure is completed.

4.2.2.3 Operation and maintenance phase

The operation and maintenance phase is considered the longest phase in the life time of road infrastructure. Different definitions are used in literature, and the phase can include a majority of activities. Replacement of components, renewal of the wearing layer, and operation are the only processes included in this study. The operation includes the electricity for lightning and in addition electricity for ventilation and pumps in the SFT.

Replacement of components

None of the major structural components of the SFT like the tubes, bracings and shafts are designed to be replaced during the life time of the structure (Haugerud, 2014). The same assumption is used for major structural components of the other two crossing concepts. A onetime replacement of the steel railings is assumed for all concepts. The SFT includes more technical installations than the other two structures since it’s a closed tunnel like structure. Components like pumps, grouting anodes for cathode protection, and ventilators are assumed to be replaced during a life time of 100 years (Haugerud, 2014). Due to lack detailed data however, only the replacement of the ventilators was included in the analysis. The omission was also done in order to compare the crossing concepts on equal terms. A 20 year life time was assumed for the ventilators based on Statens vegvesen (2012d), and a 50 year life time was assumed for railings based on the bridge railings manual from Statens vegvesen (2009b).

Renewal of the wearing layer

In both Hammervold (2013), and in the documentation of EFFEKT (Statens vegvesen 2009a) it is assumed that 65 % of the original laid amount is renewed every 10th year. The same values are applied in this study.Replacement of components and wearing layer renewal occurring for a time period beyond year 100, have been omitted.

Operation

It is assumed that the all the crossing concepts are fully lighted the whole year. Equations are based on the methodology for the EFFEKT-model:

$$EL_{lighting}[kWh] = 26{,}5\ kWh\ \times\ structure\ length\ (m)\ \times years\ of\ operation \qquad (1)$$

For the SFT the following equations are also applied:

Electricity consumption of the ventilators:

$$EL_{ventilation}[kWh] =\ 15{,}5\ \times AADT\ \times \left(\frac{Lt}{1000}\right)^2\ \times\ years\ of\ operation \qquad (2)$$

Where Lt stands for tunnel length in kilometers

Electricity consumption of the pumps:

$$EL_{pumps}[kWh] = 18\ kWh\ \times\ structure\ length\ (m)\ \times years\ of\ operation \qquad (3)$$

Equations 1-3 give the total electricity consumption over the chosen years of operation.

Omissions

Operation activities like snow removal, road marking, gritting, cleaning, and traffic management and control have not been included. The same applies for maintenance activities like repairs due to accidents.

4.2.2.4 Use phase - Traffic

GHG-emissions from traffic were included for all three crossing concepts based on their respective lengths. The resulting emissions with the inclusion of traffic will be presented separately. A 12 % heavy vehicle share was assumed, and a 40 year time horizon was chosen. The operation and maintenance phase will be shortened to 40 years when traffic is included. Passenger cars were represented by the Ecoinvent process *Transport, passenger car, EURO 4 {RER}| market for | Alloc Def, U,* and heavy vehicle traffic by *Operation, lorry 16-32t, EURO4/RER U.* The abbreviation EURO4 refers to the vehicles meeting the emissions requirements in accordance with the Euro-4 standards. (European Commission, 2014). The average AADT chosen for the given time horizon was estimated from the current traffic intensity at the ferry connection Lavik - Oppedal and future projections. The additional growth in traffic was based on experience from Norway after ferry connection replacements with a permanent crossing (Statens vegvesen, 2012c). The average AADT over a 40 year time horizon was estimated to be about 4 000 vehicles per day (see Appendix B for calculation parameters).

Traffic generated due to maintenance and repair in the use phase as put to the attention of Hammervold, et al., (2013) and Du & Karoumi (2014) will not be included in the scope of this thesis. It will however be addressed qualitatively and commented on in the discussion.

4.2.2.5 End of Life Treatment (EOL)

End of life treatment will not be included in this assessment. This is mainly due to roads bridges and tunnels rarely being torn down and demolished (Jonsson 2007). The omission of this phase will be mentioned briefly in the discussion, but will not be assessed in detail. When the EOL phase is included in literature it is not associated with a significantly large share of the total GHG-emissions.

4.2.3 Life cycle environmental impact assessment

As described in the theory a LCA can cover a wide range of environmental impact categories depending on the method. This assessment will focus mainly on GHG-emissions quantified by the Global Warming Potential (GWP) characterization method. All the environmental impact categories from the ReCiPe method by Goedkoop, et al., (2013) which is presented in Table A3 in Appendix A will be included in the analysis. The result based on ReCiPe will be presented after the results and sensitivity analysis for the GHG-emissions. The characterization method of Cumulative Energy Demand (CED) will be used to quantify the energy consumption, and includes the embodied energy in the materials.

4.2.4 Interpretation

The results will be presented in chapter 6, and interpreted afterwards in the discussion. A discussion regarding the methodological choices for this thesis as outlined in this chapter will follow. Setting system boundaries for a LCA of road infrastructure has certain implications. Regardless of where the system boundaries are drawn, it will impact the analysis in one way or another. This affects the comparability of the result as mentioned in the literature review. The implications of the chosen system boundaries and data quality will be further evaluated in the discussion.

4.2.5 Fictional fjord crossing scenario

A fictional fjord crossing scenario similar to the one in Bergsdal, et al., (2013) and Statens vegvesen (2000), was set up to further compare the infrastructure related emissions to emissions from road traffic. The emissions related to the Sognefjord crossing will be used for this purpose to illustrate their size of GHG-emissions compared to previous studies. The infrastructure related emissions are based on a rounded average of the emissions from the material production and the construction for the three crossing concepts for the Sognefjord. The length of the fjord crossing is also a rounded average of the three structures, and is set to be 4 km. A sketch illustrating the fictional scenario is shown in Figure 18.

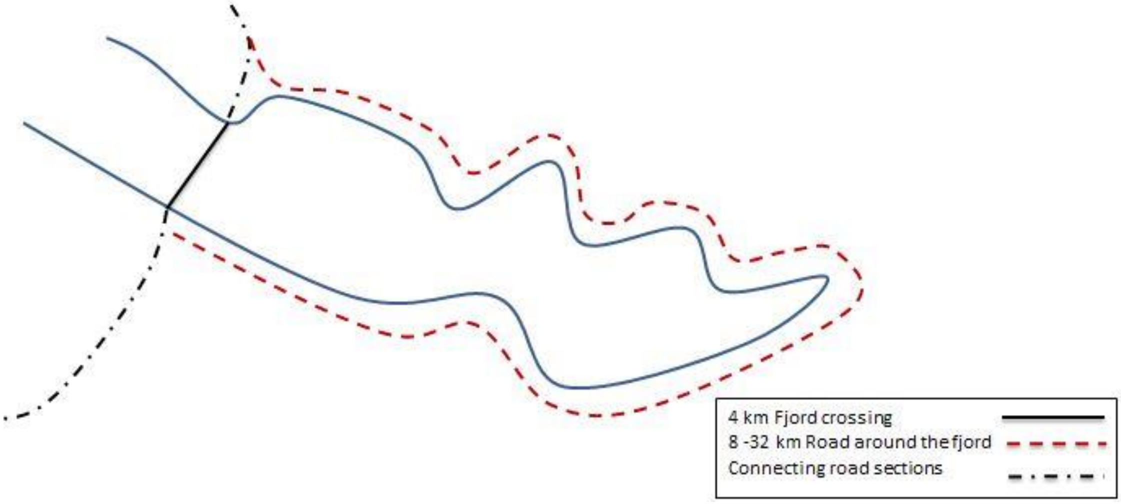


Figure 18: Illustration of the fictional fjord crossing scenario

Different emissions intensities of grams of CO_2 per km of vehicle operations, traffic intensities and open section road lengths will be applied in the different scenarios. The different scenarios to be considered are presented in Table 6. The resulting emissions will be presented similar to the payback period used for in the HSR-assessment by Bergsdal, et al., (2012). The differences between the scenarios are illustrated and discussed accordingly in the concluding chapters.

Table 6: The scenarios included in the fictional fjord crossing analysis. The different inputs describing the scenario names are given in separate columns.

Scenario name	Fjord crossing length (km)	Open section length (km)	Emission rate (gCO2/km)	AADT
AADT 2000	4	16	310	2000
AADT 4000	4	16	310	4000
AADT 8000	4	16	310	8000
AADT16000	4	16	310	16000
85g CO2 / km AADT 4000	4	16	85	4000
85g CO2 / km AADT 8000	4	16	85	8000
250g CO2 / km AADT 2000	4	16	250	2000
250 g CO2 / km AADT 4000	4	16	250	4000
250 g CO2 / km AADT 8000	4	16	250	8000
250 g CO2 / km AADT 16000	4	16	250	16000
8 km	4	8	310	4000
16 km	4	16	310	4000
24 km	4	24	310	4000
32 km	4	32	310	4000

The emissions intensity of 85g CO_2 per kilometer is taken from a report by the Institute of Transport Economics (Figenbaum et al, 2013). The value is based on a goal for passenger car GHG-emissions within 2020. It does not include heavy traffic, but is used on a basis of lower future emissions from road traffic. The value was used to represent a potential future average for the next 100 years due to new vehicle technology. The fictional fjord crossing scenario is conducted for illustration purposes, and is not based on the same detailed research as the Sognefjord crossing.

4.3 GHG-emissions due to route choice alternatives

Current and past debates regarding route choice alternatives along Coastal Highway E39 has been the starting point for this additional analysis. Several different routes have been considered for the Route E39 fjord crossings north of the Sognefjord in an evaluation by Statens vegvesen (2011a). The Hafast and Fefast route alternatives from this report were chosen to represent the findings from the analysis of the Sognefjord crossing concepts in broader road infrastructure perspective.

4.3.1 Hafast and Fefast route alternatives

A simplified analysis was set up to evaluate the emissions associated with a specific route choice scenario along E39. The current political debate of Hafast or Fefast for crossing for a permanent connection between the cities of Volda and Ålesund was chosen to further compare the emissions related to traffic and infrastructure. In a press release on the 14th of april 2014, the government decided that Hafast should be the basis for a future crossing (Ministry of Transport and Communication, 2014). However the crossing route choices of Hafast and Fefast will still be used as a case study regardless of this decision. The two route alternatives are illustrated in Figure 19.

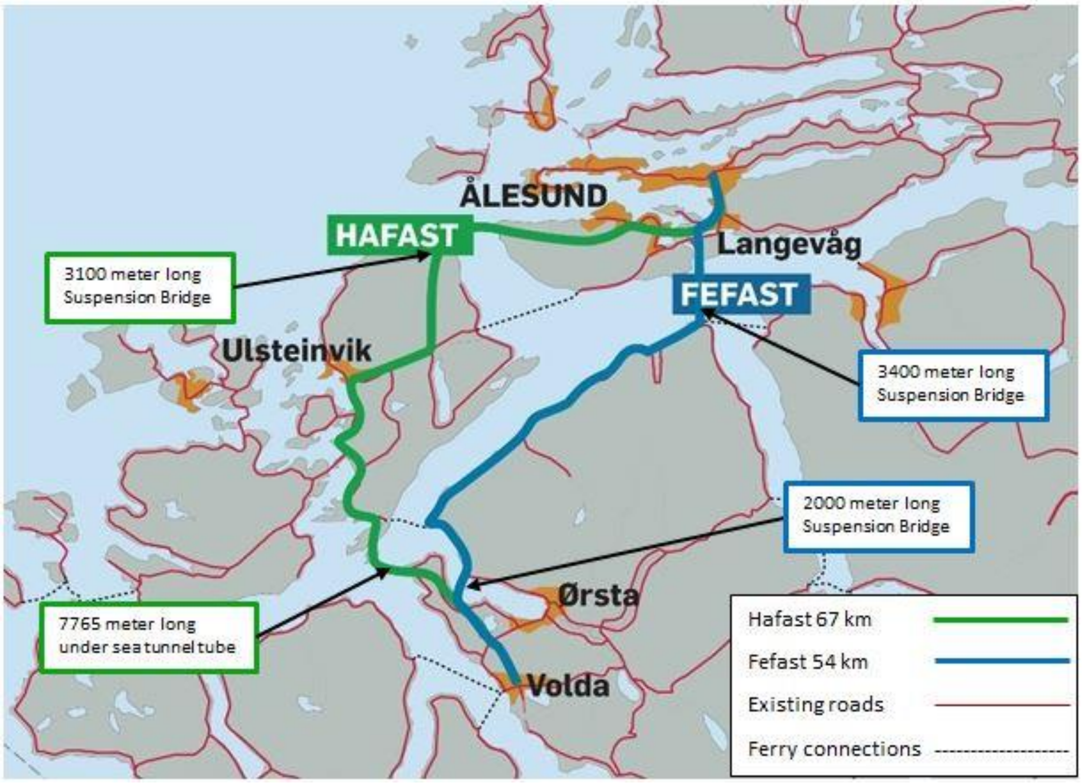


Figure 19: A map illustrating the Hafast and Fefast route choices and infrastructure investment lengths. Modified from an illustration by Kartagena/Statens kartverk

The starting point of the analysis was set to the town of Volda, and the ending point to the city of Ålesund. The Hafast route was identified to be 67 kilometers long, and the Fefast route to be 54 km in two described concepts. The Hafast route in this analysis includes a new 7 765 meter long undersea tunnel parallel to the existing Eikesund tunnel, and a 3 100 meter suspension bridge crossing Sulafjorden. The Fefast route includes a 2000 meter long suspension bridge over Ørstafjorden based on Statens vegvesen (2014b), and a 3 400 suspension bridge over Storfjorden. The dimensions for the two longest suspension bridges were taken from Statens vegvesen (2012b). The reference alternative of the current ferry connection between Festøya and Solevågen was also included in the analysis. The ferry runs at the same location as the 3 400 meter suspension bridge along the Fefast route in Figure 19. This route is currently the main road corridor between Volda and Ålesund.

4.3.2 Route choice inventory model

A simplified static model was set up in SimaPro with an average AADT of 5000 vehicles per day over a time horizon of 40 years. This approach is not consistent with proper traffic scenario modelling. The approach was taken to simplify the analysis, in order to avoid an in depth analysis of the future traffic amount. The implications of this choice will be discussed in the concluding chapters. The GHG-emissions related to constructing the suspension bridges were estimated based on the per km emission value calculated for the Sognefjord Suspension Bridge. The emissions associated with the new tunnel parallel to the Eikesund tunnel was estimated based on the per km emission value for the potential new Oslofjord tunnel from Iversen (2013) Road, tunnel and bridge maintenance was not included in the analysis. Variations in fuel consumption due to the curvature of the roads were not estimated. However an additional calculation was done based on the steep gradient in the Eikesund tunnel. An additional fuel consumption of 6 times the initial values was applied for the length of the tunnel. The parameter for increase fuel consumption was taken from the EFFEKT model (Straume, 2011). General emissions from ferries and for the relevant ferry connection were calculated with emissions data from a report by published by the Norwegian Maritime Directorate (Sjøfartsdirektoratet, 2011). The traffic intensity for the ferry connection was gathered from ferry statistics published annually by Statens vegvesen (2011b).The full calculation procedure is explaine in Appendix B. The analysis of the Hafast and Fefast route alternatives is conducted for illustration purposes, and is not based on the same detailed research as the Sognefjord crossing.

5 Results

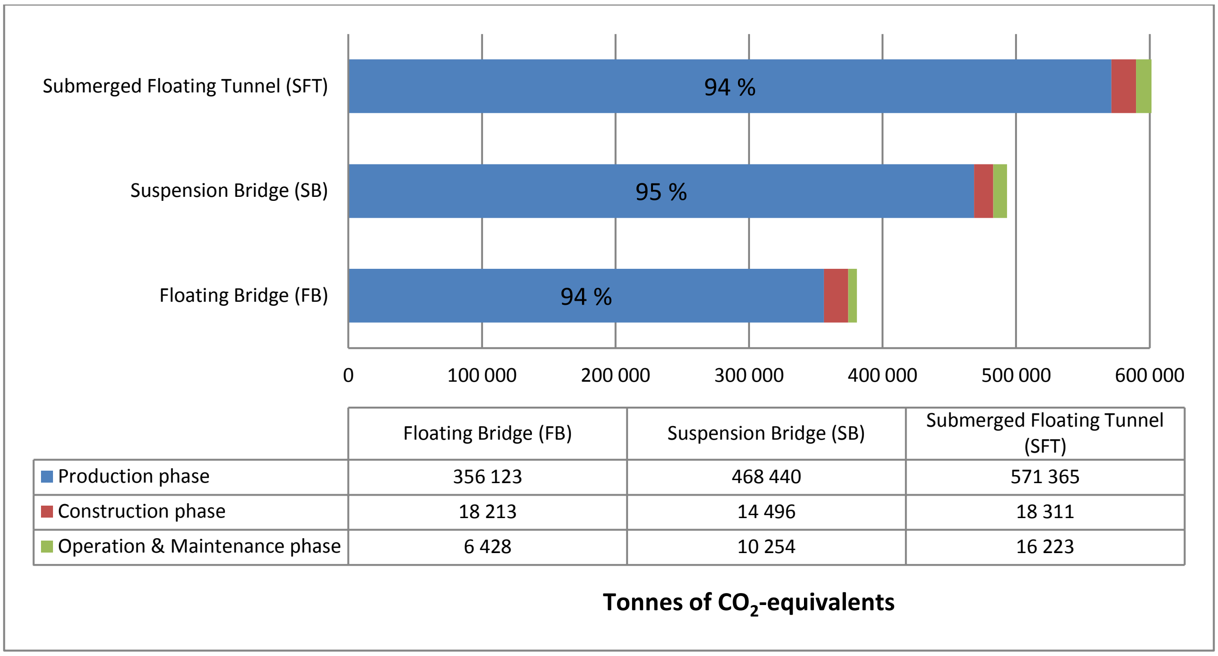
Total greenhouse gas emissions associated with the three crossing concepts for the Sognefjord will be presented first. The results are broken down on the life cycle phases of production, construction, and operation and maintenance. Results based on the other functional units will be presented afterwards. The highest contributing processes to the total GHG-emissions will be evaluated in detail, followed by a sensitivity analysis. A complete environmental impact assessment with the ReCiPe method will be presented thereafter. Emissions from traffic on a permanent Sognefjord crossing are covered in a separate subchapter. The result from the fictive fjord crossing scenario will be presented, and the analysis based on the Hafast and Fefast route choice alternatives will be given in the end. The estimated GHG-emissions will not be rounded in this presentation, but it should be noted that the accuracy of the results are not as a high as the values indicate.

5.1 GHG-emissions associated with crossing the Sognefjord

The total GHG-emissions calculated for each of the concepts claimed technically feasible for crossing the Sognefjord are presented in Table 7. A horizontal bar chart illustrating the contribution by each of the included life cycle phases over the 100 year time horizon are given in Figure 20.

Table 7: Total GHG-emissions from the three crossing concepts and their percentage difference from the FB.

Crossing concept	tonnes of CO2-eq	% Difference from FB
Floating Bridge (FB)	380 764	0 %
Suspension Bridge (SB)	493 189	30 %
Submerged Floating Tunnel (SFT)	605 899	59 %



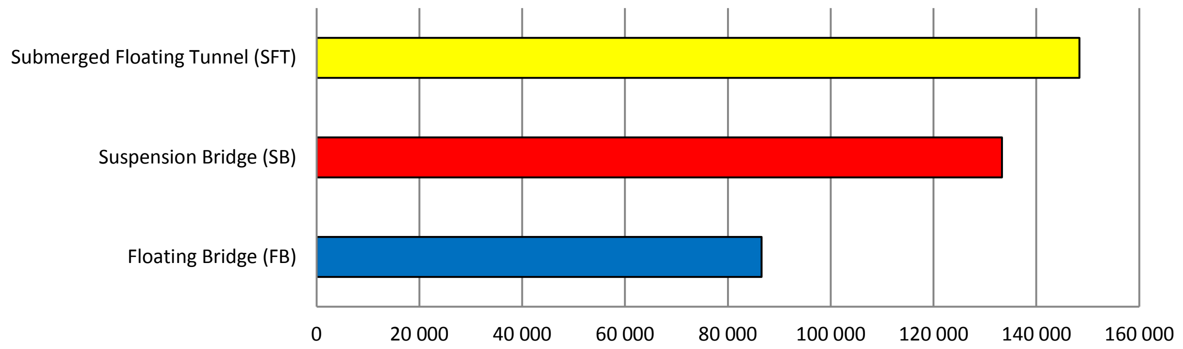
	Floating Bridge (FB)	Suspension Bridge (SB)	Submerged Floating Tunnel (SFT)
🟦 Production phase	356 123	468 440	571 365
🟥 Construction phase	18 213	14 496	18 311
🟩 Operation & Maintenance phase	6 428	10 254	16 223

Figure 20: Total GHG-emissions from the crossing concepts divided between life cycle phases of material production, construction and operation and maintenance.

The SFT was found to give the highest total GHG-emissions of the three case studies, and the FB the lowest emissions. The emissions associated with the SB are about 30 % higher than the emissions from the FB. The material production phase is the main contributor in all three cases, representing more than 94 % of the total emissions. For the SB the construction phase has slightly lower emissions than the two others. The emissions from the operation and maintenance phase of the SFT are slightly higher than for the other two structures.

5.1.1 GHG-emissions associated with crossing the Sognefjord per functional unit

Converting the total GHG-emissions to a per kilometer basis changes the picture slightly. The Floating Bridge has now even less emissions per kilometer than for the whole crossing in relation to the other two structures. This is illustrated in Figure 21.

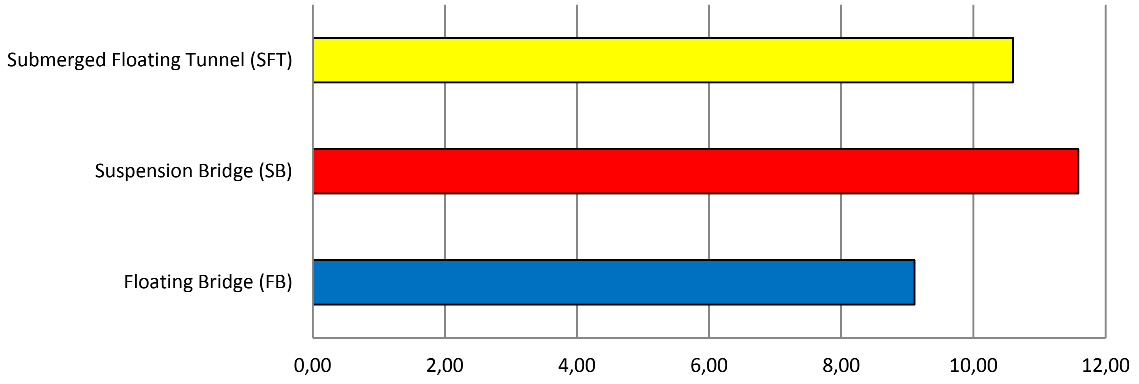


	Floating Bridge (FB)	Suspension Bridge (SB)	Submerged Floating Tunnel (SFT)
GHG-emissions per km	86 537	133 294	148 396

Tonnes of CO_2-equivalents

Figure 21: Total GHG-emissions from the crossing concepts divided per functional unit of 1 kilometer of road infrastructure.

On a per kilometer basis the SB has 54 % higher emissions than the FB, and the SFT 71 % higher. This is due to the Floating Bridge being the longest of the three, with a total length of 4 400 meters. The Suspension Bridges experiences the opposite effect, since the bridge is the shortest of the three with a total length of 3 700 meters. On a per kilometer basis only 15 101 tonnes of CO2-eq separate the SB and SFT. A third functional unit was applied for this analysis. Converting the results to a unit of 1 m^2 of effective roadway area has a different outcome (see Figure 22). The effective roadway area is the area that is used directly by vehicles, illustrated by the cars in Figure 8, 11 and 15 in the previous chapter.

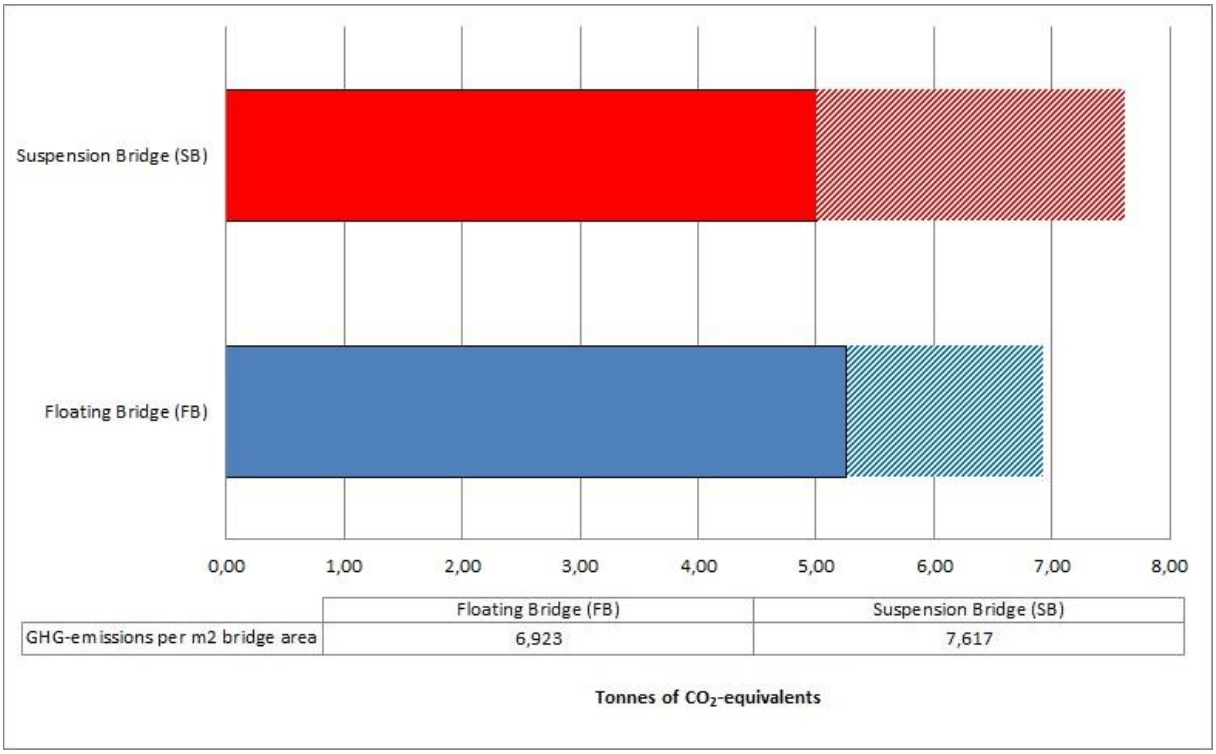


	Floating Bridge (FB)	Suspension Bridge (SB)	Submerged Floating Tunnel (SFT)
GHG-emissions per m2 roadway area	9,11	11,59	10,60

Tonnes of CO_2-equivalents

Figure 22: Total GHG-emissions from the crossing concepts divided per functional unit of 1 m^2 effective roadway area.

Applying a functional unit of 1 m^2 of effective roadway area, results in the SB becoming the highest emitting fjord crossing concept. The FB is still the lowest emitting concept, but the SFT has now only 16 % higher emissions than the FB. This is due to the SFT having the largest effective roadway area, and the FB the smallest. Including the walkways in a definition of *effective bridge area* also results in a different outcome. Figure 23 shows the emissions per m^2 of effective bridge area for the FB and the SB.



	Floating Bridge (FB)	Suspension Bridge (SB)
GHG-emissions per m2 bridge area	6,923	7,617

Figure 23: Total GHG-emissions per m^2 effective bridge area for the Floating Bridge and the Suspension Bridge. The shaded area illustrates the share accounted to the walkways.

The SB now only has 10 % higher emissions than the FB. The main reason for this is that the SB has two 3 meter wide walkways while the FB only has one. There are certain implications with an inclusion of the walkways in a definition of effective bridge area. This will be discussed in the following chapter.

5.1.2 The main sources of GHG-emissions

In this subchapter the calculated GHG-emissions will be broken down on the structural components, and material inputs of the different case studies. In Figure 24 the GHG-emissions from the *material production phase* are divided between the structural components of the different fjord crossing concepts.

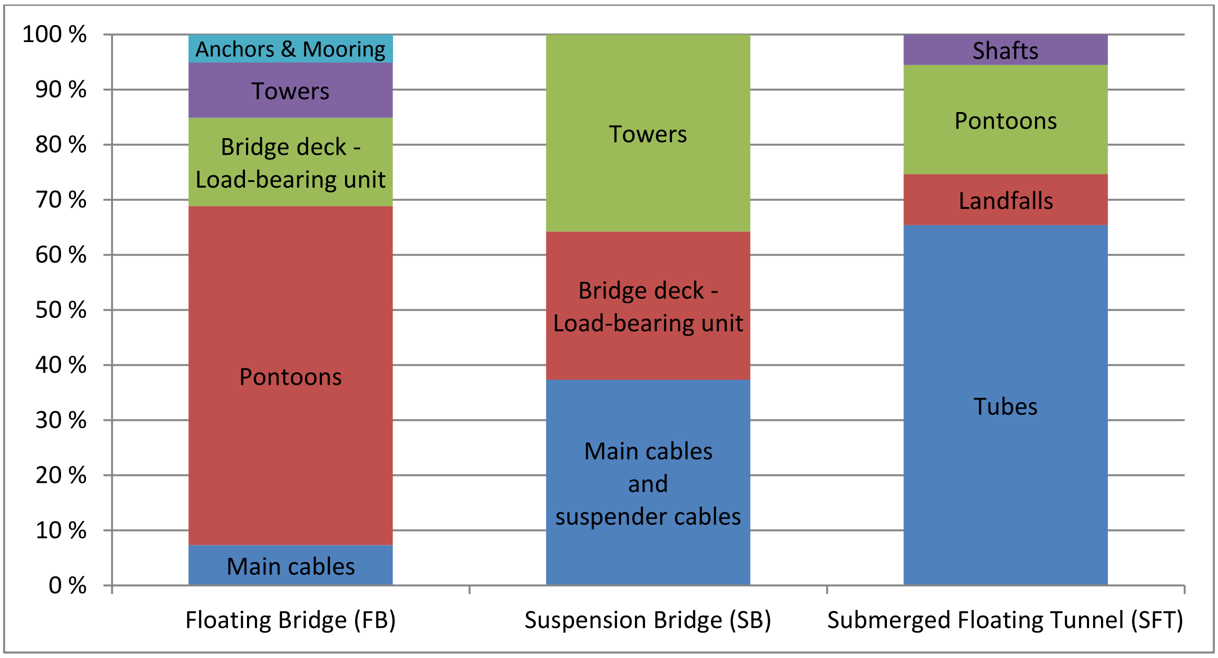


Figure 24: The GHG-emissions from the material production phase divided between the main components given in the feasibility studies

A significant share of the emissions from the FB is related to the material inputs in the pontoons. The emissions associated with the SB are more evenly distributed between the structural components. For the SFT the tube system is responsible for 64 % of the emissions and the pontoons 19 %. It is notable that the structural components with the highest material quantities and total weight are also contributing to the highest amount of emissions. This will be discussed further in the following chapter.

Dividing the total GHG-emissions between the material types gives additional insight. This is shown in Figure 25 and the background data is given in Table 8. Note that the construction and operation phases are also included in the figure, unlike the previous one.

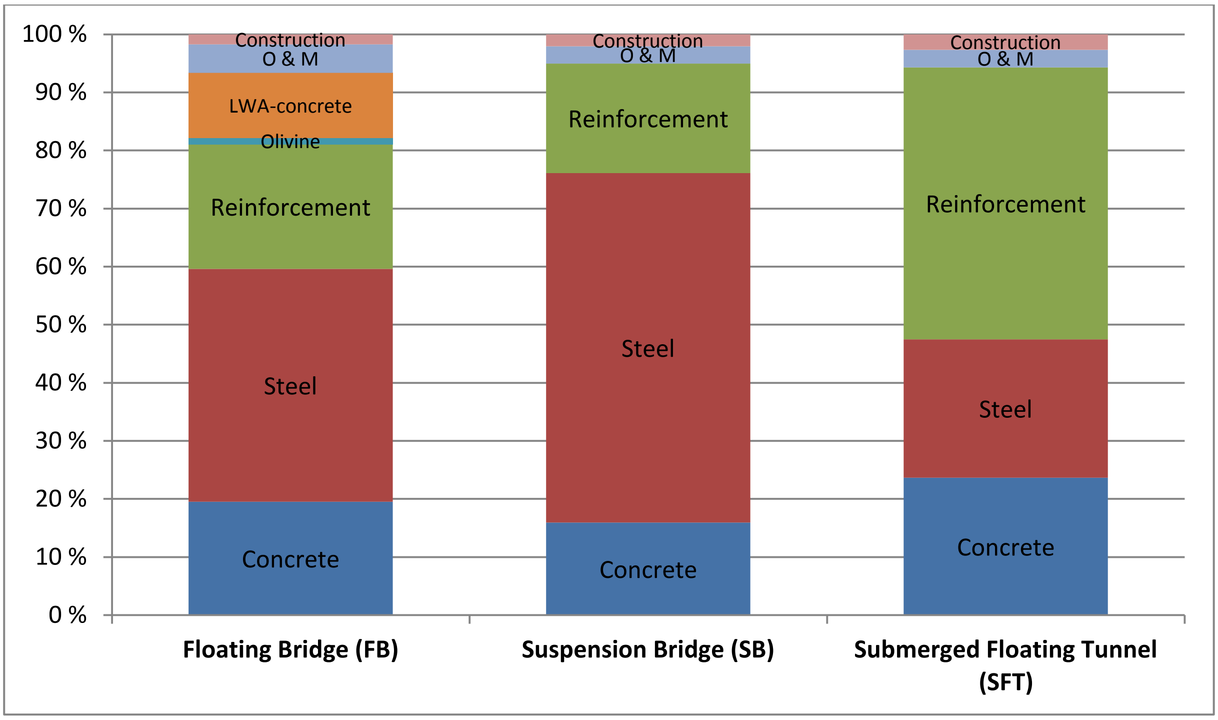


Figure 25: The total GHG-emissions from the crossing concepts divided between the main contributing materials in the production phase and for the total share from the construction phase and the operation and maintenance phase.

Table 8: The percentage share of GHG-emissions contribution from the crossing concepts. The values are the basis for Figure 25 above.

Case study	Concrete	Steel	Reinforcement	Olivine	LWA-concrete	Construction	O & M
FB	19,5 %	39,6 %	22 %	1,47 %	11,50 %	4,78 %	1,69 %
SB	15,9 %	60,3 %	18,8 %	-	-	2,94 %	2,08 %
SFT	23,7 %	23,9 %	46,7 %	-	-	3,02 %	2,68 %

Several noteworthy observations can be done when comparing Figure 24 and 25. The pontoons are responsible for almost 61 % of the emissions from the FB, but they do not contain steel which is responsible for more than 39 % of the emissions in Figure 25. However they do include the total amount of used LWA-concrete, reinforcement steel, olivine and the majority of the concrete. Steel is used in the main cables, load-bearing unit and anchors and mooring, and is the main input to the towers. For the SB, steel is responsible for more than 60 % of the emissions. Reinforcement is the main contributor to emissions for the SFT with 46,7 % of the emissions. The post-tensioning tendons used in the tubes are included in this number. Even though concrete is the major material input, it is only associated with 23,7 % of the emissions. It is clear from Figure 25, that concrete, steel and reinforcement are the main contributors to emissions. The next subchapter will cover the sensitivity of the input quantities of these materials.

5.1.3 Sensitivity analysis

The result from the traditional sensitivity analysis where the main inputs to the system were increased by 10 % one at a time is presented in Figure 26.

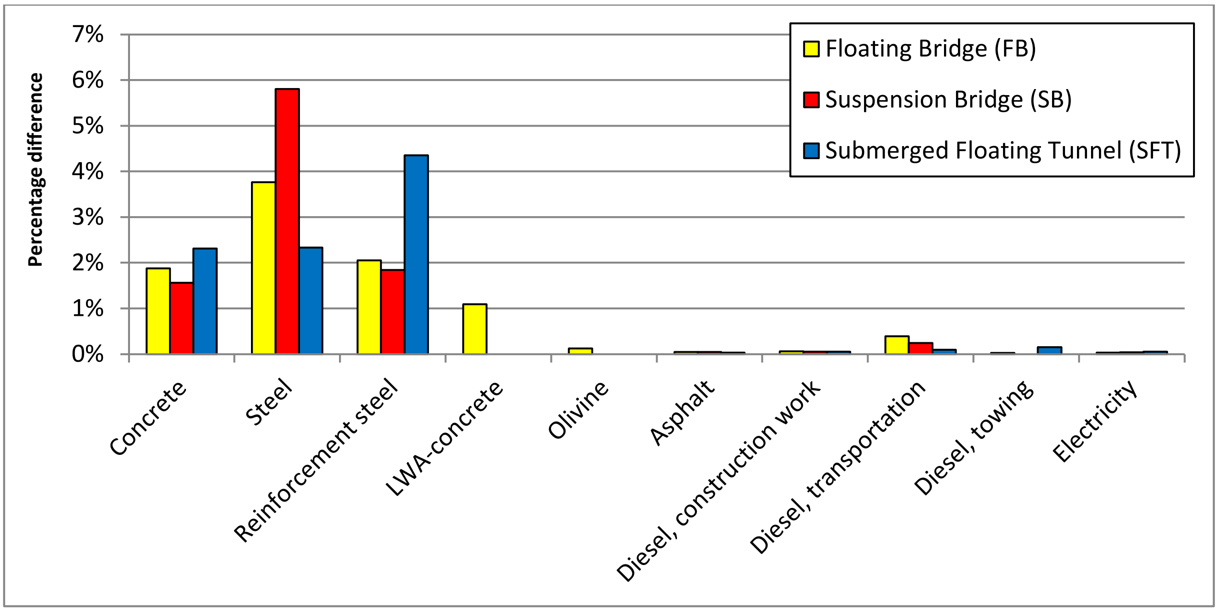


Figure 26: Traditional sensitivity analysis with a 10 % increase of one factor at a time for the most relevant inputs.

The figure above shows that concrete, steel and reinforcement are the most sensitive inputs in the analysis. This is natural since they are also the main source of emissions, as illustrated in Figure 26. The sensitivity of LWA-concrete in the FB is also noteworthy. All other inputs are of minor importance with less than a 0,5 % increase of the total emissions.

As explained in the previous chapter, the choice of background process from Ecoinvent will be evaluated for the most sensitive input for each crossing concept. A slight adjustment was made to this in order to accommodate for the three main emission contributors and each crossing concept. Concrete sensitivity was analyzed for the FB, regardless of steel being the most sensitive input. Steel was evaluated for the SB, and reinforcement for the SFT. Hence each of the highest contributing materials is assed for each of the fjord crossing structures. The result of the three analyses are presented in Figure 27-29, and explained accordingly.

The sensitivity analysis for the concrete in the FB will be presented first. The Ecoinvent background process *Concrete, for de-icing salt contact* was the default choice in the analysis.

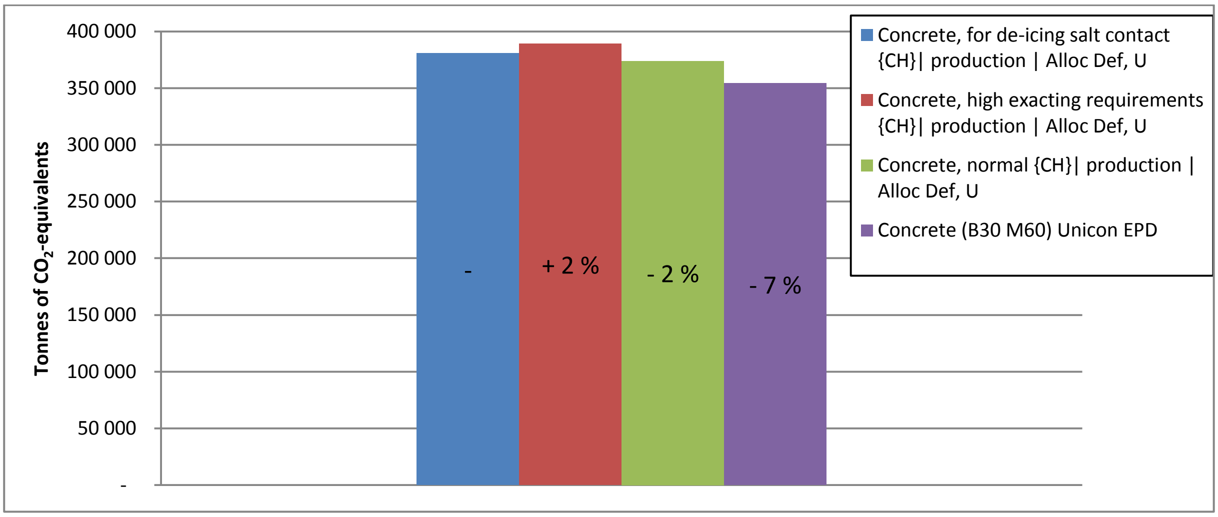


Figure 27: Sensitivity analysis for the background process representation of concrete for the Floating Bridge (FB).Concrete for de-icing salt contact was the default choice.

Applying either of the other two concrete background process changes the total emissions by ± 2 %. The EDP from Unicon (2012) gives lower emissions than all the Ecoinvent processes. The overall impact of the choice of concrete background process is not that significant, as can be seen in Figure 27.

The sensitivity analysis for the choice of steel background process for the SB is presented in Figure 28. Two other steel background processes were compared to the default in the analysis.

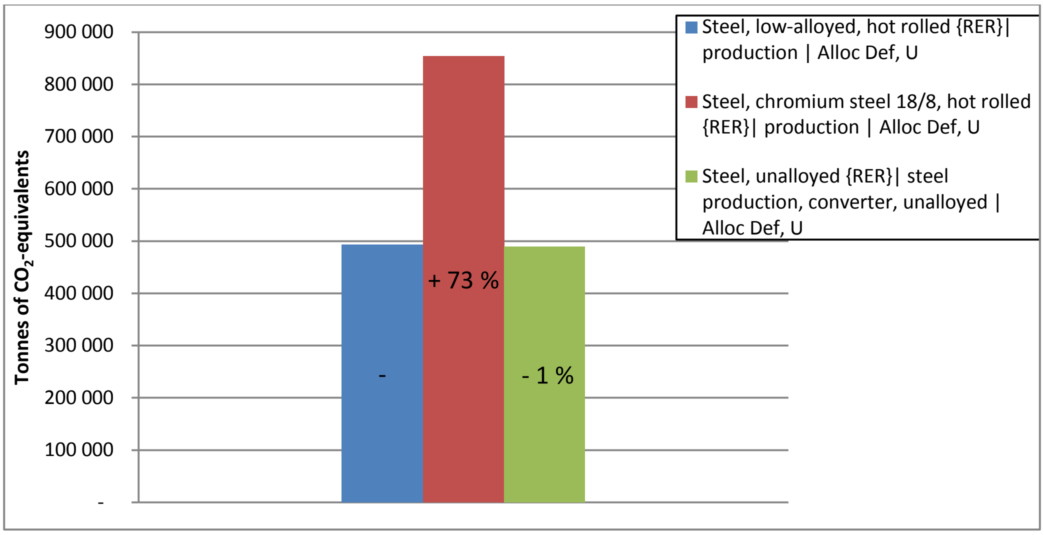


Figure 28: Sensitivity analysis for the background process representation of construction steel in the Suspension Bridge (SB). Low alloyed steel was the default choice.

The Figure illustrates that chosing chromium steel to represent the construction steel input in the Suspension Bridge will increase the total emissions with 73 %. The result indicates that the background steel process need to be chosen more carefully than the one for concrete in order to get reliable results.

The sensitivity analysis for the choice of reinforcement background process is presented in Figure 29. The chosen Ecoinvent process was only compared to the EPD by Celsa Steel Service (2012).

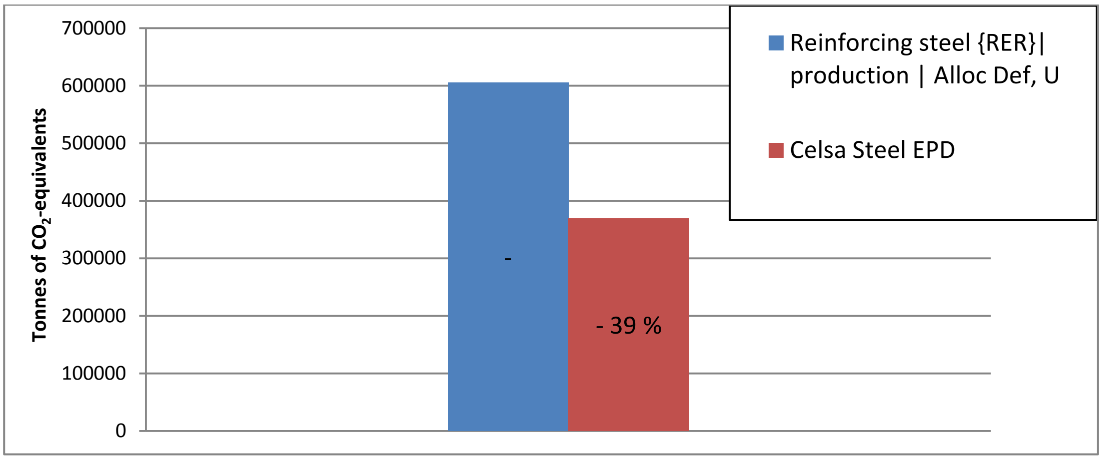


Figure 29: Sensitivity analysis for the background process representation of reinforcement for the Submerged Floating Tunnel (SFT).

Assuming that the declared emission value from Celsa Steel Service EPD is realistic, using them as a supplier can lower the total GHG-emissions from the SFT by 39 %. The use of EPDs compared to Ecoivent background processes will be discussed further in the next chapter.

Two additional sensitivity analyses were conducted for the construction phase. The results from the sensitivity analysis of the transportations process with global system boundaries for the SB are given in Table 9. In this analysis the load-bearing unit was assumed to be transported by sea from Shanghai and the cables from the UK by road and sea.

Table 9: Total GHG-emissions from the SB with global system boundaries and its percentage difference from the initial value.

Analysis	tonnes of CO_2	% Difference
Initial value	493 189	
Transport from Shanghai and UK	505 460	2,5 %

Choosing suppliers far from the construction site does not have a major impact on the total emissions. The analysis gave emissions of 12 271 additional tonnes of CO_2-eq. This increases the total emissions by about 2,5 %. The result from the sensitivity analysis for the energy consumption at site is given in Table 10.

Table 10: Results from the sensitivity analysis for energy consumption at the construction site. The table includes the estimated values along with the initial ones and their percentage difference.

Crossing concept	Default	10x increased energy consumption	% difference
Floating Bridge (FB)	380 764	382 802	0,54 %
Suspension Bridge (SB)	493 189	495 588	0,49 %
Submerged Floating Tunnel (SFT)	605 899	609 030	0,52 %

The increase in emissions are only about 0,5 % when the energy consumption is multiplied with a factor of 10. The emissions are increased with about 2 000 - 3 000 tonnes of CO_2-eq in all three cases. This increase is not very significant, but the estimate for energy consumption is a very rough and will be discussed further in the next chapter.

5.1.4 Comparison of the total environmental impact

The total environmental impact following the ReCiPe method is given in Figure 30. This figure is only given on a basis of percentage difference between the fjord crossing concepts. The main reason for this is that the total values for the quantified impacts have few comparable references in the literature. Therefore a comparison of the relative difference between the fjord crossings concepts within the environmental impact categories is concluded to be sufficient.

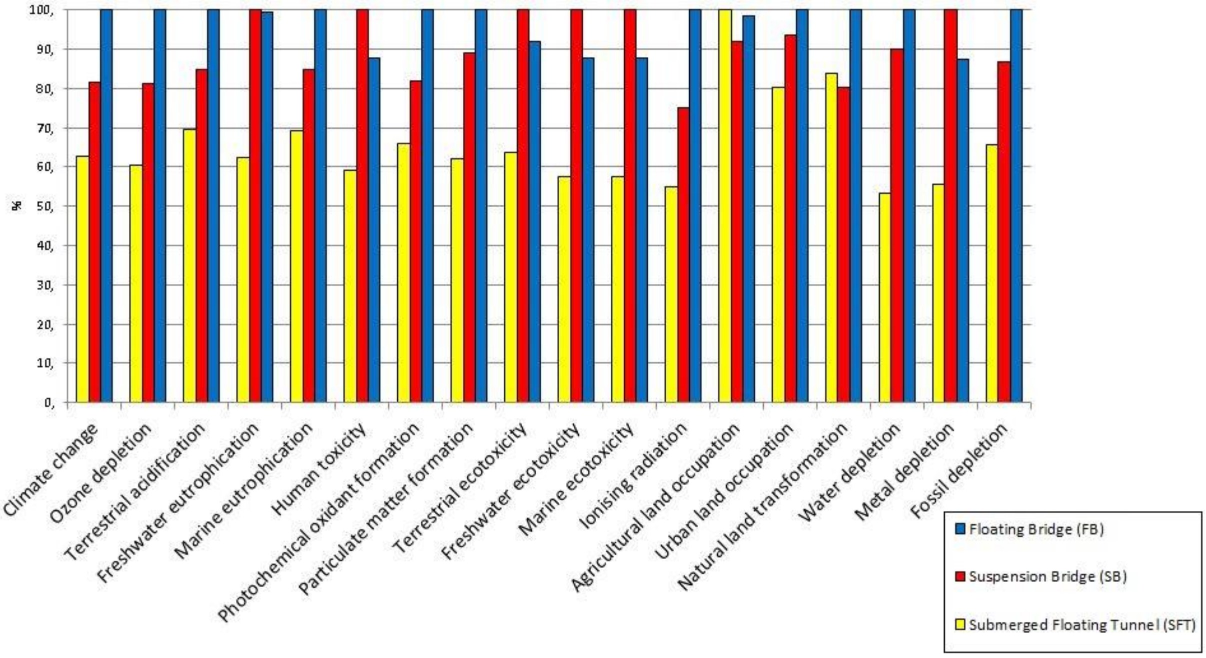
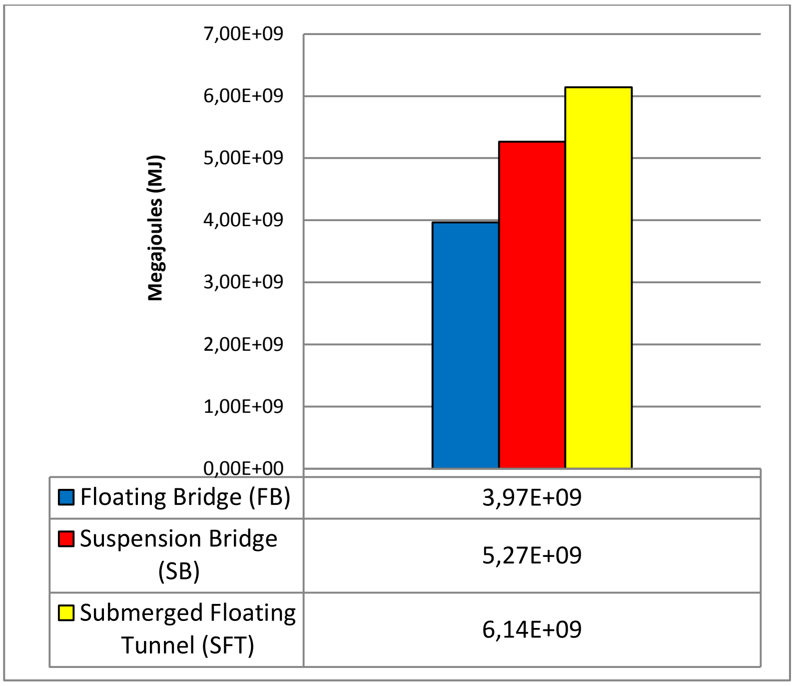


Figure 30: Percentage difference of impact between the three crossing concepts within the environmental impact categories included in the ReCiPe-method.

The result for 8 of the 18 impact categories is similar to the result for GHG-emissions, with the FB having the lowest impact and the SFT the highest. This includes ozone depletion, terrestrial acidification, marine eutrophication, photochemical oxidant formation, particulate matter formation, ionizing radiation, urban land occupation, water depletion and fossil resource depletion.

The FB has the lowest environmental impact in all categories except for agricultural land occupation and natural land transformation. The impact on natural land transformation is higher for the SFT than the FB. The SB has the highest impact in all the toxicity categories and for metal depletion. In addition it has a slightly higher impact in eutrophication potential.

Several studies also looked at the energy consumption of establishing road infrastructure. Energy consumption measured by Cumulative Energy Demand (CED) was assessed and is presented in Figure 31.



🟦 Floating Bridge (FB)	3,97E+09
🟥 Suspension Bridge (SB)	5,27E+09
🟨 Submerged Floating Tunnel (SFT)	6,14E+09

Figure 31: Energy consumption related to the Sognefjord crossing concepts. The amount of megajoules is quantified by the Cumulative Energy Demand (CED) characterization method.

The energy consumption of the SB is 33 % and the energy consumption of the SFT 54 % higher than the value for the FB. This figure is quite similar to the figure for GHG-emissions presented in Table 7. The main source of energy consumption is identified to be the production of concrete, steel and reinforcement.

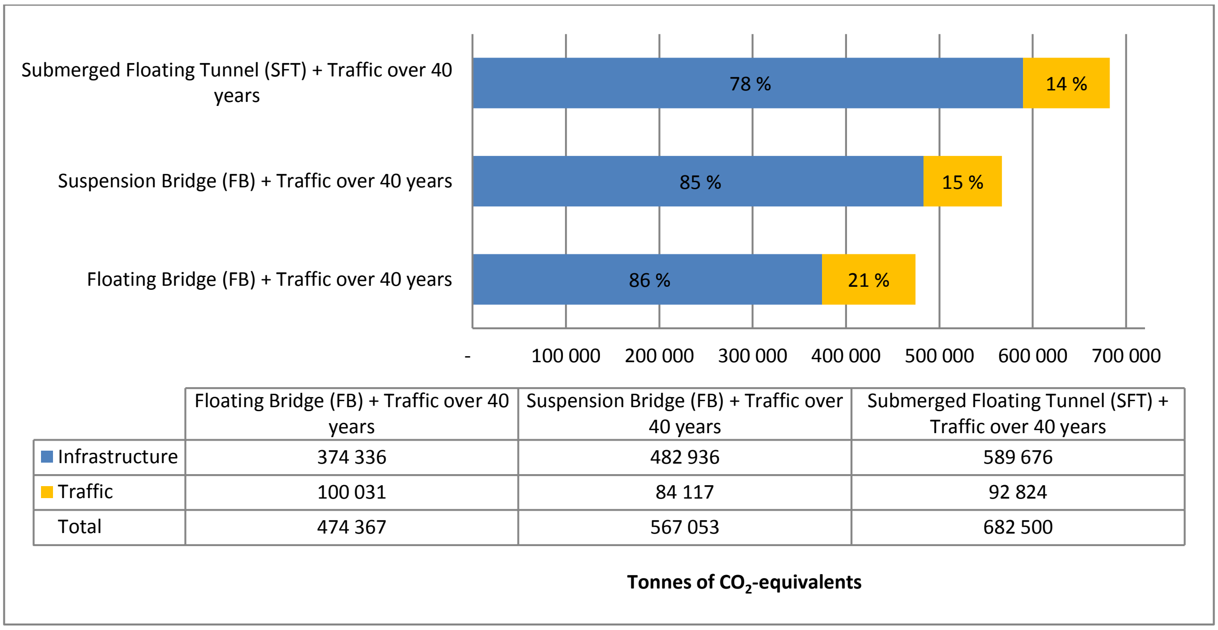
There a several other presentations and interpretations that can be done, but this will however not be elaborated further within the scope of this thesis. The presented result will be discussed and compared to other environmental factors briefly in the concluding chapters.

5.2 Traffic related emissions compared to infrastructure

The GHG-emissions from the fjord crossing concepts were compared to traffic in two different ways. GHG-emissions from road traffic were analyzed over the length of the three fjord crossing concepts for a 40 year time horizon. This implies that only the traffic on the fjord crossing concepts was assessed. The production and construction phases of the infrastructure, together with 40 years of operation and maintenance and traffic were included. The second comparison was done in fictional fjord crossing analysis. The average emissions from the three Sognefjord crossing concepts with traffic were compared to an open section road in this analysis.

5.2.1 Inclusion of traffic related emissions on the Sognefjord crossing concepts.

The result from the analysis with an inclusion of traffic related emissions on the Sognefjord crossing concepts over 40 years is given in Figure 32. A heavy vehicle share of 12 % was used, and an average AADT of 4 000 was applied.



	Floating Bridge (FB) + Traffic over 40 years	Suspension Bridge (FB) + Traffic over 40 years	Submerged Floating Tunnel (SFT) + Traffic over 40 years
🟦 Infrastructure	374 336	482 936	589 676
🟨 Traffic	100 031	84 117	92 824
Total	474 367	567 053	682 500

Figure 32: GHG-emissions associated with the Sognefjord crossing concepts with an included average traffic intensity of 4 000 vehicles per day over 40 years.

Even when traffic is included over a 40 year time horizon, GHG-emissions related to the infrastructure is still dominant. The FB has the highest share and total amount of traffic related emissions, with 21 %. This is due to the FB being the longest of the three structures. of the crossing.

5.2.2 Fictional fjord crossing scenario.

The emission related to the Sognefjord crossing were used in a fictional fjord crossing scenario similar to the one in Bergsdal, et al., (2013) and Statens vegvesen (2000). The rounded average was estimated to be a 4km long fjord crossing structure with 480 000 tonnes of CO_2-eq related to its material production and construction. Different emissions intensities per km of vehicle operations, traffic intensities and open section road lengths were applied in the different scenarios. These differences will be illustrated in the figures and explained accordingly. Operation and maintenance actives were not included in the analysis. In Figure 33 the payback period for a fjord crossing with an AADT of 4 000, and emission intensity of 310g CO_2 per km was used. The alternative road around the fjord is 16 km long. The graphs show the increase in GHG-emissions over a 100 year time horizon.

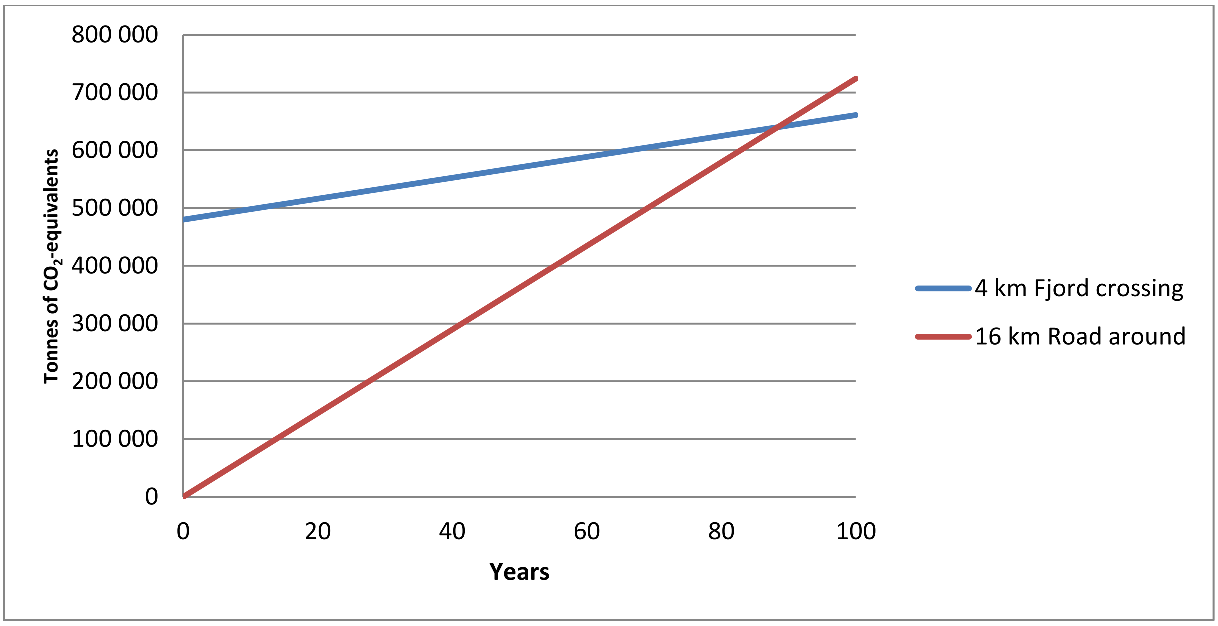


Figure 33: Payback period for the GHG-emissions in the fictional fjord crossing scenario with an AADT of 4000, emission intensity of 310g CO2 per km and a 16 km open section road.

Figure 33 indicates that it will take a long time for a fjord crossing concept similar to the ones proposed for crossing the Sognefjord to become less emission intensive than a 16 km open section road. The given scenario with an AADT of 4 000 has a payback period of 89 years. Applying a different AADT alters the payback period significantly. This is illustrated in Figure 34.

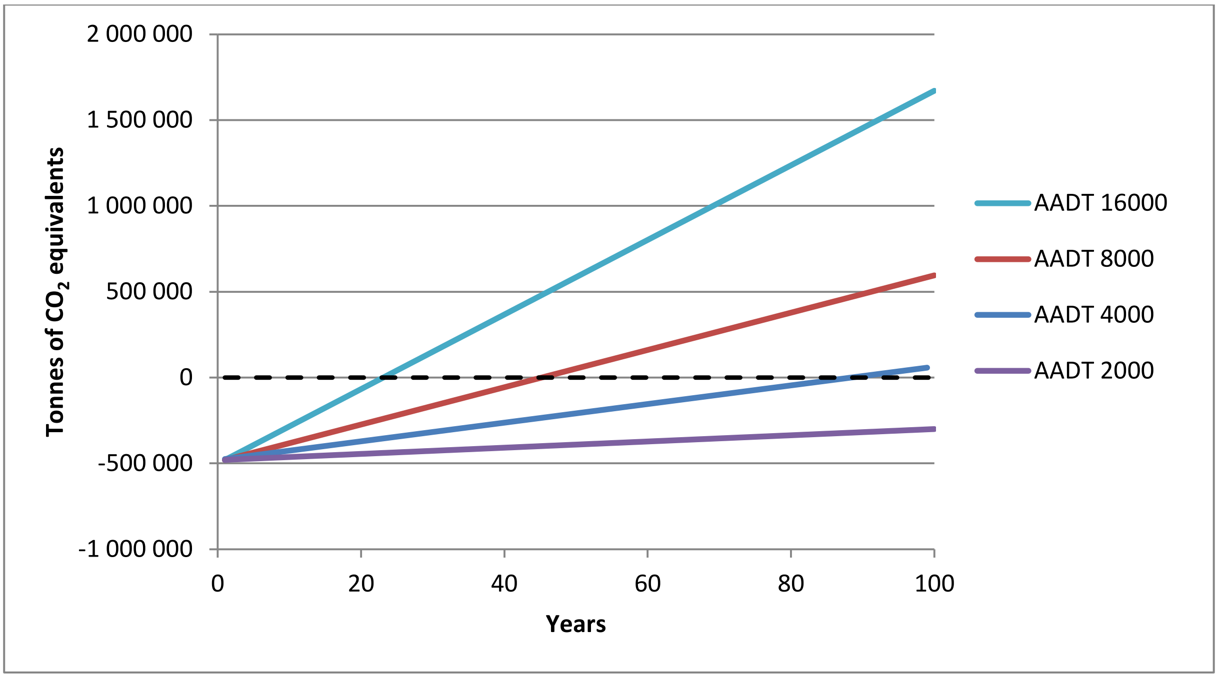


Figure 34: Payback period for the GHG-emissions in the fictional fjord crossing scenario with different AADT values. An emission intensity of 310g CO_2 per km and a 16 km open section road is considered.

The scenario with an AADT of 2000 has a payback period of more than 100 years. A 24 year payback period can be calculated with an AADT of 16000, and a 48 year payback period with an AADT of 8000. In Figure 35 the scenarios for emission variations associated with vehicle technology is presented.

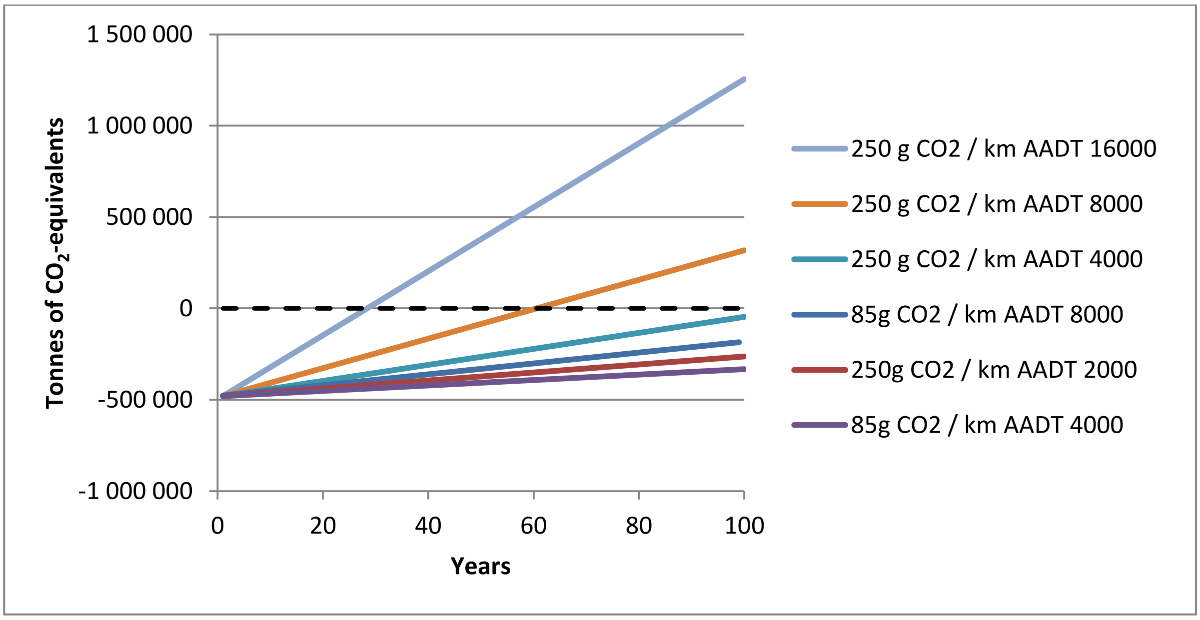


Figure 35: Payback period for the GHG-emissions in the fictional fjord crossing scenario with different AADT values and emission intensities of per km. A 16 km open section road is considered.

Both scenarios with 85 g CO_2 per km have payback periods of more than 100 years. Only the scenarios with an AADT of 8000 and 16 000 have payback periods of less than 100 years.

The last figure shows how the payback period changes with different open section road lengths. The AADT is fixed at 4000 and a high emission intensity including heavy vehicles is assumed. Figure 36 shows that even considerably long routes around the fjord have payback periods of at least 35 years.

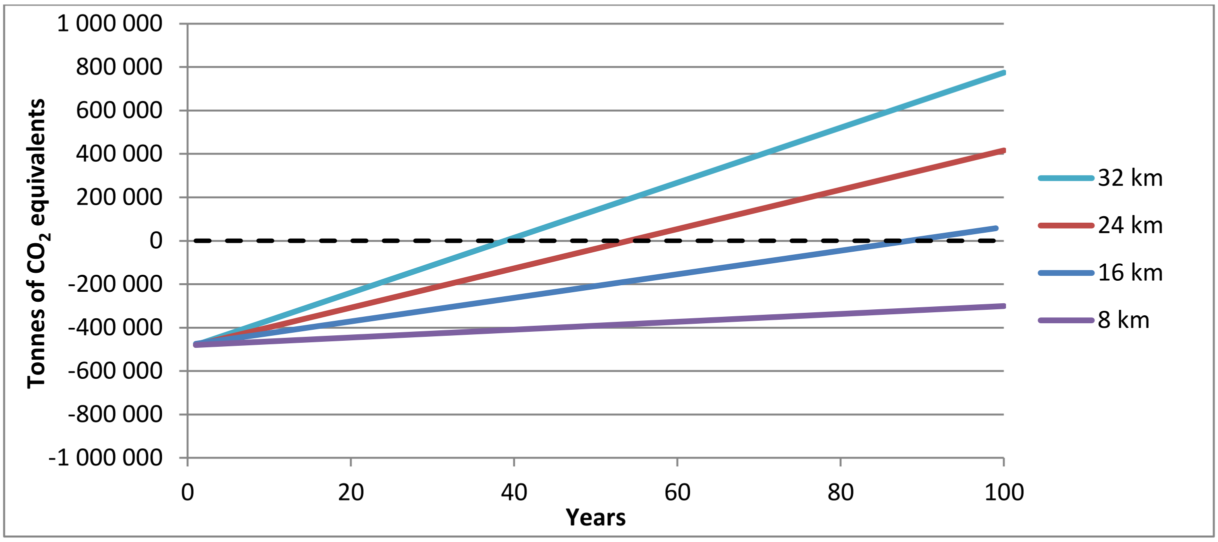


Figure 36: Payback period for the GHG-emissions in the fictional fjord crossing scenario with different lengths applied for the open section road around the fjord. An AADT of 4000, and emission intensity of 310g CO_2 per km is considered.

5.3 Route choice alternatives

The result for the Hafast and Fefast route choice analysis is given in Figure 37. The GHG-emissions are divided between the included fjord crossing structures and traffic related emissions. The traffic related emissions include an average AADT of 5000 over the whole length of the two routes in a 40 year time horizon.

5.3.1 Route alternatives Hafast and Fefast

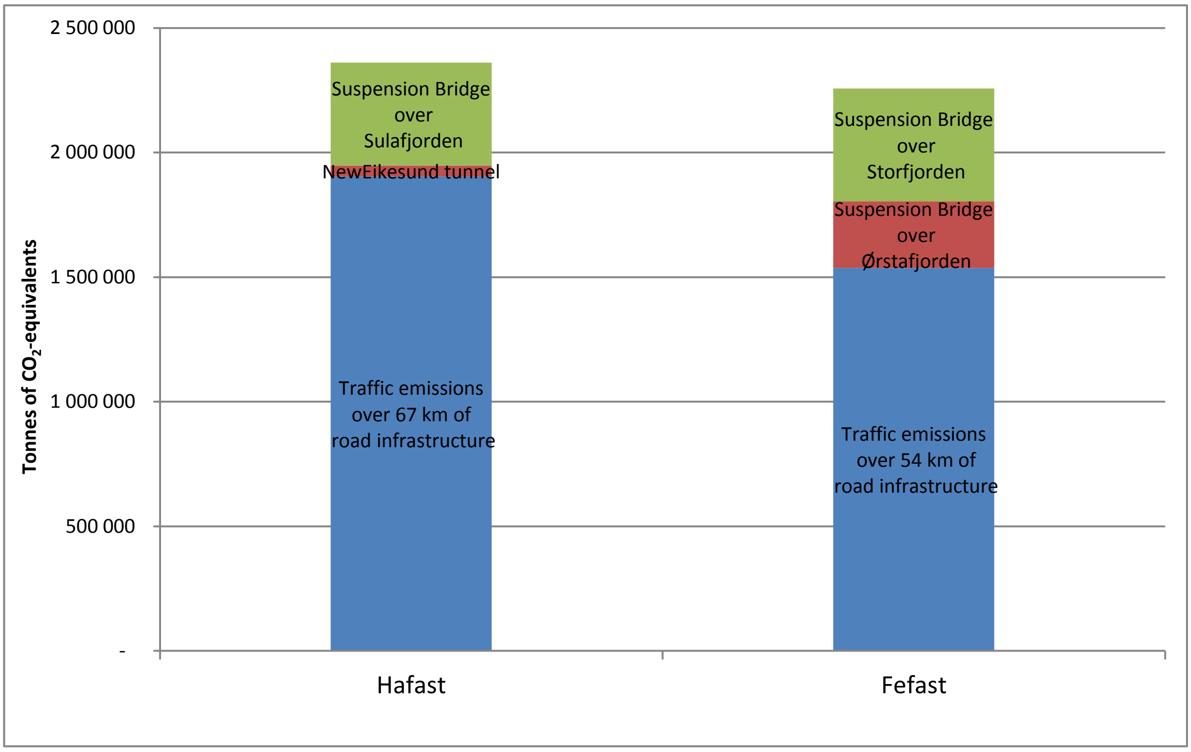


Figure 37: Total GHG-emissions associated with a future Hafast or Fefast route with an average AADT of 5000 over 40 years. The emission shares are separated between traffic and the different fjord crossing structures.

The two corridor alternatives are almost equal in a 40 year time horizon with an AADT of 5000. The Hafast route emits in total only 4,6 % more than the Fefast route. The traffic emissions are the most dominating in both cases. For the Hafast route, traffic emissions are responsible for 81 % of total GHG-emissions, while for Fefast only 68 %. The route choices were also compared to the current ferry connection. This result is given in Figure 38. The additional analysis with increased fuel consumption in the Eikesund tunnel is also included in the figure.

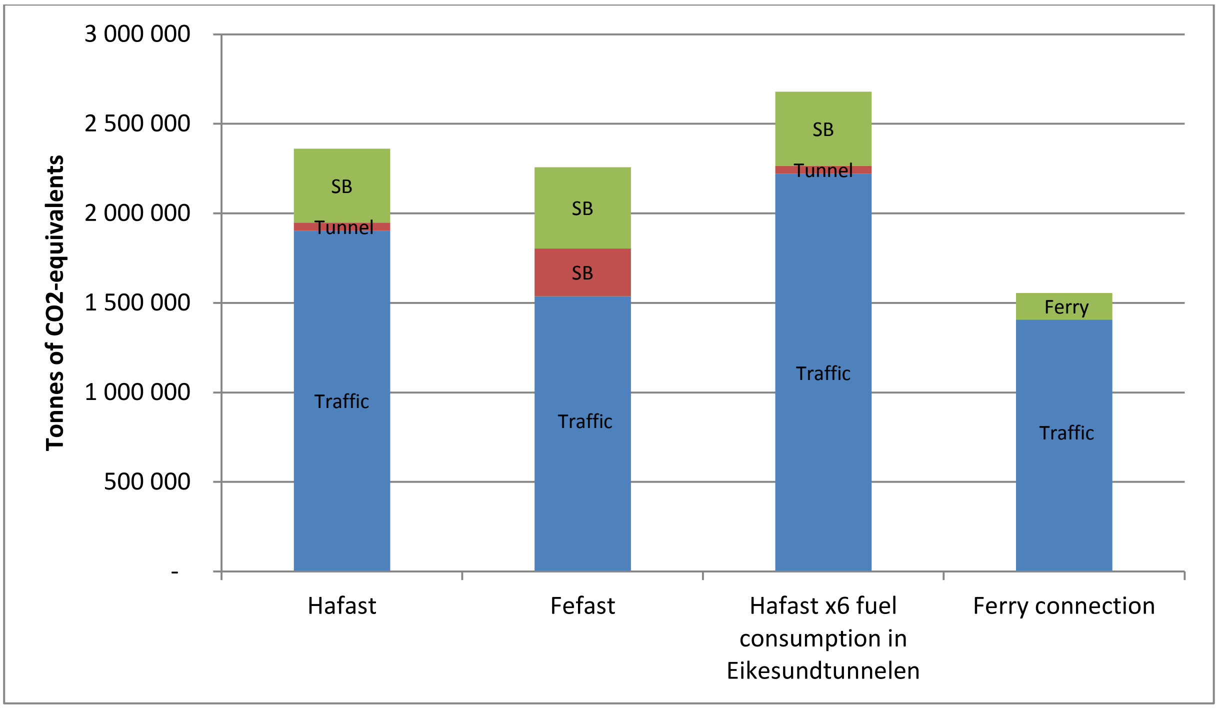


Figure 38: GHG-emissions associated with the Hafast and Fefast routes compared to the current ferry and an increased fuel consumption in the Eikesund tunnel along the Hafast route. A 40 year time horizon with an AADT of 5000 was used.

In this perspective the current system with the ferry connection has lowest emissions. The traffic related emissions from the ferry connection route are slightly lower than for the Fefast option, but responsible for 90 % of the total emissions. The increased fuel consumption in the Eikesund tunnel naturally increases the total GHG-emissions for the Hafast route. This analysis is highly simplified however, and does not take the full picture into account. It does however illustrate the importance of considering several factors apart from road corridor length when comparing route alternatives in a climate mitigation perspective.

6 Discussion

The results from the previous chapter are discussed by following the same order they were presented in. The most relevant observations regarding the contribution to greenhouse gas emissions will be discussed in detail. Other notable results will be mentioned briefly. Conclusions will be drawn based on the discussion, and given in the final chapter.

6.1 Crossing the Sognefjord

The results show that the GHG-emissions associated with constructing a permanent crossing of the Sognefjord is considerably larger than for traditional road infrastructure. This is in accordance with the paper by Bergsdal, et al., (2013) which indicated the same scale of emissions for constructing a Submerged Floating Tunnel (SFT). The calculated value for GHG-emissions from the SFT in this thesis is about 40 % higher than the values given in the paper. A higher amount of inputs in this analysis is possibly the reason behind this difference. It may also be due to another choice of background processes.

The Floating Bridge (FB) in this thesis was found to have the lowest amount of GHG-emissions among the concepts claimed technically feasible to cross the Sognefjord. The SFT had highest total amount of GHG-emissions, while the Suspension Bridge (SB) had second highest total emissions. The main reason for this difference is the material quantities and the design of the structure, which will be discussed in the following subchapter.

The material production phase is the main contributor to emissions, with more than 94 % of the emission for all three crossing concepts. The emissions related to the construction process, operation and maintenance is of low importance. This result is however influenced by the material quantities in the production phase being the main inputs to the system, and considered the most important prior to the analysis. If every potential material and energy input had been included in the analysis, it would maybe have changed this perspective slightly. However the omission of minor components in an early-phase LCA is in accordance with literature (Hammervold, et al., 2013).

6.1.1 GHG-emissions per functional unit

Adjusting the total GHG-emissions after the chosen functional units changed the outcome of the analysis slightly. The emissions were adjusted to 1 km of fjord crossing infrastructure, 1 m^2 of effective roadway and 1 m^2 effective bridge area.

Results per km of fjord crossing

The material quantities per kilometer of road infrastructure for crossing the Sognefjord are several times higher than conventional open section roads, bridges and tunnels. The FB was found to have even lower emissions compared to the other two crossing concpets on a per km basis due to the length of the bridge. This does however not take into account that the connecting roads on either side of the fjord may be shorter for the FB than for the SB and SFT. Still the GHG-emissions associated with open section road are much lower than the fjord crossing concepts per kilometer as described in the literature review. An inclusion of a certain share of open section roads in the Sognefjord crossing analysis will therefore most likely have no significant impact on the final result.

A comparison of the GHG-emissions per km of road infrastructure in the literature and the calculated emissions per km for the fjord crossing in this thesis is given in Table 11. The studies compared to the Sognefjord crossing concepts are selected from Table 1 in the literature chapter.

Table 11: GHG-emissions per km of road infrastructure in the literature compared to the fjord crossing in this thesis. The emissions are compared to the generic open section road.

Road infrastructure type	tonnes CO2-eq per km	% difference from open section	Factor of increase
Open section road	**1 020**	**0 %**	**1**
Upgrading a 2-lane road to 4-lanes	**3 175**	**211 %**	**3**
Bridge section	**7 360**	**622 %**	**7**
A standard Norwegian road tunnel	**13 000**	**1175 %**	**13**
Long bridge	**31 845**	**3022 %**	**31**
Floating Bridge (FB)	**86 537**	**8384 %**	**85**
Suspension Bridge (SB)	**133 294**	**12968 %**	**131**
Submerged Floating Tunnel (SFT)	**148 396**	**14449 %**	**145**

Both the SB and the SFT have GHG-emissions more than 100 times higher per km than the generic open section road from the paper by Bergsdal, et al., (2013). In addition they have about 10 times higher emissions per km than a standard Norwegian road tunnel (Huang, et al., 2013).

The studies from the literature vary in methodological approaches, life times considered and system boundaries. Regardless of this, it is quite evident that the fjord crossing concepts can be associated with significantly higher emissions per km than traditional road infrastructure.

Effective roadway area

The roadway area can be considered as the main part of a road infrastructure system, since it serves a direct purpose for movement of vehicles. By applying a functional unit of 1 m^2 of effective roadway area, the SB becomes the most emission intensive of the three crossing concepts. This is due to the SB having a smaller effective roadway area compared to the SFT. The result would have been different if the analysis had followed the description given in Fjeld (2012) with the right hand lanes being used for maintenance work and emergency stops. The calculated result is however assumed to be reasonable, since the area is potentially available for traffic.

Effective bridge area

With a functional unit of effective bridge area the SB only had 10 % higher emissions than the FB. The main reason for this is that the SB has two 3 meter wide walkways while the FB only has one. There are certain implications with an inclusion of the walkways in a definition of effective bridge area. The walkway area will most likely not have the same socio economic value as the roadway. Hence dividing the emissions equally by their area is not an optimal approach. Ideally a share of the walkway-area related emissions should be allocated to the roadway. This will not be done here, but an allocation like this could alter the result. It should be noted that it is the length of the structure, and not the width that most likely affects the high material requirement.

The result per m^2 of effective bridge area is significantly higher than the result from Dequidt (2014) and Hammervold, et al., (2013). Dequidt calculated GHG-emissions of 1 358 kg of CO_2-eq per m^2 of Tverlandsbrua over 100 years. From the paper by Hammervold et, al., (2013) the average GHG-emissions of the three analysed bridges can calculated to be 647 kg of CO_2-eq per m^2. In this thesis the GHG-emissions associated with a functional unit of 1 m^2 of effective bridge area gave 6 923 kg of CO_2-eq for the FB, and 7 617kg of CO_2-eq for the SB. This is 5 times higher than the value from Dequidt (2012) and more than 10 times higher than the average emissions per 1 m^2 from Hammervold et, al., (2013).

Uncertainties associated with the functional units

Most studies identified in the literature claimed that their results should not be generalized, and that a comparison would not be possible. The main reason for this is probably due to the number of uncertainties that arise along the whole analysis process. A comparison is however important to conduct in order to give suggestions for future research. The result from this study is highly influenced by uncertainties, since it is an early-phase assessment. Still it gives a decent indication of the potential size of infrastructure related GHG-emissions. The results should be compared further with similar studies in order to establish a greater number of references regarding the potential GHG-emissions from the construction of road infrastructure.

6.1.2 Material production phase

In the literature review by Du & Karoumi (2014) the material production is identified as the main source of emissions in the construction of bridges. The material production phase in this thesis has an even more distinct share than previous studies, since it contributes to more than 94 % of the total GHG-emissions. The emissions are almost exclusively generated by the production of concrete, construction, and reinforcement steel. Concrete and steel products are used in all the major structural components; the load-bearing units, cables, towers, pontoons, and the SFT tube system. Results from the different sensitivity analyses for the material inputs were presented in the previous chapter. Based on observations there regarding concrete and steel products, several conclusions can be drawn.

Concrete

In all the three feasibility studies the *concrete* is suggested to be of class B45/B55 due to potential corrosive effects from the surrounding environment. The EDP from Unicon gives lower emissions than all the Ecoinvent processes. However the EPD may not be representative since it is a declaration for a readymade concrete of a lower compressive strength class (B35). There are currently six EDPs available at the official Norwegian site for

EDPs (EDP-Norge, 2014). They are all based on concrete with a compressive strength class of B35/B30, and have emissions around 200 kg CO_2-eq per m^3 of readymade concrete. This is similar to the EPD from Unicon. The overall impact of the choice of concrete background process is not that significant, as can be seen in Figure 27. In addition the choice of background process in this analysis is assumed to be a good representation, since it is based on the Ecoinvent documentation (Kellenberger, et al., 2007). Using an EPD from a Norwegian concrete manufacturer would not necessarily be representative for the Sognefjord crossing concepts, due to the lower compressive strength class.

Construction steel

Figure 28 illustrates that chosing chromium steel to represent the *construction steel* input in the Suspension Bridge will increase the total emissions with 73 %. Chromium steel however is mainly used for high quality corrosion resistant products and is probably not representative for the majority of the steel components in the bridge. Smaller components not included in the scope of this thesis could have been made with high qualitfy steel. The result indicates that the background process for steel needs to be chosen more carefully than the background process for concrete, in order to get reliable results.

Reinforcement steel

Assuming that the declared emission value from Celsa Steel Service EPD (2012) is realistic, using them as a supplier can lower the total GHG-emissions from the SFT by 39 %. The reason for the lower emissions value per kg *reinforcement steel* in the EPD is identified to be from the high share of scrap metal used. In addition it is assumed that almost 100 % of the electricity needed for the steel works is supplied by hydro power. The Ecoinvent process *Reinforcing steel {RER}| production | Alloc Def, U* however is based on European averages of scrap metal uses. The background electricity mix is also based on averages from Europe, with certain shares of fossil, nuclear and renewable sources. These factors apply for most of the material background processes from Ecoinvent. Dequidt (2012) also compared the Ecoinvent process for reinforcement steel with the same EPD from Celsa Steel, and in addition a declared emission intensity from a German company. The emitted amount of CO_2 per kg reinforcement was lower for the German producer. However this number was not from a certified EPD and it only considered CO_2 and no other GHG-emissions. Several factors needs to be taken into account when comparing different manufacturers, like system boundaries, calculation methods and applied electricity-mix. The EDP system (ISO, 2006c) is currently the preferable way to compare the environmental performance of similar products from different manufacturers. Using steel from Celsa or a manufacturer with a similar production process, may give a significant decrease in the GHG-emissions from a road infrastructure that uses high amounts of reinforcement.

Processing of materials, like the prefabrications of the steel load-bearing units or casting the concrete tubes was not included. A proper assessment of these processes would give higher total GHG-emissions. The size of the increase is harder to predict, and the impact of omitting these processes have not been assessed in this thesis.

6.1.3 Construction phase

The construction phase of the SB had slightly lower emissions than the two others. This is identified to originate from the absence of towing operations in the construction phase. The operation and maintenance phase of the SFT has slightly higher emissions than the other two structures. The electricity consumption of the ventilators and pumps is the main reason for this difference. The sensitivity analysis shows that major adjustments to the construction process still does not change the lower importance of the construction phase compared to the material production phase. In this thesis, the main contributions from the construction phase concerns the energy consumption at site and the material transportation processes.

Energy consumption at site

The estimated value for the energy consumption at the construction site is a highly uncertain number. It is only based on a single source (Dequidt, 2012), who conducted an LCA for a smaller bridge than the Sognefjord crossing concepts. In general it should be possible to estimate the fuel and electricity consumption of the different construction site machines for the Sognefjord crossings. The challenges however is to estimate how frequently they are used.

In the assessment of the GHG-emissions and energy use associated with establishing a 4-lane highway by Phan (2012), the diesel consumption of heavy equipment was responsible for 52 % of the emissions. The GHG-emissions from construction activites estimated here was significantly higher than for similar studies. This study used energy consumption accounts from the main contractor, which should be more accurate than estimations and assumptions. However since this was an analysis for an open section road, it is not directly comparable to the Sognefjord crossings. The availability of data and references are a major obstacle when estimating the GHG-emissions from construction activities as mentioned by Du & Karoumi, (2014). A proper estimation of the energy consumption of the construction activities at site may change the share of the GHG-emissions accounted to the construction phase.

It is difficult to predict whether or not the calculated values for energy consumption of the construction phase for the Sognefjord crossing concepts is highly underestimated. Valen (2014) mentioned that most of the machinery used for constructing suspension bridges runs on electricity. The electricity-mix of Norway is assumed to have a high share of renewable energy. Taking this into account, the GHG-emissions associated with the construction activities may be assumed to be of low importance. This is although not a proper assumption and detailed investigation would be needed to draw a conclusion based on electricity consumption and its respective source.

Transportation

The overall impact of the *material transportation phase* was quite low compared to the material production. The sensitivity analysis with global system boundaries attempted to evaluate this perspective. Choosing suppliers far from the construction site did not have a significant impact on the total emissions. The analysis gave emissions of 12 271 additional tonnes of CO_2-eq. This increased the total emissions by about 2,5 %. This amount of emissions is low in comparison to the total amount of GHG-emissions in this analysis. However, 12 271 tonnes of CO_2-eq can be considered high in relation to the construction of traditional road infrastructure. The analysis only considered transportation distances, and did not look further into the difference in production location. Assuming that the production process in China has a higher share on non-renewable energy like coal may alter the result.

Du & Karoumi, (2014) raised the question of whether material transportation from the supplier to the construction site, belongs to the production phase or the construction phase. In this thesis the transportation processes were included in the construction phase. Since the material production alone was responsible for more than 90 % of the emissions, this choice is considered a reasonable approach. This way the different processes involved in the life cycle of the fjord crossings have a clearer separation. If the material transportation had been included in the production phase it would have only accounted slightly to the already high contribution from this phase.

6.1.4 Operation and maintenance phase

The operation and maintenance phase were found to be responsible for 1,69 - 2,68 % of the emissions from the three fjord crossing concepts as given in Table 8. The main inputs to the system responsible for this emission share is the production of asphalt for the wearing layer renewal, electricity for operations and the replacement of components.

Renewal of the wearing layer

For the Sognefjord analysis the renewal of the wearing layer were found to be responsible for only 0,5 % of the total emissions. GHG-emissions related to renewal of the wearing layer were found to be 20 % of the total life cycle impacts in Dequidt (2012). Dequidt (2012) however applied a more conservative renewal rate, with a complete renewal of the wearing layer every 3rd year. Removal and disposal of the old layer, including transportation of new asphalt to site was also included in the calculations. Still only the production of asphalt for the actual renewal of the wearing layer was responsible for 83 % of the asphalt maintenance related emissions. Applying the same renewal rate for the Sognefjord crossing concepts increases the total emissions by about 2 % in all three cases. The production of asphalt is now responsible for close to 3 % of the total emissions. Even with this approach, the renewal of the wearing layer is still not a significant factor compared to the production of concrete, steel and reinforcement.

Operation

The operation phase did not contribute significantly to the total GHG-emissions. The equations used for electricity consumption are assumed to be representative. The electricity consumption for the ventilators in the SFT was assumed to be similar to an undersea tunnel. Ventilation is a significant source of energy consumption and potential GHG-emissions during the life cycle of an undersea tunnel (Brattebø, et al., 2013). For the SFT, the contribution from operation of ventilators was not very significant. This is mainly due to the high material quantities per km of SFT compared to an average undersea tunnel.

Replacement of components

Only the renewal of steel railings for all three structures and the renewal of the ventilators in the SFT were included in the analysis. The impact of this was very low compared to other processes.

The operation and maintenance phase was found to have an overall low contribution to GHG-emissions. This life cycle phase was however not covered in detail, and a conclusion regarding its importance cannot be drawn. In addition, this phase was not evaluated by a sensitivity analysis. Therefore the operation and maintenance phase should be assed further to elaborate its importance.

6.1.5 Environmental impact assessment

The FB had the lowest environmental impact in all categories except for agricultural land occupation and natural land transformation. The source of this impact is identified to be the area occupied by the quarry for olivine extraction. There are certain implications with this however since Norway has a smaller share of agricultural land available than the estimate used in the ReCiPe method. The impact on natural land transformation is higher for the SFT than the FB. This is due to higher material quantities in the SFT, which are associated with a certain necessary amount of space for production. This includes both the raw material extraction and the cement production facilities. The SB was found to have the highest impact within all the toxicity impacts, and the main source was the production of steel.

The literature review by Du & Karoumi (2014) identified that mainly GHG-emissions and occasionally energy consumption is assessed in LCAs of road bridges. This thesis provides a full comparison of the all the environmental impacts included in the ReCiPe method. However, only the relative difference of the environmental impact between the three crossing concepts is given in the previous chapter. The environmental impact assessment cannot be compared to other studies by the total amounts due to this. Du & Karoumi (2014) also noted that CO_2 was the only greenhouse gas considered in most studies. Just considering CO_2 and omitting other greenhouse gases like CH_4 and N_2O when looking at the potential impact on climate change will give insufficient results.

Environmental impacts not covered

This thesis focused as mentioned several times mainly on GHG-emissions. Therefore the result cannot be used to acclaim that one crossing solution is more environmental friendly than another. In some studies, carbon footprint is described as equal to environmental impact, and hence a reduction in GHG-emissions is communicated as “environmentally friendly”.

This is not the case, since a broad range of environmental impact categories should be assessed in order to potentially acclaim one of the fjord crossings the optimal choice from an environmental perspective. To fully compare the environmental impact of the different fjord crossing concepts additional methods are required apart from LCA. Environmental impacts that should be investigated further are.

- The disturbance of the terrestrial and underwater landscape.
- Leaching of metals and organic pollutants from the constructions
- The positive and negative effects of the SFT tube system and the FB pontoons becoming a habitat for marine flora and fauna.

The FB and SB are large structures with considerably tall bridge towers. This may affect the migratory patterns of birds and other animals. The SFT has no towers compared to the other structures, and will not disturb the terrestrial landscape the same way. It might however disturb the underwater landscape. This includes the migratory patterns of marine organisms, and the current system and water flow in the Sognefjord. The pontoon and anchors system of the FB could have a similar effect. The last point should also be taken into concern due to potential operation and maintenance activities related to the removal of marine organisms.

6.2 Traffic related emissions

An important difference from previous studies is that traffic-related emissions do no longer dominate over emissions from infrastructure when included.

6.2.1 Traffic on the Sognefjord crossing concepts

In a 40 year time horizon the traffic related emissions only accounted for 14-21 % of the total GHG-emissions per km for all three crossing concepts. This differs from previous studies that include traffic like Dequidt (2014), Iversen (2013) and most of the studies covered in the literature review by Du & Karoumi (2014). In the thesis by Dequidt (2012) traffic was responsible for approximately 80 % of the emissions when included. A 100 year time horizon and an *estimated* average AADT of 11800 vehicles per day was considered. This is significantly higher than the traffic intensity over the Sognefjord. However, the traffic related emissions from the analysis in Dequidt (2012) of approximately 83 000 tonnes of CO_2-eq was found to be similar to the Sognefjord crossings, even though the analysed bridge was shorter (670 meter).

The FB has the highest share of traffic related emissions, with 21 %. This is due to the FB being the longest of the three structures. This estimate may however not be fair, due to the structures all being part of the same potential future road infrastructure system. Hence the greater length of the FB may be justified by shorter road connections on either side of the crossing. The goal of the analysis was however to elaborate the importance of traffic and these types of factors will not be discussed further. The calculations did not take into account a future reduction of traffic emissions due to new vehicle technology. Including this will result in even lower traffic related emission shares compared to the infrastructure of the Sognefjord crossing concepts.

Traffic generated by repair and maintenance activities in the use phase was not included in the scope of this study. It is however a potential source for future emissions. A full shut-down of a Sognefjord crossing at the chosen site would lead to quite long detour, assuming that the current ferry service would be phased out after an installation of a permanent crossing. From the south side of the fjord, the shortest route is to drive west to another ferry connection. This option however involves more than 60 kilometers of additional driving, and one ferry ride (see TableB14 in Appendix B). Including this potential source of impact could alter the final result. The FB is the lowest emitting structure, but it does not have two separate crossing units like the SB and the SFT. The structure may therefore be more sensitive to maintenance and repair activities.

6.2.2 The fictional fjord crossing scenario

The fictional fjord crossing scenario indicates that in order to justify a complex fjord crossing in a climate mitigation perspective several factors need to be present. The results indicate that open section roads going around fjords, with high traffic intensity, may be reasonable to replace in a climate mitigation perspective. Road corridors with a lower AADT may not be reasonable to replace with an advanced fjord crossing concept. If the traffic intensity or the emission intensity is low, or the replaced route around the fjord is short, the payback period is accordingly longer. With a future emission reduction due to new vehicle technology, advanced fjord crossing may be harder to justify from a climate mitigation perspective.

In the fictional scenario the open section road around the fjord and the fjord crossing are compared with an equal AADT. This is not in accordance with real life observations in Norway with traffic bloom after a bridge opening (Statens vegvesen, 2012c). Experience from earlier replacements of ferry connections in Western Norway show a considerable traffic increase in the following years. The AADT was however set to be equal for both route alternatives to compare the system performances on common grounds.

6.3 Route alternatives Hafast and Fefast

The result indicates that considering the infrastructure related emissions in longer road corridors is important when it includes technologically advanced fjord crossing structures. It also indicates that the shortest route is not automatically the favorable one in a climate mitigation perspective. The route with the current ferry connection was the lowest emitting alternative in the analysis. However additional fuel consumption due to idling vehicles at the ferry quays was not included in this figure, and may increase the associated GHG-emissions

When analyzing the route choice alternatives, the treatment of AADT was a major issue. The AADT was set as equal in both the Hafast and Fefast analysis and in the fictional fjord crossing scenario. This was done on a basis that the alternatives should by filling the same function, so that the technologies could be compared on the same basis.

The analysis used a time horizon of 40 years. It was identified in the literature (Du & Karoumi, 2014) that analysis horizons of 40-100 years are considered for traffic related emissions depending on the purpose. Over such long periods of time many factors may change from the current situation, including the vehicle technology. This analysis did not attempt to determine the future Norwegian vehicle fleet, and how it will evolve prior to that. Instead the traffic related emissions were assumed to be similar to the present situation. A future emission reduction due to new vehicle technology may as mentioned earlier increase the importance the infrastructure related emissions in road corridor planning.

7 Conclusion

The goal of this thesis was to analyze the potential indirect environmental impacts, mainly greenhouse gas (GHG) emissions associated with concepts claimed technically feasible for crossing the Sognefjord Based on the results discussed in the previous chapter, it can be concluded that the GHG-emissions associated with constructing a permanent crossing over the Sognefjord are significantly higher than for traditional road infrastructure.

7.1 General conclusions

The Submerged Floating Tunnel (SFT) was the fjord crossing concept associated with the highest amount of GHG-emissions and the overall highest environmental impact within the considered categories. This perspective changed however when a functional unit of 1 m^2 of effective roadway was applied. The Suspension Bridge (SB) then became the most emission intensive structure. The Floating Bridge (FB) had the least associated GHG-emissions in the analysis, but it also has the smallest effective roadway area and fewer available traffic lanes.

The GHG-emissions were of such a scale that the traffic related emissions on the infrastructure no longer dominated over the emissions related to material production, construction, operation and maintenance. The additional insight provided by the fictional fjord crossing scenario show that emissions from infrastructure can be of high importance. This occurs especially when the structures reach a certain size and complexity similar to the Sognefjord crossings. Low traffic intensity and a future reduction in emissions from vehicles make this conclusion even more apparent. The Fefast and Hafast route alternatives were found to have almost equal amounts of GHG-emissions in a 40 year time perspective. The analysis was simplified, but indicated that the route length is not the only important factor when comparing road corridor alternatives from a climate mitigation perspective.

The results from the LCA conducted in this thesis gave considerably higher GHG-emissions related to road infrastructure than previous studies. At the same time, emissions associated with the infrastructure were still significant even when traffic related emissions were included in different scenarios. If Norway wants to reach its emission reduction targets, road infrastructure related emissions of this scale should be taken into account when planning road corridors and design of fjord crossing concepts.

7.2 Recommendations for future work

Several papers have mentioned the lack of good data for the construction activities on site. A lack of good data has also been a hindrance for this thesis. In order for the fuel and electricity consumption at the construction site to be assessed properly, a reference database should be established:

- *Establish a reference database for fuel and electricity consumption during road infrastructure construction projects.*

The production of concrete, construction and reinforcement steel was responsible for the majority of the GHG-emissions. The possibilities for emissions reduction measures for these materials should be investigated in detail:

- *Investigate the emission reduction potential for the manufacturing of the main contributing materials; concrete, construction and reinforcement steel*

It is important however that emission reduction measures does not compromise the durability of the infrastructure.

The calculations from the fictive fjord crossing scenario indicated GHG-emission payback periods of more than 100 years for fjord crossings similar to the Sognefjord crossings. This analysis was however not a detailed assessment, but the observed factors altering the result should be investigated further:

- *Conduct a more in depth analysis of the trade-offs between emission intensive fjord crossing structures and longer road corridors around fjords.*

There should be a joint effort to make analyses more transparent and a mutual aim for obtaining comparable results. To achieve this, a standardized framework for LCA of fjord crossing solutions should be established:

- *Establish a standardized framework for conducting LCAs and GHG-assessments of fjord crossing infrastructure solutions.*

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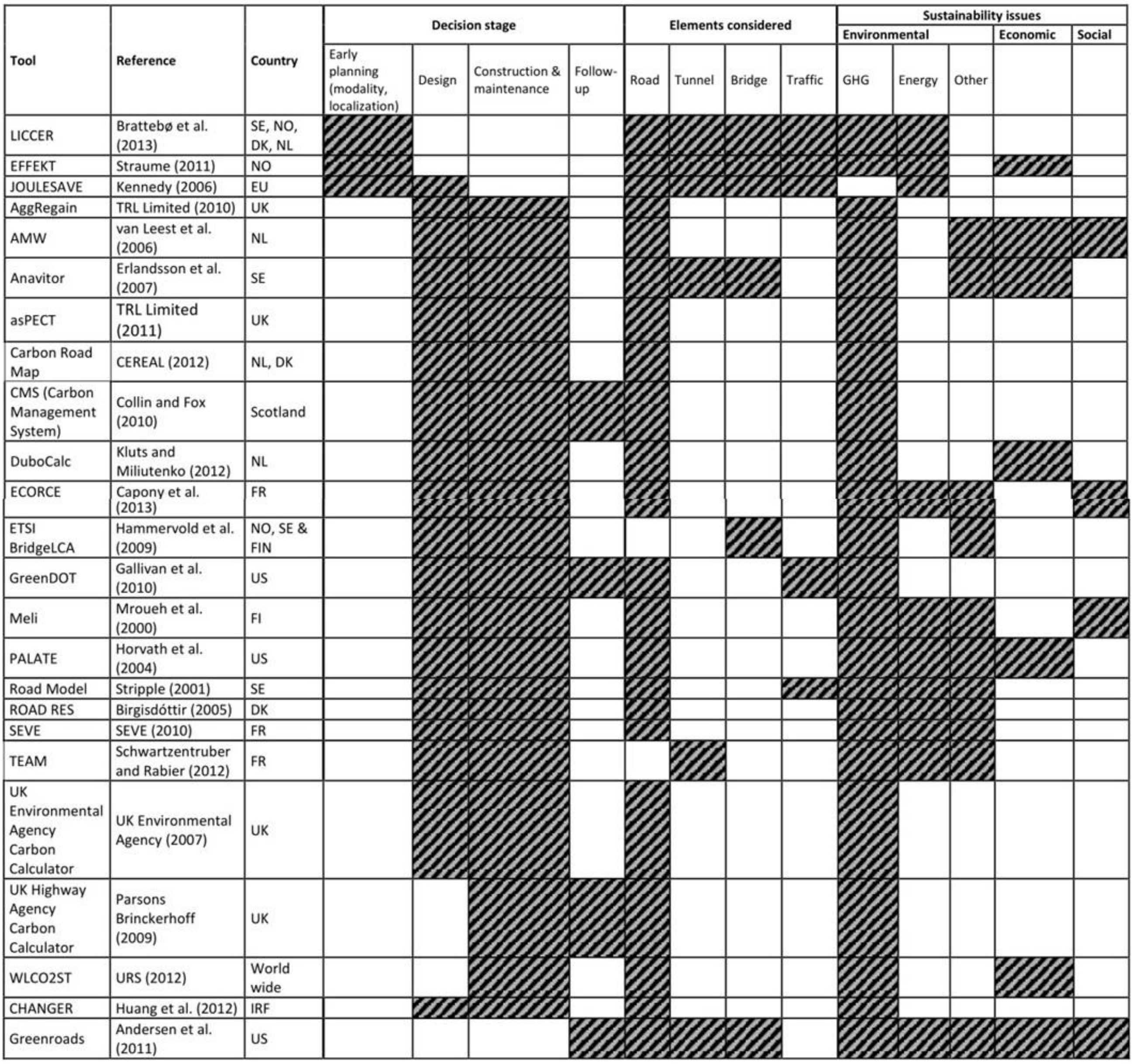
Appendix A – Additional information

Table A1: Studies covered in the literature reviews by Hammervold et al (2013), Dequidt (2012), and Du & Karoumi (2014). For a full name and description of the studies, the reader is referred to mentioned literature reviews.

Literature cited	**Hammervold et al (2013)**	**Dequidt (2012)**	**Du & Karoumi (2014)**
Bouhaya et al (2009)		x	x
Collings (2006)	x	x	x
Gervásio and da Silva (2008)	x	x	x
Hammervold et al (2009)	x		x
Hammervold et al (2011*)	x	x	
Horvath and Hendrickson (1998)	x	x	x
Horvath (2009)			x
Itoh and Kitagawa (2003)	x	x	x
Itoh, Wada, and Liu (2005)			x
Keoleian et al (2005)	x	x	x
Lounis and Daigle (2007)			x
Lounis et al (2010)		x	
Martin in (2004)		x	x
MEEDDM project (2006)		x	
San Martin in 2011		x	
Steele et al (2002)			x
Steele et al (2003)	x		x
Steele et al (2005)		x	
Widman (1998)		x	x
Zhang et al (2011)		x	

*2011 is the online publication date. In this thesis the paper is referred to by its journal publication year, 2013

Table A2: Tools and models developed for LCA and environmental impact assessments of road infrastructure. Copied from Liljenström (2013)



Tool	Reference	Country	Decision stage				Elements considered				Sustainability issues				
											Environmental			Economic	Social
			Early planning (modality, localization)	Design	Construction & maintenance	Follow-up	Road	Tunnel	Bridge	Traffic	GHG	Energy	Other		
LICCER	Brattebø et al. (2013)	SE, NO, DK, NL	▨				▨	▨	▨	▨	▨	▨			
EFFEKT	Straume (2011)	NO	▨				▨	▨	▨	▨	▨	▨		▨	
JOULESAVE	Kennedy (2006)	EU	▨	▨			▨	▨	▨	▨		▨			
AggRegain	TRL Limited (2010)	UK		▨	▨		▨				▨				
AMW	van Leest et al. (2006)	NL		▨	▨		▨				▨		▨	▨	▨
Anavitor	Erlandsson et al. (2007)	SE		▨	▨		▨	▨	▨		▨		▨	▨	
asPECT	TRL Limited (2011)	UK		▨	▨		▨				▨				
Carbon Road Map	CEREAL (2012)	NL, DK		▨	▨		▨				▨				
CMS (Carbon Management System)	Collin and Fox (2010)	Scotland		▨	▨	▨	▨				▨				
DuboCalc	Kluts and Miliutenko (2012)	NL		▨	▨		▨				▨			▨	
ECORCE	Capony et al. (2013)	FR		▨	▨		▨				▨	▨	▨		▨
ETSI BridgeLCA	Hammervold et al. (2009)	NO, SE & FIN		▨	▨				▨		▨		▨		
GreenDOT	Gallivan et al. (2010)	US		▨	▨	▨	▨			▨	▨				
Meli	Mroueh et al. (2000)	FI		▨	▨		▨				▨	▨	▨		▨
PALATE	Horvath et al. (2004)	US		▨	▨		▨				▨	▨	▨	▨	
Road Model	Stripple (2001)	SE		▨	▨		▨			▨	▨	▨	▨		
ROAD RES	Birgisdóttir (2005)	DK		▨	▨		▨				▨	▨	▨		
SEVE	SEVE (2010)	FR		▨	▨		▨				▨	▨	▨		
TEAM	Schwartzentruber and Rabier (2012)	FR		▨	▨			▨			▨	▨	▨		
UK Environmental Agency Carbon Calculator	UK Environmental Agency (2007)	UK		▨	▨		▨				▨				
UK Highway Agency Carbon Calculator	Parsons Brinckerhoff (2009)	UK			▨	▨	▨				▨				
WLCO2ST	URS (2012)	World wide			▨		▨				▨			▨	
CHANGER	Huang et al. (2012)	IRF		▨	▨		▨				▨				
Greenroads	Andersen et al. (2011)	US				▨	▨	▨	▨		▨	▨	▨	▨	▨

Table A3: Midpoint level impact categories from the ReCiPe method (Goedkoop et al, 2013).

Abbreviation	Characterized impact category	Unit
GWP	Global Warming Potential	kg CO2-eq
ODP	Ozone Depletion Potential	kg CFC-11-eq
TAP	Terrestrial Acidification Potential	kg SO2-eq
FEP	Freshwater Eutrophication Potential	kg P-eq
MEP	Marine Eutrophication Potential	kg N-eq
HTTP	Human Toxicity Potential	kg 1.4-DCB-eq
POFP	Photochemical Oxidant Formation Potential	kg NMVOC-eq
PMFP	Particulate Matter Formation Potential	kg PM10-eq
TETP	Terrestrial Ecotoxicity Potential	kg 1.4-DCB-eq
FETP	Freshwater Ecotoxicity Potential	kg 1.4-DCB-eq
METP	Marine Ecotoxicity Potential	kg 1.4-DCB-eq
IRP	Ionising Radiation Potential	kg U235eq
ALOP	Agricultural Land Occupation Potential	m2*yr
ULOP	Urban Land Occupation Potential	m2*yr
NLTP	Natural Land Transformation Potential	m2*yr
WDP	Water Depletion Potential	m3
MDP	Mineral Depletion Potential	kg oil-eq
FDP	Fossil Depletion Potential	kg Fe-eq

Table A4: Endpoint level impact categories from ReCiPe method (Goedkoop et al, 2013).

Abbr.	Characterized impact category	Indicator name	Unit
HH	Damage to Human Health	Disability-adjusted loss of life years	yr
ED	Damage to Ecosystem Diversity	Loss of species during a year	yr
RA	Damage to Resource Availability	Increased cost	$

Appendix B – Detailed calculations

Table B1: General parameters applied in the analysis.

GENERAL PARAMETERS			
Parameters	**Amount**	**Unit**	**References**
Material densities			
Density Concrete (B45)	2,45	t/m3	Kellenberger et al (2007)
Density Lightweight Concrete	1,12	t/m3	*Estimated*
Density Steel	7,85	t/m3	http://www.webcivil.com/frmsteelproperty.aspx
Density Olivine	2,86	t/m3	*Estimated*
Density Reinforced Concrete	2,55	t/m3	Statens vegvesen (2014a)
Density Asphalt in wearing layer	2,5	t/m3	Statens vegvesen (2009a).
Density Marine Gas Oil	0,86	kg/L	http://www.caltex.com.au/sites/Marine/Products/Pa
Density Diesel	0,832	kg/L	http://en.wikipedia.org/wiki/Diesel_fuel
LWA concrete unit weight	11	kN/m^3	Jakobsen (2012) p. 44
Water filled olivine rock unit weight	28	kN/m^3	Jakobsen (2012) p. 44
Asphalt composition			
Bitumen share	0,045		Statens vegvesen (2009a)
Mineral aggregates share	0,955		Statens vegvesen (2009a)
Shared parameters			
Brigde railing material	0,0665	t/m	Statens vegvesen (2009a)
Hours per day	24	h/d	
Days per year	365	d/y	
1 kilogram-force (standard gravity)	9,80665	m/s2	
Material transportation distances			
Bergen to Hanøytangen by road	25	km	google.maps.com
Bergen to the Sognefjorden site by road	150	km	Fjeld (2012)
Hanøytangen to the Sognefjorden site by sea	120	km	google.maps.com
Bergen to the Sognefjorden site by sea	160	km	searates.com
Åheim to Hanøytangen by sea	250	km	searates.com
Component life times			
Bridge railings	50	years	Statens vegvesen (2009b).
Ventilation	20	years	Statens vegvesen (2012d)
Asphalt wearing course (65 % top layer)	10	years	Statens vegvesen (2009a)

Table B2: Parameters used for the material inputs to the Floating Bridge

Case 1 - Floating Bridge (FB)			
Parameters	**Value**	**Units**	**References**
DIMENSIONS			
Total Length	4400	meter	Jakobsen (2012)
Length suspension bridge section	3700	meter	Jakobsen (2012)
Total width of the construction	18,3	meter	Jakobsen (2012)
Roadway width 2x	9,5	meter	Jakobsen (2012)
Walkway width	3	meter	Jakobsen (2012)
Effective bridge area (Roadway)	41800	m2	*Estimated*
Effective bridge area (Roadway + Walkway)	55000	m2	*Estimated*
Tower height above sea level	211	meter	Jakobsen (2012)
PRODUCTION			
Main materials			
Concrete	215 650	m3	Jakobsen (2012)
Steel	56 109	tonnes	Jakobsen (2012)
Reinforcement steel	32 000	tonnes	Jakobsen (2012)
LWA-concrete, B12	77 000	m3	Jakobsen (2012)
Olivine	310 000	m3	Jakobsen (2012)
Wearing layer height	0,08	m	Jakobsen (2012)
Wearing layer height (walk way)	0,04	m	Jakobsen (2012)
Main materials by components			
Towers axis 2 and 5 (Onshore) - Steel	405	tonnes	Jakobsen (2012)
Towers axis 2 and 5 (Onshore) - Concrete	5 650	m3	Jakobsen (2012)
Towers axis 3 and 4 (Offshore) - Steel	15 354	tonnes	Jakobsen (2012)
Deck incl viaduct - Steel	26 270	tonnes	Jakobsen (2012)
Cables (2x main cables) - Steel	12 000	tonnes	Jakobsen (2012)
Pontoons (2x) - Concrete	210 000	m3	Jakobsen (2012)
Pontoons (2x) - Olivine ballast	310 000	m3	Jakobsen (2012)
Pontoons (2x) - LWA-concrete, B12	77 000	m3	Jakobsen (2012)
Pontoons (2x) - Reinforcement	32 000	tonnes	Jakobsen (2012)
Suction anchors (32x) - Steel	2 080	tonnes	Jakobsen (2012)
Other components			
Railings (steel)	878	tonnes	*Estimated*
Asphalt (wearing layer)	3872	m3	*Estimated*

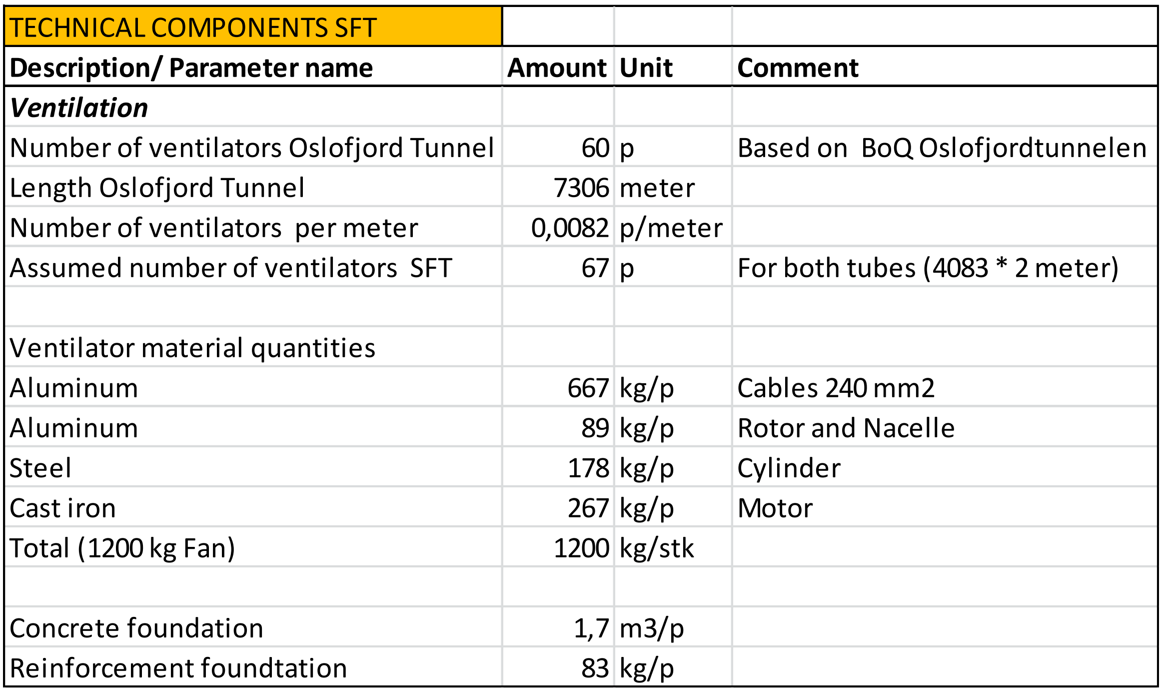
Table B3: Parameters used for the material inputs to the Suspension Bridge

CASE 2 - Suspension Bridge (SB)			
Parameters	**Value**	**Units**	**References**
DIMENSIONS			
Total length	3 700	meter	Statens vegvesen (2014a)
Total construction width	32,9	meter	Statens vegvesen (2014a)
Load-bearing portions width	25,8	meter	Statens vegvesen (2014a)
Roadway 2x width	11,5	meter	Statens vegvesen (2014a)
Walkway 2x width	6	meter	Statens vegvesen (2014a)
Effective bridge area (Roadway)	42 550	m2	*Estimated*
Effective bridge area (Roadway + Walkway)	64 750	m2	*Estimated*
Tower height above sea level	445	meter	Statens vegvesen (2014a)
Wearing layer height	0,08	meter	Statens vegvesen (2014a)
PRODUCTION			
Main material amounts			
Concrete	231 722	m3	*Estimated*
Steel	128 125	tonnes	Statens vegvesen (2014a)
Reinforcement steel	37 123	tonnes	*Estimated*
Asphalt (wearing layer)	5 180	m3	*Estimated*
Reinforced concrete (mass)	602 951	tonnes	*Estimated*
Reinforced concrete (volume)	236 451	m3	*Estimated*
Share of reinforcement in reinforced concrete	0,02		Jernbaneverket (2011)
Concrete (volume)	231 722	m3	*Estimated*
Reinforcement (volume)	4 729	m3	*Estimated*
Reinforcement (mass)	37 123	tonnes	*Estimated*
Main materials by components			
Bridge deck (load-bearing portion) - Steel	53 609	tonnes	Statens vegvesen (2014a)
Suspension cables - Steel	71 746	tonnes	Statens vegvesen (2014a)
Vertical suspender cabels - Steel	2 770	tonnes	Statens vegvesen (2014a)
Bridge towers - Reinforced concrete	602 951	tonnes	Statens vegvesen (2014a)
Other components			
Railings (steel)	1476	ton	*Estimated*
Asphalt (wearing layer)	5180	m3	*Estimated*

Table B4: Parameters used for the material inputs to the Submerged Floating Tunnel.

Case 3 -Submerged Floating Tunnel (SFT)			
Parameters	**Value**	**Units**	**References**
DIMENSIONS			
Total length SFT	4083		Fjeld (2012).
Total width tubes and bracings	65,2	meter	Fjeld (2012).
Single tube normal width	12,6	meter	Fjeld (2012).
Center distance between tubes	40	meter	Dr.Techn Olav Olsen (2012).
Construction width (including pontoons)	80	meter	Dr.Techn Olav Olsen (2012).
Driving lanes width 4x	14	meter	Dr.Techn Olav Olsen (2012).
Sidewalks, total width both tubes	6,5	m	Fjeld (2012).
Effective area (Roadway)	57162	m2	*Estimated*
Effective area (Only roadway for traffic)	28581	m2	*Estimated*
Effective area (Roadway + sidewalks)	83702	m2	*Estimated*
Wearing layer height	0,075	meter	Dr.Techn Olav Olsen (2012).
PRODUCTION			
Main materials			
Concrete	424 671	m3	Dr.Techn Olav Olsen (2012).
Steel	61 488	tonnes	Dr.Techn Olav Olsen (2012).
Reinforcement steel	113922	tonnes	Dr.Techn Olav Olsen (2012).
Main materials by components			
Tubes - concrete	349 144	m3	Fjeld (2012).
Tubes - reinforcement	78 470	tonnes	Fjeld (2012).
Tubes - post-tensioning steel	20 961	tonnes	Fjeld (2012).
Landfalls - concrete	49 668	m3	Fjeld (2012).
Landfalls - reinforcement	11 129	tonnes	Fjeld (2012).
Landfalls - post-tensioning steel	3 364	tonnes	Fjeld (2012).
32 permanent shafts - steel	10 688	tonnes	Fjeld (2012).
28 temporary shafts - steel	2 800	tonnes	Fjeld (2012).
16 pontoons - steel	48 000	tonnes	Fjeld (2012).
Other components			
Railings (steel)	543	tonnes	*Estimated*
Asphalt (wearing layer)	6278	m3	*Estimated*
Technical installations			
Ventilators SFT	67	p	*Estimated* from Iversen (2013)
Cable racks in aluminium	6	kg/m	*Estimated* from Iversen (2013)

Table B5: Approach for estimating the number of ventilators for the SFT. The parameters are taken from Iversen (2013).



TECHNICAL COMPONENTS SFT			
Description/ Parameter name	**Amount**	**Unit**	**Comment**
Ventilation			
Number of ventilators Oslofjord Tunnel	60	p	Based on BoQ Oslofjordtunnelen
Length Oslofjord Tunnel	7306	meter	
Number of ventilators per meter	0,0082	p/meter	
Assumed number of ventilators SFT	67	p	For both tubes (4083 * 2 meter)
Ventilator material quantities			
Aluminum	667	kg/p	Cables 240 mm2
Aluminum	89	kg/p	Rotor and Nacelle
Steel	178	kg/p	Cylinder
Cast iron	267	kg/p	Motor
Total (1200 kg Fan)	1200	kg/stk	
Concrete foundation	1,7	m3/p	
Reinforcement foundtation	83	kg/p	

Table B6: Estimated energy consumption at the construction site, based on Dequidt (2012)

Calcuations based on Dequidt (2012)				
The average energy consumption per month (from August 2011 to April 2012) given in the thesis				
Energy category	**Source of consumption**	**Amount**	**Unit**	
Electricity	Tower crane	15000	kWh	
Diesel	Mobile cranes	3000	liter	
Gasoline	Boat operations	800	liter	
Construction time		30	months	
Reference	http://www.vegvesen.no/Riksveg/rv80tverlandsbrua/Nyhetsarkiv/%C3%A5pning-av-tverlandsbrua			
Total energy usage for machinery and operations				
Marine diesel oil	Tugboats for the caisson construction	28700	liter	Given in thesis
Diesel	Excavation below and below water	7125	liter	Given in thesis
Diesel	Piling rig and piles boring	58000	liter	Given in thesis
Electricity	Tower crane	450000	kWh	Estimated from the construction time
Diesel	Mobile cranes	90000	liter	Estimated from construction time
Gasoline	Boat operations	24000	liter	Estimated from the construction time
Total energy usage by energy source				
Marine diesel oil		28700	liter	
Diesel		155125	liter	
Electricity		450000	kWh	
Gasoline		24000	liter	
Energy consumption per m2				
Marine diesel oil		1,8	liter/m2	
Diesel		9,9	liter/m2	
Electricity		28,6	kWh/m2	
Gasoline		1,5	liter/m2	

Table B7: Estimated energy consumption at the construction site, based on Hammervold, et al., (2013)

CONSTRUCTION PHASE - ENERGY USE AT SITE				**Hammervold et al (2013)**	
Bridge	**Length (m)**	**Width (m)**	**Area (m2**	**Diesel (liter)**	**Diesel per m2**
Klenevaagen	42,8		321	748	2,33
Fretheim	37,9		229	551	2,41
Hillersvika	39,3		417	1036	2,48
Average	40,0		322	778	2,41

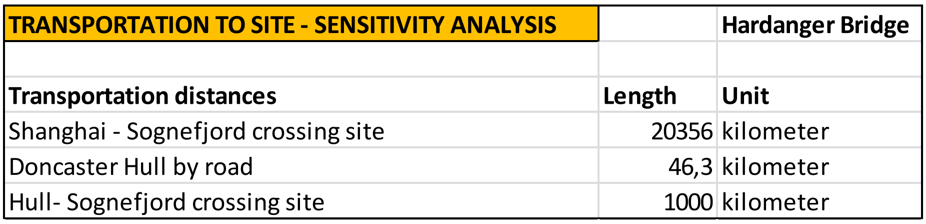
Transportation distances for the sensitivity analysis

Suppliers were gathered from the Rv.13 Hardanger Bridge page on vegvesen.no. The bridge deck sections were constructed in Shanghai and transported by heavy lift vessel ZHEN HUA 25 to Norway. The vessel has a Dead Weight Tonne (DWT) of 49 099 tonnes according to: http://www.marinetraffic.com/no/ais/details/ships/8700242/vessel:ZHEN_HUA25

The Ecoinvent process represents a ship with a DWT of 50 000 tonnes, and is hence assumed to be representative for a heavy lift vessel. In the analysis the bridge deck sections were assumed to be transported directly from Shanghai to the Sognefjord crossing site by an ocean

The main cables and suspension cables of the Hardanger Bridge were produced by Bridon LD in Doncaster in the UK. In this analysis they are assumed to be produced and transported from Doncaster to the port of Hull by truck, and from Hull to the Sognefjord by an ocean going freight.

Table B8: Transportation distances applied in the sensitivity analysis.



TRANSPORTATION TO SITE - SENSITIVITY ANALYSIS		**Hardanger Bridge**
Transportation distances	**Length**	**Unit**
Shanghai - Sognefjord crossing site	20356	kilometer
Doncaster Hull by road	46,3	kilometer
Hull- Sognefjord crossing site	1000	kilometer

Tugboats emission inventory

The data in Table B9 was gathered from Tugboat supplier. The fuel consumption is a general calculation applied by boat operators. The fuel consumption for the tube section towing operation for the SFT is covered in Table B10

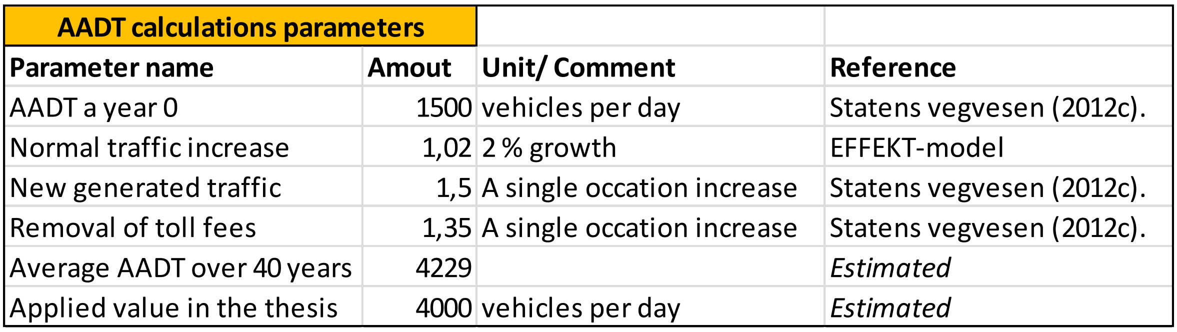
Table B9: Applied parameters for estimating the fuel consumption of tugboat movement and operations

CONSTRUCTION PHASE - TOWING TO SITE				
		Horsepower	Bollard pull (TBP)	Hp / TBP
FAIRPLAY VI and VII		3060	41	74,63
FAIRPLAY II and V		1740	30	58,00
FAIRPLAY IV		2320	25	92,80
FAIRPLAY-27	Oceangoing Tug	5440	75	72,53
FAIRPLAY-30 and 31	Oceangoing Tugs	7213	91	79,26
FAIRPLAY-32 and 33	Oceangoing Tugs	8160	103	79,22
Baltic**	Twin Screw Tug	11532	127	90,80
Ocean Class	Oceangoing Tug	10880	150	72,53
Ocean Class	Assumed 150 TBP Lead tug	10880	150	
Average FAIRPLAY	Assued 50 TBP Tractor tug	3909	50	78,18
	Diesel usage per hour per HP developed	0,05	US gallon	
	Liters per US gallon	3,7854	Liter/US gallon	
	150 TBP Lead tug	2059	Liters per hour	
	50 TBP Tractor tug	740	Liters per hour	
Sources:				
Fairplay Towage	http://www.fairplay-towage.com/en/fleetlist/tractor-tugs.html			
Crowley	http://www.crowley.com/content/view/full/9575			
Lymington Town Sailing Club	http://ltsc.co.uk/yacht-articles/564-diesel-engine-fuel-consumption-quicl-calculation			

Table B10: Estimation of fuel consumption for the SFT towing operation

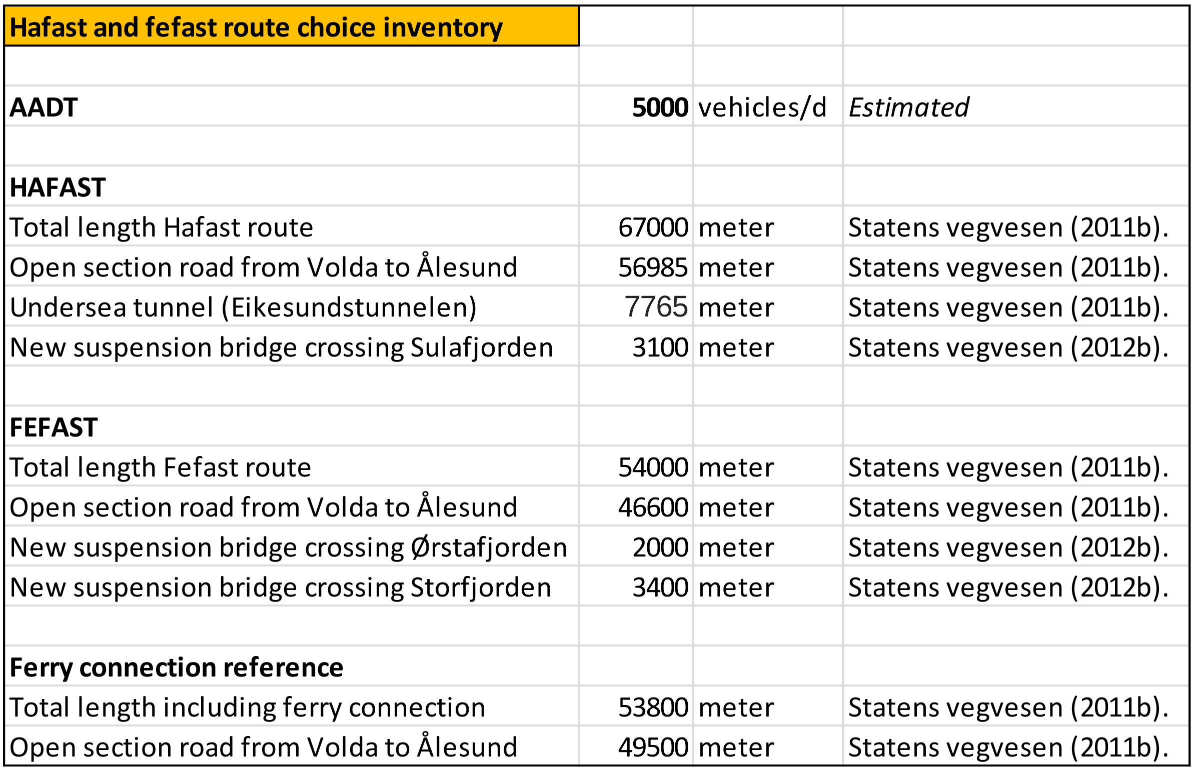
CONSTRUCTION PHASE - SFT - TOWING TO SITE			
Number of lead tugs (150 TBP)	1		
Number of assistant tugs (50 TBP)	4		
Distance in nautical miles	80	nmi	The analysis includes returning tugs
Speed of tugs during towing operations	4,5	nmi/hr	Speed 4-5 knots. One knot is a nautical mile per hour
Towing operation time	18	hrs	
150 TBP Lead tug	2059	Liters per hour	
50 TBP Tractor tug	740	Liters per hour	
150 TBP Lead tug fuel consumption per towing to site	36609	Liters fuel	Marine diesel oil
50 TBP Lead tug fuel consumption per towing to site	13153	Liters fuel	Marine diesel oil
Installation of complete SFT at the site. Towing 3-4 nautical miles (assuming 4).	18274	Liters fuel	Performed by 6 main tugs of 200 TBP each and 8 assisting tractor tugs of 50 TBP each."

Table B11: Parameters used for calculating the 40 year average AADT of 4 000



AADT calculations parameters			
Parameter name	**Amout**	**Unit/ Comment**	**Reference**
AADT a year 0	1500	vehicles per day	Statens vegvesen (2012c).
Normal traffic increase	1,02	2 % growth	EFFEKT-model
New generated traffic	1,5	A single occation increase	Statens vegvesen (2012c).
Removal of toll fees	1,35	A single occation increase	Statens vegvesen (2012c).
Average AADT over 40 years	4229		*Estimated*
Applied value in the thesis	4000	vehicles per day	*Estimated*

Table B12: Hafast and Fefast route choice inventory



Hafast and fefast route choice inventory			
AADT	**5000**	vehicles/d	*Estimated*
HAFAST			
Total length Hafast route	67000	meter	Statens vegvesen (2011b).
Open section road from Volda to Ålesund	56985	meter	Statens vegvesen (2011b).
Undersea tunnel (Eikesundstunnelen)	7765	meter	Statens vegvesen (2011b).
New suspension bridge crossing Sulafjorden	3100	meter	Statens vegvesen (2012b).
FEFAST			
Total length Fefast route	54000	meter	Statens vegvesen (2011b).
Open section road from Volda to Ålesund	46600	meter	Statens vegvesen (2011b).
New suspension bridge crossing Ørstafjorden	2000	meter	Statens vegvesen (2012b).
New suspension bridge crossing Storfjorden	3400	meter	Statens vegvesen (2012b).
Ferry connection reference			
Total length including ferry connection	53800	meter	Statens vegvesen (2011b).
Open section road from Volda to Ålesund	49500	meter	Statens vegvesen (2011b).

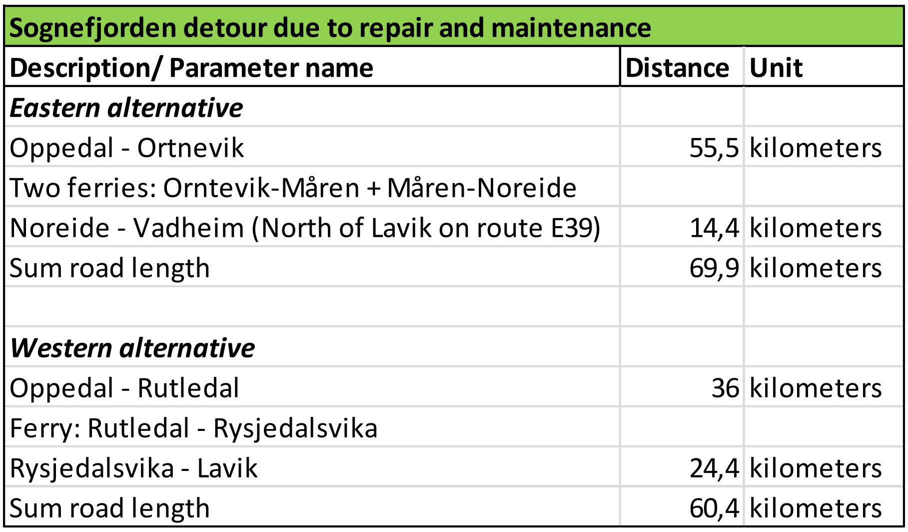
Description of the calculation procedure for ferries

Emissions from ferries and the relevant ferry connection were calculated with emissions data from a report by published by the Norwegian Maritime Directorate (Sjøfartsdirektoratet, 2011), and ferry statistics published annually by the road administration (Statens vegvesen, 2011, Hb 147).The emissions were calculated on a PBE-kilometer basis, . PBE is Norwegian an abbreviation for personbilenhet (passenger car unit/equivalent). It does not seem to have a uniform definition, and the relevant definition of PBE used in this study can be find in the ferry statistics (ibid). The emission figures per PBE-km were based on the total emissions calculated by the maritime directorate, and the total annual ferry activity given in PBE-km per year. The activity on the specific ferry connections were collected from the annual report of the ferry operator Fjord1 (2012). The report only contained emissions from combustion of fuel, aka tailpipe emissions. Emissions and resource consumption from construction of the ferries and piers were identified by Bergsdal et al (2013) of being of minor importance. In this analysis construction of the ferry was included as part of the analysis but not the pier infrastructure. The omission of this can have impacted the total calculated values.

Table B13: Parameters applied for calculation the emissions from ferries.

EMISSIONS FROM FERRIES			
Descrption/ Parameter name	**Amount**	**Unit**	**References**
Number of ferry connections (2011)	123		SVV (2011). Håndbok 157 Ferjestatistikk 2011
Number of ferrys in environmental report	197		Sjøfartsdirektoratet (2011). Miljørapport 2011
Amount of ferry kilometers for ferries in the report	1,03E+07	kilometer	Sjøfartsdirektoratet (2011). Miljørapport 2011
Total ferry traffic in Norway 2011	32947483	PBE/y	SVV (2011). Håndbok 157 Ferjestatistikk 2011
Total amount of PBE-kilometer in 2011	***2,64E+08***	***PBE-kilometer/y***	SVV (2011). Håndbok 157 Ferjestatistikk 2011
Emissions data			
GHG Norwegian ferries in 2011	***484 000***	***t CO2-eq/y***	Sjøfartsdirektoratet (2011). Miljørapport 2011
CO2 Norwegian ferries in 2011	457 000	t CO2/y	Sjøfartsdirektoratet (2011). Miljørapport 2011
CH4 Norwegian ferries in 2011	1 300	t CH4/y	Sjøfartsdirektoratet (2011). Miljørapport 2011
SO2 Norwegian ferries in 2011	114	t SO2	Sjøfartsdirektoratet (2011). Miljørapport 2011
NOx Norwegian ferries in 2011	5880	t NOx	Sjøfartsdirektoratet (2011). Miljørapport 2011
CO2 Norwegian Fjord1 ferries in 2011	211 765	t CO2/y	Fjord 1 (Årsberetning 2011)
Emissions per PBE-kilometer			
GHG-emissions per PBE-kilometer	***0,00183***	***t CO2-eq/PBE-kilometer***	
CO2-emissions per PBE-kilometer	0,00173	t CO2/PBE-kilometer	
CH4-emissions per PBE-kilometer	0,00000492	t CH4/PBE-kilometer	
NOx-emissions per PBE-kilometer	0,00000043	t NOx/PBE-kilometer	
SO2-emissions per PBE-kilometer	0,00002227	t SO2/PBE-kilometer	
Fjord 1 - Emissions per tonn CO2 /PBE-kilometer	0,00165	t CO2-eq/PBE-kilometer	
GHG-emissions per kilometer	0,0470	t CO2-eq/kilometer	
Specific ferry connections			
Festøya-Solevågen	1100000	PBE-kilometer/y	Fjord 1 (Årsberetning 2011)
Lavik - Oppedal	950000	PBE-kilometer/y	Fjord 1 (Årsberetning 2011)
GHG-emissions Festøya-Solevågen 2011	2017	t CO2-eq	
CO2-emissions Festøya-Solevågen 2011	1904	t CO2	
CH4-emissions Festøya-Solevågen 2011	5,42	t CH4	
NOx-emissions Festøya-Solevågen 2011	0,475	t NOx	
SO2-emissions Festøya-Solevågen 2011	24,5	t SO2	
GHG-emissions Lavik-Oppedal 2011	1742	t CO2-eq	
CO2-emissions Lavik-Oppedal 2011	1644	t CO2	
CH4-emissions Lavik-Oppedal 2011	4,68	t CH4	
NOx-emissions Lavik-Oppedal 2011	0,41	t NOx	
GHG-emissions Lavik-Oppedal 100 years static	174 160	t CO2-eq	
GHG-emissions Lavik-Oppedal 100 years static	33471	t CO2-eq	

Table B14 Estimated transportation distances for the closest alternative route to the permanent Sognefjord crossing.



Sognefjorden detour due to repair and maintenance		
Description/ Parameter name	**Distance**	**Unit**
Eastern alternative		
Oppedal - Ortnevik	55,5	kilometers
Two ferries: Orntevik-Måren + Måren-Noreide		
Noreide - Vadheim (North of Lavik on route E39)	14,4	kilometers
Sum road length	69,9	kilometers
Western alternative		
Oppedal - Rutledal	36	kilometers
Ferry: Rutledal - Rysjedalsvika		
Rysjedalsvika - Lavik	24,4	kilometers
Sum road length	60,4	kilometers