REPORT

Greenhouse gas strategies for cement containing products

Part of the research project CO_2 cycle in cement and concrete

Håkan Stripple

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Report Summary

Project title

Greenhouse gas strategies for cement containing products.
Part of the research project CO_2 cycle in cement and concrete

Project sponsor

Swedish consortium for financing basic research in the concrete field
and Cementa AB

Author

Håkan Stripple

Title and subtitle of the report

Greenhouse gas strategies for cement containing products. Part of the research project CO_2 cycle in cement and concrete.

Summary

The climate change issue is today one of the most important questions from a society perspective as well as from a company perspective. The construction of the society's infrastructure constitutes a very important and necessary part of the modern society. Concrete is one of the most important construction materials in a modern society today and thus a vital part for the future development. For that reason, it is important to carefully investigate the present situation as well as consequences and strategies for today and for the coming future concerning the greenhouse gas situation.

To be able to analyze complex technical systems with many interactions, a powerful and well establish methodology is required. Therefore, Life Cycle Assessment (LCA) methodology has been used for the analyses and LCA computer models have been developed for the system calculations.

This study is primarily a study of greenhouse gases and its origin in the energy production and the production processes. The LCA models have been used to calculate the primary energy use and the emissions of greenhouse gases. Also the uptake (carbonation) of CO_2 in the concrete has been included. Different concrete products and their energy and greenhouse gas behavior have been studied as well as different strategies to reduce energy use and greenhouse gas emissions. For many concrete products, a large CO_2 uptake potential exists, especially in the end of life/secondary product phase that has not been considered in the evaluation of concrete as a construction material in the society.

Keyword

Cement, concrete, climate, greenhouse gas, carbon dioxide, methane, dinitrogen oxide, LCA, strategies

Bibliographic data

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Preface

The climate change issue is today one of the most important questions from a society perspective as well as from a company perspective. Most likely, our society is facing considerably changes in the energy situation and in the climate/environmental situation in the future. For that reason, many organizations are investigating the present situation as well as consequences and strategies for today and for the coming future concerning the greenhouse gas situation. In this research project, the greenhouse gas situation for cement containing products is investigated. The overall research work, "CO_2 cycle in cement and concrete", has been performed as a co-operation project between different research organizations and the Swedish cement and concrete industry. The research organizations involved has been IVL Swedish Environmental Research Institute, CBI Swedish Cement and Concrete Research Institute and Lund Institute of Technology, Lund University (LTH). The overall project has been divided in three different sub-projects shown below.

Project	Main performing organization	Project leaders
Greenhouse gas strategies for cement containing products.	IVL	Håkan Stripple
CO_2 uptake in concrete products.	LTH/CBI	Lars-Olof Nilsson (LTH)/ Björn Lagerblad (CBI)
Surface estimations for concrete products.	Cementa AB	Ronny Andersson

The present project covered in this report is "Greenhouse gas strategies for cement containing products". In this project, overall greenhouse gas strategies for cement containing products are studied. The project work has been performed by IVL Swedish Environmental Research Institute. The project is co-financed by IVL research foundation (50 %) and the Swedish cement and concrete industry (50 %). The industry group consists of the following industries: Cementa AB, Abetong AB, Swerock AB, Strängbetong AB, AB Färdig betong, Betongindustri AB. Together they form The Swedish consortium for financing basic research in the concrete field. In connection to the projects, a reference/technical advisory group has been formed.

The entire project and reference group include the following persons and organizations.

Håkan Stripple (IVL)
Christer Ljungkrantz (Cementa AB)
Lars-Olof Nilsson (LTH)
Björn Lagerblad (CBI)
Karin Petterson (Swerock AB)
Tomas Kutti (AB Färdig betong)
Bo-Erik Eriksson (Cementa AB)
Ronny Andersson (Cementa AB)
Katja Fridh (LTH)
Jan Lillieblad (Abetong AB)
Tommy Liefvendahl (Strängbetong AB)
Mats Emborg (Betongindustri AB)

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

Gothenburg, November 2013

Håkan Stripple

Summary

The climate change issue is today one of the most important questions from a society perspective as well as from a company perspective. Most likely, our society is facing considerably changes in the energy situation and in the climate/environmental situation in the future. For that reason, it is important to carefully investigate the present situation as well as consequences and strategies for today and for the coming future concerning the greenhouse gas situation.

The construction of the society's infrastructure constitutes a very important and necessary part of the modern society. In this case, the infrastructure consists of buildings, roads, railways, bridges, tunnels, sewage disposal systems etc. Huge society investments are made yearly in these systems and a high quality of the technical performance is necessary to avoid large and costly maintenance work in the future. All these infrastructure components thus require many different materials of high and reliable quality. The invention of the Portland cement in the beginning of the nineteenth century has played an essential role for the development of the modern society and is still today an important and essential part of the society infrastructure. The Portland cement is used in many different construction materials and is the basic ingredient of concrete, mortar, stucco and most non-specialty grout. Concrete is one of the most important construction materials in a modern society today and thus a vital part for the future development.

The greenhouse gases' impact on our climate becomes a more and more important issue both from a technical/scientific point of view and on the political arena. Production of cement is a relatively energy requiring process that forms carbon dioxide as a by-product in the production process. Cement production has therefore, as a baseline today, a relatively high greenhouse gas (GHG) emission level. It is thus of great importance to analyze the present situation and to find strategies to improve the GHG performance of cement and concrete.

The carbon dioxide aspects concerning concrete are however very complex and many different aspects have to be considered. In this study, aspects concerning extraction of raw materials, production of cement, production of concrete and concrete products, use of concrete products as well as the waste handling (recycling) of the concrete have to be considered. Considerations must also be taken to the quality of the concrete and the concrete products. The entire concrete system from production via use to recycling must be studied concurrently and the consequences for the different strategies must adequately be analyzed. The different issues are interrelated and therefore difficult to handle separately. The project aim instead at creating an overall picture of the situation where the different aspects are assessed as a whole. This will hopefully give the industry and the society a better understanding of cement and concrete as materials and contribute to an improved production and use of the materials.

As shown above, there are many different aspects to consider when reducing greenhouse gases in cement and concrete production. There are aspects and strategies for the actual production of the materials (cement and concrete). An important aspect is here the choice of fuels. The access of different fuels in a national/international perspective, fuel use strategy in a society perspective and the view of waste fuel use are examples of such issues. There are aspects on the product's composition e.g. clinker content and the related quality aspects. The use of other components but clinker (e.g. slag, fly ash) in the product is another important aspect. Which consequences can the use of such material involve? These materials also involve a production history with a specific CO_2 emission that must be taken into consideration. The use of waste materials/fuels must also be considered in a society perspective. The use of old tires and blast furnace slag in cement production

is examples of such questions. How can the greenhouse gas emissions be allocated between the waste products processes and the cement production?

Both cement and other hydraulic materials take up CO_2 during the use phase of the concrete. This process is called carbonation. The carbonation process on concrete has long been known for its negative effects on the steel reinforcement in concrete. The carbonation process lowers the pH value in concrete and lowers the corrosion passivation of the steel reinforcement and in this way weakens the concrete product structure. The cement and concrete industry has long been aware of this behavior of concrete and the carbonation process is always under control in ordinary concrete products. During the lifetime of a concrete product, the product takes up CO_2 in the surface area of the product. This can in fact make the surface area even harder. Due to the molecular transportation of CO_2 in the concrete surface, the carbonation process slows down when the carbonation has reached a specific depth in the concrete surface (typically less than a few centimeters during 100 years of lifetime). In this surface area, there is no steel reinforcement that can jeopardize the strength of the concrete product.

The CO_2 uptake in concrete is thus a scientific fact and the question is rather - How can this process be handled in a CO_2 context? How is the carbonation process handled today in the national and the international CO_2 reporting and how can/should this be handled in e.g. the Kyoto system? How is this handled in connection with export? Yet another important issue is how the CO_2-balance is handled in an Environmental Impact Assessment (EIA). In this case, we are dealing with an initial emission of CO_2 in the production followed by an uptake of CO_2 during a longer time period. The question is how this is handled in different CO_2 accounting systems e.g. how is cement export handled. A parallel to this problem is for example the production of environmentally improved fuel. An increased production of environmentally improved fuels at the refineries can result in an increased emission in the production but a subsequent decrease of the emissions during use of the product (the fuel). Yet another parallel to this subject is the CO_2 emission from biofuels and the subsequent uptake of CO_2 in growing forest during a time period of 70-100 years in an ordinary forest.

The uptake rate of CO_2 varies with the exposed surface of the structure, the rate of CO_2 transport in the material and the rate of the chemical reactions. Can the geometric form of the concrete products be used as a tool for increased uptake of CO_2 and how does this influence the quality of the concrete product? How can the rate of carbonation of the concrete be influenced?

Crushed concrete materials can take up CO_2 relatively fast (<1 year for significant carbonation) while thicker concrete layers can take up CO_2 from the air for many hundred years. Is it for example desirable to crush concrete in order to accelerate CO_2 uptake in view of the energy that is needed in order to crush the material? This extra energy use will of course result in an increased CO_2 emission. If waste concrete is crushed in order to be used as for example ballast materials and thus a substitute for others crushed materials, how does that material saving influence the CO_2 balance? Which concrete waste strategies are most favorable for concrete products in a CO_2 perspective? Can this change the waste handling in the construction industry?

The situation for calculation of CO_2 emission/uptake balance in the use phase of concrete for a country is however further complicated due to the fact that CO_2 uptake also takes place in the existing stock of concrete in the society. This means that there is a large potential for uptake of CO_2 in existing concrete products in the society. How this will be handled in a CO_2 context is also an important issue.

To be able to analyze complex technical systems with many interactions, a powerful and well establish methodology is required. Therefore, Life Cycle Assessment (LCA) methodology has been used for the analyses and LCA computer models have been developed for the system calculations.

This study is primarily a study of greenhouse gases and its origin in the energy production and the production processes. The LCA models have been used to calculate the primary energy use and the emissions of greenhouse gases. Also the uptake (carbonation) of CO_2 in the concrete has been included. Different concrete products and their energy and greenhouse gas behavior have been studied as well as different strategies to reduce energy use and greenhouse gas emissions. In this summary, some results from the analyses of a concrete bridge are presented in figure A-F. In figure A and B, the baseline of primary energy use and emissions of greenhouse gases (GWP) is shown for the example bridge. Only the primary energy use for used fuels (no wastes) and the GWP emissions/uptake have been included (no biogenic CO_2). In figure C-F, some examples of the results from the reduction analyses are presented. These analyses include all greenhouse gas components such as biogenic CO_2 and CO_2 from waste as well as energy from the different waste fuels. Figure C and D show the energy use at baseline and after some strategic improvements. Figure E and F show the same analysis but with the results for greenhouse gases.

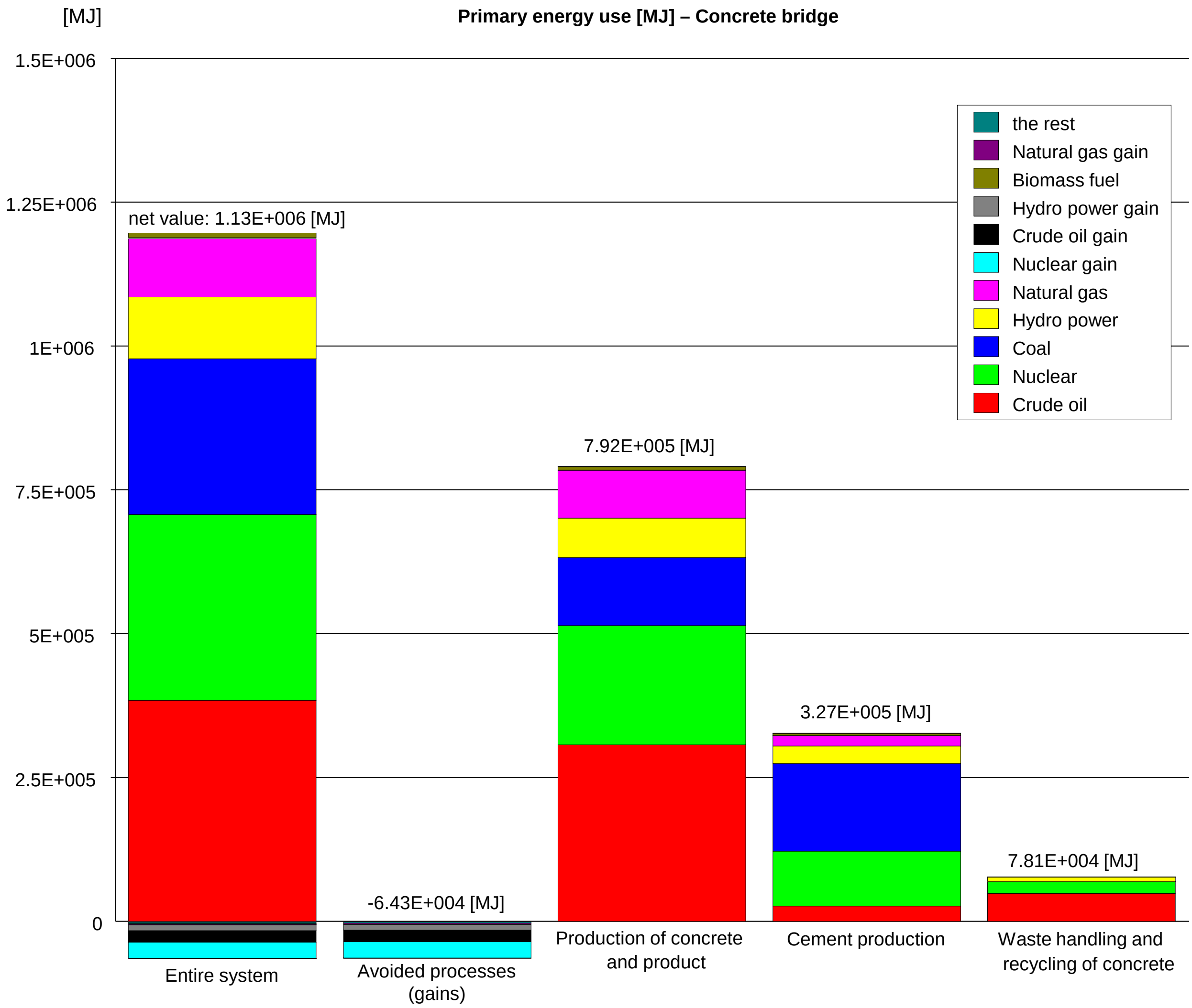

Figure A Primary energy use (excluding waste fuels) for the concrete bridge shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

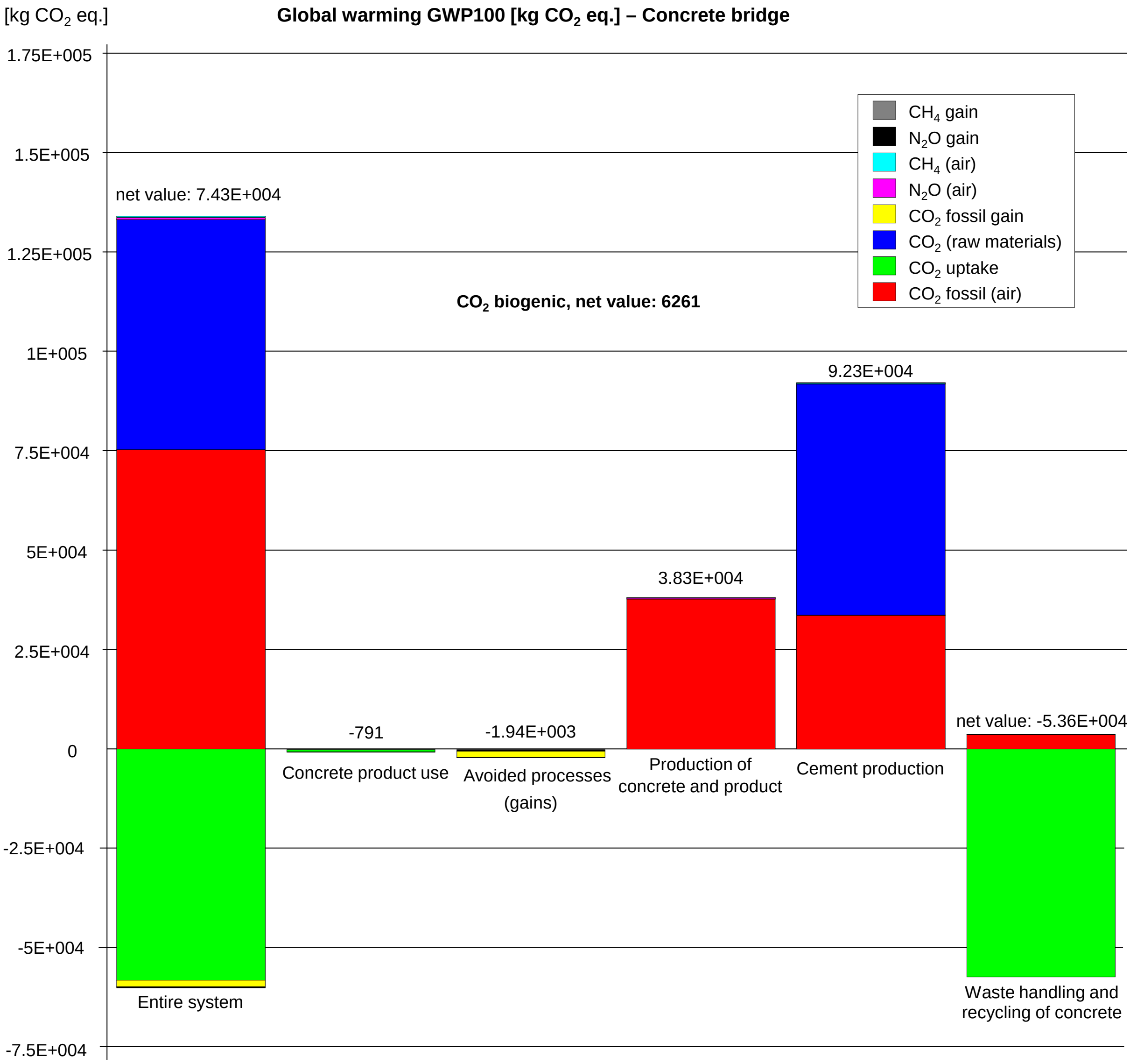

Figure B Global warming potential for the concrete bridge shown divided into different process groups and for the entire system. The CO_2 net value for the entire system shows the value when avoided CO_2 emissions and CO_2 uptake in concrete has been subtracted. The net value for the biogenic CO_2 emissions is also shown in the figure as additional information. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

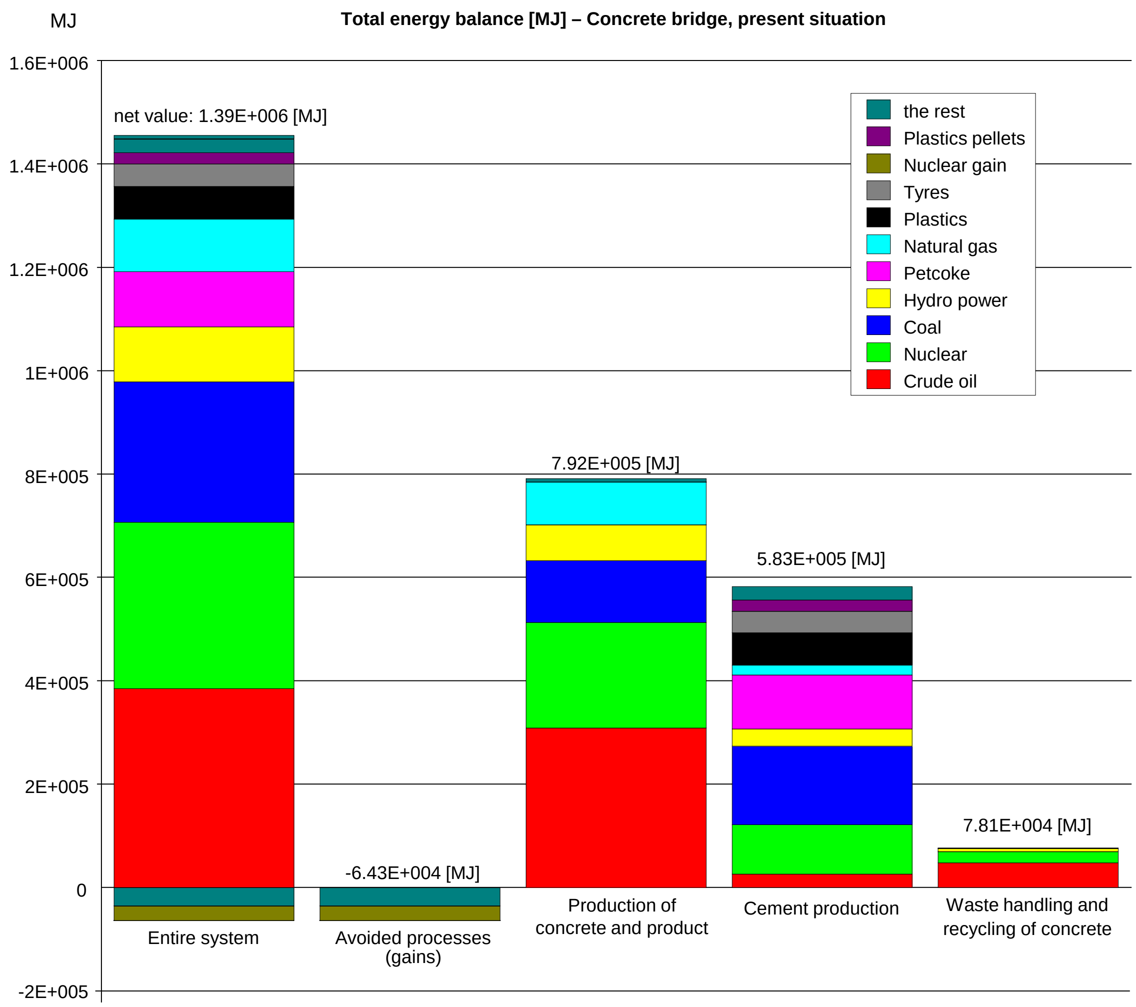

Figure C Total energy balance in present production including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

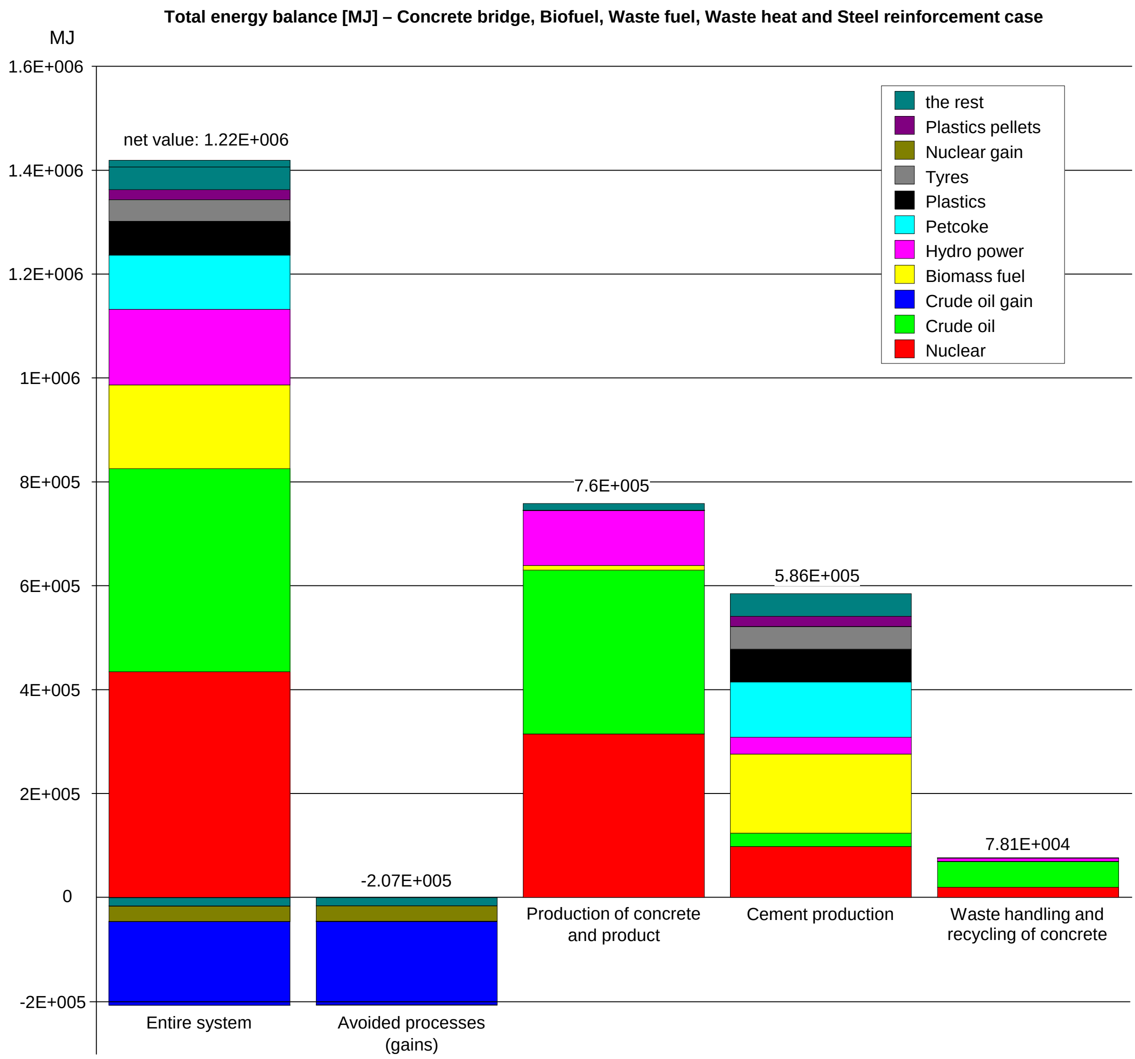

Figure D Total energy balance including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. The figure shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

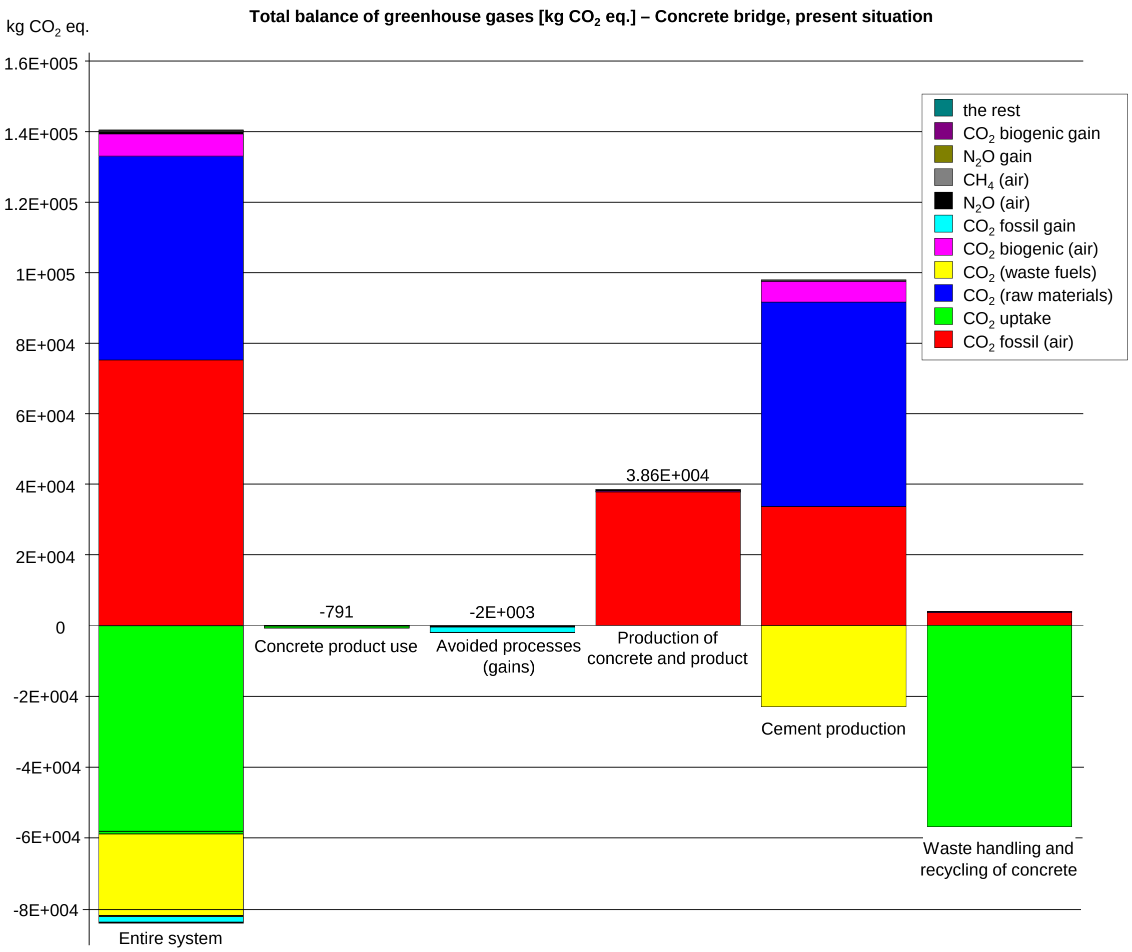

Figure E **Total greenhouse gas emissions and uptake in present production for the concrete bridge, shown divided into different process groups and for the entire system. The biogenic CO_2 emissions are thus also included in the figure. <u>The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information.</u> The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.**

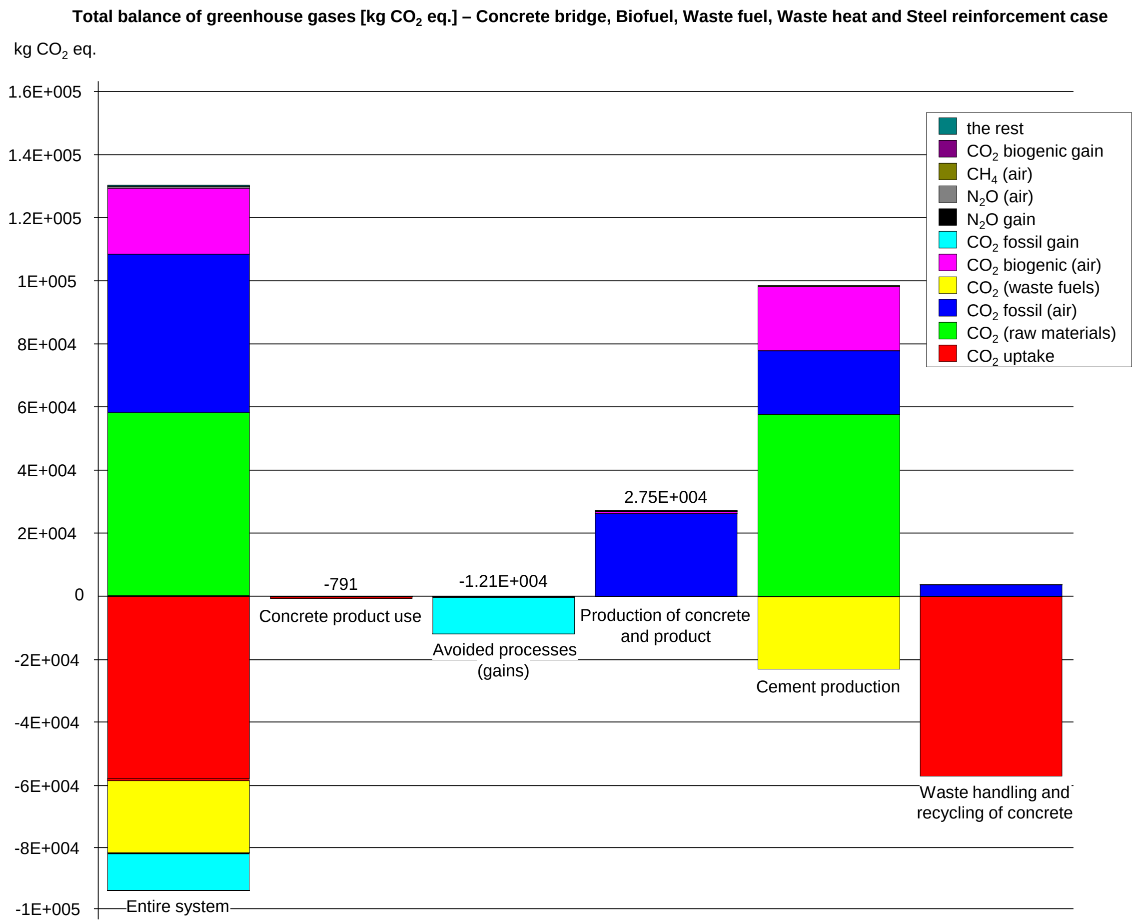

Figure F Total greenhouse gas emissions and uptake for the concrete bridge, shown divided into different process groups and for the entire system. The figure shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. The biogenic CO_2 emissions are thus also included in the figure. The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information. The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

Contents

List of abbreviations and explanations

Abbreviation/term	Explanation
IVL	IVL Swedish Environmental Research Institute/IVL Svenska Miljöinstitutet
LTH	Lund Institute of Technology, Lund University/Lunds Tekniska Högskola
CBI	CBI Swedish Cement and Concrete Research Institute/CBI Betonginstitutet
IPCC	Intergovernmental Panel on Climate Change
UNFCCC	United Nations Framework Convention on Climate Change
GHG	Greenhouse gases (in this case mostly CO_2, CH_4 and N_2O)
CO_2	Carbon dioxide
CH_4	Methane
N_2O	Dinitrogen oxide, Nitrous oxide, Laughing gas
LCA	Life Cycle Assessment
Carbonation	Uptake of CO_2 in concrete.
Marlstone	A mineral (stone) that consists of a mixture of clay materials and calcium carbonate
Low grad limestone	A limestone rock with low content of $CaCO_3$.
EIA	Environmental Impact Assessment

1 Introduction

The construction of the society's infrastructure constitutes a very important and necessary part of the modern society. In this case, the infrastructure consists of buildings, roads, railways, bridges, tunnels, sewage disposal systems etc. Huge society investments are made yearly in these systems and a high quality of the technical performance is necessary to avoid large and costly maintenance work in the future. All these infrastructure components thus require many different materials of high and reliable quality. The invention of the Portland cement in the beginning of the nineteenth century has played an essential role for the development of the modern society and is still today an important and essential part of the society infrastructure. The Portland cement is used in many different construction materials and is the basic ingredient of concrete, mortar, stucco and most non-specialty grout. Concrete is one of the most important construction materials in a modern society today and thus a vital part for the future development.

The greenhouse gases' impact on our climate becomes a more and more important issue both from a technical/scientific point of view and on the political arena. Production of cement is a relatively energy requiring process that forms carbon dioxide as a by-product in the production process. Cement production has therefore, as a baseline today, a relatively high greenhouse gas (GHG) emission level. It is thus of great importance to analyze the present situation and to find strategies to improve the GHG performance of cement and concrete.

The carbon dioxide aspects concerning concrete are however very complex and many different aspects have to be considered. In this study, aspects concerning extraction of raw materials, production of cement, production of concrete and concrete products, use of concrete products as well as the waste handling (recycling) of the concrete have to be considered. Considerations must also be taken to the quality of the concrete and the concrete products. The entire concrete system from production via use to recycling must be studied concurrently and the consequences for the different strategies must adequately be analyzed. The different issues are interrelated and therefore difficult to handle separately. The project aim instead at creating an overall picture of the situation where the different aspects are assessed as a whole. This will hopefully give the industry and the society a better understanding of cement and concrete as materials and contribute to an improved production and use of the materials.

In this introduction, it may also be appropriate to say something about the benefits and the advantage to the society of the infrastructure. The infrastructure is thus not only associated with energy consumption and different emissions but with a great benefit to society. The value of this benefit is significant and must be weighed against the disadvantages. The benefits to the society are however difficult to quantify in a comparable way and has therefore not been included in this project analysis.

2 Technical background and greenhouse gas issues

The most common cement type, the so-called Portland cement, is produced by mixing limestone with other materials such as iron, aluminium and silicon minerals, usually in the form of clay. The materials are ground, mixed to raw meal and burned to cement clinker at high-temperature (1400-1450 ºC) in a rotary kiln (cement kiln). In this process, the materials are sintered to cement clinker.

The main raw material for cement is limestone. Limestone is commonly occurring on earth. At the Swedish factories, it is mined in open mines together with marlstone (65 % $CaCO_3$ and clay). Silicate is received from low-grade limestone, marlstone and sand. In order to make the clinker reactions possible at lower temperatures (1450 ºC instead of 3000 ºC) iron and aluminium containing minerals are needed that can form a melting phase. In addition, other materials can occur in cement production such as blast furnace slag and fly ash. These are examples of the use of recycled/waste materials in the production.

The production of clinker requires high-temperature, approximately 1450 ºC, and is thereby energy demanding. The fuels that are used are mainly coal and pet-coke (waste material from oil refinery), but the cement industry strives to replace these fuels with fuel produced from residue/waste products, e.g. waste oil, used solvents, plastics, fly ash fuel, sludge pellets, meat and bone meal and used tires. In this way, the waste products are incinerated in a safe and efficient ways, in kilns with high-temperature, long residence time, basic environment and extensive cleaning of dust and acidic gases. At the same time, the energy content in the different wastes can be used. By using different wastes as fuels, the overall CO_2 emission can be reduced in the society. The waste fuels are used to replace virgin fossil fuels and in this way, they contribute to the reduction of fossil fuel use. Compared to landfilling of these wastes, the waste fuel use gives a significant reduction of greenhouse gases both as fuel substitution reduction and as avoidance of methane and carbon dioxide formation at landfill.

Yet another possible CO_2 strategy is to increase the use of biomass-based fuels. The temperature levels in the cement kiln set however, special requirements on the fuel and the large supply of biomass fuel needed can be a restriction. Requirements for use of new alternative fuels are that they do not give additional negative effects on the environment or on the cement quality compared to traditional fuels. The supplementary fuels that the Swedish cement industry uses today are residue products with well-known contents that cannot be material recycled today. Energy recycling is thus more favorable than landfilling as described above. Landfilling of combustible materials is prohibited in Sweden but exemptions can be given for specific quantities of wastes. The legal handling of CO_2 for waste products is important and can cause problems both in terms of allocation and distribution of CO_2 allowances. A restrictive allocation of CO_2 allowances for incineration of waste fuels can result in an increased use of landfilling and a reduced energy recycling.

In the production of cement, carbon dioxide is formed both from the combustion of the fuels needed for heating and from calcination of the limestone according to the reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

After the cement kiln, the sintered material is ground to desired particle size. The clinker is ground with e.g. gypsum, limestone, iron sulfate, fly ash, slag and other additives to form the final cement product. The clinker content varies presently between 80-95 % in Swedish produced cement, depending on the cement type, application area and customer requirements.

The main products in Swedish cement industry are Byggcement (Building cement), Snabbcement (Rapid hardening cement), Anläggningscement (Construction cement) and Exportcement (Export cement). Building cement is the general cement for building applications. Rapid hardening cement is used in pre-fabrication and at wintertime concreting. It is finer ground so that it hydrates more quickly and has generally more gypsum compared to other cement qualities. Construction cement is a moderate-heat cement for construction applications such as bridges and roads, where the market requests a Portland cement with high clinker content for durability reasons (e.g. frost resistant). The Export cement's quality varies from country to country but for the largest export market, USA, the market requires Portland cement with high clinker content and high quality. The building cement's clinker content lies in the lower interval and the other cement types in the upper interval.

At the product shift from Standard cement to Building cement during year 2000, the clinker content was reduced by 10 % at unchanged or somewhat increased mechanical strength for the concrete. The grinding was increased to make cement with finer particle size and the raw materials were adjusted to maintain the mechanical strength. These measures also improved the concreting properties for the concrete. In countries with cold climate, cement with larger specific surface is used to shortening the concreting process. The Building cement in Sweden has properties similar to European continental quick cement.

Cement clinker gives high mechanical strength both in short time and in long time due to its high content of tricalciumsilicate. Materials with latent hydraulic properties need clinker (also quicklime (CaO) has been used) in order to be activated. Examples of this are pozzolanic materials such as fly ash, slag from combustion plants and blast furnace slag. These materials usually have low short time strength but high long time strength. Increased grinding (finer particles) can increase the short time strength of the concrete. However, there is an upper limit for grinding that cannot be exceeded due to quality reason. In recent years, customer demands in Sweden have resulted in an increased twenty-four hour strength for Building cement on approximately 20 %. In warmer climates than Sweden, cement with lower clinker content and lower grinding can often be used.

Most of the cement is used in concrete production. Concrete consists of gravel/sand, water and cement (typically 15 % of concrete). The cement constitutes the binder that holds the concrete together. Thus, also the composition of the concrete can be altered in order to reduce the overall greenhouse gases emissions. However, the quality of the concrete always has to be in focus.

As shown above, there are many different aspects to consider when reducing greenhouse gases in cement and concrete production. There are aspects and strategies for the actual production of the materials (cement and concrete). An important aspect is here the choice of fuels. The access of different fuels in a national/international perspective, fuel use strategy in a society perspective and the view of waste fuel use are examples of such issues. There are aspects on the product's composition e.g. clinker content and the related quality aspects. The use of other components but clinker (e.g. slag, fly ash) in the product is another important aspect. Which consequences can the use of such material involve? These materials also involve a production history with a specific CO_2 emission that must be taken into consideration. The use of waste materials/fuels must also be considered in a society perspective. The use of old tires and blast furnace slag in cement production is examples of such questions. How can the greenhouse gas emissions be allocated between the waste products processes and the cement production?

A very special measure for CO_2 reduction that can be used is the so-called "carbon capture and storage" (CCS). In this technique, the CO_2 gas in the exhaust gas (from the cement kiln) is captured (usually with a scrubbing technique). The CO_2 gas is then liquefied and transported for storage in for example deep underground storages (aquifers, oil fields, gas fields). The technique is of special interest for cement kilns due to its high concentration of CO_2 in the exhaust gases. However, the technique is completely new and untested.

Both cement and other hydraulic materials take up CO_2 during the use phase of the concrete. This process is called carbonation. The carbonation process on concrete has long been known for its negative effects on the steel reinforcement in concrete. The carbonation process lowers the pH value in concrete and lowers the corrosion passivation of the steel reinforcement and in this way weakens the concrete product structure. The cement and concrete industry has long been aware of this behavior of concrete and the carbonation process is always under control in ordinary concrete products. During the lifetime of a concrete product, the product takes up CO_2 in the surface area of the product. This can in fact make the surface area even harder. Due to the molecular transportation of CO_2 in the concrete surface, the carbonation process slows down when the carbonation has reached a specific depth in the concrete surface (typically less than a few centimeters during 100 years of lifetime). In this surface area, there is no steel reinforcement that can jeopardize the strength of the concrete product.

The CO_2 uptake in concrete is thus a scientific fact and the question is rather - How can this process be handled in a CO_2 context? How is the carbonation process handled today in the national and the international CO_2 reporting and how can/should this be handled in e.g. the Kyoto system? How is this handled in connection with export? Yet another important issue is how the CO_2-balance is handled in an Environmental Impact Assessment (EIA). In this case, we are dealing with an initial emission of CO_2 in the production followed by an uptake of CO_2 during a longer time period. The question is how this is handled in different CO_2 accounting systems e.g. how is cement export handled. A parallel to this problem is for example the production of environmentally improved fuel. An increased production of environmentally improved fuels at the refineries can result in an increased emission in the production but a subsequent decrease of the emissions during use of the product (the fuel). Yet another parallel to this subject is the CO_2 emission from biofuels and the subsequent uptake of CO_2 in growing forest during a time period of 70-100 years in an ordinary forest.

The uptake rate of CO_2 varies with the exposed surface of the structure, the rate of CO_2 transport in the material and the rate of the chemical reactions. Can the geometric form of the concrete products be used as a tool for increased uptake of CO_2 and how does this influence the quality of the concrete product? How can the rate of carbonation of the concrete be influenced?

Crushed concrete materials can take up CO_2 relatively fast (<1 year for significant carbonation) while thicker concrete layers can take up CO_2 from the air for many hundred years. Is it for example desirable to crush concrete in order to accelerate CO_2 uptake in view of the energy that is needed in order to crush the material? This extra energy use will of course result in an increased CO_2 emission. If waste concrete is crushed in order to be used as for example ballast materials and thus a substitute for others crushed materials, how does that material saving influence the CO_2 balance? Which concrete waste strategies are most favorable for concrete products in a CO_2 perspective? Can this change the waste handling in the construction industry?

The situation for calculation of CO_2 emission/uptake balance in the use phase of concrete for a country is however further complicated due to the fact that CO_2 uptake also takes place in the existing stock of concrete in the society. This means that there is a large potential for uptake of CO_2

in existing concrete products in the society. How this will be handled in a CO_2 context is also an important issue.

3 Analytical methods and methodological aspects

3.1 General methodology

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

A system is a unit that consists of different parts working together. By applying a system perspective, i.e. taking the entire system into account, one can get a better and more accurate picture of the production system and one can for example avoid sub-optimization. For example, when evaluating materials in terms of energy and environmental aspects it is important not to evaluate only the production process of the material but also ensure that the environmental load does not increase due to e.g. increased maintenance and operation activities. Analyzing production systems rather than individual production processes make higher demands on the methodology and the implementation. A logical and structured methodology and a well thought-out analysis are required. Computer based calculations and models are also required. For this type of system analysis, the most common method is Life Cycle Assessment (LCA). The LCA method offers a fully developed and standardized method with available computer software platforms. This method is also the base for certified Environmental Product Declarations (EPD). In the next chapter, a short presentation of the LCA method is shown. LCA is a comprehensive tool comprising many different environmental aspects. Even if an analysis has a focus on just a few of these aspects (such as CO_2 in this case), an LCA analysis can and should be used to keep track of e.g. eventual side effects of different CO_2 reduction measures.

3.2 Life Cycle Assessment - LCA

A system analysis is a tool that allows a product to be analyzed through its entire life cycle, from raw material extraction and production, via the material's use to waste handling and recycling. The most common tool for system analysis is the life cycle assessment (LCA) methodology. The LCA methodology is described in, for example, the standards EN ISO 14040:2006 and 14044:2006[1]. In a life cycle assessment, a mathematical model of the system is designed. This model is of course a representation of the real system, including various approximations and assumptions. The LCA

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

methodology allows us to study complex systems, where interactions between different parts of the system exist, to provide as complete a picture as possible of the environmental impacts of, for example, a product.

An LCA is usually made in three steps with an additional interpretation step, see ISO standard. In the goal and scope definition, the model and process layout are defined. The functional unit is also specified. The functional unit is the measure of performance that the system delivers. In the life cycle inventory analysis (LCI), the material and energy flows are quantified. Each sub-process has its own performance unit and several in- and out-flows. The processes are then linked together to form the mathematical system being analyzed. The final result of the model is the sum of all in- and out-flows calculated per functional unit for the entire system. The life cycle impact assessment (LCIA) is defined as the phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. The impact assessment is performed in consecutive steps including classification, characterization, normalization and weighting. The LCIA phase also provides information for the life cycle interpretation phase, where the final environmental interpretation is made. In this study, only classification and characterization have been included in the impact assessment part. Here, the same classification and characterization scheme as proposed in the EPD system[2] have been used.

4 The system model of concrete

An important part of this study is to describe the entire greenhouse gas balance for concrete used today but also to analyze greenhouse gas strategies for concrete as a construction material of today and for the future. To be able to make a complete analysis of concrete, a system perspective has to be applied. The system needs to cover the entire life cycle of concrete from extraction of raw materials to the waste handling of the used concrete. The model also needs to be detailed so that changes in many different parameters can be studies and the greenhouse gas emissions can be calculated. Flexibility is also an important aspect. The model should be flexible both in terms of possibilities to make changes in the existing model structure but also in the possibilities to easily change the model structure to analyze more complex changes of the production processes.

The natural choice of methodology and modeling is of course Life Cycle Assessment (LCA). As a base for the analyses in this study, a LCA model of concrete has been developed. The model has been developed in the LCA software KCL-ECO. The model structure is shown in Figure 1. Due to the size of the model, it is difficult to show the entire model in the report in a readable form. However, it is important to show the entire model for the understanding of the study and the different analyses. The solution to this problem is to show the model as it is in the report and then use the zoom function in the computer to look at the figure on the screen. In this way, both the details and the overview will be available.

The model is built-up of different process modules and transports representing different processes in the life cycle of concrete. The model starts with the production of clinker in the cement kiln including the clinker process as well as the production of all raw materials and fuels needed in the

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

production. All materials are calculated back to its material resource in the earth crust. The materials cover mostly, either materials for the clinker or fuels to the kiln. Several different materials and fuels have been included for the possibility to vary the production in the scenario analyses. The heat recovery from the cement kiln used for example in a district heating system has also been included and the recovered heat has been calculated as an avoided use of fuel oil. The effect of this is always shown separately.

The next step includes the cement production (cement mill) with the different materials used for different cement types. Also here, the model can simulate different cement types/compositions. Cement is then used in the production of a specific concrete product. In principle, the model has two different production routes, site cast production and precast production. The model includes all production steps from concrete production with different composition to the concrete casting on site or assembly of the precast products. The use of the product is also included in the model but the aim of this study is to analyze concrete as a material and thus only pure concrete products without e.g. energy use (for instance heating of a building) have been studied. No maintenance of the concrete product during use has been assumed. The only process that occurs during use phase is the uptake of CO_2 in the surface of the concrete (carbonation).

After the concrete product's use, the product is entering the end of life processes. The product is usually demolished in some way including a crushing of the concrete and separation of the steel reinforcement bars which is sent to steel recycling. The model in its present form includes four different waste handling methods:

- Landfilling of waste concrete.
- Crushing and sieving of concrete for accelerated CO_2 uptake.
- Crushing and sieving of concrete for use as macadam/filler.
- Crushing and sieving of concrete for recycling to concrete production.

Also in the waste handling phase, the concrete will continue to take up CO_2 from the atmosphere. However, the different waste handling alternatives offer different possibilities for CO_2 uptake and include different processes characteristics (energy use, emissions etc.). However, crushing to different particle sizes is a fundamental process for all alternatives. In the landfill alternative, the concrete is crushed into relatively large fraction and placed in a landfill. The carbonation process will continue in the landfill but the carbonation rate will depends on the type/organization of the landfill. To promote further carbonation, exposure to CO_2 containing air is important. In the accelerated CO_2 uptake alternative the concrete is crushed to promote a fast carbonation in a subsequent process step with an accelerated CO_2 uptake. No developed process exists for this alternative so the scenario calculations have to include a great deal of assumptions. Crushed concrete is regularly used today as ballast in different constructions for instance road bases and in new concrete. The CO_2 uptake in ballast use depends on the application and thus on the possibility for CO_2 exposure. The use of crushed concrete as ballast also implies avoided production of ballast from stone materials, which will save rock resources and reduce the amount of landfill waste. These calculations are also included in the model.

Figure 1 The LCA model flow chart showing the life cycle system of concrete used in the study. (Use pdf file/zoom and read figure from screen for improved readability).

5 Life cycle inventory calculations

This study has a focus on greenhouse gases from cement and concrete production. This covers mainly three different gases: carbon dioxide (CO_2), methane (CH_4) and dinitrogen oxide (N_2O). Even if the focus of the analyses has been on the greenhouse gases, it is important to cover also other parameters in order to avoid undesired effects in the entire system. Of the same reason, a system perspective (LCA methodology) has been used in the analyses. Other parameters, such as energy resource use and acidification are thus also presented and discussed in the study to put the climate change aspects in a somewhat larger perspective.

An important criterion for the selection of data and system boundaries is the strategic choice of data representation. LCI data in a model can represent different types of data e.g. data for a specific process, average data for a number of processes (European average, country average etc.), data for a certain technology standard or data for a certain type of plant. The selected strategy depends for example on the aim of the study and data availability. The choice of data strategy will also influence the data quality achieved. Reliable average data, e.g. European average, are usually very difficult to achieve and evaluate. It is usually difficult to define the technology level because the data represent different types of processes and different technology levels. Therefore, average data are best used in background processes in a LCI study where no detailed evaluation of the process will be performed.

The overall data selection criterion for this study has been to identify and specify certain technology levels of processes and based on that defines energy, resource and emission data. This is achieved by studying specific and modern production units both for cement and concrete production. Production plants representing the entire production chain from raw material extraction to the finished concrete products has been selected and production/energy/emission data has been collected from the entire production chain. In this way, reliable technical data can be obtained. A production chain representing a south Swedish production has been chosen. The disadvantage of this choice is of course that the results will reflect only a specific production chain. It is anyhow difficult to draw conclusions from average production data from many different production plants so the strategy has been to study one production chain carefully and draw conclusions from that even if the representativity will be somewhat reduced. The production of cement and concrete products are however relatively standardized so the results and conclusions will also be relatively general and applicable to other production chains.

The waste handling data are calculated based on general data. The waste handling can thus vary significantly even if the quality of the estimations in this case has a relatively good quality. The estimations of the CO_2 uptake in the concrete product during product use is performed in other research activities in this project ("CO_2 cycle in cement and concrete") and thus a result of both theoretical calculations and practical measurements. These data can be considered to have an acceptable quality. The CO_2 uptake in the waste handling phase is difficult to estimate. Waste processes optimized for this uptake is not developed and the uptake rate depends very much on the handling and storage/use of the crushed waste. In a very long term perspective, the concrete will be almost completely carbonated and thus all CO_2 driven off from the raw meal in the cement kiln will be taken up by the concrete. Therefore, the maximum CO_2 uptake is shown in the result figures as a potential uptake and the real uptake is discussed in the text.

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

LCI data for this project have been obtained from different sources such as literature data, data from single plants and processes in operation and data from equipment supplier. The Swedish cement and concrete industry have been involved in the project, which means that the project has had access to production data from many different production plants. Transport data (per tonne-km) for different transports has been obtained from NTM[3], Sweden. All data sets have been described carefully in the models with references.

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

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

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

Table 1 General specification of inventory data.

Data quality subject	Coverage and strategies for inventory data
Time-related coverage	Generally, the most recent data available has been used in the study. For cement and concrete production, data from year 2009 has been used. The concrete product lifetime has been set to 100 years.
Geographic coverage	A cement, concrete and concrete product production in south of Sweden has been assumed.
Technology coverage	A standard and modern Swedish production level has been assumed for cement, concrete and the concrete product production.
Precision, completeness and representativeness of the data	The model together with the included base data represents a specific production chain even if the data can be considered as typical production data. However, raw material use, fuel use and other energy use can vary significantly and thus influence the result considerable. Data for the cement and concrete production is obtained directly from the producers and thus of a relatively good quality. The LCA data are calculated from the original resource use to waste handling including CO_2 uptake. The waste handling data are calculated based on general data. The waste handling can thus vary significantly even if the quality of the estimation has a relatively good quality. The estimations of the CO_2 uptake in the concrete product during product use is performed in other research activities in this project and thus a result of both theoretical calculations and practical measurements. These data can be considered to have an acceptable quality. The CO_2 uptake in the waste handling phase is difficult to estimate. Waste processes optimized for this uptake is not developed and the uptake rate depends very much on the handling and storage/use of the crushed waste. In a very long term perspective, the concrete will be completely carbonated and thus all CO_2 driven off from the raw meal in the cement kiln will be taken up by the concrete. Therefore, the maximum CO_2 uptake is shown in the result figures as a potential uptake and the real uptake is discussed in the text. Data for production of production equipment such as steel plants, cement and concrete plants, trucks, rollers etc. have not been included.
Consistency and reproducibility of the methods used throughout the LCI	The model calculates the overall results from the analysis based on the input data used in the model. Each production chain is unique to some extent due to type of plant, used material and energy, process conditions, transport distances etc.
Sources of the data and their representativeness	Data for cement, concrete and concrete product production is obtained from Swedish producers. Other LCA data such as fuel and energy production data, transport data etc. have been obtained from general LCA data sets.
Uncertainty of the information	Exact figures of the uncertainty of the data are not possible to achieve.

6 Technical conditions and CO_2 uptake

6.1 Overview of the carbonation process for concrete

The reason for the carbonation reactions of concrete is that the hardened cement is not a chemically stable form. When CO_2 is driven off from the limestone in the cement kiln, reactive CaO-compounds are formed with hydraulic properties when mixed with water. These properties are used in the concrete and cement reactions to give concrete its characteristic quality. However, in nature, limestone ($CaCO_3$) is the chemically stable form. Thus, the concrete system have a naturally tendency to take up CO_2 in order to return to its stable form as $CaCO_3$. The CO_2 uptake in concrete proceed through reaction with e.g. $Ca(OH)_2$ and calcium silicate hydrate ($CaOSiO_2H_2O$, C-S-H). A key question of carbonation is to what extent the concrete compounds take up CO_2 and the corresponding time frame. The carbonation processes can actually strengthen the concrete but will also decrease the pH-value of the concrete and can thereby cause corrosion of the reinforcement bars, which can have negative effects on the mechanical strength and on the concrete construction as a whole. It is therefore important to avoid carbonation in the reinforcement regions of a concrete construction during the use of the product.

The CO_2 uptake occurs at the surface of a concrete object. CO_2 from the surrounding of the object is transported into the concrete where it reacts with the concrete, which thereby will change its chemical structure and material property. This carbonation process is controlled by many different factors such as CO_2 concentration in the surrounding, moisture content at the concrete surface, physical and chemical structure of the concrete. This means that the CO_2 uptake in a specific concrete product depends on the geometry of the product and the weather/climate conditions where the concrete object is located. For quantification of CO_2 uptake in concrete products, it is thus not possible to study a general concrete volume. Instead, one has to study and analyze specific concrete products located in their normal environment. In this project, four common concrete products have been chosen for the analysis. The products have been selected to exemplify different carbonation behavior. The products are a concrete bridge, a site cast house frame for an apartment house, a precast house frame for an industrial storehouse and a roof with concrete tiles.

The CO_2 uptake in concrete also takes place in the waste handling/material recycling of the concrete from the different concrete products in the society. This is an important aspect of the CO_2 balance of concrete. In this chapter, the technical conditions and CO_2 uptake for the different example products as well as the end of life aspects for concrete are presented and discussed.

6.2 Uptake of CO_2 in various concrete surfaces

An important part of the CO_2 uptake calculations is to find a reliable method to calculate the CO_2 uptake in a specific concrete surface during a defined period of time. The uptake rate varies for different surfaces and different conditions. Factors that can play an essential role in the CO_2 uptake process are listed below:

- Concrete type (e.g. cement content, cement constituents, water/cement ratio, additives)
- CO_2 exposure of the concrete surface (e.g. CO_2 concentration and supply surrounding in air)
- Moisture content at concrete surface (e.g. rain protected/rain exposed, indoor/outdoor surfaces)
- Coverage of different materials (plastic carpets, wallpapers, glues, paint etc.)
- Underground constructions (concrete surfaces covered by different ground materials etc.)

To some extent, theoretical calculations of the carbonation rate can be made but experiences have shown that practical measurements of carbonation in different existing old concrete objects is still necessary to achieve a reliable result. In other parts of this project[4] (see also preface section) measurements of carbonation have been performed and calculation methods have been developed. A CO_2 uptake calculation model has also been developed. The model can handle the carbonation process including the factors mentioned above. In Table 2 below, this carbonation model has been used to calculate typical CO_2 uptake in different common concrete surface types. The uptake figures cover in this case the uptake during product use for a product lifetime of 100 years. However, figures of this type can also be used for crushed material in end-of-life processes. There is of course a limit for the maximum uptake in small particles and thin concrete structures due to the maximum CO_2 uptake in the concrete. This limitation has for example been used for the roofing tile example.

Table 2 Uptake of CO_2 in different concrete structures during 100 years of product use[4].

	Concrete structure	**Absorbed amount of carbon dioxide ($kg\ CO_2/m^2$) after 100 years**
1.	*Indoor structures*	
1.1	without surface coatings (with SDC, self-desiccating concrete)	6.1 (1.7)
1.2	with somewhat permeable surface coatings (“paint”)	3.6
1.3	with almost impermeable surface coatings (PVC, linoleum, parquet, floor paint)	0.9
2.	*Slab-on-grade (bottom surface)*	
2.1	with mineral wool (with SDC, self-desiccating concrete)	4.1 (1.4)
2.2	with EPS, expanded polystyrene	0
2.3	with coarse drainage layer	0.7
2.4	with sand/gravel	0.1
3.	*Outdoor structures*	
3.1	exposed to rain	0.9
3.2	sheltered against rain	2.8
4.	*Bridges*	
4.1	parts exposed to rain	0.5
4.2	parts sheltered from rain	1.8
4.3	underground parts (with no CO_2 exposure)	0

[4] Nilsson Lars-Olof, Fridh Katja, CO_2 cycle in cement and concrete, Part 7: Models for CO_2-absorption. A new model for CO_2 absorption of concrete structures. Lund institute of technology, Lund University, Division of building materials, Sweden, Report TVBM-3158 (2010).

6.3 Concrete products for the scenarios

This chapter describes the various concrete products used in the study to exemplify the uptake of CO_2 into various products. The products used in the study are a concrete bridge, a site-cast house frame, a precast industrial storage frame and a roof with concrete roofing tiles. The examples show how to calculate the uptake of CO_2 in different products taking into account the ambient conditions that apply to different surfaces in the different products. Additional product examples have been developed within the framework of the overall project, including the development of mathematical models to determine the total amount of concrete surfaces in a country and thus to develop techniques to calculate the CO_2 uptake in an entire country every year. The additional uptake calculations for this purpose are also presented in this report in Appendix 1. The country-wide model for the CO_2 uptake calculations is published in a scientific paper [5].

6.3.1 Concrete bridge

Bridges varies significantly in size and technical design. For this example, a very typical and common bridge type has been chosen. The bridge is a portal frame bridge in a highway construction. This type of bridge is used for example to cross another road. It is thus a relatively small bridge (total bridge length is 28 m) made entirely in concrete and with some parts of the bridge underground (covered with soil). The bridge is made of construction cement (CEM I) with a high content of Portland cement clinker. The concrete specification for the bridge can be found in chapter 6.5, Table 9. The concrete construction is compact and the carbonation (CO_2 uptake) is thus slow. The concrete surfaces are all exposed to outdoor conditions but some are direct exposed to rain and some are rain protected. The carriageway of the bridge is assumed to be covered with asphalt. Some surfaces are also covered with soil or ballast. A schematic picture of the bridge is shown in Figure 2. The areas of the different of concrete surfaces and the total amount of concrete used have been calculated for the bridge. The total CO_2 uptake for the bridge can then be calculated based on the specific CO_2 uptake for the different concrete surfaces. The bridge specifications and CO_2 uptake calculations are shown in Table 3.

[5] R. Andersson, K. Fridh, H. Stripple and M. Häglund, Calculating CO_2 Uptake for Existing Concrete Structures during and after Service Life, Environmental Science & Technology, 2013, 47 (20), pp 11625–11633.

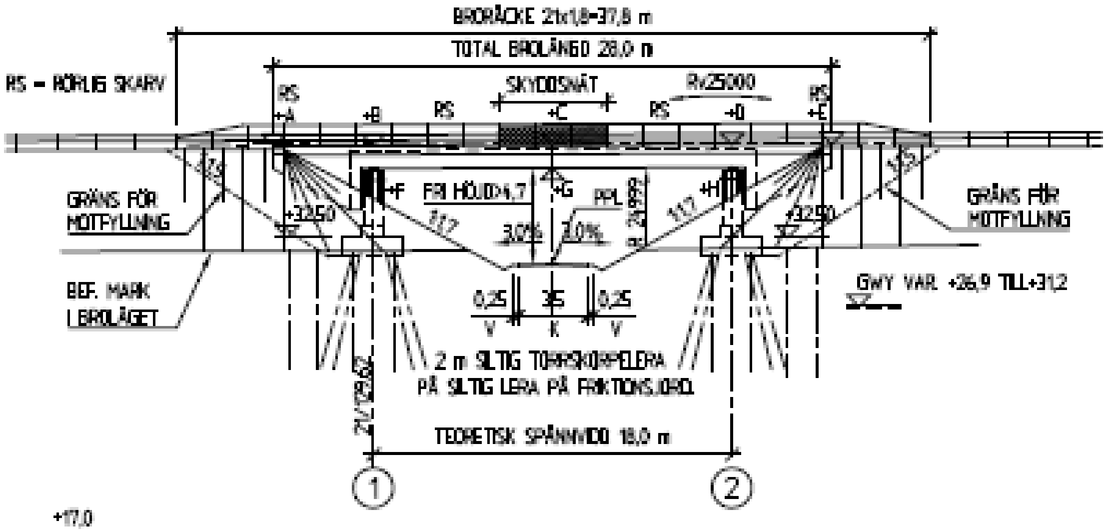

Figure 2 Schematic figure of the portal frame bridge used in the scenario example.

Table 3 Specifications and CO_2 uptake calculations of the bridge during a product use phase of 100 years.

Concrete surface types	**Concrete surface area (m^2)**	**Specific CO_2 uptake (kg/m^2 and 100 years)**	**CO_2 uptake (kg during 100 years)**
Foundation under ground with pure concrete surface	94	0	0
Foundation above ground with pure concrete surface, rain protected	71	1.8	129
Bridge piers rain protected above ground with pure concrete surface	102	1.8	184
Carriageway (upper side) with asphalt layer	195	0	0
Carriageway (under side) with pure concrete surface, rain protected	195	1.8	351
Side face of carriageway, rain exposed pure concrete surface	21	0.5	11
Inner side walls, rain protected	54.0	1.8	97
Inner side walls, exposed to ground	54.0	0	0
Triangular wing guide, rain exposed	22.8	0.5	11
Triangular wing guide, exposed to ground	22.8	0	0
Total concrete surface area	*832.0*		
Total CO_2 uptake			**782**
Steel reinforcement	120	kg steel/m^3 concrete	
Concrete product volume (m^3), foundations and pillars	70	m^3	
Concrete product volume (m^3), carriageway	207	m^3	
Total concrete product volume (m^3)	*277*	*m^3*	
Overall concrete surface area/concrete volume ratio	*3.0*	*m^2/m^3*	
CO_2 uptake per concrete volume (kg CO_2/m^3 concrete and 100 years)	**2.9**	**kg/m^3**	

6.3.2 Site cast concrete house frames

Many residential buildings are today constructed with a site cast concrete frame. This is a very common type of building and thus important in terms of CO_2 uptake in the concrete product stock. The situation is however complex because the house frame is usually built-in and thus covered with other material in walls, roofs and floors. The frame is also very often covered with paints, different glues, wallpapers, plastic carpets etc. This can prevent the molecular transport of CO_2 into the concrete construction and thus slow down the carbonation process. To be able to calculate the CO_2 uptake in a house frame, the different surfaces in the concrete structure have to be described in terms of area and surface cover.

Site cast concrete house frames are usually made of Building cement CEM II/A. The concrete specification for the house frame can be found in chapter 6.5, Table 9. The areas of the different concrete surfaces and the total amount of concrete used have been calculated for the specific building. The CO_2 uptake for the building can then be calculated based on the specific CO_2 uptake for the different concrete surfaces. Specifications and CO_2 uptake calculations for the site cast house frame is shown in Table 4. The house is an ordinary apartment building with basement (no garage) and a total gross floor area of 2264 m². The building area on ground is 455 m². The building has five floors with 23 apartments and basement.

Table 4 Specifications and CO_2 uptake calculations for the site cast concrete house frame during a product use phase of 100 years. The house is an apartment building with total gross floor area of 2264 m². Note that the site-cast and precast house frames does not show the same house frame and is thus not directly comparable.

Concrete surface types	**Concrete surface area (m^2)**	**Specific CO_2 uptake (kg/m^2 and 100 years)**	**CO_2 uptake (kg during 100 years)**
Outdoor below ground			
Surfaces on mineral wool	12	4.1	47
Surfaces on EPS	0	0	0
Surfaces on crushed ballast	642	0.7	449
Surfaces on sand and gravel	384	0.1	38
Outdoor above ground			
Surfaces exposed to rain	398	0.9	358
Surfaces sheltered from rain	179	2.8	502
Indoor surfaces			
Interior walls, painted surface	5 982	3.6	21 536
Interior walls, pure concrete surface	1 111	6.1	6 776
Interior walls, tiled	591	0.9	532
Framing of joists, parquet/laminate floor	1 631	0.9	1 468
Total concrete surface area	*10 930*		
Total CO_2 uptake			**31 708**
Total concrete volume (m^3)	*1388*	*m^3*	
Steel reinforcement	*50*	*kg steel/m^3 concrete*	
Overall concrete surface area/concrete volume ratio	*7.9*	*m^2/m^3*	
CO_2 uptake per concrete volume (kg CO_2/m^3 concrete and 100 years)	**23**	**kg/m^3**	

6.3.3 Precast concrete frame for industrial storage

This example illustrates the situation for a house frame made in a precast concrete design. Precast elements can be made of either Construction cement (CEM I) or Building cement (CEM II/A). Wall elements and slab-on-grade can be made of Building cement while other bearing elements such as pre-stressed pillars, beams, roof elements and floor frame work elements can be made of Construction cement. In this case, the amount of CEM I is 39.4 % and the amount of CEM II is 60.9 % of the total used cement. The concrete specification for the precast elements can be found in chapter 6.5, Table 9. The example chosen is a precast house frame for an industrial storage building in Sweden. The storage building has a size of 120 m × 96 m and an adjacent office building of 10.5 m × 48 m in two floors. The precast frame is built on a site casted bottom slab with a total area of 12 024 m^2. The amount of concrete for the bottom slab is estimated to 300 kg concrete/m^2 of bottom slab. The indoor concrete surfaces have no paint or other coverage. We thus have an indoor condition with pure concrete surfaces. The outdoor concrete surfaces have isolation and a waterproof layer. The frame is in principle made of the following precast elements: wall elements (440 kg/m^2), floor elements (HD/F elements 440 kg/m^2), roof elements (215 kg/m^2) and pillars. For assembly, some joint concrete is also used. The areas of the different concrete surfaces and the total amount of concrete used have been calculated for the specific building. The CO_2 uptake for the building can then be calculated based on the specific CO_2 uptake for the different concrete surfaces. Specifications and CO_2 uptake calculations for the precast house frame is shown in Table 5.

In the context of comparisons between in-situ cast and precast house frames it should be noted that these are not calculated for the same house frame but shows two different real objects (apartment house frame for the site-cast and an industrial storage for the precast house frame). Table data are thus not directly comparable.

Table 5 Specifications and CO_2 uptake calculations for the precast house frame during a product use phase of 100 years. Note that the site-cast and precast house frames does not show the same house frame and is thus not directly comparable.

Concrete surface types	**Concrete surface area (m^2)**	**Specific CO_2 uptake (kg/m^2 and 100 years)**	**CO_2 uptake (kg during 100 years)**
Indoor ceiling with pure concrete surface and free exposure	20 700	6.1	126 270
Indoor wall with pure concrete surface and free exposure	4 500	6.1	27 450
Indoor pillars and beams and with pure concrete surface and free exposure	1 700	6.1	10 370
Outdoor free rain exposed pure concrete surface	5 000	0.9	4 500
Outdoor surface with isolation and waterproof layer	12 000	0	0
Site cast slab-on-grade, upper side indoors	12 024	6.1	73 346
Site cast slab-on-grade, underside+sides to ground	12 100	0	0
Total concrete surface area	*68 024*		
Total CO_2 uptake			**241 936**
Concrete quantities	*Weights below incl. reinforcement*		
STT roof	2 600 000 kg	1 082	m^3 concrete excl. reinforcement
Walls	2 200 000 kg	916	m^3 concrete excl. reinforcement
Framing of joists	600 000 kg	238	m^3 concrete excl. reinforcement
Pillars and beams	500 000 kg	202	m^3 concrete excl. reinforcement
Slab-on-grade foundation	3 607 200 kg	1 455	m^3 concrete excl. reinforcement
Total concrete use	*9 507 200 kg*	*3 892*	*m^3 concrete excl. reinforcement*
Steel reinforcement	*40 kg*	*kg steel/m^3 concrete*	
Overall concrete surface area/concrete volume ratio	*17.5*	*m^2/m^3*	
CO_2 uptake per concrete volume (kg CO_2/m^3 concrete and 100 years)	**62 kg/m3**		

6.3.4 Concrete roofing tile

The concrete roofing tile has been selected as an example of a concrete product that has a large surface area and a thin concrete structure. This will give a high surface/concrete volume ratio and thus a high CO_2 uptake per concrete volume. Carbonation occurs both from the upper and under side of the tile. This also means that there is one side that is rain exposed and one side that is rain sheltered. This gives good conditions for CO_2 uptake in the tile. In fact, it is expected that an ordinary roofing tile will be carbonated in the entire concrete volume during its lifetime of approximately 50-100 years. However, no complete carbonation during product lifetime is expected. A degree of carbonation of 80 % of theoretic maximum has been assumed during lifetime of the tiles. This means that the maximum potential uptake during end of life treatment is only 20 % of the theoretic maximum uptake. The theoretic maximum uptake is here defined as an equal amount of CO_2 is taken up as was driven off from the raw meal (limestone) in the cement kiln.

The roofing tile is in principle made of Building cement CEM II/A, sand, water and eventually some pigments. A picture of a typical roofing tile is shown in Figure 3 and the specifications used in the project are shown in Table 6. The concrete specification for the tiles can be found in chapter 6.5, Table 9. The CO_2 uptake has been calculated as per m^3 concrete, per roofing tile and per m^2 of roof covered with roofing tile. The calculated CO_2 uptake is also shown in Table 6.

Figure 3 Picture of a typical Swedish concrete roofing tile.

Table 6 Specifications of a typical Swedish concrete tile roof with corresponding CO_2 uptake during a lifetime of 50-100 years.

Length of roofing tile (mm)	420
Width of roofing tile (mm)	330
Cover length of roof (mm)	310-370
Cover width of roof (mm)	300
Weight of roofing tile (kg)	4.1
Weight of roofing cover (kg/m^2)	36
Number of tiles per m^2	8.9
Density of roofing tile concrete (kg/m^3)	2390
Total concrete surface area of one roofing tile (m^2/roofing tile)	0.35
Overall concrete surface area/concrete volume ratio (m^2/m^3)	*204.0*
Maximum CO_2 uptake in roofing tile concrete (kg CO_2/m^3 concrete)	*200.9*
Maximum CO_2 uptake in a roofing tile (kg CO_2/roofing tile)	*0.34*
Maximum CO_2 uptake in a roof with concrete tiles (kg CO_2/m^2 roof)	*3.07*
CO_2 uptake during use phase (50-100 years) in a 100 m^2 roof with 80 % carbonation (kg CO_2)	**245.4**
CO_2 uptake during use phase per concrete volume and 80 % carbonation (kg CO_2/m^3 concrete and 50-100 years)	**160.7**

6.4 CO_2 uptake in waste and recycled concrete

6.4.1 Background and technical aspects

Especially in the waste and recycling phase of the concrete's life cycle, the carbonation process can be an advantage. The waste and recycled concrete will, by the carbonation process, continue to take up the CO_2 that was driven off in the cement kiln and the carbonation process can also strengthen the recycled concrete when used for example as ballast in a road construction. The carbonation process is normally very slow in large concrete blocks due to a relatively small surface to volume ratio (m^2 surface/m^3 concrete) and thus a long transport of molecular CO_2 into the inner of the concrete block. If however the used concrete is crushed and/or grinded into smaller fractions, the uptake of CO_2 can be much more efficient and both the maximum practical uptake and the uptake rate can be increased. Usually, waste concrete is crushed in order to recover the steel rebars. The concrete is crushed into a mixed size fraction, the rebars are removed and the concrete is stored in large stockpiles.

The CO_2 exposure time factor is important. In an infinite time perspective, almost all CO_2 that was driven off in the cement kiln will be reabsorbed by carbonation. In a practically and technically perspective, the carbonation rate is important. The carbonation rate is also important for the greenhouse effect (CO_2 concentration in the atmosphere). However, it does not seem fully clear if indeed all the CO_2 can be taken up by the concrete even after a very long time. For practical considerations, a maximum degree of carbonation is estimated to 50-85 %. We refer this as maximum practical degree of carbonation. We also define a maximum theoretical degree of carbonation as 100 % carbonation and this is defined as the corresponding amount of CO_2 that was driven off in the cement kiln. As we can see, the practical degree of carbonation is not as well defined as the theoretical.

The reduction of concrete particle size will increase the exposed surface area and thus reduce the transport distance of CO_2 into the material and thereby increase the carbonation rate of the material. However, crushing of a material to fine particle size requires energy. Uptake of CO_2 also requires an airflow with CO_2 around the particles. A too fine particle fraction will on the other hand prevent the airflow around the particles. One can thus assume that there is an optimal particle size that will promote a fast carbonation of waste or recycled concrete. Waste concrete from for example demolition of different concrete objects in the society occur in large quantities. It is thus important that the handling of the concrete waste is efficient both in terms of energy use and in terms of economy. Technically accelerated carbonation such as exposing the crushed concrete for high CO_2 concentration for example from exhaust gases is so far not a developed technique. Further development can show the potential of such techniques. In any way, the technique has to be efficient in every possible way and easy to apply in large scale.

Some research activities exist to study both the uptake in waste and to develop methods for handling of concrete waste in order to improve the carbonation behavior. Also in this project, attempts have been made to study the carbonation rate of the waste handling system of today but it is a difficult task. Concrete samples from crushed storage piles have been taken out and analyzed for carbonation depth of the crushed material. Samples have been taken out from different depth of the piles in order to study the carbonation rate of the entire pile over time. The results were difficult to interpret but the carbonation show a tendency to decrease inside the pile and only a layer of approximately 30 cm show some degree of carbonation. However, the pile contained a mixed fraction, which means that smaller fractions have made the pile compact and tight. The airflow through the pile and thus the CO_2 transport was low. Anyhow, the experiment was only a test experiment of a waste concrete pile in an ordinary concrete waste handling system of today.

The discussion above and the experiment show that this is a complex issue that will require both improved analytical/test methods and technical development of waste handling systems. Uncertainties exist both for the carbonation in today's waste handling system and for future waste handling systems. Most likely, an efficient waste handling system can be developed that will have a low energy use for handling and crushing followed by an application phase where the crushed concrete can be used (for example as ballast used in base courses for roads) in such a way that carbonation can occur rapidly and that most of the concrete will be completely carbonated within a relatively short period of time.

For the analyses of the waste handling in this study, the complete carbonation of the waste/recycled concrete has been taken as a reference. The complete carbonation is calculated as the theoretic maximum uptake and defined as the amount of CO_2 that was driven off from the raw meal (limestone) in the cement kiln. Due to lack of information concerning the exact uptake of CO_2 during the waste phase, theoretical calculations and a qualitative discussion has replaced exact values for uptake and time scale. In the next chapter, two different concrete waste handling scenarios are shown with its corresponding CO_2 uptake.

6.4.2 Concrete waste / secondary product scenarios and CO_2 uptake

The concrete waste handling of today is not developed and adapted for CO_2 uptake. This means that there is a potential for increased uptake of CO_2 in concrete wastes in the future. There is also a lack of reliable measurement data concerning uptake of CO_2 in different concrete wastes. In this chapter, we have chosen to show two different waste scenarios representing the estimated CO_2 uptake in today's concrete waste handling in Sweden and an assumed CO_2 uptake for a future concrete waste handling system. The two scenarios shall be considered as estimated examples and large variations can be expected for a real case. The two scenarios below show the CO_2 uptake in the waste handling phase. In addition to this, there is also carbonation that already has occurred in the use phase. The total carbonation in the use phase can vary significantly. The example calculations shown in the tables assume a low carbonation in the use phase (< 10 %).

6.4.2.1 Concrete waste / secondary product scenario - Today

A good starting point for an analysis of the CO_2 uptake in waste concrete is to analyze the current waste management systems and the uptake of CO_2 in that system. The main current concrete waste handling system in Sweden can be divided into the following steps:

1. Demolition of used concrete products resulting in a concrete fraction with relatively large concrete pieces (including rebars).
2. Intermediate stockpiling of demolition concrete (storage time ~0.5 - 4 years).
3. Crushing of concrete demolition waste resulting in a mixed size fraction of concrete. The steel rebars are removed for recycling at this stage.
4. Intermediate stockpiling of mixed concrete fraction (storage time ~1 - 4 month).
5. Use of the mixed concrete fraction in construction applications. Examples of applications can be construction landfilling, road base coarse or building foundations. The concrete fraction is usually covered with soil or other materials which prevent a good contact with CO_2 in air. The use in constructions can be estimated to 100 - 200 years but the material will exist after that (probably in an infinite time period) and will continue to take up CO_2.

In the present concrete waste handling system, large concrete products (house frames, bridge etc.) are usually demolished into relatively large transportable pieces. The old concrete surfaces are already carbonated to some extent and will thus take up CO_2 very slowly. However, the demolition process releases new uncarbonated concrete surfaces which can take up CO_2 much faster. This will result in an increased carbonation rate. In the demolition process, smaller pieces/particles of concrete are also formed which have an even higher surface/volume ratio and thus can carbonate even faster. The concrete demolition waste is usually stored for a time period of 0.5 to 4 years. During this time, carbonation occurs.

The demolition waste is usually crushed into a mixed size aggregate fraction in order to recycle the steel rebars and to produce a useful concrete product of the waste concrete. This mixed crushed concrete fraction is then stockpiled prior to use in a construction application. The stockpile time is usually 1 to 4 month. This mixed concrete aggregates contain a large amount of small size concrete which can easily carbonate. A problem is however that the small fraction prevents an air circulation in the stockpile and thus reduces the carbonation rate. This results in a good carbonation of the outermost layer of the stockpile. In large piles, the total carbonation will thus be relatively small.

The mixed concrete fraction is then used in different construction applications. A common use is as landfilling material or as road base or house foundation materials. The present applications are usually underground or covered with a soil material. This means that practically no air or CO_2 can reach the waste concrete and the carbonation will thus be slow and small. The lifetime of this construction (application) can be estimated to 100 - 200 years. The faith of the concrete waste is then unknown. However, the concrete will not disappear and will still continue to take up CO_2. In an infinite time period, one can expect that almost all of the CO_2 that was released by the cement material in the cement kiln will be taken up by the concrete.

In Table 7, a rough estimate has been made of the CO_2 uptake in the various concrete fractions for the Swedish concrete waste handling system of today. The demolition waste is stockpiled with free air (CO_2) circulation. The CO_2 uptake occurs mainly at the fresh concrete surfaces. The amount of fresh surfaces can vary greatly and can therefore be difficult to estimate. 4.8 m^2 of fresh concrete surfaces has been assumed for 1.2 m^3 of concrete[6]. A carbonation depth of 5 mm has been assumed for large concrete pieces. A 1 % additional carbonation share has been added for carbonation in small concrete fragments and concrete meal. This gives a total carbonation share of 2 %+1 % = 3 %.

The crushed concrete mix is assumed to be stored in piles with a height of 5 m, a carbonation depth of 5 cm in the piles and a degree of carbonation of 70 %. The use phase of the crushed concrete is calculated for 100 years. The degree of carbonation and the carbonated share of concrete are estimated. There is actually no way of calculating these values but they can be estimated based on significant carbonation factors. In this case, a low carbonated share of concrete has been use based on the fact that much of the crushed concrete used today is used as landfilling material underground where the supply of CO_2 is low.

As indicated in the table, only 11 % of the theoretic maximum CO_2 uptake occurs in the waste handling phase. The reason for this can be found in an air protection cover and low air circulation in the crushed concrete material. The low air circulation in the crushed material, both at use and at stockpiling, can be explained by the particle size distribution of the crushed material (see Figure 4). As shown in the figure, there is a large fraction of very fine particles (20 % of the particles are smaller than 0.5 mm in diameter) that will form a very compact material that can prevent air (CO_2) circulation in the material. A mixed fraction also gives a very compact material compared to a narrow size distribution range. An indication of the possibility for air circulation in the material can be obtained by studying the void volume in the crushed material. An estimation based on expert judgment of the void volume for the mixed crushed fraction has been made in Table 7. The void volume has been estimated to 30 % of the total crushed material volume (bulk volume). A reason for the low void volume is the presence of very fine particles. However, the effect of the very fine particles is probably not only related to the void volume per se but to the very narrow gas channels this particle fraction will form which effectively prevent gas circulation. Another contributory effect could be moisture adsorbed on the inner surface of the very fine channels and thereby further reduce the gas throughput.

[6] A concrete block with a size of 2 m*2 m*0.3 m = 1.2 m^3 is divided with in 6 pieces with 4 cuts.

Table 7 Uptake of CO_2 in various concrete fractions of a concrete waste handling system. The table shows an example of a typical waste handling system in Sweden today.

Current concrete waste handling									
CO_2 uptake process	Amount of concrete (kg)	Normal storage period	Theoretic max CO_2 uptake in the concrete (kg CO_2/kg concrete) 1)	Degree of carbonation (%)	Carbonated share of concrete (%)	CO_2 uptake (kg)	Comments	Share of total CO_2 uptake (%)	Void space 2) (%)
Intermediate stockpiling of demolition concrete	1	0.5-4 years	0.077	70	3	0.00163		20.0	
Intermediate stockpiling of mixed crushed concrete fraction	1	1-4 month	0.077	70	2	0.00108		13.3	30
Use of mixed crushed concrete fraction	1	> 100 years	0.077	70	10	0.00542	Within 100 years	66.7	30
Total						0.00813			
Share of theoretic maximum CO_2 uptake	11	%							

1) Calculated as an average between concrete for bridges (0.0911 kg CO_2/kg concrete) and concrete for house frames (0.0638 kg CO_2/kg concrete). The theoretic uptake is calculated from the chemical composition of the raw meal to the clinker kiln.

2) defined as V_V/V_T, where V_V is the volume of void-space and V_T is the total or bulk volume.

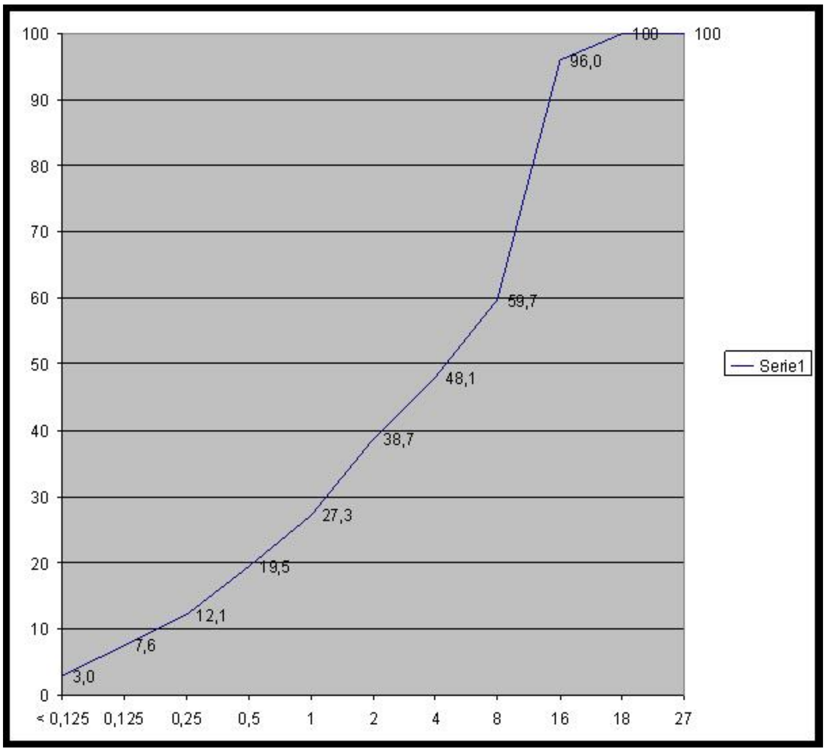

Figure 4 Example of a particle size distribution for a typical crushed concrete material. The maximum mesh size is here smaller than in a normal crushed concrete fraction. The figure shows the distribution in percent as a function of particle size in mm in a cumulative function.

6.4.2.2 Concrete waste/secondary product scenario - Future

The CO_2 uptake in the present concrete waste handling system is thus relatively small in a 100 years perspective as waste or secondary products. A future waste handling system must thus be improved in terms of CO_2 uptake in the concrete waste handling. The demolition phase of the waste handling is difficult to improve. However, the storage time is relatively long and the CO_2 uptake rate is slow in the large concrete pieces. A shorter time to crushing and storage in crushed form can increase the overall carbonation rate. A problem with the mixed crushed concrete is that the small size particles will create a compact material that prevents air (CO_2) circulation in the material and thus also carbonation. If the crushed material is sieved into specific size fractions, a less compact material will be formed that allow air circulation. This is the main proposed method to improve carbonation in the waste/secondary product phase. This also has to be combined with a use application that is open for air circulation i.e. not entirely covered or underground applications. In the process items below, the proposed modifications of the waste handling system is shown.

1. Demolition of used concrete products resulting in a concrete fraction with relatively large concrete pieces (including rebars).
2. Intermediate stockpiling of demolition concrete (storage time ~0.5 - 4 years).
3. Crushing and sieving of concrete demolition waste resulting in different size fractions of concrete. The steel rebars are removed for recycling at this stage.
4. Intermediate stockpiling of the different concrete fractions (storage time ~1 - 4 month).
5. Use of the different size fractions in different applications designed for an increased CO_2 uptake (air circulation) e.g. road base course, building foundations. The use in constructions can be estimated to 100 - 200 years but the material will exist after that (probably in an infinite time period) and will continue to take up CO_2.

The demolition phase is practically unchanged compared to the present situation while the crushing phase has been changed by adding a sieving process and the use phase has been modified to promote air (CO_2) circulation in the construction application.

In Table 8, the estimated CO_2 uptake for the modified future waste/secondary product handling system is shown. The CO_2 uptake in the stockpile phase of demolition concrete blocks is assumed to be the same as for the present system (see chapter 6.4.2.1). In the future system, the crushed concrete is sieved into a number of different aggregate fractions. In this case, 5 fractions have been used. The weight distribution for the different fractions has been estimated based on experiences from different screening curves. The selected fractions and the estimated weight distribution are shown below.

Screening fraction (mm)	Weight distribution (%)
0-4	45
4-8	15
8-16	15
16-32	15
32-64	10

The crushed and sieved fractions are stockpiled separately during approximately 1-4 month. The CO_2 uptake during the intermediate stockpiling shows different behavior for different fractions. Important factors are gas permeability and aggregate size. The uptake has been calculated (estimated) based on various carbonation information. The 0-4 mm fraction has low gas permeability and thus low deep carbonation but a fast surface carbonation due to the small cement paste particles. The void space for this fraction has been estimated to 35 %. This fraction also gives rise to very fine gas channels which reduce gas throughput in the same way as for the mixed fraction used today. Based on stockpile measurements in the project and estimations, a degree of carbonation of 70 % has been chosen. Only 2 % of the low size fraction concrete pile is carbonated due to low gas permeability. For the other stockpiled fractions, a free access to air (CO_2) has been assumed and therefore a higher carbonated share of the crushed concrete has been chosen. The void volume for these fractions has been estimated to 50 %. (All void spaces can be found in Table 8). The gas channels are here larger for these narrower particle fractions which result in a better gas circulation in the material. The carbonated share of concrete for these fractions have been calculated based on the assumption that the carbonation depth is 1 mm of the particles.

The use phase of the crushed material is calculated to a practical CO_2 maximum uptake. This uptake is thus reached in different time periods indicated in the comments. The use applications assume a relatively free access to air (CO_2). For the fractions larger than 4 mm, this can probably be achieved by using the material as filling materials in different construction applications and leaving openings in the aggregate construction for air circulation. The smaller fractions (0-4 mm) have a relatively compact structure due a large share of very fine particles. This indicates that the material should be used in thin structures. Examples of this can be top surface layers or slip control on roads. The applications for high uptake of CO_2 are relatively new and further development work is required. The CO_2 uptake is estimated for each application based on aggregate size and type of application.

For large aggregates it is important to keep in mind that CO_2 is only taken up by the cement paste and not the ballast materials. Larger aggregates can thus consist of a stone covered with cement paste. A schematic figure of such an aggregate is shown in Figure 5. Usually the stone material is stronger than the cement paste so the crushing fractures occur in the cement paste leaving a stone with a relatively thin layer of cement paste. This means that the size distribution of the ballast used in the concrete can influence the CO_2 uptake. Thus, a relatively large aggregate can show a fast carbonation. The thickness of the cement paste layer is, in this case, of significant importance.

Table 8 Uptake of CO_2 in various concrete fractions for a future concrete waste handling system.

Future concrete waste handling									
CO_2 uptake process	Amount of concrete (kg)	Normal storage period	Theoretic max CO_2 uptake in the concrete (kg CO_2/kg concrete) [1)]	Degree of carbonation (%)	Carbonated share of concrete (%)	CO_2 uptake (kg)	Comments	Share of total CO_2 uptake (%)	Void space [2)] (%)
Intermediate stockpiling of demolition concrete	1	0.5-4 years	0.077	70	3	0.00163		2.6	
Intermediate stockpiling of specific fraction 0-4 mm	0.45	1-4 month	0.077	70	2	0.00049		0.8	35
Intermediate stockpiling of specific fraction 4-8 mm	0.15	1-4 month	0.077	70	40	0.00325		5.3	50
Intermediate stockpiling of specific fraction 8-16 mm	0.15	1-4 month	0.077	70	20	0.00163		2.6	50
Intermediate stockpiling of specific fraction 16-32 mm	0.15	1-4 month	0.077	70	12	0.00098		1.6	50
Intermediate stockpiling of specific fraction 32-64 mm	0.1	1-4 month	0.077	70	6	0.00033		0.5	50
Use of specific fraction 0-4 mm	0.45	> 100 years	0.077	85	90	0.02666	Within 5 years	43.2	35
Use of specific fraction 4-8 mm	0.15	> 100 years	0.077	85	85	0.00839	Within 10 years	13.6	50
Use of specific fraction 8-16 mm	0.15	> 100 years	0.077	85	70	0.00691	Within 20 years	11.2	50
Use of specific fraction 16-32 mm	0.15	> 100 years	0.077	85	70	0.00691	Within 60 years	11.2	50
Use of specific fraction 32-64 mm	0.1	> 100 years	0.077	85	70	0.00461	Within 100 years	7.5	50
Total						0.06178			
Share of theoretic maximum CO_2 uptake	80	%							

[1)] Calculated as an average between concrete for bridges (0.0911 kg CO_2/kg concrete) and concrete for house frames (0.0638 kg CO_2/kg concrete).

[2)] defined as V_V/V_T, where V_V is the volume of void-space and V_T is the total or bulk volume.

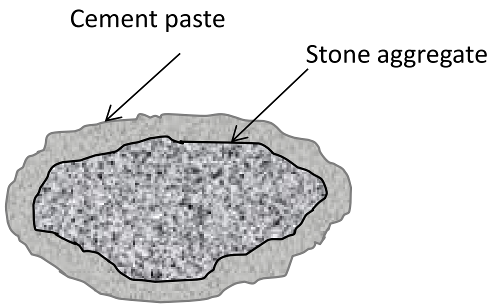

Figure 5 Schematic figure of a crushed concrete aggregate.

6.5 Specification of cement and concrete

For cement, it is normally the clinker part that gives the largest contribution to the CO_2 uptake. Therefore can the CO_2 uptake vary for different cement types[7]. In this study, two different cement types have been used for the base model calculations. Both types are standard cement used in the Swedish market. Here we call them "Construction cement" and "Building cement".

Construction cement is a CEM I Portland cement manufactured in Sweden. It is adapted for use in solid constructions with demands for moderate heat development, if there is a risk of alkali silica reactions and if there is a demand for higher sulfate resistance. A typical use is in concrete bridges. The content specification of the Construction cement is shown below.

Construction cement formulation in weight per cent.
95.5 % cement clinker
4.0 % gypsum
0.5 % iron sulfate

Building cement is a CEM II Portland-limestone cement. It has normal compressive strength development and is used in standard concrete work for example in house building. The mean content specification of the Building cement is shown below.

Building cement formulation in weight per cent.
82.2 % cement clinker
4.8 % gypsum
12.5 % limestone
0.5 % iron sulfate

[7] CO_2 uptake can also occur in for example other material such as hydraulic slag. Some minor variation in CO_2 uptake can also exist between different raw materials in clinker production.

Table 9 Standard specifications of concrete for the different scenario objects.

Concrete component	**Concrete bridge**	**Concrete house frame (site cast production)**	**Concrete house frame (precast production)**	**Concrete roofing tile**
Construction cement CEM I (kg/m^3 concrete)	410			
Building cement CEM II/A (kg/m^3 concrete)		340	400	450
Crushed aggregates (kg/m^3 concrete)	900	950	900	
Pit run sand and gravel (kg/m^3 concrete)	850	900	900	1750
Water (kg/m^3 concrete)	175	190	180	190
Specific concrete weight (kg/m^3)	**2335**	**2380**	**2380**	**2390**

7 Energy and greenhouse gas balance in concrete products of today

Both cement/concrete as materials and different concrete products can vary significantly in terms of production conditions, energy consumption, emission etc. In this report, we will make a deeper analysis of the consequences of these variations and analyze the possibilities for further improvements of concrete products to meet future requirements. For these analyses, we need a reference or starting-point. The starting-point will describe the present situation and will lead us into further analyses of improved products. However, there is no natural starting-point or typical production of concrete products. Instead, example products have been used that represent an ordinary Swedish production including the entire life cycle of the products. The products are defined and described in chapter 6 and the scenarios will be further explained in this chapter. The selected products exemplify pure concrete products where the sole concrete behavior can be studied without influences of external factors. For example, a pure concrete house frame has been chosen instead of an entire concrete house to avoid the influence of the energy use and the isolation/design of the house. This means that other materials but concrete has been excluded from the analyses and that more complex effects of the concrete house frame such as energy storage (heat/cool reservoir effects) have not been taken into account.

7.1 Concrete bridge

A concrete bridge is an example of a concrete product made of high quality construction cement with an high clinker content and a high cement content in the concrete (see chapter 6.5). The concrete surfaces are usually not covered with paint or other materials. The roadway is usually covered with an asphalt layer and some parts of the bridge are below ground level and thus covered with soil or crushed aggregates. Due to the concrete composition and the robust design of the bridge, the carbonation rate of the concrete is slow during the lifetime of the bridge (see chapter

6.3.1). The “concrete surface area/concrete volume” ratio has been calculated to 3.0 m^2/m^3 with a CO_2 uptake level of 2.9 kg CO_2/m^3 concrete during lifetime of the bridge. The theoretical maximum uptake of CO_2 in the concrete is in this case 212.8 kg CO_2/m^3 concrete. For supporting constructions like a bridge, it is important that the carbonation does not influence the reinforcement of the bridge. The carbonation process can otherwise lower the pH value in the concrete and a corrosion process of the steel reinforcement can start.

In Figure 6, the energy resource use (excluding waste fuels) from the entire model of the example bridge is shown. The energy use cover the entire system over the entire lifetime (100 years) of the bridge and the following waste handling phase after the end of the lifetime. The figure shows the use of primary energy resources for the entire system and divided in different activity areas. Note that energy from waste fuels used in the cement kiln has not been included as primary energy resources in this figure but we will come back to this issue later on in the report.

As shown in the figure, the production of concrete and the on-site production of the bridge stand for the largest energy use even if the cement production also makes a large contribution. It is however worth to note that the data for the site cast production is taken from energy data for a real construction site (a large new built concrete bridge) where the data has been allocated per m^3 of concrete. Uncertainties exist for the production data at the real site and this construction site can include more construction activities on the site than just the casting of the bridge. Thus, the energy and emission data can include significant uncertainties. The energy use in the waste handling phase is relatively small even if it includes both demolition of the bridge and crushing for recovery of the steel reinforcement. The energy resource use reflects the fuel use in the production. Crude oil is mainly used in the on-site cast production of the bridge. The use is mainly related to diesel use for transports and other machines/construction equipment. Coal is mainly used for heating of the cement kiln and for production of the steel reinforcement. The steel reinforcement is usually made of recycled steel in an electric arc furnace (EAF) but the production is, in this case, assumed to be a world average production (due to the origin of most steel reinforcement) and the electric power production mix contains a significant part of coal condensing power production. The coal use can be reduced by purchase of EAF steel made of electric power based on a different production mix e.g. hydropower, nuclear power, biofuel power or wind power. The use of natural gas is also related to EAF steel production (80.6 %) but also to production of ammonia (17.7 %) for production of explosives (ANFO) used in limestone mining.

The main use of electric power in the system is shown as use of hydropower and nuclear power due to use of a Swedish electric power production mix. Note that the resource use of nuclear power is proportionally larger than the actual Swedish power production mix because the resource use of nuclear power has been calculated as heat production in the nuclear power station and not as the electric power output from the nuclear power station. Avoided processes are output products from the entire system that can be used to replace other external products and in that way, it can save energy resource use, material resource use and emissions. In this case, the avoided processes consist mainly of produced electric power at the cement plant that directly can replace electric power used in the cement plant and heat recovery from the cement kiln used in a small district heating system in a nearby village. The avoided heat production is calculated as a saving of crude oil and a reduction of emissions from fuel oil combustion. Not all waste heat from the cement kiln can be recovered due to shortage of heat customers in the neighborhood. There is thus an unused heat potential that could be used. Such a heat potential can be a resource for other industrial production that also can create new jobs.

Figure 7 also shows the use of primary energy resources (excluding waste fuels) in the entire system but now divided in the different energy resource uses. As shown in the figure, this production system is mainly based on coal, crude oil and electric power produced from hydropower and nuclear power (Swedish electric power production mix). Note that the use of electric power from hydropower and nuclear power is of approximately the same magnitude (because the Swedish electric power production mix consists approximately of the same amount of nuclear power and hydropower) but calculated as a resource use, using the heat produced in the nuclear power plant and with an overall electric power efficiency of 31 %, the resource use of nuclear power is approximately 3 times larger than the resource use of hydropower.

Figure 8 shows the global warming potential balance for the entire system and divided into different process areas. Biogenic-based CO_2 emissions are not included in this figure but given as additional information in the figure. From the figure, we can see that the contribution from methane (CH_4) and dinitrogen oxide (N_2O) to the global warming potential is small. The main emissions of greenhouse gases emanates from the cement production even if production of the concrete and the concrete bridge also gives a significant contribution. Of the CO_2 emissions from cement production, 63.1 % emanates from CO_2 driven off from the raw meal and 36.9 % is fossil-based CO_2. Of the total fossil-based CO_2 emissions, 41.0 % emanates from the cement kiln and 23.7 % from EAF steel production. Avoided emissions are small. Fossil-based avoided CO_2 emissions comes from avoided use of heavy machines due to avoided rock based ballast production when external ballast can be replaced by crushed concrete from the waste handling of the bridge (54.1 %). Fossil-based avoided CO_2 emissions also comes from avoided use of fuel oil when the fuel oil is replaced by waste heat from the clinker production (20.1 %).

Uptake of CO_2 in the concrete occurs direct in the concrete bridge during the lifetime of the bridge and in the waste handling phase of the bridge. Due to the high quality of the concrete the carbonation process is slow during the lifetime of the bridge and only a small fraction of CO_2 (791 kg of CO_2) is taken up during the lifetime of 100 years, as shown in the figure. This means that a large uptake potential remains for the waste handling phase. How much of this potential that can be used during a specific time period depends very much on how the waste concrete is handled and stored (see chapter 6.4). Today, no special process for improved uptake of CO_2 exists but research activities exist. In the carbonation process, the CO_2 gas will react with the concrete surface and the CO_2 molecules needs to be transported into the concrete. The normal procedure in waste handling of today is that the concrete is crushed to recover the steel reinforcement. The remaining concrete is used as ballast material, to replace ballast in different constructions such as roads, foundations and as filler material. To benefit from the CO_2 uptake potential, the crushed concrete waste have to be crushed to an appropriate size and used in a way that promote gas transport in the ballast bed. The technical method needs to be developed and optimized. A rough estimation is that with an acceptable technical method, more than 30 % of the uptake potential can be achieved during the first 10 years after demolition.

As a background and additional information, the acidification potential from the system is shown in Figure 9 as SO_2 equivalents. The main substances are NO_X and SO_2. The larges contribution to the acidification potential comes from the production of concrete and production of the bridge. The total emission of NO_X is 424 kg from the system. The main sources are the use of different diesel engines. The NO_X emission from clinker production stands for 13.6 %. The total emission of SO_2 is 83.7 kg from the system. The larges contributions come from EAF steel production (62.3 %) and production of ammonia (16.6 %).

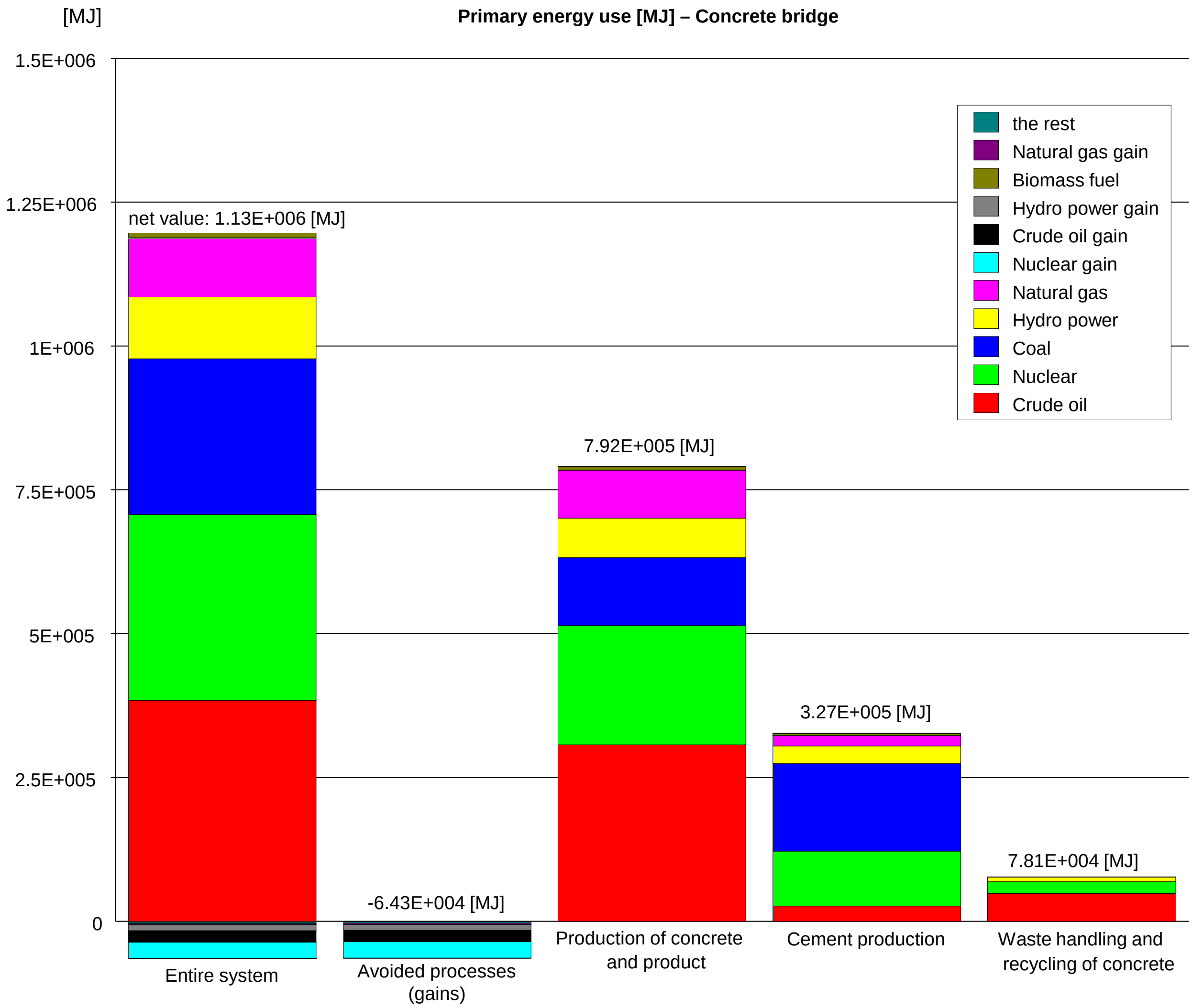

Figure 6 Primary energy use (excluding waste fuels) for the concrete bridge shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

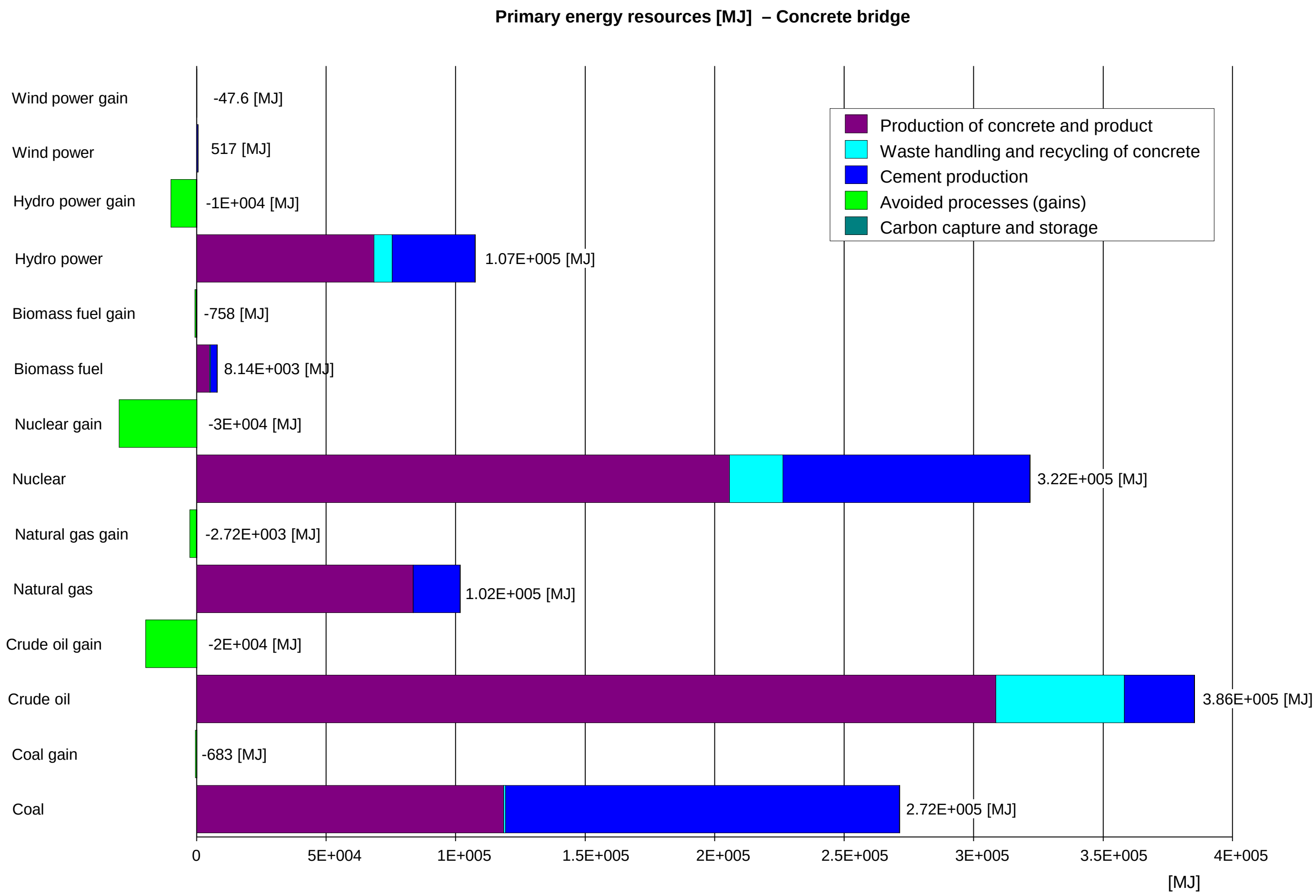

Figure 7 Primary energy resources (excluding waste fuels) and avoided resource uses (gains) for the concrete bridge. Contributions from the different process groups are shown. The figure includes the entire system.

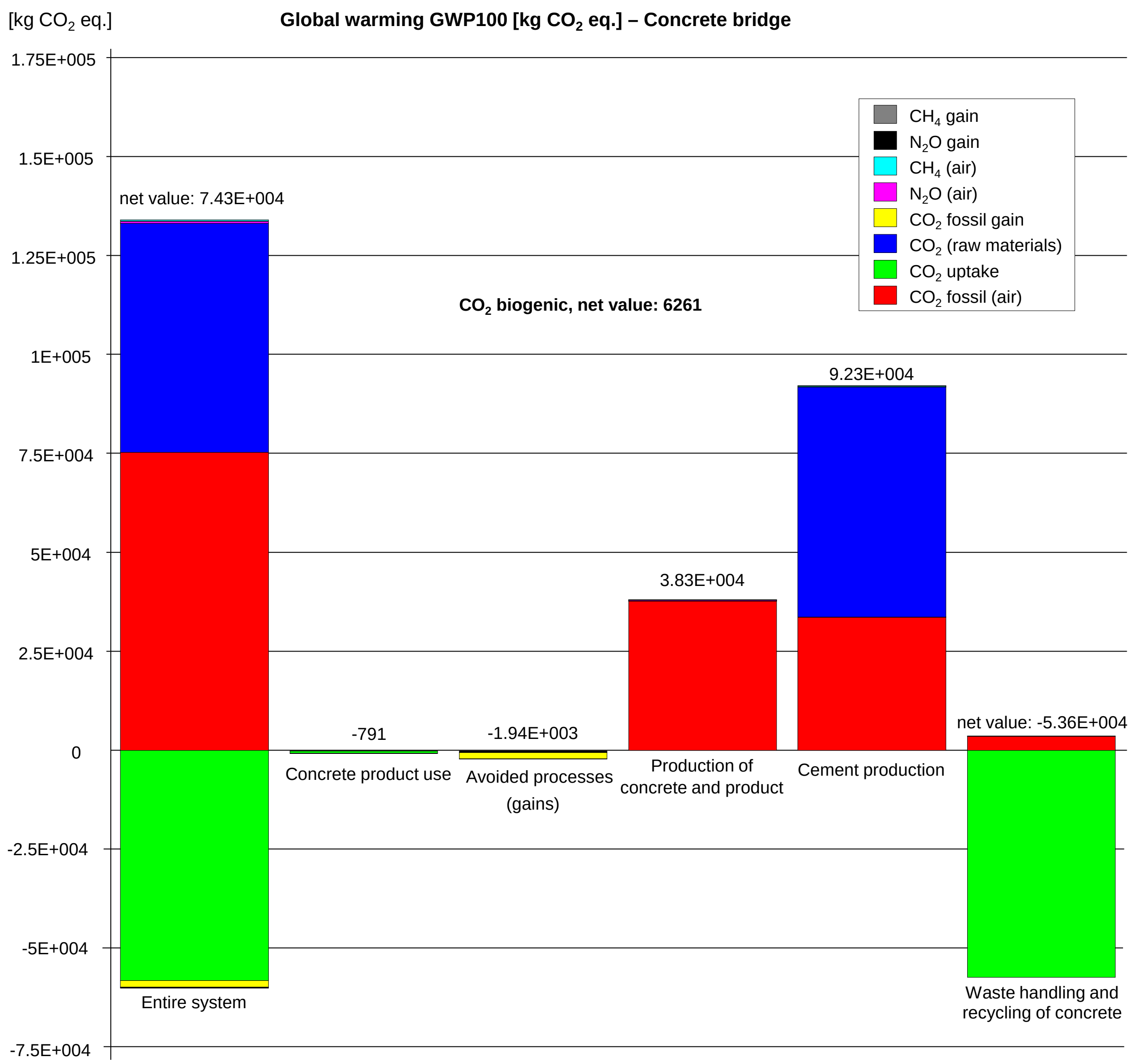

Figure 8 Global warming potential for the concrete bridge shown divided into different process groups and for the entire system. The CO_2 net value for the entire system shows the value when avoided CO_2 emissions and CO_2 uptake in concrete has been subtracted. The net value for the biogenic CO_2 emissions is also shown in the figure as additional information. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

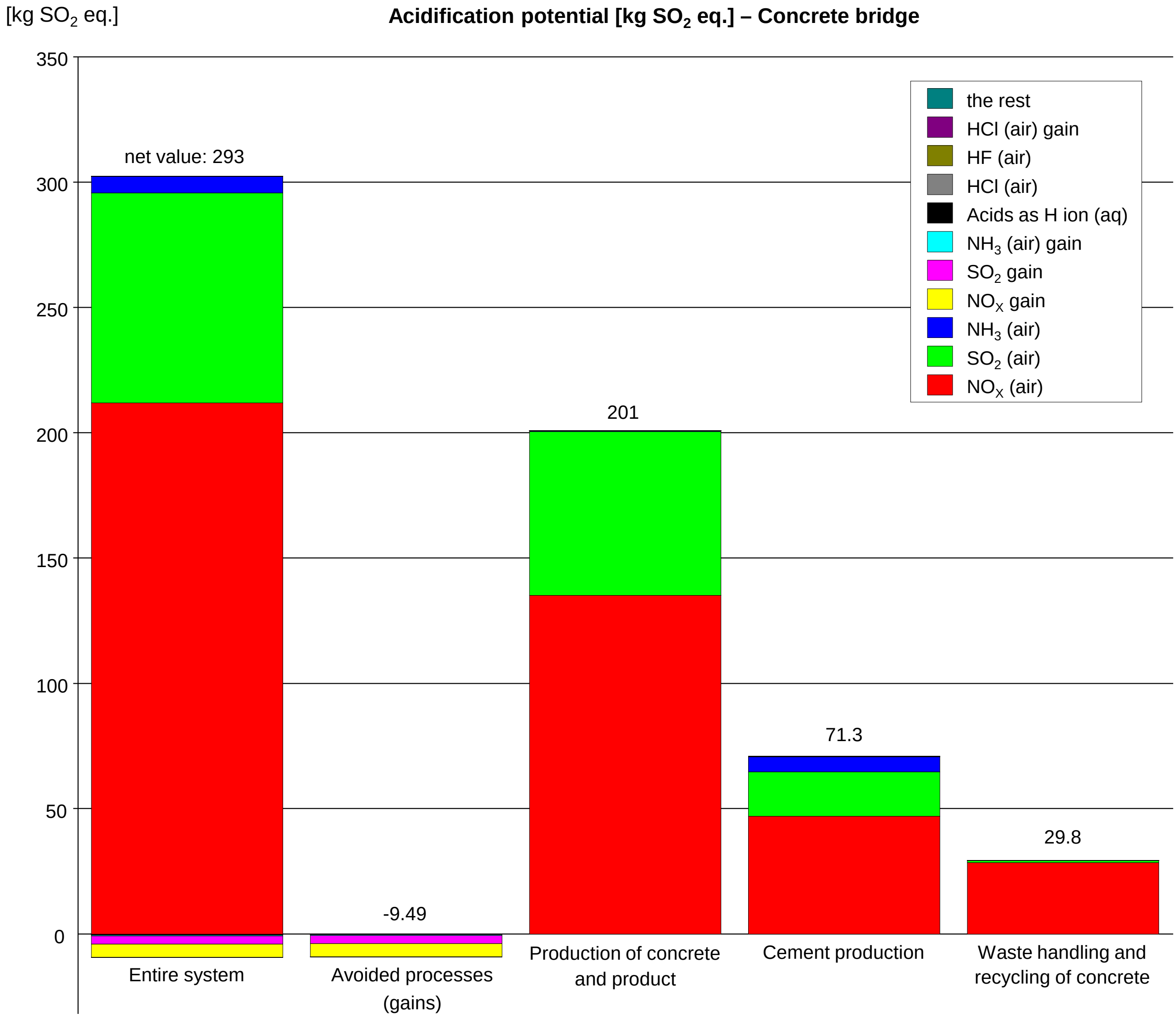

Figure 9 Acidification potential for the concrete bridge shown divided into different process groups and for the entire system. The net value for the entire system shows the value when avoided emissions have been subtracted. The acidification potential is calculated as kg SO_2 equivalents.

7.2 Site cast concrete house frame

A site cast house frame is an example of a concrete product with an indoor CO_2 exposure (no rain or wet conditions) but with concrete surfaces that are covered with different materials such as paint, glue, plastic carpets, wallpapers, clinker tiles, cover materials etc. The design of a house frame is also slimmer compared to the small but robust bridge in the previous example. This results in a higher surface to volume ratio with an accompanying higher CO_2 uptake potential during the lifetime of the house frame. The "concrete surface area/concrete volume" ratio has been calculated to 7.9 m^2/m^3 with a CO_2 uptake level of 23 kg CO_2/m^3 concrete during lifetime of the house frame. The specific CO_2 uptake during lifetime is thus higher than in the concrete bridge in the previous example. The theoretical maximum uptake of CO_2 in the concrete is in this case 151.9 kg CO_2/m^3 concrete due to a reduced use of clinker in the concrete. The house frame is made of building cement and the cement content in the concrete is 340 kg/m^3 concrete (see chapter 6.5). The house frame also has a lower use of steel reinforcement (50 kg steel/m^3 concrete) than the example bridge. The specification of the house frame and the calculated CO_2 uptake is shown in chapter 6.3.2.

In Figure 10, the energy resource use (excluding waste fuels) from the entire model of the site cast house frame system is shown. The energy use covers the entire system over the entire lifetime (100 years) of the house frame and the following waste handling phase after the end of the lifetime. The figure shows the use of primary energy resources for the entire system and divided in different activity areas. The energy resource use pattern is in fact very similar to the pattern of the concrete bridge example. In Figure 11, the same energy use is shown but divided into the different primary resources. It is also here worth to note that the data for the site cast production is taken from energy data for a real construction site (a large new built concrete bridge) where the data has been allocated per m^3 of concrete. Uncertainties exist for the production data at the real site and this construction site can include more construction activities on the site than just the casting of the house frame. Thus, the energy and emission data can include significant uncertainties.

Figure 12 shows the global warming potential balance for the entire system and divided into different process areas. Biogenic-based CO_2 emissions are not included in this figure but given as additional information in the figure. From the figure, we can see that the contribution from methane (CH_4) and dinitrogen oxide (N_2O) to the global warming potential is small. The emission pattern is very similar to the emission pattern of the concrete bridge example. The CO_2 uptake during lifetime of the house frame is however significant larger than the corresponding uptake in the concrete bridge example. The carbonation rate is higher for the house frame compared to the example bridge due to the composition of the concrete, the shape of the house frame (surface to volume ratio) and the surface conditions. This also means that the carbonation rate is higher in the waste handling phase of the concrete.

As a background and additional information, the acidification potential from the system is shown in Figure 13 as SO_2 equivalents. The main substances are NO_X and SO_2. The emission pattern is relatively equal compared to the example bridge.

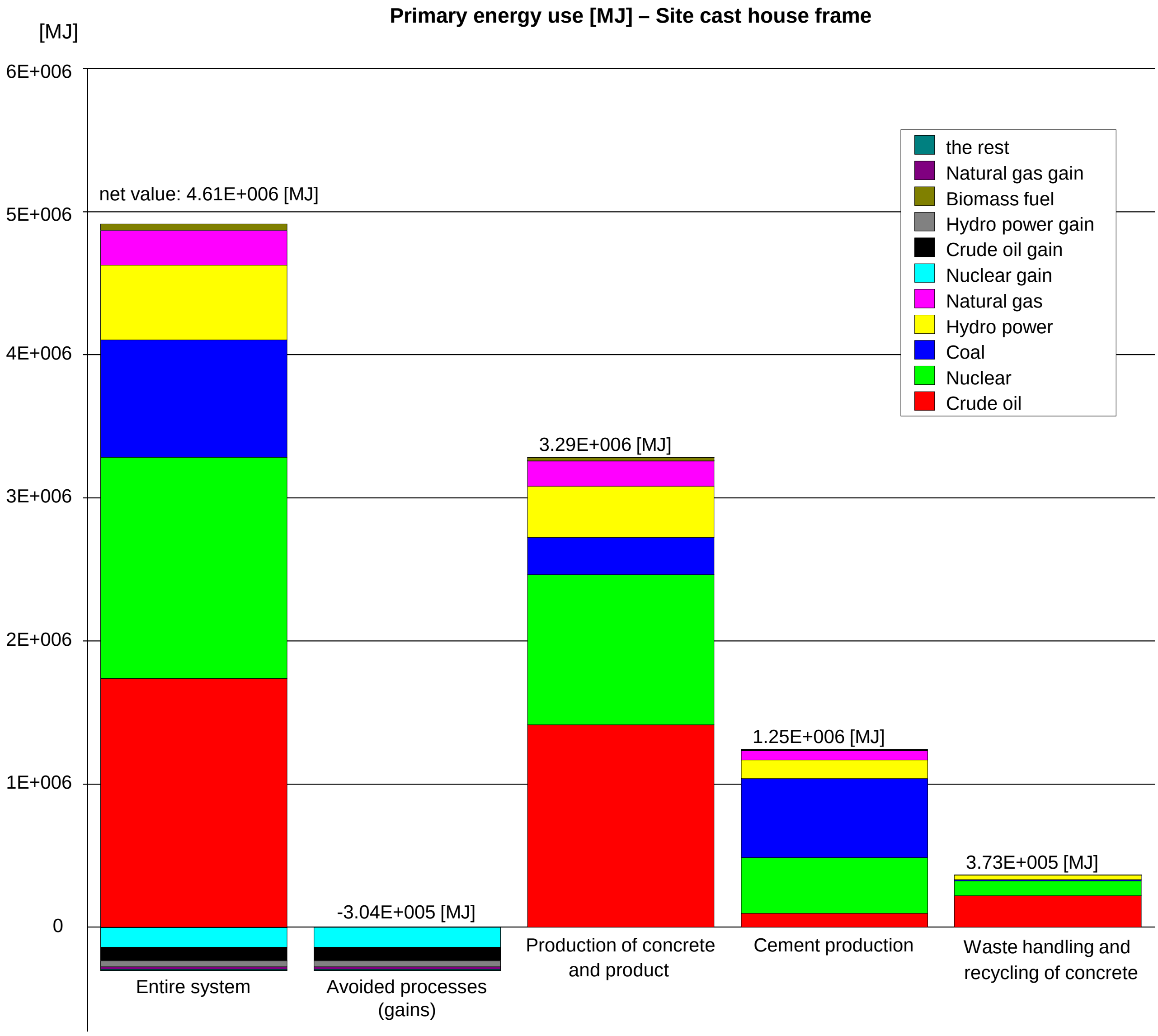

Figure 10 Primary energy use (excluding waste fuels) for the site cast house frame shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

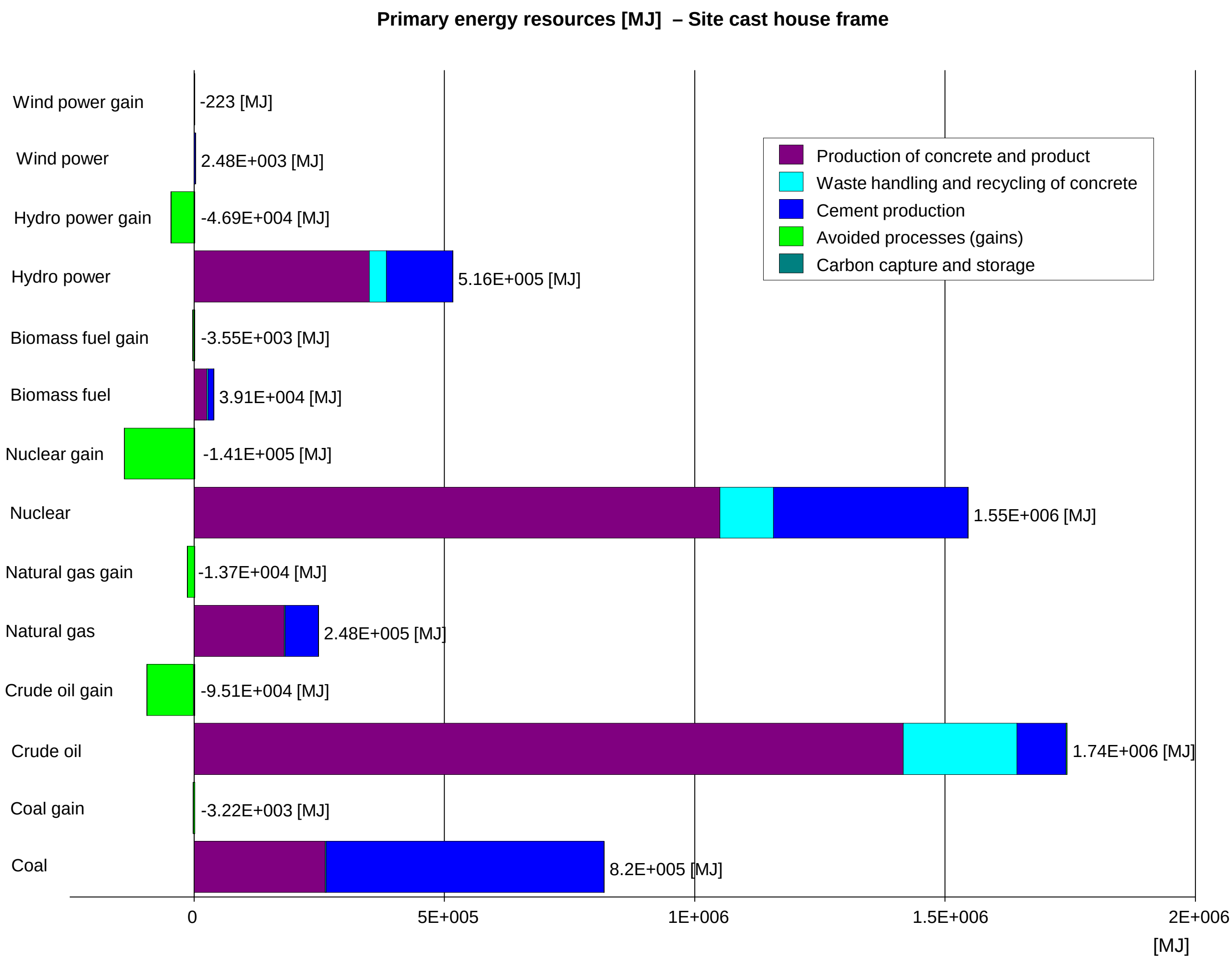

Figure 11 Primary energy resources (excluding waste fuels) and avoided resource uses (gains) for the site cast house frame. Contributions from the different process groups are shown. The figure includes the entire system.

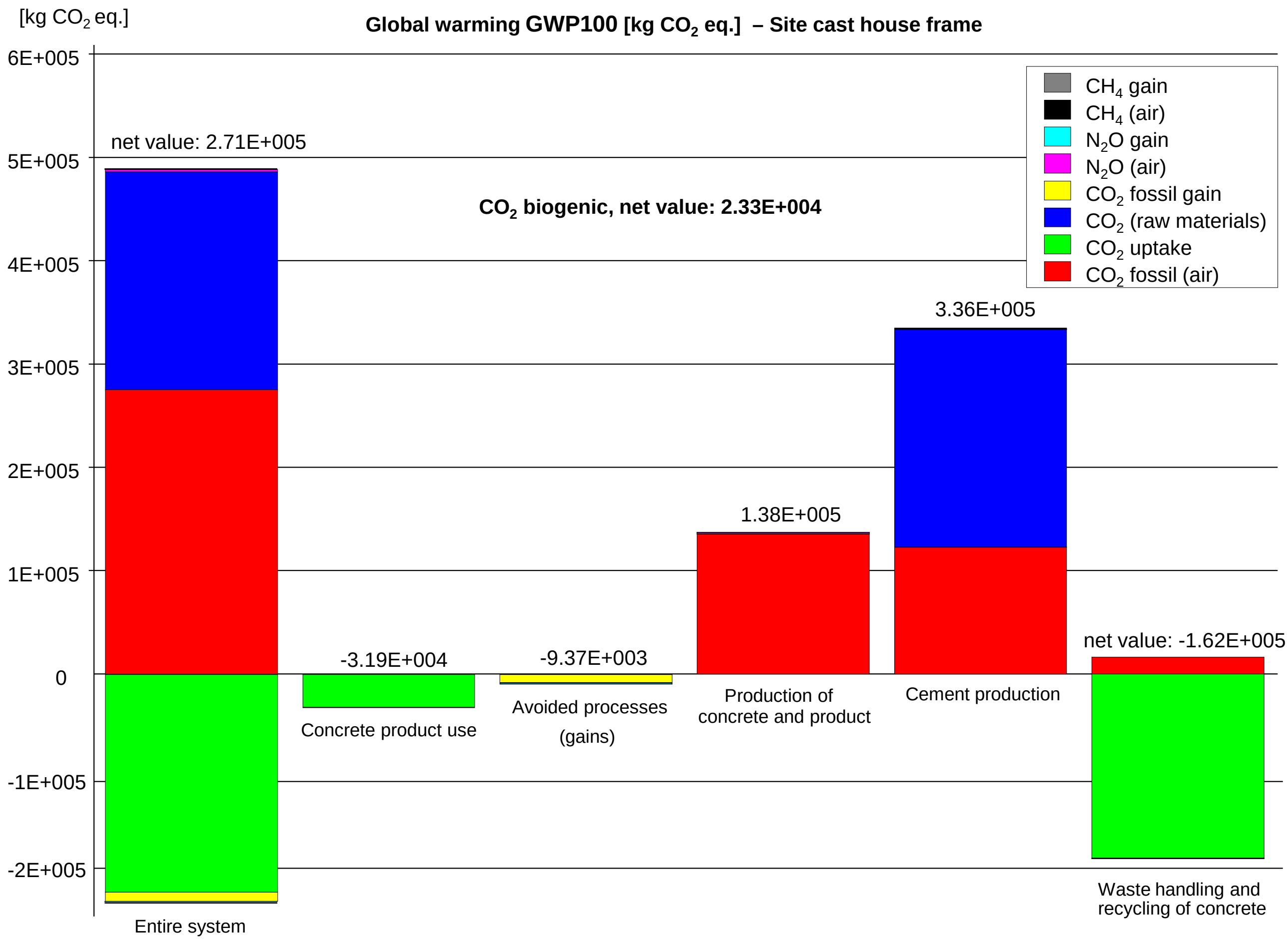

Figure 12 Global warming potential for the site cast house frame shown divided into different process groups and for the entire system. The CO_2 net value for the entire system shows the value when avoided CO_2 emissions and CO_2 uptake in concrete has been subtracted. The net value for the biogenic CO_2 emissions is also shown in the figure as additional information. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

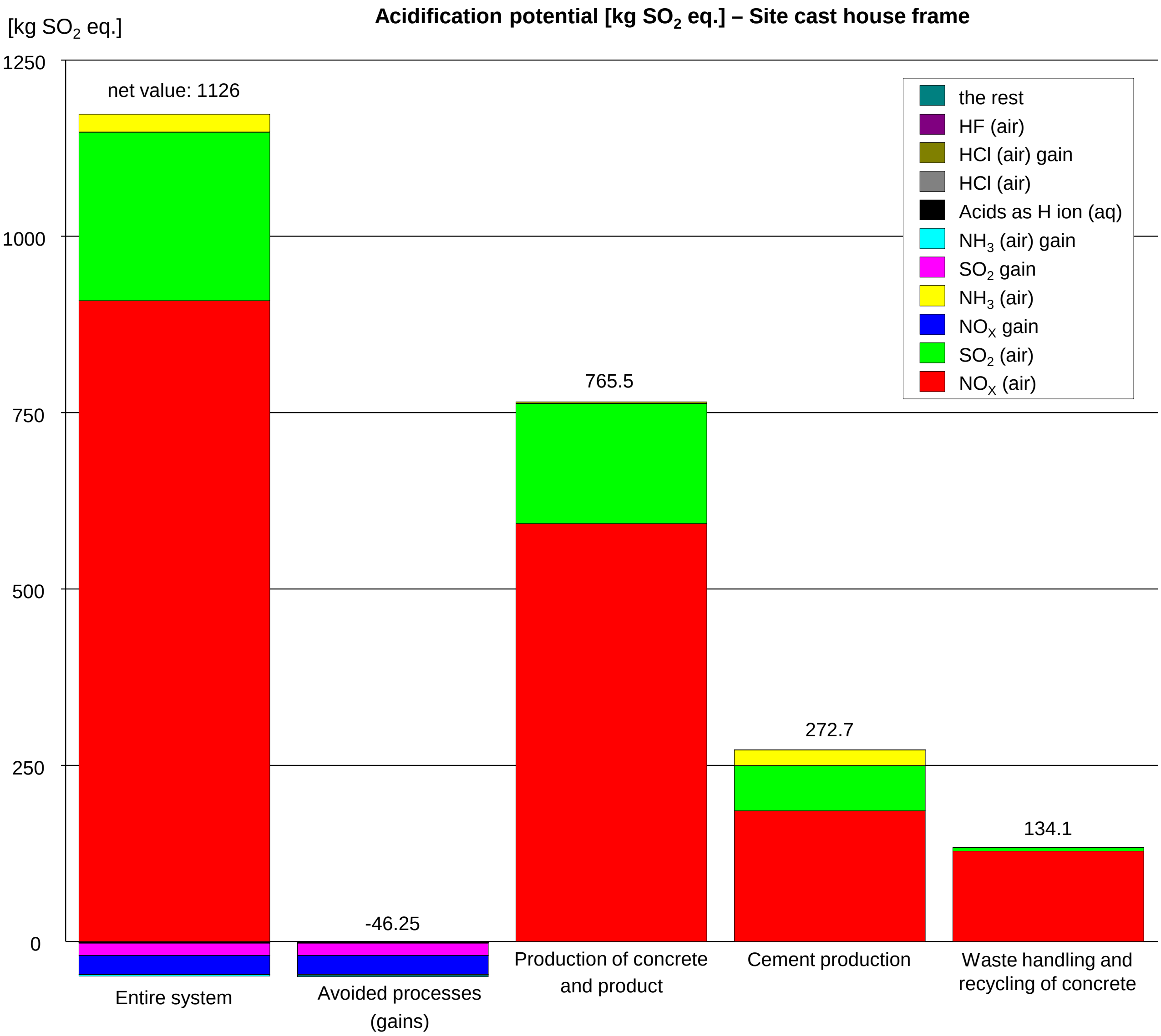

Figure 13 Acidification potential for the site cast house frame shown divided into different process groups and for the entire system. The net value for the entire system shows the value when avoided emissions have been subtracted. The acidification potential is calculated as kg SO_2 equivalents.

7.3 Precast concrete frame for industrial storage

A precast house frame is also an example of a concrete product with an indoor surface CO_2 exposure. In this case, the example is a house frame in an industrial storage building and the concrete surface is thus not covered with any material (only pure concrete surfaces). The design of a precast house frame is, in this case, even slimmer than the site cast house frame in the previous chapter. This results in an even higher surface to volume ratio with an accompanying higher CO_2 uptake potential during the lifetime of the house frame. The "concrete surface area/concrete volume" ratio has been calculated to 17.5 m^2/m^3 with a CO_2 uptake level of 62 kg CO_2/m^3 concrete during lifetime of the house frame. The specific CO_2 uptake during lifetime is thus even higher than in the site cast house frame example. The theoretical maximum uptake of CO_2 in the concrete is in this case 193.6 kg CO_2/m^3 concrete. The precast house frame is made of building cement and the cement content in the concrete is 400 kg/m^3 concrete (see chapter 6.5). The precast house frame also has a relatively low use of steel reinforcement (40 kg steel/m^3 concrete). The specification of the house frame and the calculated CO_2 uptake is shown in chapter 6.3.3.

In Figure 14, the energy resource use (excluding waste fuels) from the entire model of the precast house frame system is shown. The energy use covers the entire system over the entire lifetime (100 years) of the house frame and the following waste handling phase after the end of the lifetime. The figure shows the use of primary energy resources for the entire system and divided in different activity areas. The energy resource use pattern shows many similarities but we can see somewhat increased savings from avoided processes and a somewhat changed proportion between "Production of concrete and its product" and Cement production even of the former still is larger than the later. In Figure 15, the same energy use is shown but divided into the different primary resources.

Figure 16 shows the global warming potential balance for the entire system and divided into different process areas. Biogenic-based CO_2 emissions are not included in this figure but given as additional information in the figure. From the figure, we can see that the contribution from methane (CH_4) and dinitrogen oxide (N_2O) to the global warming potential is small. The emission pattern is similar to the emission pattern of both the concrete bridge and the site cast house frame example. The CO_2 uptake during lifetime of the house frame is however significant larger than the corresponding uptake in both the concrete bridge and the site cast house frame example. The carbonation rate is higher for the precast house frame compared to the bridge and site cast house frame example due to the composition of the concrete, the shape of the house frame (surface to volume ratio) and the surface conditions. The carbonation rate in the waste handling phase depends mainly on the concrete composition, surface to volume ratio of the crushed concrete and the CO_2 exposure of the crushed concrete. Due to higher cement content in the concrete and use of building cement, the carbonation rate in the waste phase can probably be slightly higher compared to the site cast house frame.

As a background and additional information, the acidification potential from the system is shown in Figure 17 as SO_2 equivalents. The main substances are NO_X and SO_2. The emission pattern is relatively equal compared to both the concrete bridge and the site cast house frame example.

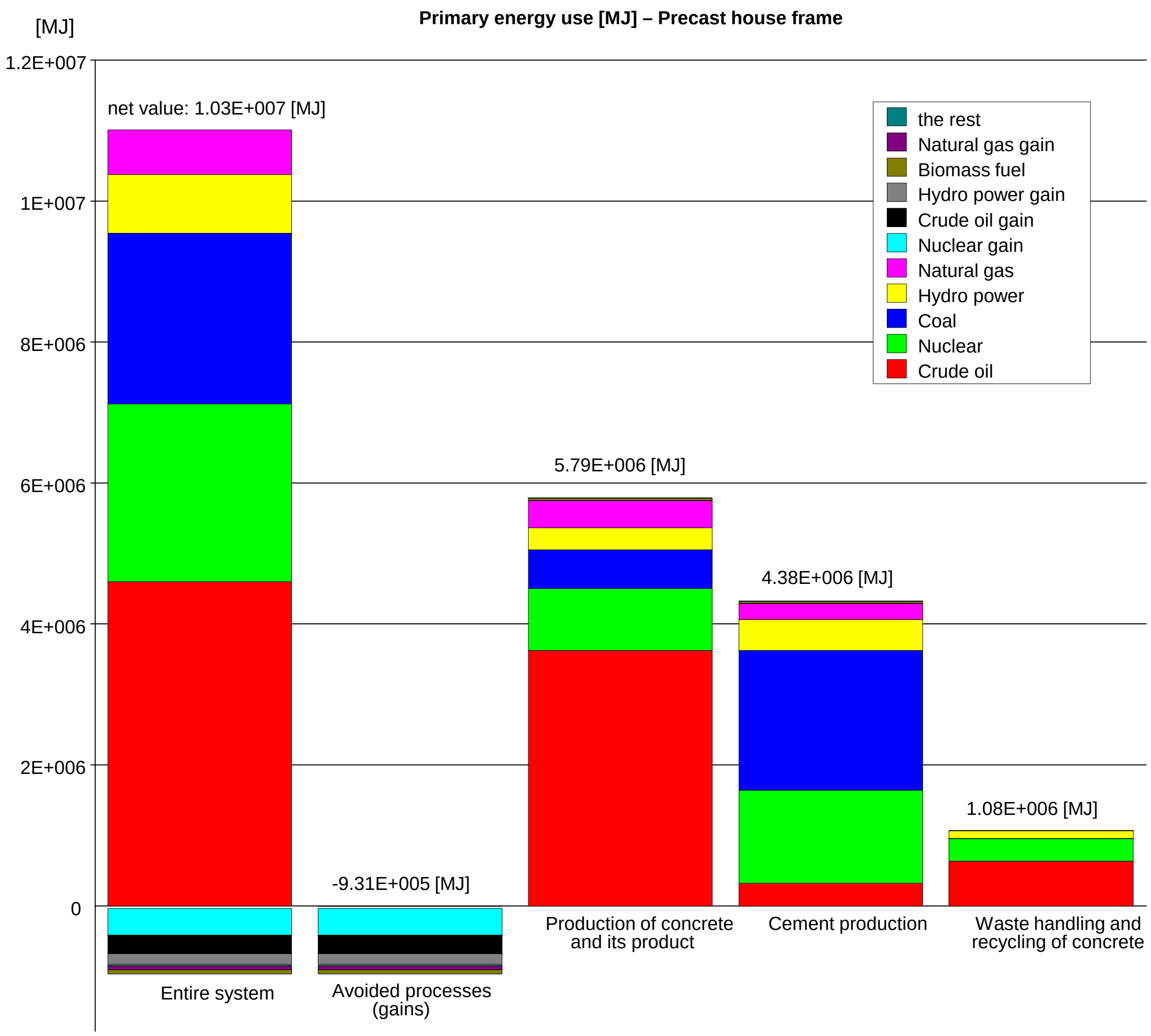

Figure 14 Primary energy use (excluding waste fuels) for the precast house frame shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

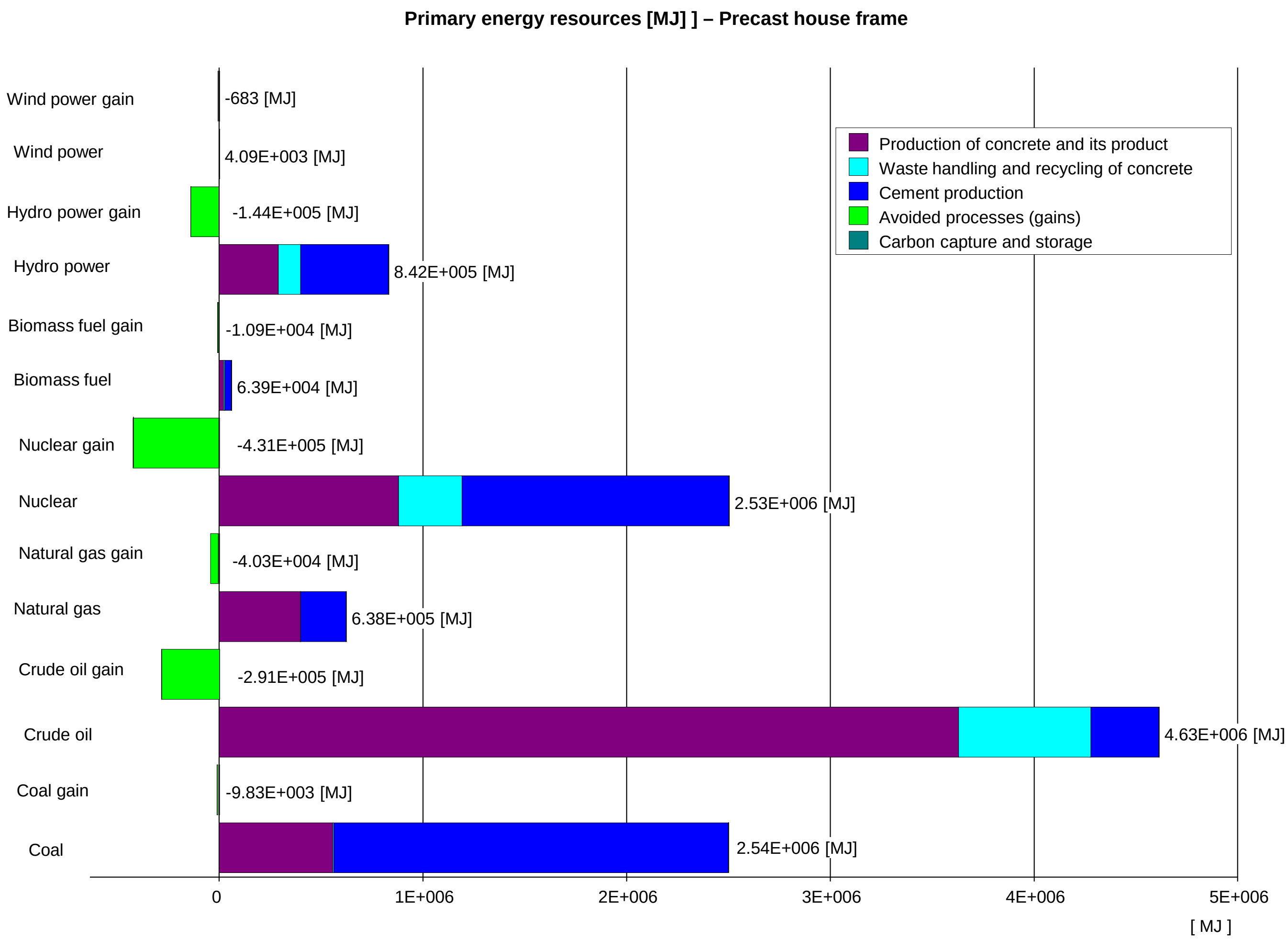

Figure 15 Primary energy resources (excluding waste fuels) and avoided resource uses (gains) for the precast house frame. Contributions from the different process groups are shown. The figure includes the entire system.

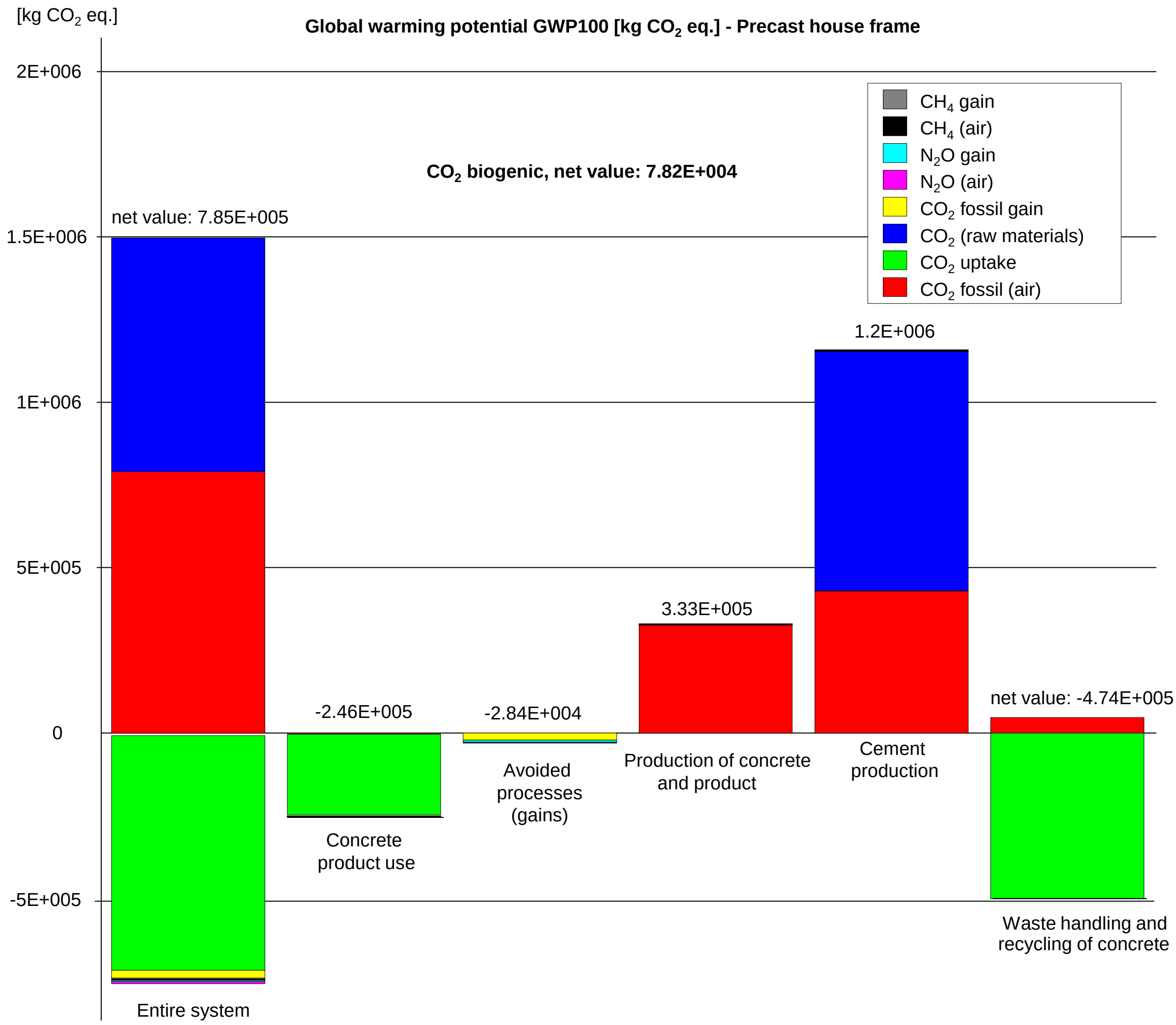

Figure 16 **Global warming potential for the precast house frame shown divided into different process groups and for the entire system. The CO_2 net value for the entire system shows the value when avoided CO_2 emissions and CO_2 uptake in concrete has been subtracted. The net value for the biogenic CO_2 emissions is also shown in the figure as additional information. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.**

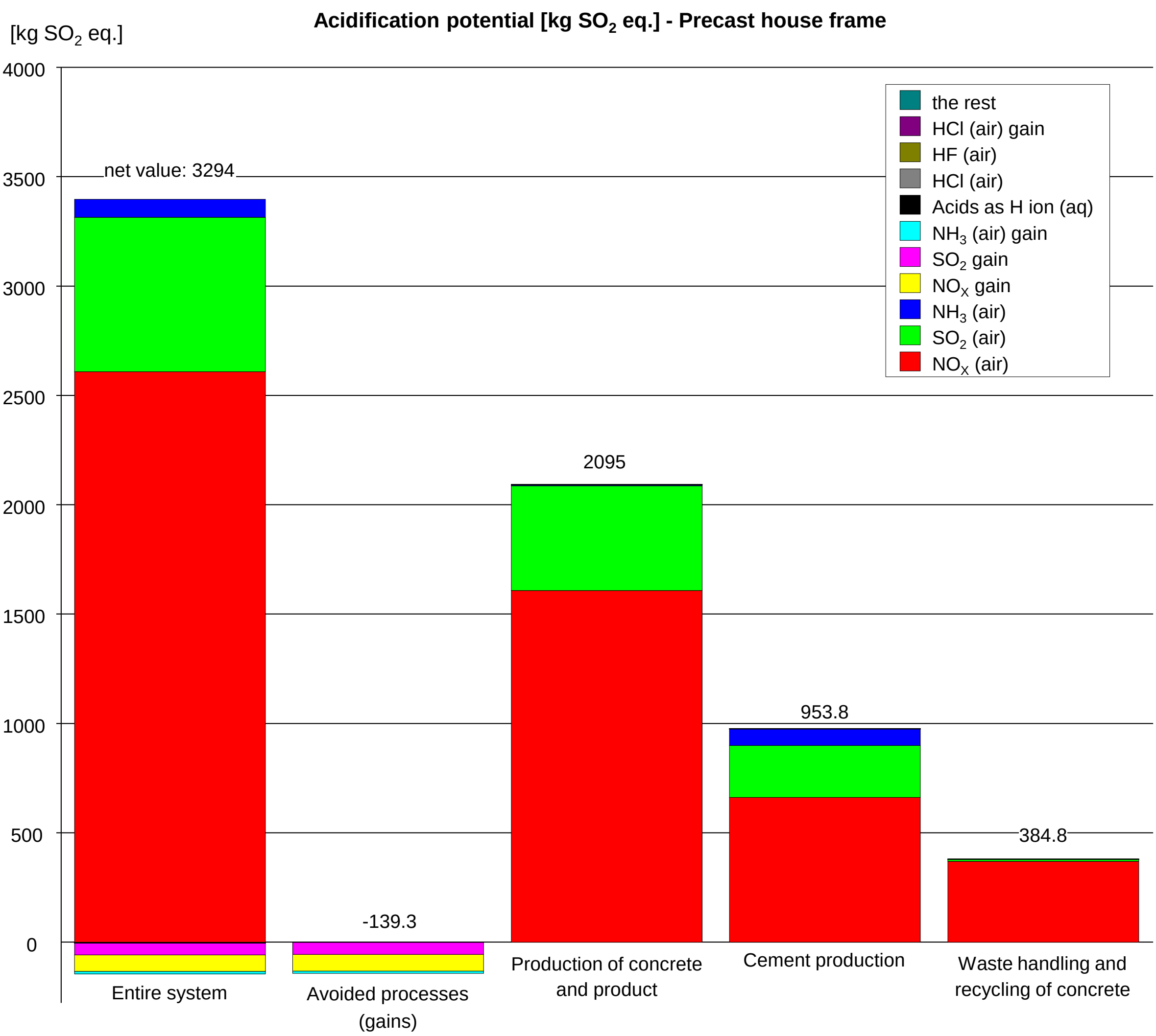

Figure 17 Acidification potential for the precast house frame shown divided into different process groups and for the entire system. The net value for the entire system shows the value when avoided emissions have been subtracted. The acidification potential is calculated as kg SO_2 equivalents.

7.4 Concrete tile roof

A concrete tile roof differs slightly from the other example products in several ways. The design is very thin which gives a high surface to volume ratio. The "concrete surface area/concrete volume" ratio has been calculated to 204 m^2/m^3. This facilitates the transport of CO_2 in the concrete structure during lifetime of the product. The product is used in outdoor constructions with CO_2 exposure on both sides of the tile. The upper side of the tile roof is exposed to rain and the under side is sheltered from rain. Normally, the surfaces are not covered with paint. No steel reinforcement is used for the concrete tiles. The concrete tiles are made of building cement and the cement content in the concrete is 450 kg/m^3 concrete (see chapter 6.5). The theoretical maximum uptake of CO_2 in the concrete is in this case 200.9 kg CO_2/m^3 concrete. The specific CO_2 uptake during lifetime of the roof is thus very high. It is difficult to estimate the degree of carbonation during lifetime but measurements of old roofing tiles in this project has shown carbonation in the entire concrete material. It is difficult to specify an exact degree of carbonation but in this example, we have assumed an 80 % degree of carbonation during lifetime of the tile roof. This gives a CO_2 uptake of 160.7 kg CO_2/m^3 concrete during lifetime and thus 40.2 kg CO_2/m^3 concrete during waste phase. The specification of the concrete roofing tiles and the calculated CO_2 uptake is shown in chapter 6.3.4. The results from the calculation are given for an example roof of 100 m^2.

In Figure 18, the energy resource use (excluding waste fuels) from the entire model of the concrete tile roof (100 m^2) is shown. The energy use covers the entire system over the entire lifetime (50-100 years) of the concrete tile roof and the following waste handling phase after the end of the lifetime. The figure shows the use of primary energy resources for the entire system and divided in different activity areas. The energy resource use pattern shows many similarities with the previous examples but we can see a significant lower energy use for the production of concrete, roofing tiles and the roof. In Figure 19, the same energy use is shown but divided into the different primary resources.

Figure 20 shows the global warming potential balance for the entire system and divided into different process areas. Biogenic-based CO_2 emissions are not included in this figure but given as additional information in the figure. From the figure, we can see that the contribution from methane (CH_4) and dinitrogen oxide (N_2O) to the global warming potential is small. The emission pattern is similar to the emission patterns for the previous examples but the uptake of CO_2 in the concrete product during the lifetime of the product is significant larger. The fossil CO_2 emissions from the production of concrete and the product are also relatively lower. The carbonation rate is also high for this product due to the concrete composition and the geometric shape of the product. The carbonation rate in the waste handling phase depends mainly on the concrete composition, surface to volume ratio of the crushed concrete and the CO_2 exposure of the crushed concrete. Due to higher cement content in the concrete and use of building cement, the carbonation rate in the waste phase can probably be higher compared to the previous examples.

As a background and additional information, the acidification potential from the system is shown in Figure 21 as SO_2 equivalents. The main substances are NO_X and SO_2. The emission pattern is relatively equal compared to the previous examples.

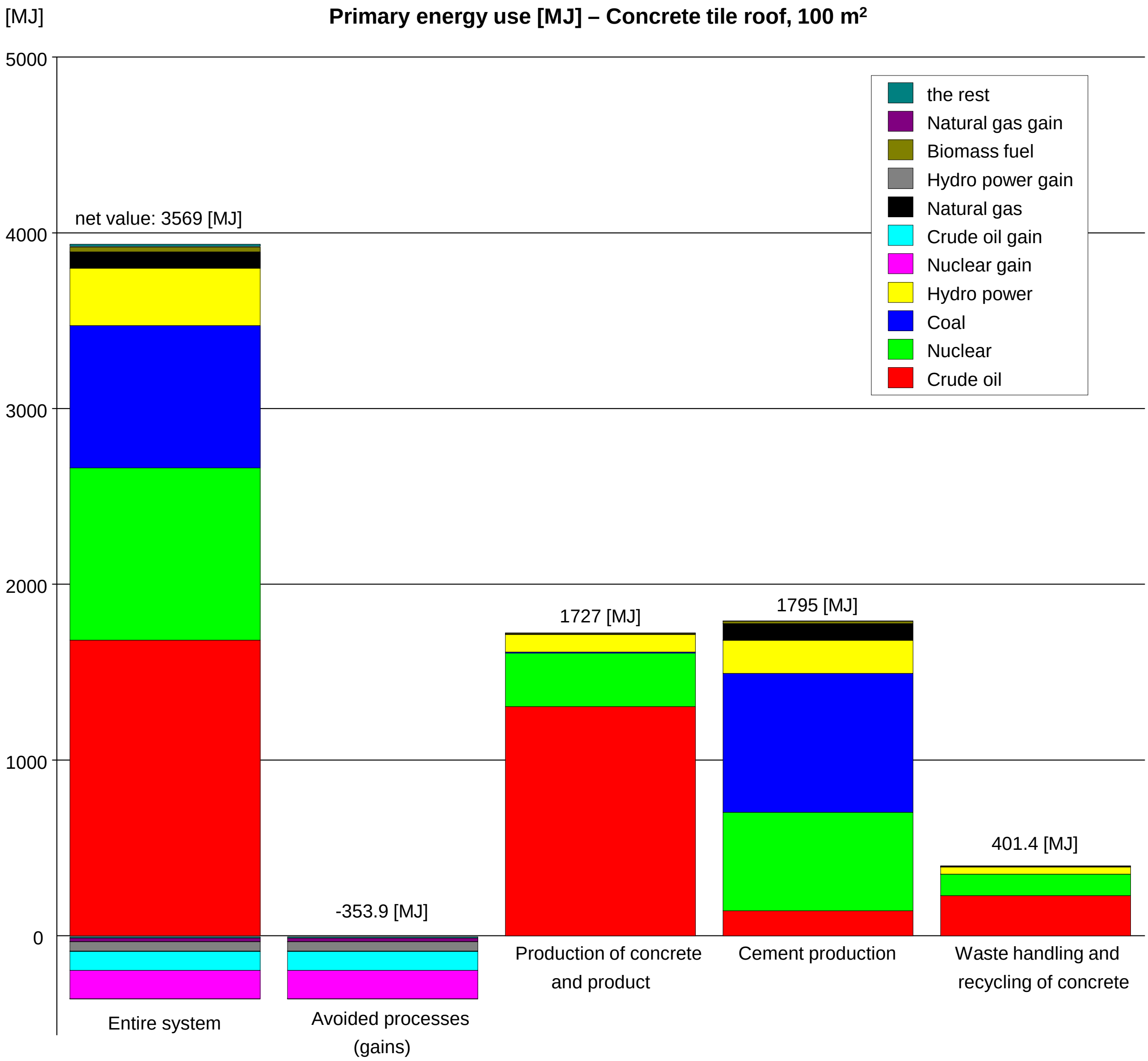

Figure 18 Primary energy use (excluding waste fuels) for 100 m² concrete tile roof. The figure shows the result divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

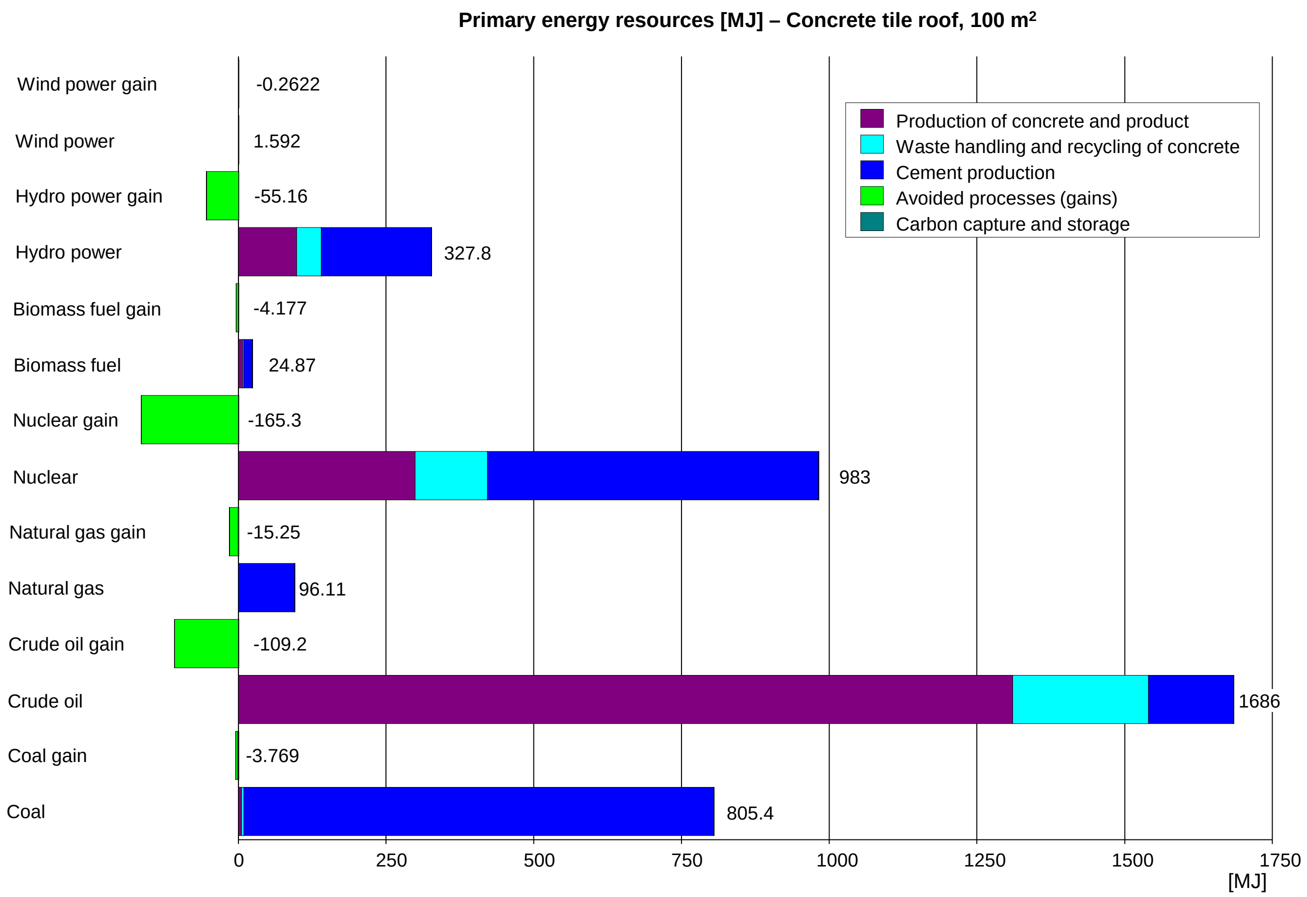

Figure 19 Primary energy resources (excluding waste fuels) and avoided resource uses (gains) for 100 m² concrete tile roof. Contributions from the different process groups are shown. The figure includes the entire system.

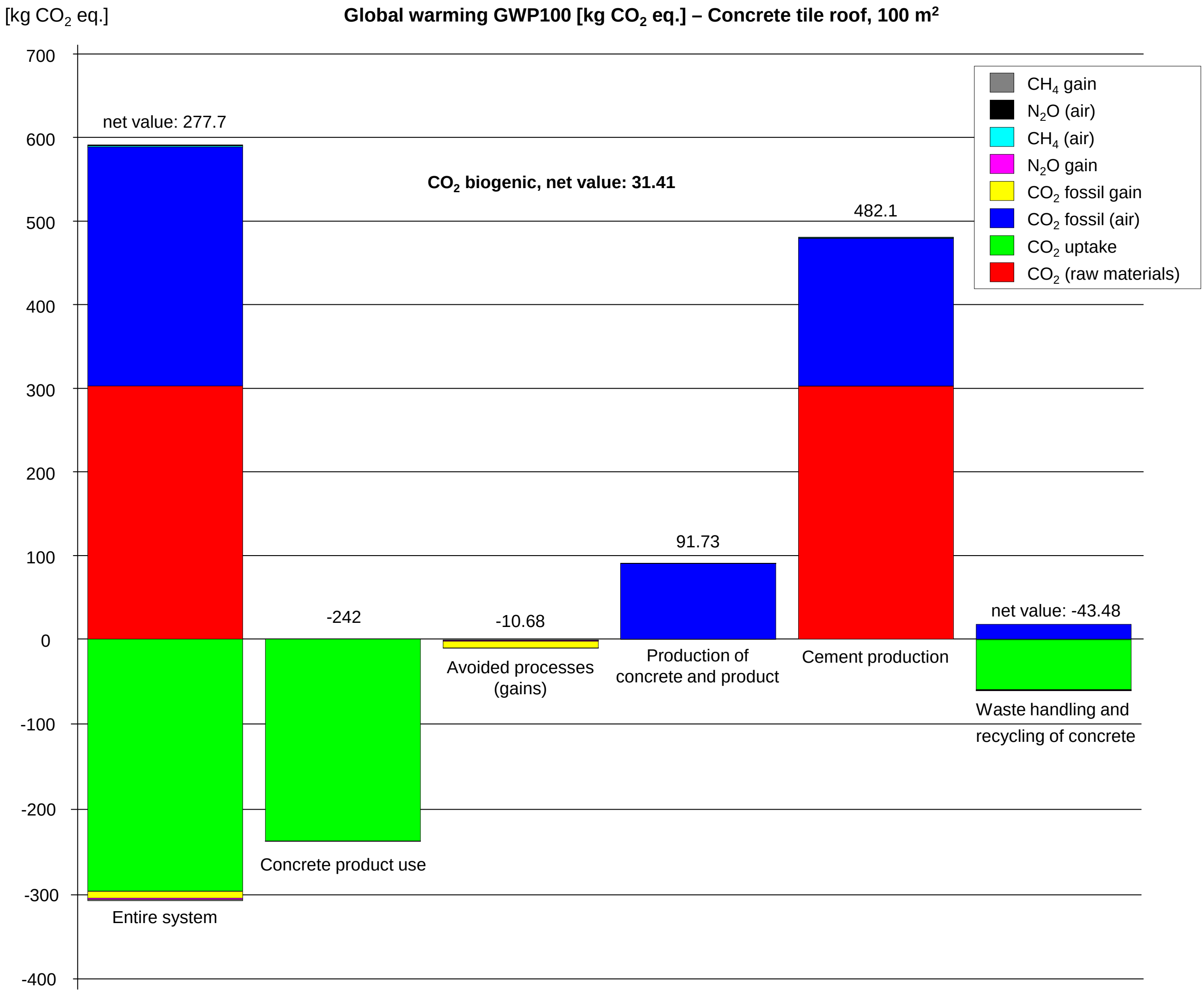

Figure 20 Global warming potential for 100 m² concrete tile roof, shown divided into different process groups and for the entire system. The CO_2 net value for the entire system shows the value when avoided CO_2 emissions and CO_2 uptake in concrete has been subtracted. The net value for the biogenic CO_2 emissions is also shown in the figure as additional information. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

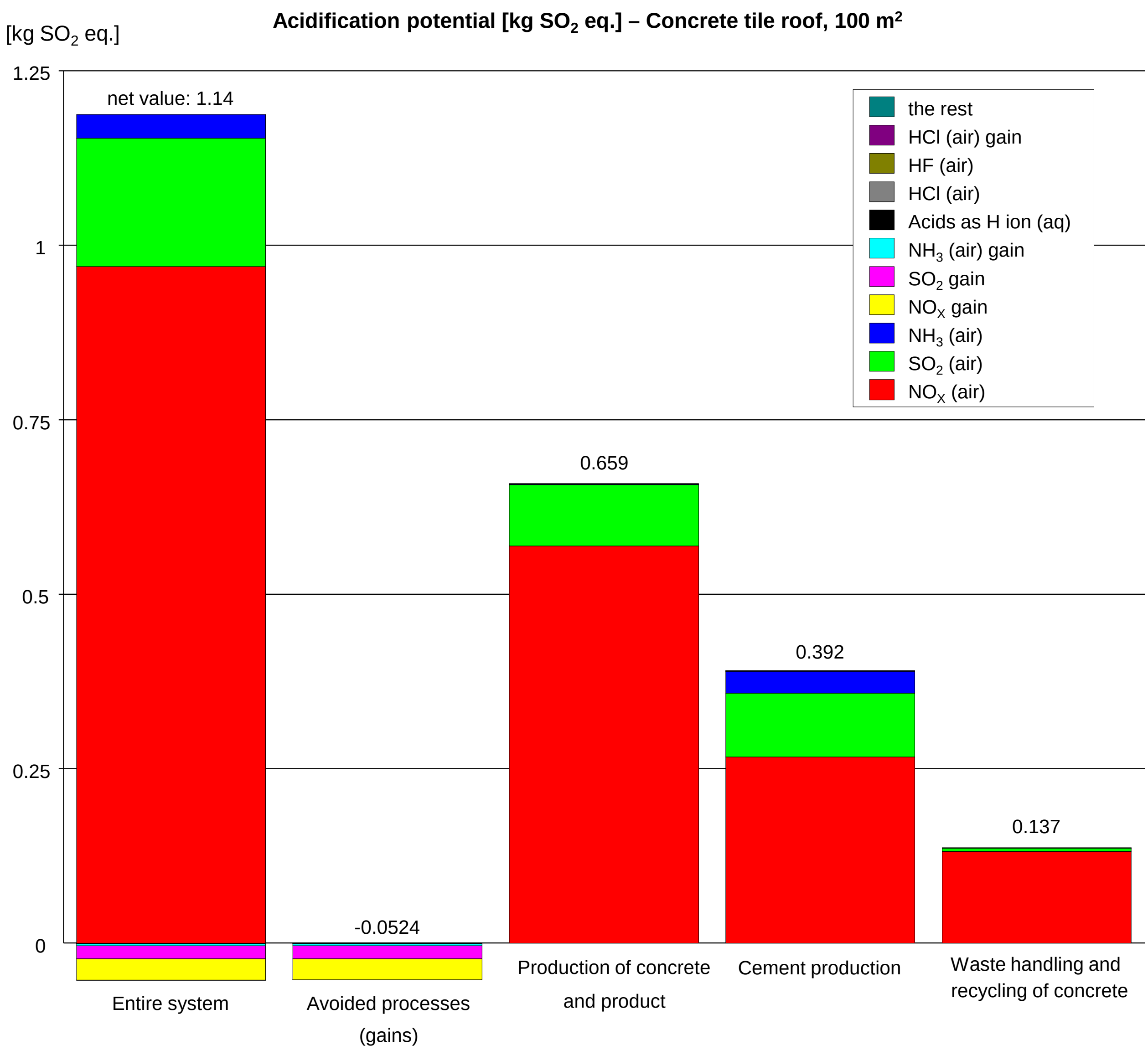

Figure 21 Acidification potential for 100 m² concrete tile roof, shown divided into different process groups and for the entire system. The net value for the entire system shows the value when avoided emissions have been subtracted. The acidification potential is calculated as kg SO_2 equivalents.

8 Greenhouse gas strategies for cement, concrete and its products

8.1 Background and strategic overview

In the previous chapter, chapter 7, we have taken a closer look at the greenhouse gas situation for some very common concrete products of today. The results have been analyzed which have given us a relatively good picture of the present situation and also some indications of the effect of e.g. changed concrete composition for the different example products. With the previous example analysis in mind, we can now ask a more general question – How can this system be altered in order to improve the greenhouse gas situation and which consequences will that have? In this chapter, we will take the analysis one step further and look at some general strategies to reduces the emission of greenhouse gases and analyze these strategies both from a production perspective and from a society perspective.

Based on the LCA model and the previous examples, a number of different strategies will be developed and analyzed. It is important to stress that the different strategies does not represent any proposed or recommended strategies. The purpose of the analyses is instead to increase the knowledge base concerning greenhouse gas strategies for the cement and concrete industry by analyzing some basic strategies and ideas. This also means that we try to develop example strategies that clearly exemplify both a strategy and its effect on the entire system rather than develop realistic and commercial scenarios for direct implementation in the industry. The purpose is primarily to show the potential of different strategies even if we try to analyze and comment the practical application from both a production and society perspective.

The first step in an analysis of potential reduction strategies is to identify different potential reduction alternatives in the entire system. When the potential reduction alternatives are identified, the LCA model can be used to calculate the effect of the proposed reduction method and the potential of the method can be analyzed and discussed. A good starting-point to identify different reduction alternatives is the LCA model. An LCA model includes most of the important processes in the technical system of the product and it is build up in a logical way with a graphic presentation of the model. A very strait-forward way to identify reduction possibilities and potentials is to analyze the different part of the LCA model. This will also be the starting point for the analyses in this chapter.

A figure of the LCA model is shown in Figure 1. Let us start the analysis with the production of cement, which is an important part of concrete. The production begins with mining of limestone and marlstone. The stone material proceeds to a crusher and then to the raw meal mill where it is milled with sand sludge and other external materials needed in the production. Neither the mining nor the raw meal milling process require large amount of energy so the reduction potentials are relatively small. The energy type is also mainly diesel oil for vehicles and electric power for the raw meal mill, which both are difficult for the cement industry to change. The production of other external material such as iron ore, fly ash or LD dust is also difficult to do anything about for the cement industry. However, some of these materials are waste materials that are used in the cement industry so the allocation of emission to these materials can be discussed.

The cement kiln stands for the major energy use in cement production. Many different fuels are used for the operation of the kiln and the kiln also produces waste heat that can be used. Some of the fuels are also wastes that are incinerated in the kiln. These circumstances offer some opportunities for improvement of the greenhouse gas emissions. The fuel composition can be altered in a direction that gives less greenhouse gas emission, for example to use more biofuels. The emission calculations of the waste fuels can be discussed in order to promote use of waste materials. An increased use of waste heat can also reduce other external fuel use and in that way reduce emissions of greenhouse gases. A more advance but less developed technique is to use the so-called Carbon Capture and Storage (CCS) technique. The concentration level of CO_2 in the exhaust gases from a cement kiln is high due to CO_2 emissions from both the limestone materials and the fuels. This is an ideal situation for removal of CO_2 from the exhaust gases for storage, for example, in empty natural gas fields or in deep underground water-bearing reservoirs so called aquifers. These technics are relatively new and not tested in full scale. The lack of reliable process data is obvious. These technics show a large potential but are thus not in operation. We will therefore discuss and comment the technique in general terms in order to give a complete picture of the different possibilities.

The cement mill where the Portland cement clinker is mixed with other cement components require relatively small amount of energy in form of electric power. The reduction potential in terms of energy is thus small but this is also the process where the cement composition is made. The cement composition can play a role both for the emission of greenhouse gases in the production and for the uptake of CO_2 in the product and in the waste phase of the product.

The concrete production itself requires relatively small amount of energy but the composition of the concrete can play a role for the CO_2 balance and can thus offer some reduction potential. Like the cement composition, the composition of the concrete can play a role both for the emission in the production and for the uptake in the concrete. The influence of waste hydraulic materials such as fly ash, blast furnace slag and other hydraulic materials can influence the CO_2 balance and the calculation methods can play a role for the emission levels. Both the cement and concrete compositions offer some complex reduction potential that have to be analyzed. However, an important factor and restriction is, in this case, the concrete quality. A poor concrete quality can shorten the lifetime of the product and cause increased maintenance or even rebuilding and in this way increase the CO_2 emission from the entire system over a specific time period.

As shown in chapter 7, the production of the concrete and the concrete product stands for a relatively large part of the energy use in the system. The corresponding fraction of the CO_2 emissions is smaller but significant. These emissions are emissions from the concrete industry generated in the concrete factory/precast fabrication or at the construction site. The emissions are generated by many different operations in combination and it is difficult to find any large reduction potential. In this case, the strategy should include a more general increase of efficiency in the overall production line. This could have a reduction potential of a few per cent of the emissions from these processes.

No energy is used and no greenhouse gases are emitted during the products lifetime so no reduction strategies are needed for this case. The only process to consider for the use phase is the uptake of CO_2 in the concrete, which however can be influenced by other strategies like cement and concrete composition. The uptake during use phase can also be influenced by for example the design of the product (surface to volume ratio), climate/weather condition (rain-protected surfaces) or surface cover (paint, soil, carpets, wallpaper etc.). Indirect CO_2 reduction effects of concrete structures such as for instance isolation effects and heat storage in heavy buildings are not included in this study.

The waste or end of life/secondary product phase of the concrete can play an essential role for the uptake of CO_2 and thereby the entire CO_2 balance of the system. Four different waste alternatives are included in the model:

1. Landfill[8] of demolished concrete (without crushing).
2. Crushing of demolished concrete and use as replacement for crushed rock in for instance road bases (main use today and in the examples).
3. Crushing of demolished concrete and use as aggregate in new concrete.
4. Crushing of demolished concrete followed by an accelerated CO_2 uptake process. The processed concrete can then be used to replace aggregates in e.g. road bases or new concrete. This alternative is very little investigated.

Some of these processes are not very well developed such as accelerated CO_2 uptake and in-situ promoted CO_2 uptake for crushed concrete used in different applications such as road bases. This makes it difficult to quantify the effect but the methods will be analyzed and discussed.

For the further analyses, the above mentioned and proposed strategies have been summarized below and aggregated into a list of strategies that will be used in the analyses. The greenhouse gas (GHG) strategy list is shown below including potential effects to test. In the following chapters (8.2 - 8.5) the result from the analyses are shown. To save space in the report and to create a better overview of the results, the different analyses have been aggregated into four different chapters. The chapters are also indicated in Table 10 below.

[8] In this case, landfill means a useful filling of land area in different construction projects and not a municipal solid waste landfill or a landfill for industrial waste which are seldom used for concrete materials.

Table 10 Overview of the effect analyses of the different CO_2 measure.

Strategic measure for GHG reduction	Effect to test	Chapter
Changes of fuels in cement kiln	Increased use of biofuels; Use of fuels from waste	8.2
Altered energy efficiency in cement production	Efficiency of the cement kiln and overall cement production	8.2
Increased use of waste heat from cement production	Increased use of waste heat from the cement kiln in e.g. district heating or by co-locating with other industries	8.2
Changes in cement composition	Altered clinker content; Use of hydraulic additives; Use of waste/recycled materials; Use of fillers	8.3
Altered concrete composition	Altered cement content; Use of hydraulic additives; Use of waste/recycled materials; Use of fillers	8.3
Altered production of reinforcement bars	Change in electric power production for the electric arc furnace.	8.2
Design of concrete products (CO_2 uptake)	Uptake of CO_2 during use phase of the concrete product	8.3
Changes in waste management and recycling (CO_2 uptake)	Different waste management for handling, replacement of crushed aggregates and increased uptake of CO_2 during waste handling	8.4
Carbon capture and storage (CCS)	Effect of the process	8.5

8.2 Scenario: Biofuel, Waste heat, Waste fuels, Energy efficiency and Reinforcement case

In this chapter, we will take a closer look at some of the central measures that can reduce the CO_2 emissions from cement and concrete products. A system perspective of the entire system has been used, as in chapter 7, but in this case all energy use (not only direct primary energy but also waste fuels) and all CO_2 emissions (i.e. also biogenic emissions) has been included in the analysis. The energy and CO_2 effects that are analyzed in this chapter is:

1. Increased use of biofuel in the cement kiln.
2. Use of waste fuels in the cement kiln.
3. Increased use of waste heat from cement production (cement kiln).
4. Altered production of steel reinforcement bars.
5. An overall improved energy efficiency in the cement production.
6. Comments on concrete product production.

The concrete bridge example from chapter 7.1 has been used for this analysis. The LCA model of the concrete bridge has been used to calculate the effects and the effects of measure 1 to 4 has been changed in the model and the results are shown in bar chart figures and in tabular form to make it possible to see the details of the changes. The results are shown first as the baseline situation (Figure 22, Figure 24, Table 11, Table 13, same as chapter 7.1) and then for the altered situation (Figure 23, Figure 25, Table 12, Table 14). The effects of measures 5 and 6 are only discussed in the text based on the result figures.

8.2.1 Increased use of biofuel and use of waste fuels in the cement kiln

A very common method to reduce the fossil-based CO_2 emissions is to substitute fossil fuels with biomass fuels. The largest single combustion source in the system is the cement kiln so a focus on this process is obvious. The total energy use (all fuels) in the cement kiln is 3798 MJ/tonne clinker[9]. The main fuels are hard coal and different waste fuels. The hard coal contribution is 1402 MJ/tonne clinker. The waste fuels are converted fuel oils, fly ash fuels, meat bone meal, petcoke (residue from oil refineries), plastics, plastics pellets, solvent waste and old tyres. The scenario used here is to replace the entire hard coal with biomass fuels (in this case wood powder combustion). The results of this fuel change are shown in the "Cement production" group.

As shown from the figures, the change has very little effect on the energy use. Note that we have assumed an equal energy amount of coal and biomass fuel use in the cement kiln. This can however differ slightly due to different combustion behavior. The change of the absolute value of the CO_2 emission is also very small. However, for the bridge example, the fuel substitution result in a decrease of fossil based CO_2 emission from 33 876 kg CO_2 eq. to 19 913 kg CO_2 eq. i.e. a reduction of 131 kg CO_2 eq./tonne clinker. The biogenic CO_2 emissions increase from 5 911 kg CO_2 eq. to 20 271 kg CO_2 eq. However, the biogenic CO_2 emissions are considered to have zero emission due to the corresponding uptake of CO_2 in growing forests. The CO_2 emission from the raw meal is not change for this CO_2 reduction measure.

Even if this action reduces the fossil based CO_2 emission with 41 % it is not obviously a good strategic action. The biomass quantities needed for the kiln is relatively large and the supply of biomass fuel is limited. The lower heating value compared to coal can also make it difficult to achieve the high temperature that is needed to obtain a high quality clinker product. A higher cost for biofuels will also make such an environmental improved cement product more expensive, which can have a negative effect for such a product on the world market. The market demand for such a product is mainly decided by strategic decisions in the society. An important aspect for the society is the strategic use of different fuels. Different fuels have different behavior and positive and negative characteristics. For example, liquid and gaseous fuels are most suitable for engine applications and shall there be avoided for stationary applications. Even if coal has a high specific CO_2 emission, it can be an acceptable choice as long as coal is considered as an acceptable fuel in the world due to the climate change aspects. The choice of fuels to the cement kiln is thus more of a strategic society decision than an inherent characteristic of the material.

Another important aspect is the assessment of waste fuels used in the cement kiln. As shown in Figure 22, a large amount of fuels from different wastes is used. From a society perspective, it is important to reduce the use of primary fuels and especially from fossil-based fuels such as crude oil, coal and natural gas. By using waste as fuels instead of landfilling one can reduce the use of primary fuels. The high combustion temperature in cement kilns make them also suitable for incineration. It is thus of importance from a society perspective to promote the use of waste fuels. One can define

[9] The corresponding amount of clinker for the bridge is 106 790.75 kg.

an energy use hierarchy model in a similar way as the commonly used waste hierarchy model. A suggestion can be as follows:

1. Try to avoid or eliminate the energy use.
2. If energy is used, optimize the use and increase the efficiency.
3. First, use energy that is already formed into heat or other irreversible or uncontrolled forms (e.g. waste heat, wind/solar power).
4. Use fuels from waste or other sources what will be lost if not used.
5. Use renewable energy resources with low CO_2 impact (e.g. biomass fuels, hydropower).
6. Use other fuels (e.g. crude oil, coal, natural gas, nuclear power). However, use right fuel for right application (e.g. liquid/gas fuels for engines, solid fuels for stationary plants).

In addition to an energy strategy as shown above, there can also be a need for an overall energy strategy for the society especially if there is a scarcity of resources and a priority is needed. For the society, it is also important to promote and create incitement for application of the lowest number as possible in the hierarchy especially if natural incitements are lacking.

In a CO_2 context, the emission from combustion of waste fuels is today allocated to the site where the waste fuels are combusted (in this case the cement kiln) and not to the product, that has generated the waste. This is a difficult question. It seems logic that the product that has generated the waste also bears the environmental burden for the waste but at the same time, the general calculation method today is that the CO_2 is allocated to the process where it is emitted and the energy is used. Based on the energy use hierarchy and the incentives for waste fuel use it can be justified to promote a stronger allocation to the product that has generated the waste. Today, the same emission allocation is used for waste fuels as for primary fuels as coal and fuel oil. This can be questioned in light of the intentions to promote use of waste fuels.

8.2.2 Increased use of waste heat from cement production (cement kiln)

In many combustion processes, there is residue heat that can be recovered and used. The residue heat is, in this case, mainly related to the cement kiln. The amount of heat that is available depends on the process conditions and technical solutions. The amount of heat that is actually recovered and used depends also on the external heat demand for the location of the plant. Of practical reasons, the cement plants have been located near the limestone resource. The consequence of this is that the production is located to relatively remote areas, far from large district heating systems that could use the heat.

In the example we have used in this chapter, the total energy supply to the cement kiln is 3798 MJ/tonne clinker calculated from lower heating value of the different fuels. The energy needed for the chemical/mineralogical reactions of the clinker burning process (theoretical) is estimated to 1700 - 1800 MJ/tonne clinker[10]. The energy use for drying of the ingoing material is approximately 150 MJ/tonne clinker[10] assuming a moisture content of 3 % in the material. This is a low value and can be higher for other plants. A theoretic energy residue can then be calculated to 3798-1800-150=1848 MJ/tonne clinker. In addition to the theoretic energy use, there are also energy losses in the plant such as heat radiation losses and exhaust gas losses. In this calculation example we have

[10] Reference document on best available technique in the Cement, Lime and Magnesium oxide manufacturing industries. BREF European Union May 2010.

assumed that 60 % of the theoretical available heat can be recovered and used if the heat demand can be solved.

Today, heat is recovered from both the exhaust gases and from the clinker cooler to produce steam and hot water. The steam is used to produce electric power in an existing turbine and district heating is supplied to a small community in the neighborhood. In total, 48 MJ electric power/tonne clinker is produced and 29.4 MJ heat/tonne clinker is delivered externally. Thus, only a small amount of energy is recovered compared to the potential even if the maximum potential energy recovery is uncertain. In the calculation example used for this chapter we have taken a closer look at the effect of an increased energy recovery. We have assumed that the turbine is kept as it is and producing the same amount of electric power and that the heat recovery is increased to 60 % of the theoretic available heat i.e. 1848*0.6-48=1060.8 MJ/tonne clinker. The result of this measure is shown in the process group "Avoided processes" in the figures and tables of this chapter. For the bridge example, the avoided energy use changes from -64 345 MJ to -206 838 MJ or -603 MJ/tonne clinker to -1937 MJ/tonne clinker.

The corresponding changes in avoided CO_2 emissions when the recovered heat is substituting fuel oil combustion in a district heating network has been calculated from -1996 kg CO_2 to -12 075 kg CO_2 for the bridge. This corresponds to a change from -18.7 kg CO_2/tonne clinker to -113 kg CO_2/tonne clinker. All these are of course only theoretical calculation and the effects can not be accomplished without a customer for the heat. From a pure theoretical perspective this can be achieved by for example an expanded heat pipeline to a near city or by location of an energy demanding industry near the cement plant that can form an energy co-operation to a win-win situation for both companies and at the same time create jobs on the countryside.

Another question is – Is the location of the cement plant to the limestone mine a good strategy? An alternative can be to locate the cement plant near a big city with an existing district heating network that can use the waste heat from the plant. The difference in transport work for the two locations is, may be, not as big as one could expect. The difference in weight between the limestone and the clinker is mainly the weight of CO_2 driven off in the clinker process. The cement product will, to a large extent, be sent to the big city near the alternative location anyway. Further analyses have to show how realistic such a strategy can be. The energy demand in the district heating network is a crucial factor. The heat demand is usually driven by a cold climate where district heating is needed for household heating even if industrial demands also exist. This also implies that the overall energy efficiency can be higher if the cement plants are located to places where heat is needed for household heating i.e. places with long cold winters and a relatively large population. A drawback is that heating is only required during wintertime. In summertime (May-September), the heat demand is much smaller. This can of course have negative effects for the overall energy efficiency in cement production. The increased energy demand in the factory due to a cold climate is assumed to be much smaller than the anticipated delivered waste energy. The exact outcome of this strategy has to be analyzed further.

8.2.3 Altered production of steel reinforcement bars

In the production of concrete and concrete products, it is more difficult to find specific CO_2 reduction targets due to its process complexity. The process group consists of several different process activities which have to be handled separately. To give a better overview of this process group, the energy and CO_2 behavior of these processes are shown. An analysis of Figure 22 "Production of concrete and product" show that the coal resource use in this group is almost entirely (96.2 %) used for steel reinforcement production. The crude oil resource use emanates to a very large extent from different transports and machinery but 10.2 % is used in the steel reinforcement production. Natural gas is almost entirely (97.9 %) used for steel reinforcement production. The use of nuclear power and hydro power is used in electric power production which is distributed to many different activities. Of the electric power production, 89.7 % is used in concrete product production (site cast construction of the bridge), 6.6 % is used in concrete production and 3.8 % is used for production of crushed aggregates. Of the CO_2 emissions from "Production of concrete and product", almost all is fossil based CO_2 emissions. Of that emission, 47.2 % emanates from steel reinforcement production, 35 % emanates from different diesel driven machines and 14.3 % emanates from different transports.

A CO_2 reduction measure that can be used in the production of the concrete product is related to the purchase and production of steel reinforcement. The reinforcement bars for concrete is today a world commodity that is purchased on a global market. The production of the steel is thus a world average production from steel scrap in an electric arc furnace (EAF) using a global electric power production mix. The question is – Which CO_2 reduction effect will be achieved by using an electric power production with a lower CO_2 emission? For this purpose, an alternative EAF steel production has been used driven by electric power produced with a Swedish electric power production mix. This power mix consists mainly of hydropower and nuclear power which both have low CO_2 emissions.

From the figures and tables in this chapter we can see that there are only small variations in energy use but significant changes in energy resource type. The differences in energy use are mainly an effect of calculations of primary energy from fuels and of detailed data set differences for the two steel production processes. The CO_2 emissions show a significant reduction when Swedish electric power was used. In the bridge example, the CO_2 emissions went from 38 646 kg CO_2 eq. to 27 466 kg CO_2 eq. for the group "Production of concrete and product". The difference (-11 180 kg CO_2 eq.) is entirely an effect of the changed electric power production.

8.2.4 Overall improved energy efficiency and concrete product production

In addition to the above mentioned CO_2 reduction measures, it can be appropriate to discuss some more general CO_2 measures. As shown in the figures, the main sources of CO_2 are "Cement production" and "Production of concrete and product". The overall construction phase of a concrete product is somewhat difficult to model in terms of energy and CO_2 emission. Data for the concrete production plant/precast fabrication can be obtained with an acceptable accuracy. The on-site activities are more difficult to calculate and the results can also vary between different construction objects. The data used in the model represent real data for a bridge construction. The on-site construction process consists of many different small operations which are difficult to quantify. It is therefore difficult to propose CO_2 reduction measures for these types of activities. The energy supply to the concrete plant is relatively small compared to the on-site activities but the energy supply can of course be improved by a low CO_2 energy supply. No quantification or calculation has been performed of this case due to lack of relevant data.

The more general energy efficiency of cement production is mainly related to the cement kiln. Several factors can influence the energy efficiency such as type of process/plant, raw material and moisture content, technical standard of the plant etc. The raw material and moisture content can be difficult to handle but with exhaust gas condensation, an increased energy recovery can be achieved.

For an existing modern plant, it can be difficult to achieve any major increase in energy efficiency. No specific calculation of general changes for energy and CO_2 reduction of a plant have been performed due to lack of relevant data.

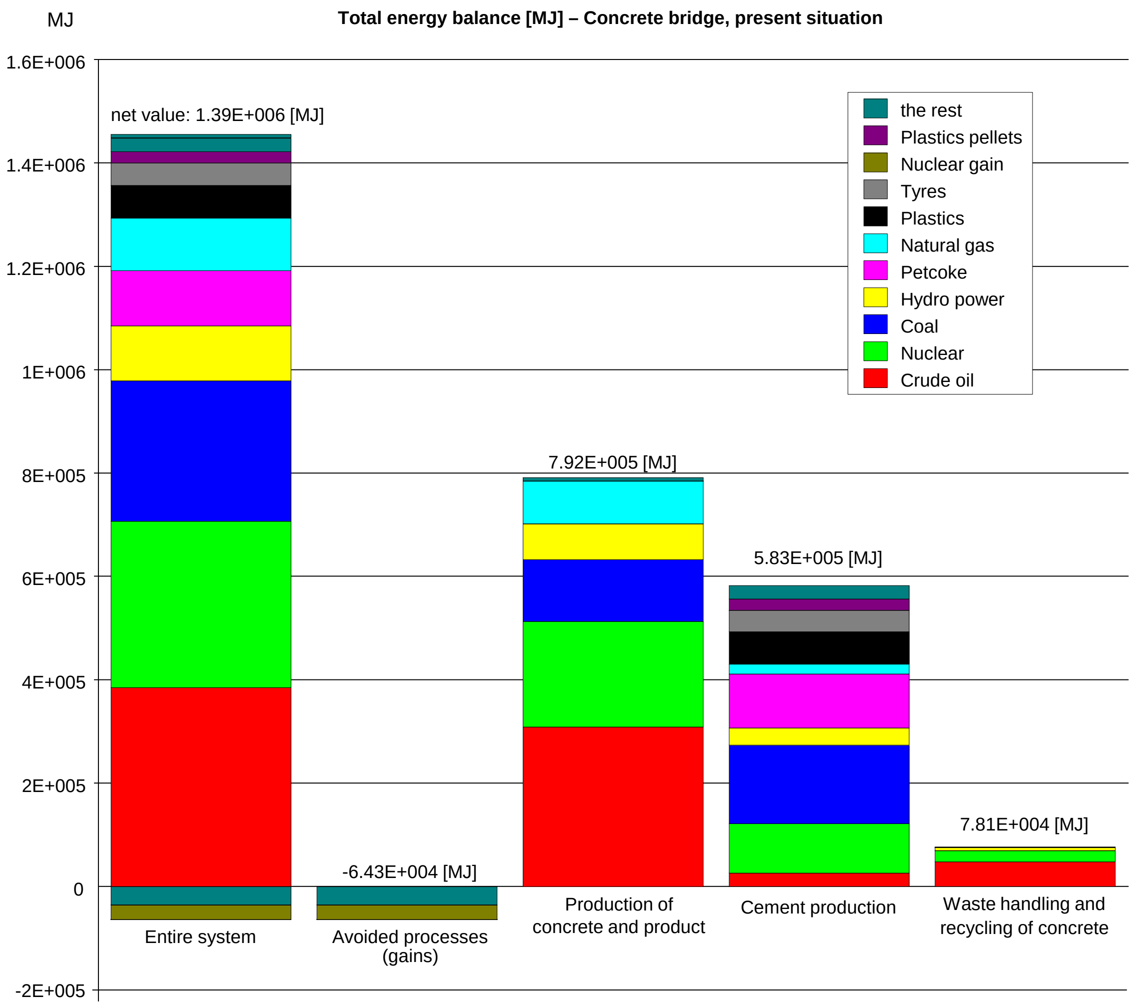

Figure 22 Total energy balance in present production including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

Table 11 Total energy balance in present production including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. (Figure 22 in tabular form.)

Fuels (MJ)	Avoided processes (gains)	Production of concrete and product	Cement production	Waste handling and recycling of concrete	SUM
Crude oil		308 699	26 933	49 813	**385 445**
Nuclear		205 900	95 690	20 390	**321 981**
Coal		118 826	152 368	443	**271 636**
Hydro power		68 752	31 870	6 809	**107 431**
Petcoke		0	105 962	0	**105 962**
Natural gas		83 832	17 987	84	**101 903**
Plastics		0	63 755	0	**63 755**
Tyres		0	41 994	0	**41 994**
Nuclear gain	-29 980	0	0	0	**-29 980**
Plastics pellets		0	20 489	0	**20 489**
the rest	-34 365	5 535	25 976	548	**-2 306**
SUM	**-64 345**	**791 545**	**583 024**	**78 087**	**1 388 311**

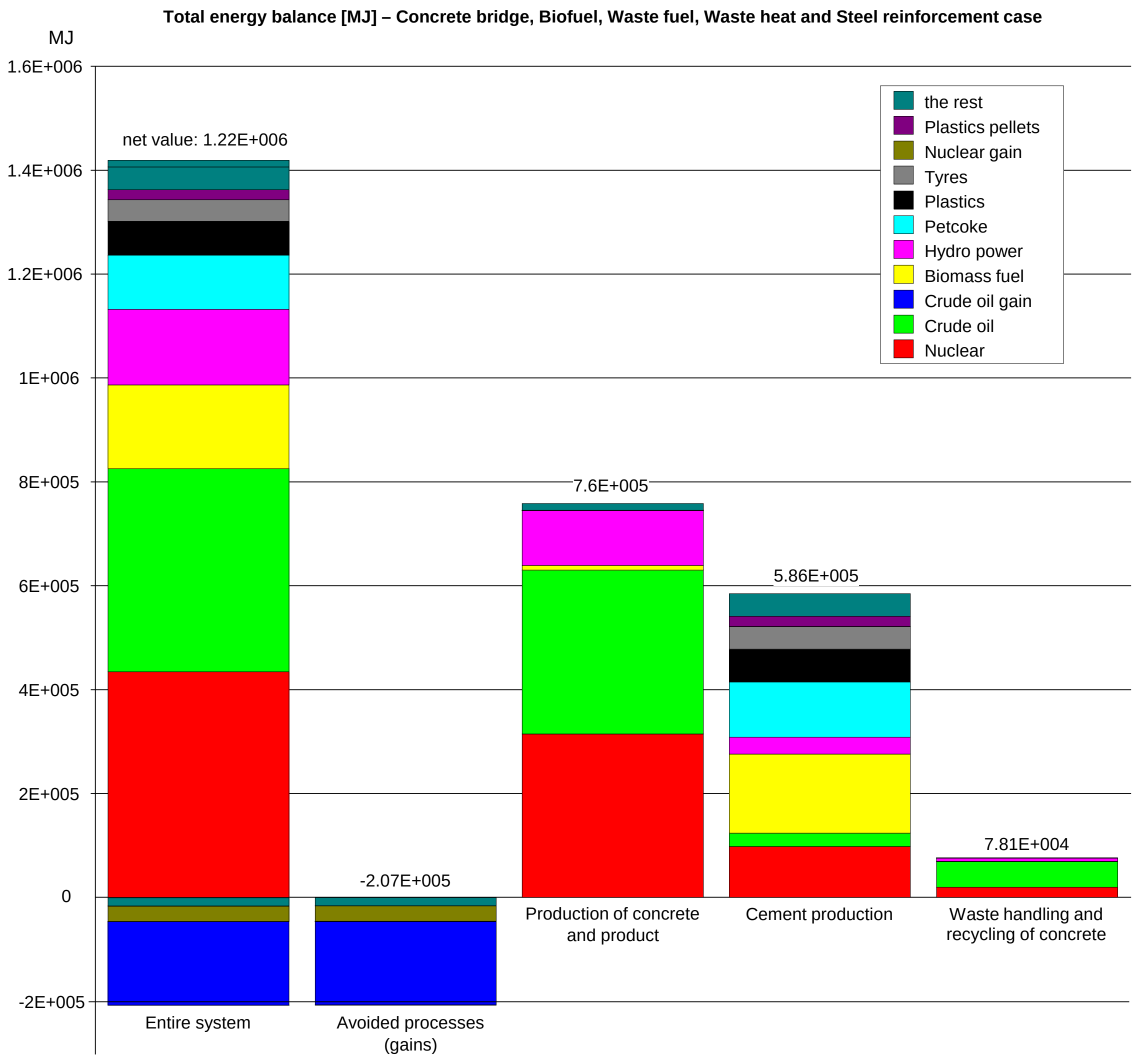

Figure 23 Total energy balance including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. The figure shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

Table 12 Total energy balance including waste fuels for the concrete bridge shown divided into different process groups and for the entire system. The table shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. (Figure 23 in tabular form.)

Fuels (MJ)	Avoided processes (gains)	Production of concrete and product	Cement production	Waste handling and recycling of concrete	SUM
Nuclear		316 379	99 972	20 390	**436 742**
Crude oil		315 928	24 428	49 813	**390 169**
Crude oil gain	-162 644	0	0	0	**-162 644**
Biomass fuel		8 003	152 299	516	**160 818**
Hydro power		105 643	33 333	6 809	**145 785**
Petcoke		0	105 962	0	**105 962**
Plastics		0	63 755	0	**63 755**
Tyres		0	41 994	0	**41 994**
Nuclear gain	-29 980	0	0	0	**-29 980**
Plastics pellets		0	20 489	0	**20 489**
the rest	-14 213	13 556	43 338	559	**43 240**
SUM	**-206 838**	**759 509**	**585 570**	**78 087**	**1 216 329**

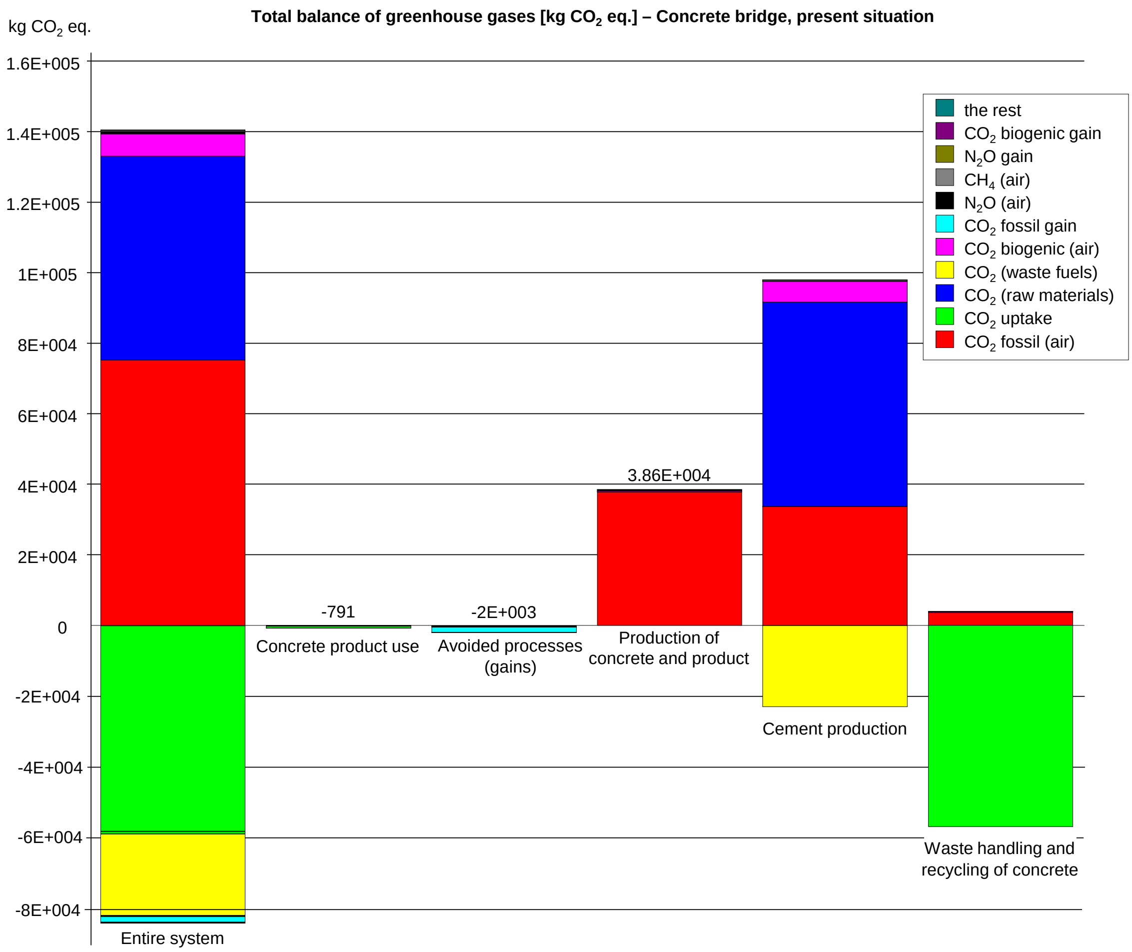

Figure 24 Total greenhouse gas emissions and uptake in present production for the concrete bridge, shown divided into different process groups and for the entire system. The biogenic CO_2 emissions are thus also included in the figure. <u>The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information.</u> The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

Table 13 Total greenhouse gas emissions and uptake in present production for the concrete bridge, shown divided into different process groups (Figure 24 in tabular form.). The biogenic CO_2 emissions are included as well as CO_2 from waste fuels. The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information. The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

Greenhouse gases (kg CO_2 eq.)	Concrete product use	Avoided processes (gains)	Production of concrete and product	Cement production	Waste handling and recycling of concrete	SUM
CO_2 fossil (air)	0		37 951	33 876	3 648	**75 474**
CO_2 uptake	-791		0	0	-57 240	**-58 031**
CO_2 (raw materials)	0		0	58 031	0	**58 031**
CO_2 (waste fuels) [1)]	0		0	-22 921	0	**-22 921**
CO_2 biogenic (air)	0		367	5 911	36.4	**6 315**
CO_2 fossil gain	0	-1 647	0	0	0	**-1 647**
N_2O (air)	0		308	144	6.3	**459**
CH_4 (air)	0		19.1	283	0.6	**302**
N_2O gain	0	-276	0	0	0	**-276**
CO_2 biogenic gain	0	-53.5	0	0	0	**-53**
the rest	0	-20.4				**-20**
SUM	**-791**	**-1 996**	**38 646**	**75 323**	**-53 548**	**57 632**

[1)] CO_2 (waste fuels) is given as an additional value. The emissions is included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. Thus, the table values include the CO_2 (waste fuels) with a negative value which show the results when no CO_2 emission has been included for the waste fuels and thus all CO_2 emissions has been allocated to the previous product that generated the waste.

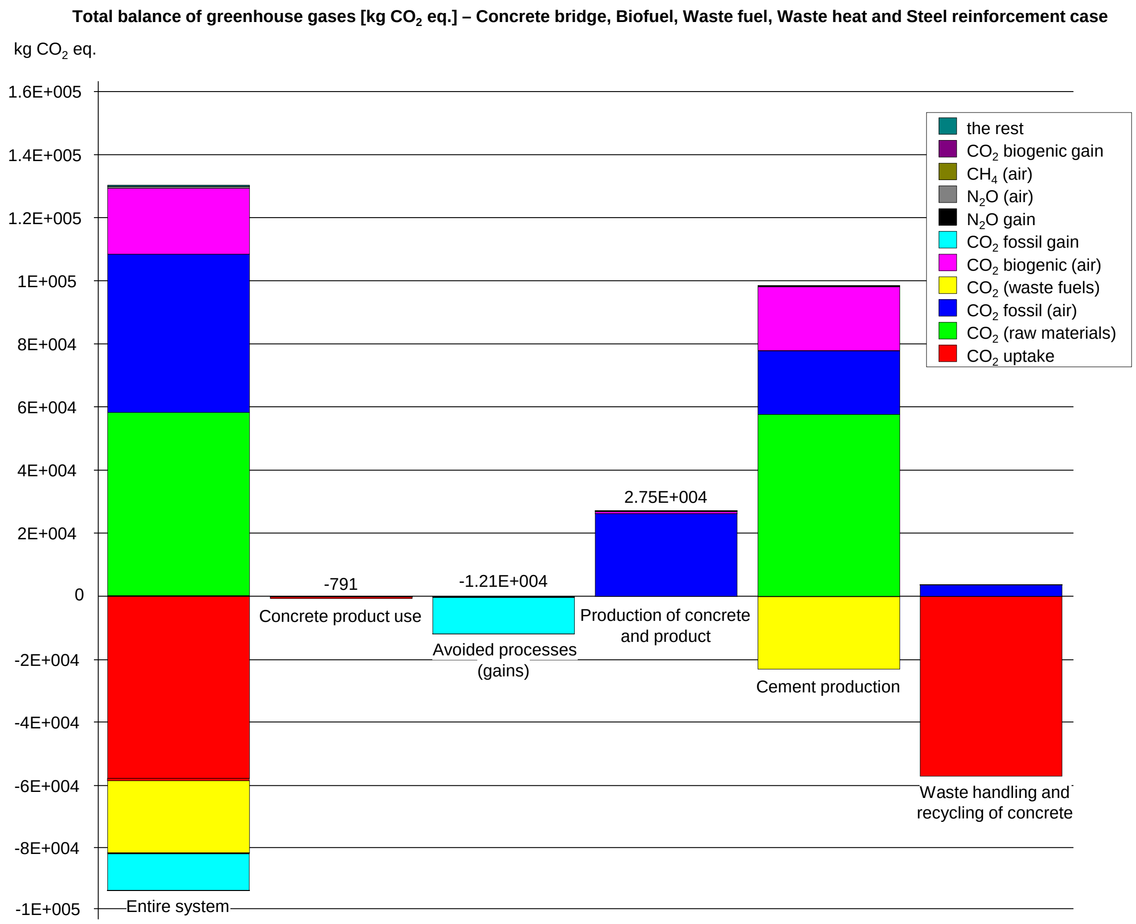

Figure 25 Total greenhouse gas emissions and uptake for the concrete bridge, shown divided into different process groups and for the entire system. The figure shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. The biogenic CO_2 emissions are thus also included in the figure. <u>The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information.</u> The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

Table 14 Total greenhouse gas emissions and uptake for the concrete bridge, shown divided into different process groups (Figure 25 in tabular form.). The figure shows the new scenario case with coal replaced with biofuel in the cement kiln, waste fuels as today, increased waste heat recovery and steel reinforcement produced by Swedish EAF. The biogenic CO_2 emissions are included as well as CO_2 from waste fuels. The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information. The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2.

Greenhouse gases (kg CO_2 eq.)	Concrete product use	Avoided processes (gains)	Production of concrete and product	Cement production	Waste handling and recycling of concrete	SUM
CO_2 uptake	-791		0	0	-57 240	**-58 031**
CO_2 (raw materials)	0		0	58 031	0	**58 031**
CO_2 fossil (air)	0		26 551	19 913	3 648	**50 111**
CO_2 (waste fuels) [1)]	0		0	-22 921	0	**-22 921**
CO_2 biogenic (air)	0		565	20 271	36.4	**20 872**
CO_2 fossil gain	0	-11 520	0	0	0	**-11 520**
N_2O gain	0	-469	0	0	0	**-469**
N_2O (air)	0		328	111	6.3	**446**
CH_4 (air)	0		22.6	125	0.6	**149**
CO_2 biogenic gain	0	-53.5	0	0	0	**-53**
the rest		-32.5				**-33**
SUM	**-791**	**-12 075**	**27 466**	**75 529**	**-53 548**	**36 581**

[1)] CO_2 (waste fuels) is given as an additional value. The emissions is included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. Thus, the table values include the CO_2 (waste fuels) with a negative value which show the results when no CO_2 emission has been included for the waste fuels and thus all CO_2 emissions has been allocated to the previous product that generated the waste.

8.3 Scenario: Effects of cement and concrete composition and of product design

In this chapter, we will take closer look at the energy and CO_2 effects of the following measures:

- Changes in cement composition.
- Altered concrete composition.
- Design of concrete products and CO_2 uptake.

In chapter 7, four different concrete products with different geometric forms and different types of concrete were analyzed. From these analyses, it is clear that both the geometric form and the concrete type can play an essential role in the CO_2 balance of a concrete product. The concrete composition can change the CO_2 balance in two ways. It can change the CO_2 uptake rate in the concrete and it can change the CO_2 balance in the production of the concrete/cement. The geometric form determines the surface to volume ratio and thereby the transport distances for CO_2 in the carbonation process of the concrete product. This has a major influence on the overall carbonation rate of a concrete product. A thin geometric form (e.g. a concrete roofing tile) result in short transport distances for CO_2 in the concrete and a high degree of carbonation during the lifetime of the product. A thicker concrete construction (e.g. a concrete bridge) gives only a small surface carbonation during the lifetime of the product and most of the remaining carbonation will occur in the waste-handling phase of the concrete product. This effect is well illustrated in chapter 7.

Can the design promote CO_2 uptake? The answer to this must be yes, but to a limited extent. First of all, it mainly shift the uptake between the use phase and the waste phase of the product. This can however be a tool to speed up the CO_2 uptake. However, the uptake in the use phase is usually relatively small and the design constrains are many due to other aspects then CO_2 uptake so it will probably not have any major effects. Design measures in order to change the concrete surface environment (such as rain shelter, CO_2 permeable cover etc.) can however be implemented more easily and may have some effect on the CO_2 uptake during product lifetime.

The effect on the CO_2 uptake of changing from the bridge example (construction cement) to the house frame example (building cement) is also shown in chapter 7 and covered in other reports in this project[4]. The difference in uptake rate between the bridge and the house frame can mainly be explained by differences in e.g. water/cement ratio (wct) and the different concrete surface conditions for the two objects. The differences due to cement type specifically are relatively small.

In this chapter, we will instead focus on a new proposed fly ash cement and analyze the effects with respect to cement production. The composition of the new base cement, which will be used as ordinary building cement, is shown below.

Clinker	75 %
Fly ash	15 %
Limestone	5 %
Gypsum	5 %

The new cement contains fly ash that will replace clinker. In this way, energy use and CO_2 emissions for cement production can be reduced. Fly ash is a hydraulic waste material from coal combustion. Its property cannot be compared to clinker but fly ash can be used as a replacement for clinker to a limited extent. This CO_2 reduction measure is very sensitive because it can directly influence the quality of the concrete. Thus, when clinker substitution materials are used, the quality control of the concrete is essential. From an environmental point of view, the fly ash can be added both in the cement and directly in the concrete with the same environmental performance. From a society perspective, the concrete quality aspects are very important and it is important that the production of concrete will not be used as a way to get rid of different wastes. The quality of the concrete must be guaranteed both when fly ash is added to concrete or cement. The quality control can eventually be easier and safer if the control can be restricted to the cement production. Otherwise, the quality control has to include all concrete producers, also local on-site production and small producers. Concrete is used in many large infrastructure investments in the society and a quality reduction of these investments with a resulting increase in maintenance and shortening of product lifetime can have severe negative effects on the society and increase the environmental load (energy/resource use and emissions).

Also for fly ash, there is an allocation aspect. Fly ash is a waste material from a coal combustion plant producing usually electric power and heat. Normally, all emissions and resource use from the coal combustion plant is allocated to the two products, electric power and heat in the coal power plant. No emissions and resource use is thus allocated to the fly ash because it is treated as a waste. As an alternative, the fly ash can be handled as a product from power plant and some of the emissions and resource use at the power plant can be allocated to the fly ash. In that case, an allocation principle for fly ash has to be developed by which one can calculate the energy use, resource use and emissions for the fly ash. This will also increase the environmental load on concrete compared to zero allocation on fly ash. This line of argument is also applicable for other waste additives in the concrete such as blast furnace slag.

In this chapter, we have analyzed the effect of using the new type of cement. The new cement is assumed to be used as building cement. No allocation burden has been added on the fly ash in this case. The site cast house frame from chapter 7.2 has been used also in this example (all fuels included). The same CO_2 uptake rate as for the ordinary building cement has been assumed[11]. The maximum potential uptake of CO_2 has been adjusted (decreased) because the fly ash contains very little calcium and other materials that can take up CO_2. In this case, we have assumed no CO_2 uptake in the fly ash.

The results from the analysis are shown in Figure 26 - Figure 29. As shown in the figures, the effects of replacing clinker with fly ash can be found in the cement production. For the house frame example, the energy use is reduced from 2 180 000 MJ to 2 050 000 MJ but at the same time, the avoided emissions are reduced from -304 000 MJ to -299 000 MJ. This gives a net energy reduction from 1 876 000 MJ to 1 751 000 MJ. This corresponds to a 6.7 % energy reduction in the cement production. Expressed per tonne clinker, this gives an energy reduction from 5 300 MJ/tonne clinker to 4 947 MJ/tonne clinker[12] and expressed per volume concrete[13] a saving of 90 MJ/m^3 concrete.

The corresponding change in greenhouse gas emissions is from 347 663 kg CO_2 eq. to 318 349 kg CO_2 eq. corresponding to an 8.5 % emission reduction. These figures include Cement production (CO_2 from waste included) and Avoided processes. Expressed per m^3 concrete, the change will be from 250 kg CO_2 eq./m^3 to 229 kg CO_2 eq./m^3. The corresponding maximum potential uptake changes from -210 844 kg CO_2 eq. to -192 383 kg CO_2 eq. The potential final net result change is thus from 136 819 kg CO_2 eq. to 125 966 kg CO_2 eq. which corresponds to a 7.9 % CO_2 net reduction.

The reduction potential is thus relatively small for this measure and if the measure reduces the concrete quality and by that can shortening the lifetime and increase the maintenance of the concrete product, this measure can be questioned.

[11] No measured uptake data for CO_2 have been found for fly ash cement.
[12] The clinker use for this house frame has been calculated to 353951 kg.
[13] The concrete volume of the house frame is 1388 m^3.

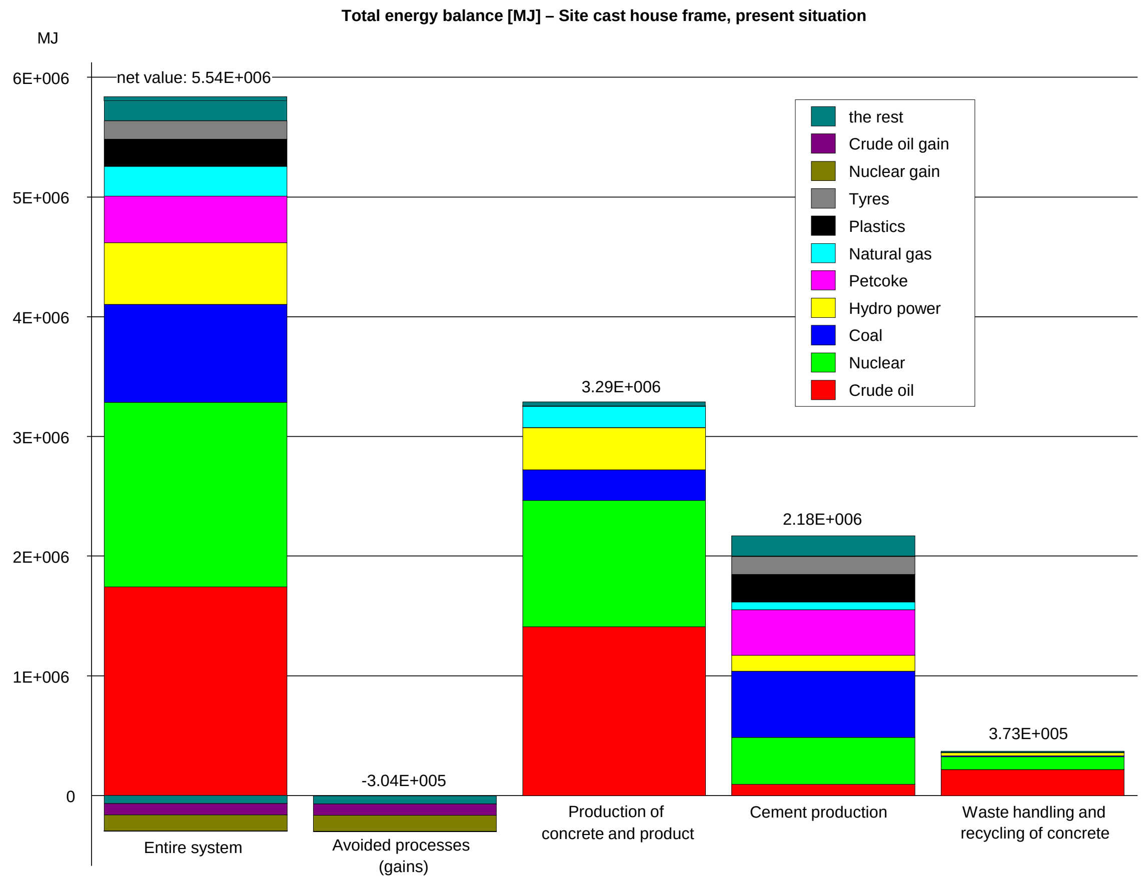

Figure 26 Total energy balance in present production including waste fuels for the site cast house frame shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

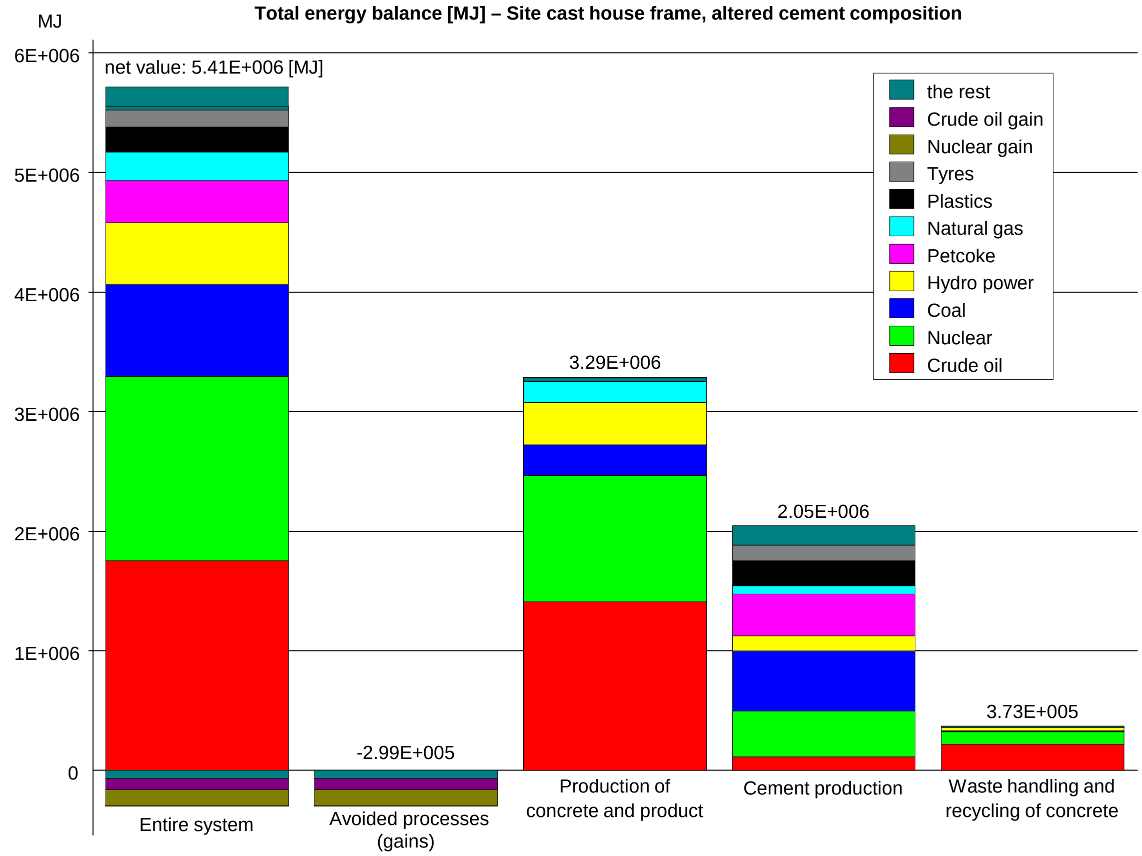

Figure 27 Total energy balance including waste fuels for the site cast house frame produced with an altered cement composition shown divided into different process groups and for the entire system. The energy net value for the entire system shows the value when avoided energy use has been subtracted.

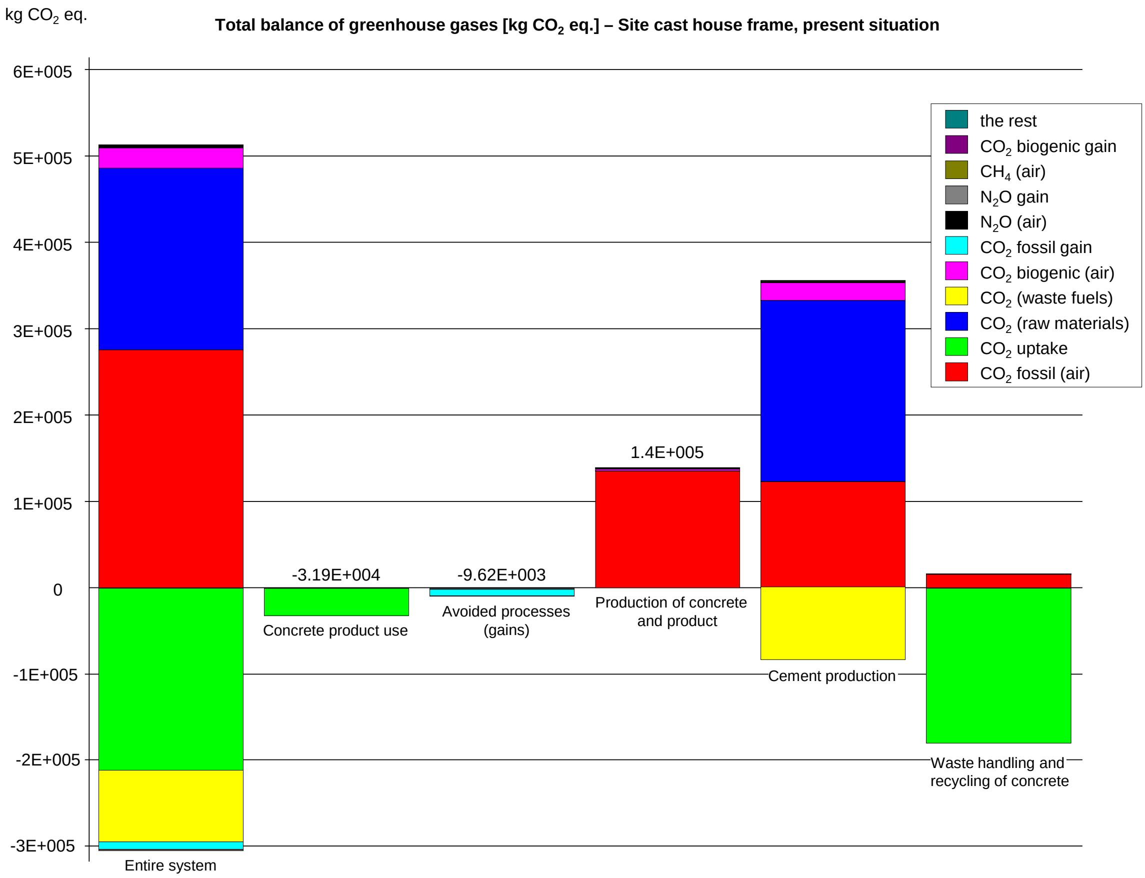

Figure 28 Total greenhouse gas emissions and uptake for the site cast house frame, shown divided into different process groups and for the entire system. The biogenic CO_2 emissions are thus also included in the figure. <u>The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information.</u> The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2. The figure shows the present situation.

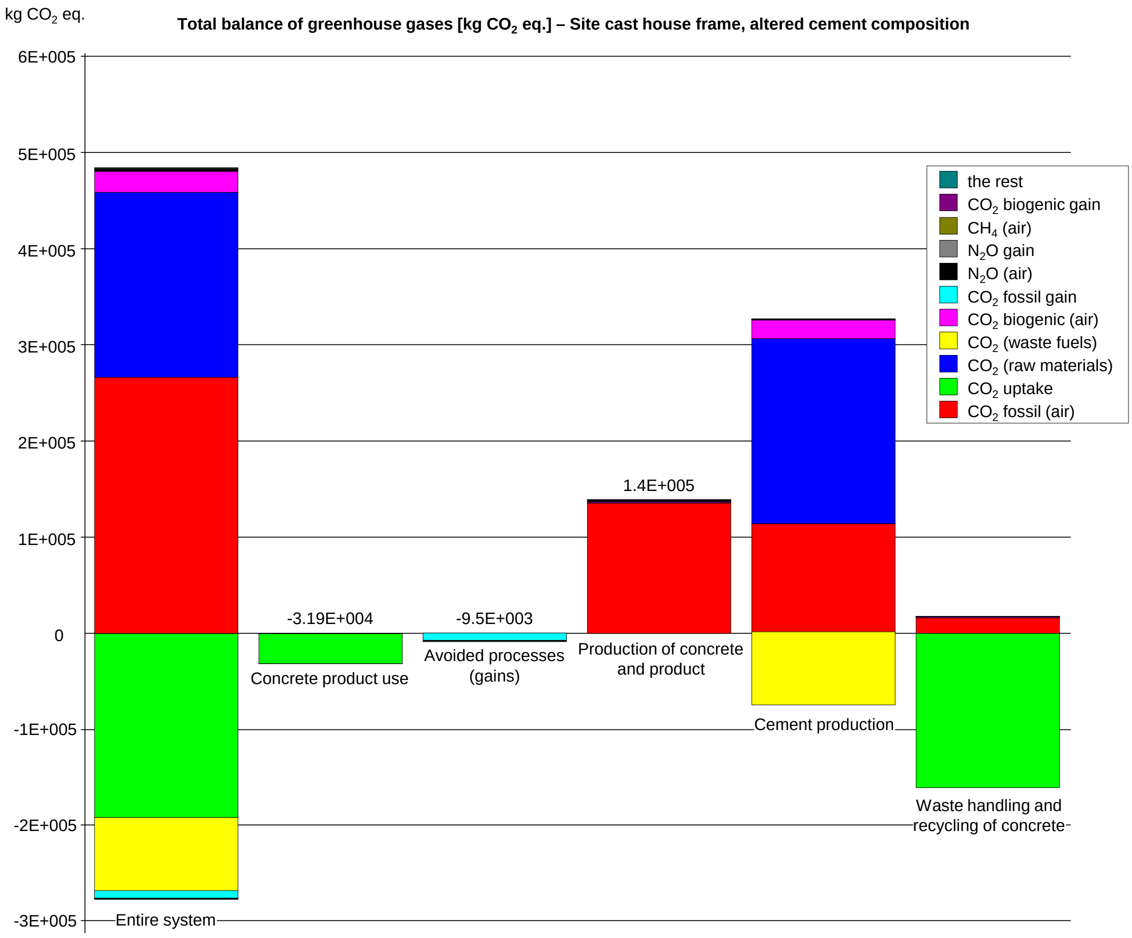

Figure 29 Total greenhouse gas emissions and uptake for the site cast house frame, shown divided into different process groups and for the entire system. The biogenic CO_2 emissions are thus also included in the figure. <u>The CO_2 emissions emanating from incineration of waste fuels are shown in the figure as additional information.</u> The CO_2 (waste fuels) emission is also included in CO_2 fossil (air) and in CO_2 biogenic (air) respectively. The CO_2 uptake for waste handling shows the maximum potential uptake of CO_2. The figure shows situation for the altered cement composition.

8.4 Scenario: Effects of waste management

As shown in chapter 7, the different example products have a different CO_2 uptake behavior. Some concrete products, like the concrete roofing tile, have a very high CO_2 uptake during its lifetime and only a minor CO_2 uptake remains for the waste phase of the product. However, for the majority of the concrete products, the CO_2 uptake in the use phase of the product is relatively small compared to the maximum potential uptake and a large CO_2 uptake potential remains for the waste phase of the product. From, for example, Figure 8 we can see that the uptake of CO_2 in the waste phase is an essential aspect of the entire CO_2 balance for the product. It is thus important to analyze the different waste handling strategies in terms of CO_2 uptake.

After the lifetime of the concrete product, the product is usually demolished and crushed and the steel reinforcement is regained. The steel reinforcement goes back as scrap to the steel recycling process usually in an electric arc furnace (EAF). This is an important part in order to save iron resources and to reduce energy resource use and CO_2 emissions especially if the EAF is driven by low CO_2 emission electric power. The energy use for crushing/sieving has been estimated to 21.2 MJ electric power/tonne of crushed concrete or 1 liter diesel oil/tonne of crushed concrete if a mobile diesel driven crusher is used. For the bridge example (Figure 22) this corresponds to 13 511 MJ electric power[14] or 22 509 MJ diesel oil[15] (see notes for the comparison in the figure). After crushing and removal of the steel reinforcement, the remaining crushed concrete can be used for many different purposes. Today, it is mainly used as landfill material in different construction projects or as aggregate base for roads, houses etc.

In the LCA model, different alternatives for concrete waste handling have been added in order to analyze different CO_2 behavior. The alternatives are:

1. Crushing of demolished concrete including steel recycling and use as replacement for crushed rock in for instance road bases (main use today and in the examples).
2. Landfill[16] of demolished concrete (without crushing and steel recycling).
3. Crushing of demolished concrete including steel recycling followed by an accelerated CO_2 uptake process. The processed concrete can then be used to replace aggregates e.g. in road bases or in new concrete.
4. Crushing of demolished concrete including steel recycling and use as aggregates in new concrete.

1. *Crushing of demolished concrete including steel recycling and use as replacement for crushed rock in for instance road bases*

This method is the most common waste handling method for concrete in Sweden today. It requires only some energy for crushing and sieving (shown above and in the notes) but includes the opportunity to recover the steel reinforcement bars for steel recycling. The uptake of CO_2 occurs in the regular storage of the material and in the use phase of the crushed aggregates (e.g. in a road base). To promote this uptake, the application of the crushed concrete needs to be adapted and improved for CO_2 uptake. This means that the crushed concrete needs to be used in such a way that CO_2 containing air can penetrate the entire volume of crushed materials. The concrete thickness has to be balanced against the size of the aggregates (see chapter 6.4). The practical meaning of this is most likely that the concrete needs to be crush and sieved in such a way that the particle fraction is large enough to allow air to circulate inside the ballast and that the end surfaces of the installations is covered with materials that can allow air to flow into the construction (e.g. a layer of crushed stone materials). This technique is not fully developed or tested so the CO_2 uptake rate in the construction cannot be verified. An estimation is however that approximately 70 % of maximum potential uptake in the waste phase can be absorbed during a time period of 20 years.

[14] 13 511 MJ electric energy corresponds to, in total, the following resources: 20 357 MJ nuclear, 6797 MJ hydro power, 515 MJ biomass fuel, 442 MJ coal, 340 MJ crude oil, 84 MJ natural gas and 32 MJ wind energy. The corresponding greenhouse gas emissions are: CO_2 fossil (air) 76.9 kg, CO_2 biogenic (air) 36.3 kg, N_2O 3.7 kg CO_2 eq., CH_4 0.4 kg CO_2 eq.

[15] 22 509 MJ diesel oil corresponds to, in total, the following resource: 23 860 MJ crude oil. The corresponding greenhouse gas emissions are: CO_2 fossil (air) 1767 kg, N_2O 10.7 kg CO_2 eq., CH_4 1.1 kg CO_2 eq.

[16] In this case, landfill means a useful filling of land area in different construction projects and not a municipal solid waste landfill or a landfill for industrial waste which are seldom used for concrete materials.

This technique offers thus a relatively good uptake potential with a minimum of additional waste handling. Only small adjustments of present waste handling are needed.

2. *Landfill of demolished concrete (without crushing and steel recycling)*

Direct landfill of concrete as waste material is today rare in Sweden due to high landfill fees and the lack of steel recycling. If large concrete pieces from demolition are landfilled in a landfill for ordinary waste, the uptake of CO_2 in the concrete will be slow. Ordinary landfills are usually, sooner or later, covered with soil which will slow down the CO_2 uptake rate. The positive effects of steel recycling and use of crushed concrete as replacement for rock resources will be lacking. The only positive effect is that only demolition energy is used and no energy for crushing.

3. *Crushing of demolished concrete including steel recycling followed by an accelerated CO_2 uptake process. The processed concrete can then be used to replace aggregates e.g. in road bases or in new concrete.*

This method is very similar to method 1. but instead of a passive uptake of CO_2 in the crushed materials during a use phase of the concrete the concrete will be exposed for an accelerated uptake of CO_2 in some kind of process. In the time of writing, there are no such processes developed. One can think of everything from controlled storage in the waste handling system to more active processes involving smaller particles and high CO_2 concentration, which will increase the CO_2 uptake rate. The secondary use of the produced product from the process is however important so this can limit the uptake rate. Anyhow, such active processes always require energy and will increase the CO_2 emissions in the waste phase. No estimation of energy use or CO_2 emissions has been possible to do in this project.

4. *Crushing of demolished concrete including steel recycling and use as aggregates in new concrete*

In this method, the crushed waste concrete is used in new concrete to replace ballast materials (crushed rock). It can be used both for fine fractions and for larger particle sizes of the concrete. Recycling of waste concrete to new concrete is today used in locations lacking in rock resources. Relatively small amounts of waste concrete are used for this purpose in Sweden today. The amount of virgin ballast that can be replaced varies with concrete quality and application. As a rule of thumb, one can say that 15 % of the crushed ballast can usually be replaced without any problem in most cases. 100 % replacement can be achieved in rare cases and for special applications.

The effect of an increased use of crushed concrete in new concrete depends somewhat on the baseline assumptions. Both rock based ballast and old concrete ballast need to be crushed so in that respect there are small differences. However, if we assume that the waste concrete needs to be crushed to recover the steel reinforcement the energy for crushing of rock can be save by replacing rock-based ballast with crushed concrete. On the other hand, if one assumes that the waste concrete is not crushed, one loses the positive effect of the steel recycling process i.e. the difference between recycled steel produced by an electric arc furnace process (EAF) and a virgin steel production from iron ore in a blast furnace process. However, there are two more significant effects. The first is the saving of rock resources by recycling of crushed concrete but that saving can also be achieved by replacing ballast externally in, for example, aggregate bases as in case 1. The second effect is that by using the crushed concrete, the uptake of CO_2 is stopped and postponed to the next product cycle.

8.5 Scenario: Carbon Capture and Storage (CCS)

Carbon capture and storage (CCS), also known as CO_2 sequestration, is a technical method to prevent form CO_2 to enter the atmosphere and thereby contribute to global warming. The process is based on capturing carbon dioxide (CO_2) from large point sources, such as power plants or cement kilns, and storing it in such a way that it does not enter the atmosphere for a very long time. This technique is based on scrubbing the exhaust gases from CO_2, transport CO_2 to a permanent storage and store the CO_2 in such a way that it does not enter the atmosphere.

In post combustion capturing, the CO_2 is removed (captured) after combustion of the fossil fuel. This is usually the case for large combustion plants where the CO_2 is scrubbed from the flue gases. A high concentration of CO_2 in the flue gases is an advantage. The CO_2 concentration in flue gases from cement kilns is relatively high because CO_2 is released from both the burning fuels and the raw meal (limestone, $CaCO_3$). The technology is well known but usually applied in smaller scale than this application. In a CO_2 scrubbing process, approximately 80-90 % of the CO_2 in the flue gases from the cement kiln can be captured. The technique can be applied both on fossil-based plant and on biofuel-based plants. If biofuel is used, the CO_2 reduction effect can be twofold, the CO_2 is removed and stored and the CO_2 released from the combustion of the biofuels is taken up by the new growing forest. However, the CO_2 capture and compressing process also requires energy in form of electric power and heat. Some chemicals and materials are also needed. Some of the required heat can be covered with waste heat from the exhaust gases of the cement kiln.

No exact figures of the energy and chemical consumption are available today for the cement industry but research activities are going on in this field. In addition, there is also energy consumption for the transport of the CO_2 to the storage and storage activities. The location of CO_2 storages is usually dependent on some geologic formation such as oil/natural gas wells or aquifers while the cement plants are located near limestone resources. Eventually, this can cause relatively long transports for the CO_2. A rough energy estimation for the CCS process can be that this process will increase the energy use in the range of 10 % - 90 % of the energy use in the cement kiln.

If we apply the CO_2 reduction potentials and the rough energy approximation on the example bridge in chapter 8.2 (Figure 22 and Figure 24) we end up with the following estimation:

CO_2 reduction (CO_2 emission from cement kiln 94 708 kg): 75 766 – 85 237 kg CO_2
Energy increase for the CCS process (energy to cement kiln 410 544 MJ): 41 054 MJ – 369 490 MJ
Overall energy efficiency for the CO_2 reduction: 0.5 – 4.9 MJ/kg reduced CO_2

Note that this is just a calculation example and shall not be used for any practical application. The technical situation is for the moment uncertain.

9 The CO_2 balance of concrete and its greenhouse gas impact

So far, we have analyzed the CO_2 balance for different specific concrete products. This gave us a good picture of how the CO_2 balance look like from a product perspective and this knowledge has to be the basis for further calculations. However, the main question is – How does the use of concrete in the society influence the CO_2 concentration in the atmosphere?

In a product perspective, CO_2 is released in the production process of the product. These emissions are released in a relatively short period of time (from weeks to a few years). CO_2 is then taken up by the product during its lifetime (typically 50-100 years). The remaining CO_2 will then be taken up in the waste/secondary product phase of the product. The length of time and CO_2 uptake rate for this phase can vary and depends on the waste management strategy. However, this information says little about the entire CO_2 concrete balance in the society today. In more than 100 years, concrete products have been produced in the society. This production has resulted in a yearly CO_2 emission. The concrete product production has also resulted in a large number of concrete products. This stock of concrete products has a yearly uptake of CO_2 during its lifetime. Each year, a specific number of concrete products are wasted and crushed. The wasted stock of concrete also has a yearly uptake of CO_2 both as waste and as secondary products. During the years, the CO_2 balance for concrete products will form a varying balance where one have CO_2 emissions from production of new concrete products and uptake of CO_2 in the stock of concrete products and concrete waste every year. The greenhouse gas effect of using concrete as a material in the society is thus the net emission from this balance each year.

The calculation of this net CO_2 emission from concrete use in the society is complex but necessary to achieve a correct picture of the greenhouse gas characteristics of this construction material. In addition to the CO_2 emissions and uptake for the concrete material, there can also be emissions and savings related to the use of concrete products such as emissions and energy use for a concrete houses with different characteristics compared to other construction materials for houses. Such effects have not been included in this study. Only the effect of the pure concrete has been included. The emissions from concrete use each year as a construction material can be obtained from statistic information of cement or concrete production. Both direct emission data from the production and calculated data from emission models can be used. A system perspective or a direct emission perspective from the production can be applied. The yearly uptake of CO_2 in the concrete stock in the society needs to be calculated. This CO_2 uptake needs to be calculated by a computer model. The model will probably be a semi-empirical model including data for quantification and characterization of concrete surface areas in the society as well as CO_2 uptake data for different concrete surfaces. The concrete surface calculations can for example be based on known area/volume ratio for different concrete products. The uptake rate also varies with time for a specific product. This has to be taken into account in the calculations.

In other parts of this CO_2 project, a computer model has been developed that can calculate the CO_2 uptake for a country, based on information that is available in most countries[5]. The model has then, as an example, been applied to Sweden. The development of this type of calculation models is important to obtain a correct picture of the concrete material. A very practical application is for the international CO_2 reporting of greenhouse gases to IPCC and for regulations connected to, for example, UNFCCC. Today, no CO_2 uptake in concrete is taken into consideration.

10 Legal and economic aspects of CO_2 reduction measures

As we have seen in this study, an overall system perspective is very important for the understanding of CO_2 and energy related aspects of concrete and these aspects may be crucial for the view of concrete as a material in the future. It is therefore important that these aspects will be considered when assessing various materials and in strategic considerations of building materials in the society. This also implies an opening and integration of these aspects in the legal control systems of CO_2. This also includes international CO_2 systems such as national greenhouse gas reporting (IPCC) and the Kyoto protocol. Also for applications in for example Environmental Impact Assessment (EIA), an overall system approach can be applied. In that case, an emission in the production will be taken up later on in the product chain. It is thus important to cover the entire product chain and not only the production when assessing production of different materials. An equivalent example from another material is when environmental improvements in fuel production cause increased emission in the production but decreased emissions when using the fuel in, for example, the traffic. Also in this case an overall perspective in the calculations and in the assessment is needed.

However, a system approach introduces other legal difficulties. One important question is - Who is responsible for a CO_2 emission and who can take advantage of the CO_2 uptake in the product and in the concrete waste? A supplementary question to this is - How does export and import of cement influence the CO_2 calculations? For the national emission calculations, the present praxis is that emissions that take place in one country also are accounted in that country. Most likely, the uptake will be handled in the same way. The national CO_2 calculations are centralized for each county and based on emission reporting from the emission sources and other calculation methods. In calculations of the CO_2 balance for single products or materials, the calculation situation is more difficult especially when handling a comparative situation between different products or materials. The production situation is usually relatively clear concerning the emissions. The other parts of the life cycle are more difficult to handle. From a decision/comparative point of view, it can be justified that the entire life cycle chain is included for a material or a product even if the uptake also can be allocated to the owner of the product during the products lifetime or to the waste owner. A problem is that in many cases, neither the product owners nor the waste owners are involved in any CO_2 reporting system. Perhaps, can an upstream allocation be applied to the CO_2 uptake so that the CO_2 uptake is allocated to the cement and concrete product production. These are complicated issues and have not been fully analyzed in this study. In this study, we can only highlight some of the legal issues related to the CO_2 balance of entire production and use systems.

The economic aspects of CO_2 reduction measures are also complex and depend very much on the type of measure and the specific production situation. In addition, there are aspects concerning the specific CO_2 costs such as CO_2 tax and CO_2 trading systems. An aspect for the later cost is how these costs are handled in relation to the CO_2 uptake in both the concrete product and in the concrete waste. This depends very much on the legal acceptance of the CO_2 uptake. No specific economic analysis has been possible to accomplish within the framework of the project due to the complexity of the issue and the high requirements that must be applied for such an analysis. Large scale strategic measures like implementation of Carbon Capture and Storage (CCS) and location of cement production plants are always difficult to analyze in economic terms. Also for the economic analysis, it is important to have a system perspective where all the different costs are analyzed and assessed. Life Cycle Cost (LCC) is a method that can be used for this type of analyses.

11 Discussion and conclusions

In chapter 7, we have seen that different concrete products already today show different characteristics concerning energy use and greenhouse gas emissions and in chapter 8, we have analyzed several CO_2 reduction measures and we can conclude that there are several possible ways to reduce greenhouse gases for cement and concrete products but also society consequences of the measures. In this chapter, we will try to summaries the results and highlight some of the overall strategic possibilities.

The analyses from chapter 8.2 and Figure 22 - Figure 25 can again be a good start for an overall analysis. The possibilities for energy savings are several in the entire systems. In the cement production, the energy reduction is focused on the cement kiln. General energy saving potentials in the process depends on the present energy efficiency of the process but for a modern plant, it can be difficult to achieve larger savings (> 10 %) but smaller savings (< 3 %) can usually be achieved. It really, depends on the technical standard of the plant. However, an important aspect is the possibility to recover waste heat from the plant. The larges obstacle for this method seems to be to find a use for the heat. For this reason, many plants have no energy recovery. A result of this is also that technical methods for improved heat recovery in the plants do not show a strong development. It is also relatively difficult to estimate how much waste heat that it is possible to recover from a plant. Electric power production can be integrated but a large amount of heat will still remain. A better energy integration in the society could improve the situation. If the carbon capture and storage (CCS) techniques will be applied, some of the waste heat can be used in that process but the overall energy use for the cement production will be significantly increased with the CCS technology of today.

In addition to the energy saving aspects, there are also changes in energy resource use (fuels). The direction is especially from non-renewable energy resources to renewable energy resources. For the bridge example, a change from coal to biomass fuels has been used in order to exemplify an improvement towards a more sustainable fuel with a lower CO_2 impact. Another energy resource aspect is the use of waste fuels in order to reduce the use of primary fuels. All these measures have a saving effect on the use of non-renewable primary fuels such as coal, crude oil and natural gas.

The energy use for the production of concrete and construction work for the bridge is surprisingly high. In the previous analyses, we have tried to analyze the effect of changing production process of the steel reinforcement. This has actually very little effect on the energy use for the Electric Arc Furnace (EAF) process. The effect can mainly be found in the fuel use for electric power production. Thus, the change in steel production had small effects on the overall energy use but reduce the use of fossil fuels significantly. The effect of changes in concrete and cement composition is difficult to analyze. First of all, quality requirements on the bridge (or many concrete products in general) limit the possibilities to change or reduce the quality of the concrete. Secondly, it is difficult to fully analyze the energy effect of a reduced quality of concrete. If such a quality change will change the lifetime of the product or increase the maintenance of the product during its lifetime, these effects have to be taken into consideration. No such analysis has been performed in this study. However, from the previous analyses in this study we have shown that the energy saving potential is relatively small for this measure so only a small increase in maintenance or a small shortening of lifetime for the product will erase the positive effect of such a reduced quality of the concrete. The economic effects of poor concrete quality can be even more negative than the energy balance. Further analysis can show the full potential of this CO_2 reduction measure.

The energy use for waste handling is small and it is important to keep it small and to develop processes that improve CO_2 uptake in the waste concrete but not increase energy use in the waste-handling phase.

By the different energy saving methods covered in this study and with the assumed available waste heat, an energy reduction for the bridge from 1 388 311 MJ to 1 216 329 MJ can be achieved. This corresponds to a reduction of 171 982 MJ (equivalent to 4872 litre diesel oil). Expressed per volume concrete, this corresponds to 631 MJ/m^3 concrete[17] (equivalent to 18 litre diesel/m^3 concrete). In addition to this, there can thus be energy savings in the concrete production, in the cement kiln and in the concrete product construction work. By the measures taken in this example, both coal use and use of natural gas has been reduced to a minimum. Both the use of nuclear power and hydropower has been increased due to the increased use of Swedish electric power but both of these energy resources have low specific CO_2 emissions.

The conditions for greenhouse gases are somewhat more complex than the energy situation. The greenhouse gas situation is shown in Figure 24 and Figure 25. The CO_2 emission from the raw material (raw meal) is for the bridge 58 031 kg (212.8 kg CO_2/m^3 concrete). This emission does not change unless the composition of cement or concrete change. The emission is a result of a calcination process where CO_2 is driven off. This process is reversible and the reverse process is called carbonation and is thus the process that drives the CO_2 uptake. The theoretic potential uptake has, for this reason, been set to an equal amount that has been driven off in the calcination process. The maximum practical CO_2 uptake is somewhat uncertain but the time factor is important. In a long time perspective, the CO_2 uptake can most likely be close to amount of CO_2 formed in the calcination process. If we can assume that the concrete material is crushed and stored in an optimal way for CO_2 uptake one can, at least from a theoretical point of view, assume a CO_2 uptake close to the theoretical value assuming a waste/secondary product uptake time in the range of 20-100 years in crushed condition.

By the proposed measures, the fossil CO_2 emissions from the entire system are reduced from 75 474 kg (276.8 kg/m^3 concrete) to 50 111 kg (183.8 kg/m^3 concrete) including fossil based CO_2 emissions from waste fuels. A CO_2 reduction of 25 363 kg CO_2. 55 % of this reduction can be attributed to the replacement of coal with biomass fuels in the cement kiln (Cement production) and 45 % can be attributed to the change in steel reinforcement production (Production of concrete and product). The total CO_2 emissions from waste fuels in the cement kiln is 22 921 kg. Of this can 17 189 kg CO_2 be attributed to a fossil fuel origin and 5 740 kg CO_2 be attributed to a biogenic fuel origin. If thus the CO_2 emissions from the waste fuels are allocated to the product that generated the waste instead of the incineration process (cement kiln), a zero allocation can be applied to the CO_2 emissions from the fossil-based waste fuels. In this case, the CO_2 fossil emission from the entire system will be reduced from 58 285 kg CO_2 to 32 922 kg CO_2.

The biogenic CO_2 emissions from the entire system are increased from 6 315 kg CO_2 to 20 872 kg CO_2 including biogenic CO_2 from biogenic based waste fuels. The increased emission can be attributed to the increased use of biomass fuels in the cement kiln. However, biogenic CO_2 emissions is considered to have a zero contribution to the greenhouse effect due to the corresponding CO_2 uptake in growing biomass so the biogenic CO_2 emissions are zero in the greenhouse gas calculations.

[17] The amount of concrete in the bridge is 272.7 m^3.

If thus all greenhouse gases are considered, avoided emissions are included and a zero allocation is applied to CO_2 from fossil waste fuels and for all biofuels, the net emissions are reduced from 115 134 kg CO_2 eq. to 79 526 kg CO_2 eq. The CO_2 share that emanates from the raw material is in both cases 58 031 kg CO_2. If that amount is also considered as a long-term uptake of CO_2 in the concrete (in both the product and the waste phase), the reduction will be from 57 103 kg CO_2 eq. (209.4 kg CO_2 eq./m^3 concrete) to 21 495 kg CO_2 eq. (78.8 kg CO_2 eq./m^3 concrete). This may however require a very long time and may therefore be seen as a theoretical calculation example even if the CO_2 uptake rate is uncertain.

As shown from the analyses in this study there are several possibilities to reduce the emissions of greenhouse gases from cement and concrete products. The possibilities have, in this study, been shown by different examples. A real overall strategy for cement or concrete products has to be developed for each individual case. The examples used in the study are just examples and can be difficult to implement in reality. The purpose of the examples has been to show a development direction and to give inspiration for further work.

An overall strategy for an entire industry sector involves not only the industry but is an integrated part of the society and a responsibility for the development of the society. For example, an appropriate fuel choice for an industry sector can be a strategic choice for the society but also a responsibility for the society and not only for the industry sector. This is shown in, for example, society's view of the use of coal and waste fuels. Should we use coal as fuel, and if so where? How do we promote the use of waste fuel to reduce the use of primary fuels? The society's view and the legal aspects of uptake of CO_2 in concrete is also a similar important aspect.

The study is also an example of a method or an approach that can be used for this type of very complex analyses. The computer model developed in the project has been the most vital tool in the analysis. A personal point of view from this project is to stress the importance of the overall strategic aspects. They are in many cases neglected due to its complexity but the strategic aspects are important to control the development of the details. However, there is no overall strategy without the details and the computer model integrates the details into an overall strategy.

Appendix

Appendix 1: Additional examples of CO_2 uptake from other parts of the overall project

A major goal for the overall project has been to develop a method to calculate the total CO_2 uptake in an entire country. In this way, one can calculate the total CO_2 balance for the concrete material each year on a country basis. If this is combined with an LCA perspective, a complete a picture as possible will be achieved. This methodology has been tested for CO_2 uptake in Sweden. A representative group of concrete products have been selected for the calculation of the total concrete surface area in Sweden. The areas for the representative products have been calculated. The CO_2 uptake for each surface type is known and combined with the cement market shares for each products, an uptake model can be designed.

In this appendix, the concrete products used for the CO_2 uptake model calculations are presented. Table 15 shows the calculated surface areas for each product. These example products have been chosen to represent the entire use of concrete in Sweden with respect to surface areas and have been used for the model calculations which are presented in a scientific paper shown in footnote [[18]]. The uptake calculations are based on the same principles as used in this report.

Table 15 Additional examples: CO_2 uptake area calculations in concrete for application examples used in the overall project[18].

Scenarios		Concrete sleeper		Bridge		Apartment buildings		Office building		Concrete roofing tile		Concrete paving stones		Shotcrete	
		per sleeper		per bridge		per apartment		per m^2 Gross Floor Area (GFA)		per tile		per stone		per m^2	
	Units --->	m^2	Mpa	m^2	Mpa	m^2	Mpa	m^2	Mpa	m^2	Mpa	m^2	Mpa	m^2	Mpa
Surfaces															
Indoor	Without paint	0		0		93	20-25	0.84	30-45	0		0		0	
	Painted surface	0		0		247	20-25	0.61	30-45	0		0		0	
	With tiles	0		0		20	20-25	0.08	30-45	0		0		0	
	Covered with plastics/linolium	0		0		0.3	20-25	0.64	30-45	0		0		0	
	With parquet / laminate flooring	0		0		68	20-25	0.03	30-45	0		0		0	
Slab on ground	With mineral wool	0		0		0.1	30-45	0		0		0		0	
	With closed-cell polystyrene foam	0		0		18	30-45	0.26	30-45	0		0		0	
	Without thermal insulation with shingle/macadam	0		170.8	>45	12	30-45	0.01	30-45	0		0		0	
	Without thermal insulation with sand/gravel	0		0		22	30-45	0.32	30-45	0		1	30-45	0	
Outdoor	Exposed to rain	1.61	>45	43.8	>45	38	30-45	0.06	30-45	0.2	>45	1	30-45	0	
	Sheltered from rain	0.694	>45	422	>45	8	30-45	0		0.15	>45	1.19	30-45	1	30-45
	Total Area (m^2/unit)	2.304		636.6		526		2.85		0.35		3.19		1	
	Volym (m^3/unit)	0.119		277		67.4		0.29		0.002		0.05		0.04	

[18] R. Andersson, K. Fridh, H. Stripple and M. Häglund, Calculating CO_2 Uptake for Existing Concrete Structures during and after Service Life, Environmental Science & Technology, 2013, 47 (20), pp 11625–11633.

Specification and description of the additional products for the total Swedish uptake model.

Concrete bridge
The concrete bridge is already described in chapter 6.3.1.

Concrete roofing tile
The concrete roofing tile is already described in chapter 6.3.4.

Shotcrete
The CO_2 uptake is calculated per m² of shotcrete area. The choice of CO_2 uptake surface is made based on Table 2. Shotcrete is mainly used in rock tunnels. The choice of uptake surface is based on that assumption.
Uptake surface: 3.2 Outdoor structures, sheltered against rain: 2.8 (kg CO_2/m^2) after 100 years. Average thickness of the existing shotcrete in Sweden has been estimated to about 4 cm. Older shotcrete may have a somewhat lower content of cement due to the dry-spraying techniques that was used at that time.

Typical shotcrete composition:

Ingredients	Quantity (kg/m³ ordinary shotcrete)
Aggregate (0-8 mm)	1550
Portland Cement (SR)	480
Silica Fume	20
Water	216
Polypropylene fibers	2
Water/cement ratio	0.45

Surface	m² CO_2 uptake surface/m² shotcrete area	CO_2 uptake (kg CO_2/m^2 uptake surface, 100 år)	CO_2 uptake (kg CO_2/m^2 shotcrete area)
Outside of the shotcrete (sheltered from rain)	1	2.8	2.8
Totalt			**2.8**
Average thickness of the shotcrete:	0.04	m	
Shotcrete volume:	0.04	m³/m² shotcrete	
Area weight of shotcrete:	90.7	kg shotcrete/m² shotcrete	
Specific CO_2 uptake per kg:	0.031	kg CO_2 uptake/kg shotcrete	
Density of shotcrete:	2268	kg/m³ shotcrete	
Specific CO_2 uptake per m³:	70	kg CO_2 uptake/m³ shotcrete	
Theoretical maximum CO_2 uptake in shotcrete:	0.104	kg CO_2/kg shotcrete	
Carbonation share of maximum uptake in 100 years	29.7	%	

Concrete paving stones

CO_2 uptake is calculated per m² paving stone area (top side of the stone). The choice of CO_2 uptake surface is made based on Table 2. Concrete paving stones are mainly used outdoors with surfaces unprotected from rain. The choice of uptake surface is based on that assumption.

Uptake surfaces:

Top surface: 3.1 Outdoor structures, exposed to rain: 0.9 kg CO_2/m^2 after 100 years.

Side and bottom surfaces: These are intermediate positions between the outdoor structures, exposed to rain (0.9 kg CO_2/m^2 after 100 years) and 2.4 slab-on-grade (bottom surface), with sand/gravel (0.1 kg CO_2/m^2 after 100 years). Paving stones, however, are located near the ground surface giving easier access to CO_2 from the air. A mean uptake value has been set to: (0.5 kg CO_2/m^2 after 100 years).

Typical dimensions: 210 mm × 140 mm × 50 mm with a weight of 3.4 kg.

Concrete volume: 0.00147 m³/paving stone

Paving stone area (top surface): 0.0294 m²/paving stone

CO_2 uptake surface area for the paving stone: 0.0938 m²/paving stone

Concrete volume per paving stone area: 0.00147/0.0295=0.05 m³/m² paving stone area

Surface distribution	m² uptake surface/m² paving stone area	CO_2 uptake (kg/m² uptake surface, 100 år)	CO_2 uptake (kg CO_2/m² paving stone area
Top side	1	0.9	0.9
Bottom	1	0.5	0.5
Side edges	1.190	0.5	0.595
Total	**3.190**		**1.995**
Area weight concrete:	115.6	kg concrete/m² paving stone area	
Specific CO_2 uptake per kg:	0.017	kg CO_2 uptake/kg concrete	
Concrete density:	2313	kg/m³ concrete	
Specific CO_2 uptake per m³:	39.9	kg CO_2 uptake/m³ concrete	
Theoretical maximum CO_2 uptake in concrete:	0.064	kg CO_2/kg concrete	
Carbonation share of maximum uptake in 100 years	27.0	%	

Analysis of concrete surfaces in apartment and office buildings[19]

Apartment buildings

For the calculation of total concrete surfaces in new built apartments have seven types of apartment buildings been studied in detail. The conditions of the seven construction types are described in the footnotes of the Table 16.

Concrete surface areas of the 11 different concrete surface structures for each apartment building type is calculated as the surface area in m^2 per apartment and have been enumerated to reflect the total new apartment constructions with the surface structure distribution for each type of apartment building.

Cementa AB has studied each commenced apartment buildings in Sweden during the years 2005, 2007 and 2009. Data have been collected for different building constructions (e.g. with and without basement, prefabricated or site cast). Material types and corresponding amounts have been calculated based on type of construction. Determination of different concrete surfaces characteristics (e.g. painted surface or surface exposed to rain) has been an important task. This information is then used to determine the CO_2 uptake for each surface. Details of the concrete quality may also be important. Total number of completed apartments in newly constructed apartment buildings for the calculation year (2008) is 19 949 according to Statistics Sweden.

The results from the analysis are shown in Table 16.

[19] Jens Linderoth, Industrifakta och Ronny Andersson, Cementa AB, Analysis of concrete surfaces in apartment and office buildings (2011).

Table 16

Area (m²) of concrete surfaces per apartment (flat) and surface types for seven construction types of apartment buildings.

Construction type	1	2	3	4	5	6	7	m²
Part of the construction	**m² concrete surface per flat**	**m² concrete surface per flat**	**m² concrete surface per flat**	**m² concrete surface per flat**	**m² concrete surface per flat**	**m² concrete surface per flat**	**m² concrete surface per flat**	**surface per flat total for 19 949 flats**
Indoor constructions								
Without paint	106.1	48.3	58.8	168.6	109.6	95.2	26.9	93
Painted	373.0	260.1	185.2	301.9	281.5	181.0	0.8	247
Covered with tiles	28.1	25.7	26.1	14.9	14.7	14.6	0.0	20
Covered with plastics/linoleum	0.0	0.0	1.7	0.0	0.0	0.0	0.0	0.3
Covered with parquet/laminate	80.8	70.9	68.0	70.4	70.4	70.4	0.0	68
Slab-on-grade								
With mineral wool	0.0	0.5	0.0	0.0	0.0	0.0	0.0	0.1
With EPS, expanded polystyrene	1.7	0.0	52.4	0.5	0.0	25.9	37.1	18
Without isolation, with coarse drainage layer	45.4	27.9	0.9	0.0	0.0	0.0	0.0	12
Without isolation, with sand/gravel	1.4	16.7	0.8	87.5	41.2	15.3	0.0	22
Outdoor structures								
Exposed to rain	16.1	17.3	0.0	75.2	74.7	74.7	0.0	38
Sheltered against rain	18.2	7.8	0.0	9.2	9.2	9.2	0.0	8
Total	670.8	475.2	393.9	728.2	601.3	486.3	64.8	525

1) Basement garage, site cast frame in the entire building. GFA: 9420 m², BA: 2395 m², number of floors: 6 + basement, 54 apartments.

2) With basement, site cast frame in the entire building. GFA: 2264 m², BA: 455 m², number of floors: 5 + basement, 23 apartments (part of construction with 89 apartments in total).

3) Without basement, site cast frame in the entire building, integrated and fully glazed balconies. GFA: 8415 m², BA: 1715 m², number of floors: 5, 80 apartments.

4) Basement garage, site cast frame in the entire basement. Prefabricated outer and inner walls. Intermediate joists of prefabricated hollow core, prefabricated bathroom modules. GFA: 35027 m², BA: 10500 m², number of floors: 5 + basement, 212 apartments.

5) Traditional basement, site cast frame in the entire basement. Prefabricated exterior and interior walls. Intermediate joists of prefabricated hollow core, prefabricated bathroom. modules. GFA: 28977 m², BA: 5510 m², number of floors: 5 + basement, 212 apartments.

6) Without basement, Site cast slab-on-grade. Prefabricated exterior and interior walls. Intermediate joists of prefabricated hollow core, prefabricated bathroom modules. GFA: 23587 m², BA: 5510 m², number of floors: 5, 212 apartments.

7) Prefabricated modules in wood. Concrete slab. Frame, joists and beams of wood. Facade of wood or plaster, roof of roofing felt or plate. GFA: 1140 m². BA: 380 m², number of floors: 3, 14 apartments.

The estimated amount of concrete per average apartment: 67.42 m³.

Building area (BA) = The horizontally projected area of the house on the ground.
Gross Floor Area (GFA) = The total floor area inside the building envelope, including the external walls, and excluding the roof.

Office buildings

For the calculation of the total concrete surface in newly produced office buildings has three different types of office buildings been studied in detail. The specifications of the three design conditions are shown in the footnotes to Table 17.

Concrete surface areas of the 11 different concrete surface structures for each office building type is calculated as the surface area in m² per Gross Floor Area (GFA) and have been enumerated to reflect the total new office buildings with the surface structure distribution for each type of office building. Data have been collected for different building constructions (e.g. with and without basement, prefabricated or site cast). Material types and corresponding amounts have been calculated based on type of construction. Determination of different concrete surfaces characteristics (e.g. painted surface or surface exposed to rain) has been performed. This information is then used to determine the CO_2 uptake for each surface. Details of the concrete quality may also be important. Total number of completed office areas in newly constructed office buildings for the calculation year (2008) is 302 290 m² GFA in Sweden. The results from the analysis are shown in Table 17.

Table 17

Area (m²) of concrete surfaces per m² GFA and surface types for three construction types of office buildings.

Construction type	1	2	3	m² concrete surface per m² GFA total for 287175 m²
Part of the construction	**m² concrete surface per m² GFA**	**m² concrete surface per m² GFA**	**m² concrete surface per m² GFA**	
Indoor constructions				
Without paint	1.16	0.96	0.74	0.84
Painted	0.80	1.35	0.51	0.61
Covered with tiles	0.05	0.01	0.09	0.08
Covered with plastics/linoleum	0.49	0.004	0.72	0.64
Covered with parquet/laminate	0.01	0.54	0.00	0.03
Slab-on-grade				
With mineral wool	0.00	0.00	0.00	0.00
With EPS, expanded polystyrene	0.11	0.16	0.30	0.26
Without isolation, with coarse drainage layer	0.01	0.01	0.01	0.01
Without isolation, with sand/gravel	0.41	0.26	0.30	0.32
Outdoor structures				
Exposed to rain	0.28	0.03	0.00	0.06
Sheltered against rain	0.01	0.00	0.00	0.00
Total	**3.32**	**3.32**	**2.69**	**2.84**

1) Basement garage, site cast frame in basement with prefabricated hollow core joists. Elevator shaft in precast concrete.

Frame above ground with column and beam system in steel. Intermediate joists of prefabricated hollow core. GFA: 6640 m², BA: 2545 m², number of floors: 4 + basement.

2) Basement garage, site cast frame in basement and site cast joists. Site cast walls above basement.

Remaining frame above ground with column and beam system in steel. Site cast intermediate joists. GFA: 2533 m², BA: 656 m², number of floors: 3 + basement

3) Without basement. Site cast slab-on-grade. Site cast stair and elevator shafts. Remaining frame above ground with column and beam system in steel.

Intermediate joists of prefabricated hollow core. GFA: 1525 m², BA: 460 m², number of floors: 3.

The estimated amount of concrete per m² GFA: 0.29 m³.

Building area (BA) = The horizontally projected area of the house on the ground.
Gross Floor Area (GFA) = The total floor area inside the building envelope, including the external walls, and excluding the roof.

Concrete railway sleepers

Concrete railway sleepers are common products for concrete and thus also for CO_2 uptake. For the model calculations, a Swedish standard sleeper has been assumed (model A26). This concrete sleeper has a weight of approximately 298 kg without fastenings, a length of 2500 mm and a maximum width of 300 mm. The used concrete surface area and concrete volume are shown in Table 15 and in the table below. The main surfaces of sleepers can be classified as outdoor constructions exposed to rain or sheltered from rain. The main surfaces have good access to CO_2 even if most of the surfaces (80 %) are covered with track ballast. A high quality and dense concrete is used so the CO_2 uptake is relatively slow during use phase but with a high potential uptake due to a high cement content in the concrete.

Surface distribution	m^2 uptake surface/sleeper	CO_2 uptake (kg/m^2 uptake surface, 100 år)	CO_2 uptake (kg CO_2/sleeper)
Topside, sides and ends (exposed to rain)	1.61	0.9	1.449
Bottom (sheltered from rain)	0.694	2.8	1.943
Total	**2.304**		**3.392**
Concrete weight:	298	kg concrete/sleeper	
Specific CO_2 uptake per kg:	0.011	kg CO_2 uptake/kg concrete	
Concrete density:	2400	kg/m^3 concrete	
Specific CO_2 uptake per m^3:	27.3	kg CO_2 uptake/m^3 concrete	
Theoretical maximum CO_2 uptake in concrete:	0.091	kg CO_2/kg concrete	
Carbonation share of maximum uptake in 100 years	12.5	%	