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Water footprint of widely used construction materials

Steel, cement and glass

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Value of Water

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WATER FOOTPRINT OF WIDELY USED CONSTRUCTION MATERIALS – STEEL, CEMENT AND GLASS

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Summary

Although water is an abundant and renewable substance on earth, the available amount of water to man is limited as the amount of precipitation, water flowing through a river or ground water aquifer is always limited in a certain time period. Furthermore, the water demand is expected to increase in the future. When water use is not properly managed this can result in unsustainable water use.

After agriculture, the industrial sector is responsible for the largest amount of water withdrawal, and the water use by this sector is expected to increase. In contrast to agricultural products where quite some research has been done on the water footprint of several products, industrial products have not been researched as much.

This research focusses on widely used construction materials. Five end products are chosen to be researched: unalloyed steel, chromium-nickel alloyed steel, ordinary Portland cement, Portland composite cement and soda-lime float glass. These are the most produced types of steel, cement and flat glass. The water footprint concept introduced by Hoekstra takes indirect water consumption into account. This means that beside direct water consumption like cooling and cleaning water also water consumption for the input products is accounted for in the water footprint of the end product. In order to determine the water footprint of the end product the entire supply chain is considered in the research.

For steel cement and glass, the supply chain begins with acquiring the raw materials. Transport of materials is left out of the scope of this research, because it is expected that the water footprint of transport is to be negligible unless biofuels are used for transportation. After acquiring the raw materials they are processed though different production processes. Some processes for the production of materials like steel, cement and glass require large amounts of energy. The supply of the fuels and generation of electricity also requires water and therefore the energy required for the production of these materials results in a water footprint which have to be allocated to the final product. Furthermore, production processes for these materials can lead to an effluent containing certain polluting substances leading to a grey water footprint.

Major processes along the supply chain and their direct process water consumption are taken into account for this research leaving the water footprint tied to the energy consumption as the remaining indirect blue water footprint. The study uses existing knowledge about the blue water footprint of some energy sources. For other fuel sources, i.e. petroleum products and cokes, the blue water footprint is calculated. Depending on the fuel type used for production processes the water footprint tied to energy use can be a significant part of the total blue water footprint. Water and energy consumption data as well as pollution data is mainly obtained from the ecoinvent database version 3.2.

It was found that the blue water footprint of chromium nickel alloyed steel with 77 L/kg is much larger than that of unalloyed steel with 11 L/kg. This is attributed to the energy demanding ferroalloy production which usually occurs in electric arc furnaces using electricity as energy source. For cement, clinker production by pyroprocessing is one of the most energy and water consuming processes. Reducing the ratio of clinker in

cement by using supplementary materials can reduce the water footprint of cement. A blue water footprint of ordinary Portland cement was calculated between 2.0 – 2.6 L/kg, depending on the source of gypsum. For CEM II/B Portland composite cement with 21-35% supplementary materials a blue water footprint was calculated between 1.7 – 1.8 L/kg. Choosing a Portland composite cement over an ordinary Portland cement can be beneficial for minimising the water footprint of structures. For soda-lime float glass it was found that, beside the energy consuming glass melting, the Solvay process for soda ash production is a large contributing process to the water footprint of float glass. Large amounts of water is used for the Solvay process. Water uses are for brine and milk of lime production, process steam and cooling. Overall the water footprint tied to energy consumption is a significant part of the blue water footprint of the researched materials. This is attributed to the energy demanding processes and to the large water footprint of electricity.

The grey water footprint of the end products is calculated per process and polluting substance by using ecoinvent version 3.2 data for effluent loads and the lowest value from maximum concentration guidelines from Canada (CCME), Europe (EU) and the United States (US-EPA) and maximum concentrations from the EEC (1975) guideline.

For steel it was found that the largest grey water footprint is produced by concentrating iron ore. The grey water footprint for unalloyed steel is 2,300 L/kg steel for the polluting substance cadmium. For chromium-nickel alloyed steel the grey water footprint was found to be 1,500 L/kg steel for the polluting substance cadmium. For cement, the grey water footprint depends on whether gypsum through flue gas desulphurisation is used and whether the grey water footprint from this process is allocated to gypsum and ultimately to cement or not. If this is the case then the grey water footprint for ordinary Portland cement and Portland composite cement was found the be 210 L/kg. If the grey water footprint from flue gas desulphurisation is not applicable then the grey water footprint of ordinary Portland cement was found to be 0.63 L/kg cement for cadmium and for Portland composite 0.45 L/kg cement for cadmium. For float glass the grey water footprint is largely dependent on the Solvay process. The effluent contains heavy metals and suspended solids resulting in a grey water footprint of 1,300 L/kg glass where suspended solids are the determining material for the grey water footprint. Overall the grey water footprint is potentially much larger than the blue water footprint of the researched materials.

1 General introduction

1.1 Introduction

Society depends on water for drinking, food, energy and leisure. Without water we cannot live; it is essential to life. Although water is the most widely occurring substance on earth, only 2.53 percent is freshwater while the remainder is salt water. Some two thirds of this freshwater is locked up in glaciers and permanent snow cover. (United Nations Educational, 2003). Most of the freshwater available to man is renewable. However, the amount of fresh water available is limited, because over a certain period the amount of precipitation in an area, recharging groundwater and flow through a river is always limited to a certain amount. (Hoekstra, 2013). Furthermore, the distribution of fresh water is unequal over different parts of the world and there is wide variation in seasonal and annual precipitation in some parts of the world. (United Nations Educational, 2003). Beside the limited availability of fresh water, it is expected that the global demand for fresh water will increase (Organisation for economic co-operation and development [OECD], 2012). This increase in water use can be unsustainable where water supplies are scarce and its use is poorly managed. (United Nations World Water Assessment Programme [WWAP], 2015).

Hoekstra (2013) states that human impacts on fresh water systems can ultimately be linked to human consumption and that water shortages and pollution can be better understood and addressed by considering production and supply chains as a whole. In 2002 Hoekstra introduced the water footprint concept. Previously mostly only the direct water use by a consumer or producer was considered. Input products usually also require water consumption to produce. The water footprint concept also incorporates the indirect water use; the water used along the supply chains and the water that essentially becomes unusable by pollution.

Quite a lot of research has already been done on the water footprint of agricultural products which are responsible for the largest amount of water withdrawal. Figure 1 shows the distribution of water withdrawal per sector. In the year 2007, 70 percent of the water withdrawal worldwide is used for agriculture (The World Bank, 2010). However, on the second biggest water user, the industrial water users, with 20 percent of the water withdrawal worldwide, the research on water footprint has not been as extensive as for the agricultural sector. For higher income regions the amount of water withdrawal for industrial use is even higher with 39 percent and for the Euro area this is 52 percent of the total water withdrawal (The World Bank, 2015). Global annual water use by industry is expected to rise from an estimated 725 km^3 in 1995 to about 1,170 km^3 by 2025, by which time industrial water usage will represent 24 percent of all water abstractions worldwide (United Nations Educational, 2003).

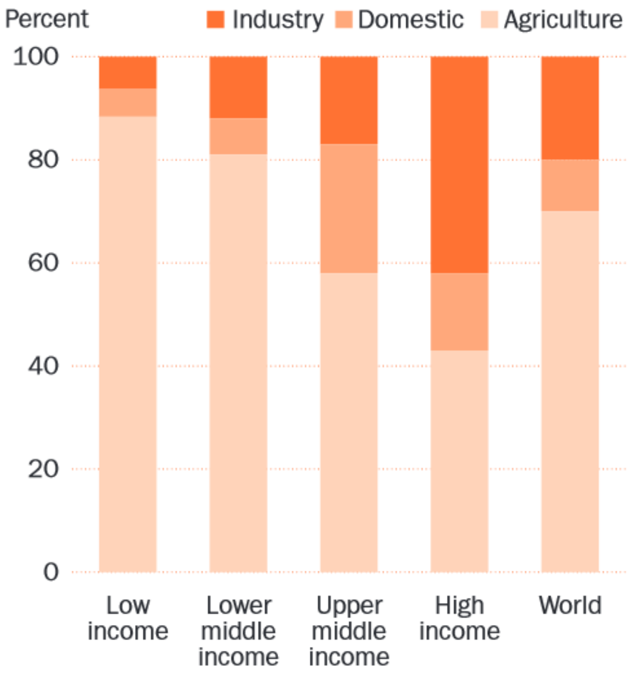

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Figure 1: Water withdrawal per sector (source: World Bank, 2010)

Beside water used during production processes, the production of products often requires energy. Depending on the type of energy used (e.g. bioenergy, coal, oil or gas) this requires a certain amount of water as well. According to the water footprint concept this should be incorporated into the water footprint of products. Furthermore, pollution of water can be a consequence leading to a grey water footprint.

Steel, cement and glass are construction materials produced in millions of tons globally per year which require large amount of energy to produce on top of water used during production processes. The water footprint of these materials are potentially large. Investigating where the biggest water footprint comes from with the production of these widely used materials can be beneficial for managing water resources. Secondly, when estimating a water footprint of for instance structures, the results from research like this can be used to calculate an estimation.

1.2 Research objective

The objective of this research is to contribute to the knowledge about the water footprint for widely used construction materials by calculating the water footprint of the production processes of the most used types of steel, cement and glass in volume per mass end product using the water footprint concept proposed by Hoekstra et al. (2011).

1.3 Research questions

By answering the following research questions the research objective will be met:

- How large is the blue water footprint of the most produced type of steel, cement and flat glass, produced by the currently most used production process routes?
- How large is the grey water footprint of the most produced type of steel, cement and flat glass, produced by the currently most used production process routes?
- Which stages or processes are the largest contributors to the water footprints of the materials?
- Which substances determine the grey water footprint of the materials?

1.4 Outline

After this general introduction in Chapter 2 of this report some useful background information about the production of steel, cement and glass is given. In Chapter 3 the seven steps of the research methodology is explained. In Chapter 4 the results from the research, the blue and grey water footprints, are presented in bar graphs. The results are sorted by material. A discussion about the accuracy of the results and shortcomings of the research is done in Chapter 5. Finally, the conclusions of this report can be found in Chapter 6.

2 System analysis

In this chapter some necessary background information about the production processes of steel production, cement production and flat glass production are described from the viewpoint of water footprint assessment. This means that the production chain including raw materials provision is discussed in short as well as the actual production of the materials, because they all contribute to the water footprint of the materials. Also the water uses for the processes are mentioned. First, iron and steel are discussed, then cement and concrete and as last flat glass is discussed.

2.1 Iron and steel

Steel is a product derived from iron from which the carbon content, which is used for iron production, is reduced. When metals are added to steel, so termed alloys are produced. Stainless steel is an example of an alloy, in which for instance chromium, nickel and manganese are added. The majority of steel that is produced is the first mentioned type of steel, also called carbon steel or unalloyed steel. Of the worldwide steel production, 89 percent is unalloyed steel and 11 percent is alloyed steel (Steel and metal market research [SMR], 2016).

Iron and steel have played an important role in the development of human civilisation. They have been used for several millennia. In at least as early as the 13th century BC, steel was first produced and the Iron Age began, where iron use became wide spread (Worldsteel association, 2016a). In modern society, iron and steel have many applications, such as for construction, for the automotive industry and for tools and machinery. The construction industry is the largest steel using industry, accounting for more than 50% of the world steel production. In 2015, the total world steel production was 1,622.8 Mt (Worldsteel association, 2016b).

2.1.1 Production chain of steel

There are several production routes for steel. The most common production route is the blast furnace (BF)/basic oxygen furnace (BOF) route. The BF is a furnace where the oxygen is removed from the iron ore by binding it to carbon. The BOF is a furnace where the carbon content in the iron is lowered again by blowing pure oxygen onto the metal. According to Worldsteel association (2015), in 2014 the BF/BOF production route is used for 74% of the total steel production. Figure 2 shows the steel production chain including six steps:

1. mining of raw materials;
2. processing of raw materials:
    a. beneficiation
    b. calcination
    c. coking
1. iron ore reduction;
2. air separation;
3. ferroalloy production;
4. steel production.

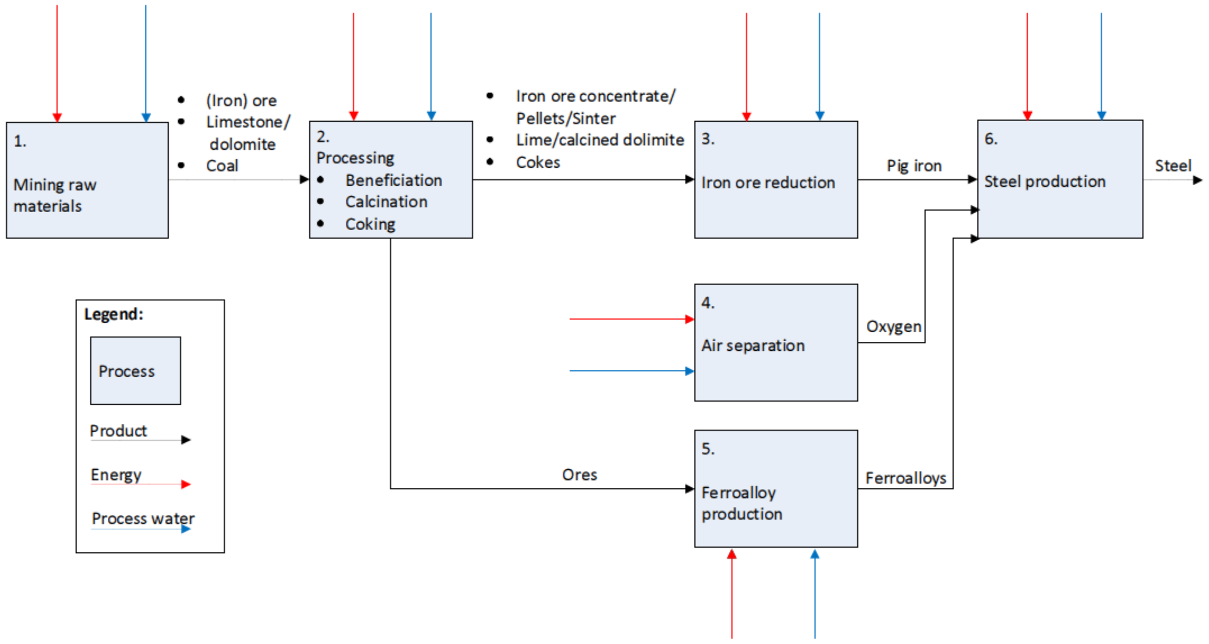

Figure 2: The steel production chain including six steps, mining raw materials, processing, iron ore reduction, air separation, ferroalloy production and steel production

Step 1: mining of raw materials

The raw materials, mainly consisting of iron ore, limestone ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), coal and other ores for alloyed steel such as chromite and laterite are mined.

Step 2: processing of raw materials

The properties of the raw materials are improved by the following processes:

a. Beneficiation. This is the process where the concentration of the ores is increased and fine ore particles are bound to form so called pellets or sinter. Fine coke (step 2c) is used as the main energy source for sinter production. (Remus et al., 2013). For the beneficiation process, water is used for dust emission control, sorting material, cleaning, cooling and gas treatment (U.S. EPA, 1994).

b. Calcination. This is the process to produce lime (CaO) and calcined dolomite (CaO.MgO) from limestone ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$). Then, these products are used further in the production process to remove impurities from steel, among other uses (British Lime Association, n.d.). Water can be used for washing of limestone, but is not applied most of the time. Mostly gas and solid fossil fuels are used for calcination (Schrocht et al., 2013).

c. Coking. This is the process in order to improve the properties of coal, the material goes through the process of coking in a coke oven resulting in cokes. Cokes have a higher purity of carbon than coal and are strong enough to carry the other materials inside the blast furnace (Arcelor Mittal, n.d.). Water can be used for wet quenching of the cokes (Remus et al., 2013).

Step 3: iron ore reduction

After processing, the improved materials: iron ore and cokes together with limestone are introduced in the blast furnace to form the so called pig iron by iron ore reduction. Pig iron is reduced iron oxide. The oxide from iron ore is bound to carbon from cokes and emitted as carbon oxide, leaving behind the pig iron as hot metal. The limestone acts as a slag former, removing impurities from the iron and forming BF slag as a by-product from this process. (Remus et al., 2013), (Verver & Fraaij, 2004). Water is used for blast furnace gas treatment, slag granulation, and cooling (Remus et al., 2013).

Step 4: air separation

Oxygen is produced by separating oxygen from the air (Althaus, et al., 2007). Oxygen is used for steel production in the BOF. By blowing pure oxygen over the hot metal, the carbon content is lowered in the metal. Water is used for cooling and electricity provides the energy required for air separation. (Althaus, et al., 2007).

Step 5: ferroalloy production

When alloyed steel is produced, ferro-alloys are introduced in the basic oxygen furnace. Ferro-alloys are a mix of iron with other metals. Ferro-chrome and ferro-nickel are the major alloys used in the production of stainless steel. The production of ferro-alloys generally require large amounts of electricity. Water is used for gas treatment, slag granulation and cooling. (European Integration Polution Prevention Bureau [EIPPCB], 2001).

Step 6: steel production

The pig iron from the iron ore reduction process (step 3), which contains approximately 4% carbon, is transported to the BOF where the carbon content is reduced by blowing pure oxygen onto the hot metal. The end product from this process is steel. Slag formers such as lime are used to remove impurities from steel, forming BOF slag (Remus et al., 2013), (Verver & Fraaij, 2004). Water is used for BOF gas treatment, vacuum generation, cooling and washing (Remus et al., 2013).

2.2 Cement and concrete

Cement is an inorganic binder used to bind materials like sand grains or gravel together. Cement is a hydraulic binder. This means that water is needed for the chemical reactions in order to harden. Concrete is a mixture of cement, water, sand and other aggregates such as gravel or crushed stone (Verver & Fraaij, 2004). Cement and concrete are widely used materials in the construction and the world production of cement has been growing steadily, especially in developing countries. In 2006, world production of cement was 2,540 Mt (Schrocht et al., 2013). Every year, more than 10,000 Mt of concrete is produced (Meyer, 2009).

2.2.1 Production chain of cement

Figure 3 shows the cement production chain including three main steps:

1. extraction and pre-processing of raw materials;
2. pyroprocessing;
3. grinding and mixing.

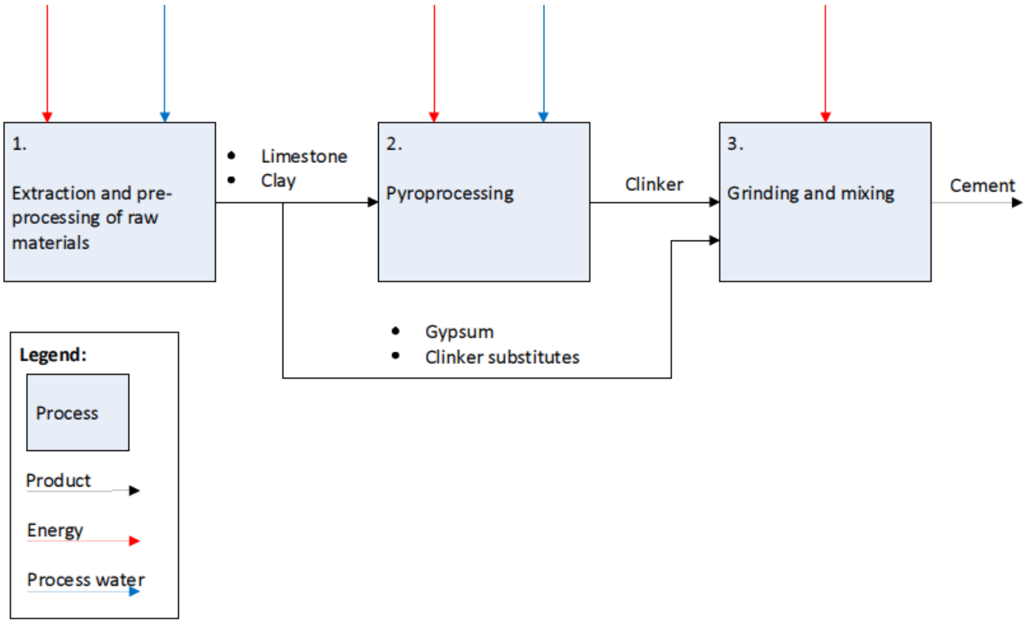

Figure 3: The cement production chain including three steps, extraction & pre-processing of raw materials, pyroprocessing and grinding & mixing

Step 1: extraction and pre-processing of raw materials

The raw materials needed to produce cement are limestone, or other $CaCO_3$ containing materials, sand, clay and gypsum. These materials are extracted from quarries. Gypsum can also be extracted as a by-product from flue gas desulphurisation (FGD), which is a cleaning process applied at hard coal fired power plants. Other waste products can also be used. Examples are: ground granulated blast furnace slag (GGBFS), this is a waste product from iron and steel production. Fly ash is another waste product that is often used. It is produced from electrostatic precipitation (ESP) of hard coal flue gas. After extraction, limestone is ground and washed to prepare for pyroprocessing.

Step 2: pyroprocessing

Pyroprocessing is the process of producing clinker from limestone and clay. By using high temperatures in a rotating oven, limestone and clay react with each other to form fist and marble sized hard clumps, called clinker. Pyroprocessing is an energy intensive process. The amount of energy required for pyroprocessing depends on the moisture content of the raw materials and on the oven type used. For the heating of the rotating ovens, coal, fuel oil, natural gas or waste material can be used. In special cases, water is used for cooling of the clinker (Schrocht et al., 2013).

Step 3: grinding and mixing

The clinker produced from pyroprocessing is mixed with approximately 4% gypsum and is finely ground to Portland cement. A large amount of electricity is necessary for the grinding of the clinker. Since the production of clinker by pyroprocessing and grinding is such an energy intensive process, other additives can be used to reduce the amount of clinker in cement and to change properties of cement. An example of such a clinker substitute is blast furnace slag, a waste product from steel production (Schrocht et al., 2013), (Verver & Fraaij, 2004).

2.3 Glass

In the glass industry, the term glass usually refers to silicate glass. Silicate glass is a substance containing a high proportion of silica (SiO_2) and which naturally forms glass after cooling from its molten state. Glass is produced in many forms and used for many purposes, but can be classified into four main categories: (i) container glass; (ii) flat glass; (iii) fibre glass and (iv) specialty glass. Of these categories, glass production is dominated by container glass and flat glass. The construction industry is very important for the glass industry where flat glass is applied in new buildings and for replacing old glass (Scalet et al., 2013). In 2009, the global market demand for flat glass was approximately 52 Mt (Nippon Sheet Glass [NSG], 2010).

2.3.1 Production chain of flat glass

Figure 4 shows the flat glass production chain including three main steps:

1. extraction and processing of raw materials;
2. melting;
3. annealing and cutting.

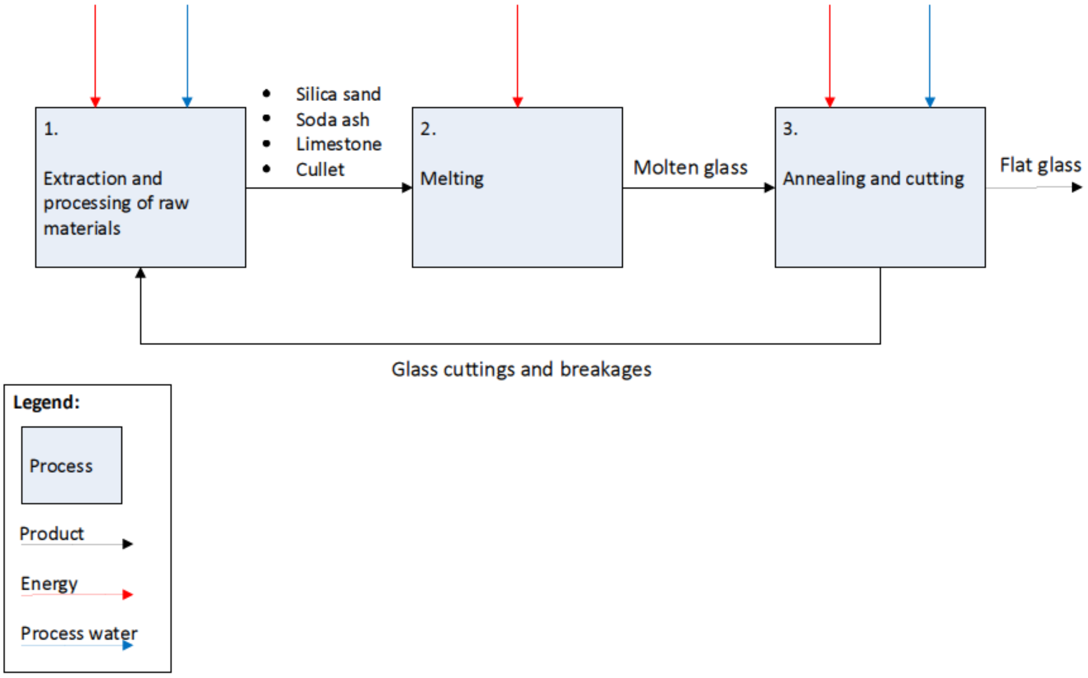

Figure 4: The flat glass production chain including three steps, extraction & processing of raw materials, melting and annealing & cutting

Step 1: Extraction and processing of raw materials

Most raw materials are extracted from mines or quarries. The raw materials used for flat glass production can be numerous, but a typical composition of flat glass shown in Appendix I, contains mainly silica sand, soda ash, limestone and often cullet. (IEA, 2007), (Verver & Fraaij, 2004). Cullet is recycled glass or waste glass from manufacturing. The cullet used for flat glass is usually only from internal origin, such as from cuttings and breakages. Before reuse, the cullet is ground and washed. (EMEP/EEA, 2013). Soda ash can be mined in some places in the world, but can also be chemically produced by the so called solvay process. The solvay process needs large amounts of water for cooling, washing and as medium for the chemical process (IPPC, 2007).

Step 2: Melting

After grinding and mixing of the materials, the mixture is heated in a furnace. At temperatures between 1,300 and 2,000 °C, depending on the type of glass, the mixture of materials is melted and becomes liquid glass. By chemical reactions, silicate bonds are created and gas is emitted (Verver & Fraaij, 2004), (Scalet et al., 2013), (EMEP/EEA, 2013). Furnaces are in most cases heated by natural gas or fuel oil. Electricity can also be used for melting glass, but is rarely used on its own. Mostly electricity is used in addition to fossil fuelled glass production (EMEP/EEA, 2013), (IEA, 2007).

Step 3: Annealing and cutting

In step 3, the process of annealing and cutting of the material takes place. Annealing is a stage where the temperature is lower than the melting stage. The glass is being cooled to a temperature between 900 and 1350 °C. At this stage, the impurities are being disposed of and all remaining soluble bubbles are reabsorbed into the melt (Verver & Fraaij, 2004), (Scalet et al., 2013). Water is used for cooling (Verver & Fraaij, 2004), (IFC World Bank, 2007). After cooling, the edges of the glass are trimmed and the glass is cut to the desired shape. The edge trimmings and broken glass usually return to the furnace to be remelted.

3 Method

In the previous chapter the production chain of steel, cement and glass were schematised into a limited number of processes linked by product flows. The processes require water and energy and can have an effluent with certain pollutants. The processes contribute to a blue water footprint of the end product as water is consumed during the process. The energy consumption for the processes also contributes to the water footprint of the end product, because the water footprint tied to the fuel supply and electricity generation are ultimately allocated to the end product. A grey water footprint can be the result of pollutants in process waste water. In this chapter the methodology of this research is described. Beginning by specifying which type of end products are researched, followed by describing the calculation steps that are applied in order to calculate the blue and grey water footprint of the end products.

3.1 Product types included into the research

Many different product types for steel, cement and glass exist, and a choice has to be made which products are included into the research. The most used or most produced types of products are researched, in order for this research to have a broad application. For steel, the most produced type is unalloyed steel with 89% of the global production (Steel and metal market research [SMR], 2016). Of the alloyed steels, the chromium nickel grades are the most produced (International stainless steel forum [ISSF], 2013). Portland cement and Portland composite cement are the two most supplied groups of cement, accounting in 2005 for 86% supplied in the EU-25 (Schrocht et al., 2013). The majority of industrial produced glass is soda-lime glass, this also applies to float glass which is the most produced type of flat glass (Scalet et al., 2013). For this research a typical soda-lime float glass composition (Appendix I) is used to determine the input materials used for the calculation of the water footprint of float glass. The researched end products for the water footprint calculations are:

1. unalloyed steel;
2. chromium-nickel alloyed steel;
3. ordinary Portland cement;
4. Portland composite cement;
5. soda-lime float glass.

3.2 Steps of research methodology

In this research the blue water footprint is divided in a process water WF ($WF_{proc,blue}$) and an energy related WF ($WF_{energy,blue}$), because they require a different approach for calculation. Figure 5 shows the steps taken of the research methodology. The research methodology starts with determining the scaling factors for the processes (step 1). Followed by calculating $WF_{proc,blue}$ in step 2 by using water abstraction and water discharge data. Step 3 and 4 are intermediate steps, to first calculate the value fractions of petroleum products and hard coal cokes (step 3) and then the water footprint of the energy sources (step 4). Step 3 and 4 are followed by calculating

$WF_{energy,blue}$ in step 5. Effluent loads are scaled in step 6, using the corresponding scaling factors from step 1, resulting in scaled effluent loads per kilogram end product. From these loads, the grey water footprint (WF_{grey}) is calculated in step 7.

On the left side of the figure the input data required for the calculation steps is shown. The main source of input data is the ecoinvent database, which for many processes contains the input materials, output materials, by products, waste products, water abstraction, water evaporation, water discharge, energy use and contaminating substances in the effluent. For the energy use and water use, IEA, (2007) and several best available techniques reference documents from EIPPCB are used as a secondary source. Especially the sources: Remus et al., (2013) for steel, Scalet et al., (2013) for glass and Schrocht et al., (2013) for cement are mostly used for comparing ecoinvent data with these sources. Unless mentioned otherwise data is used from the ecoinvent database using global (GLO) datasets.

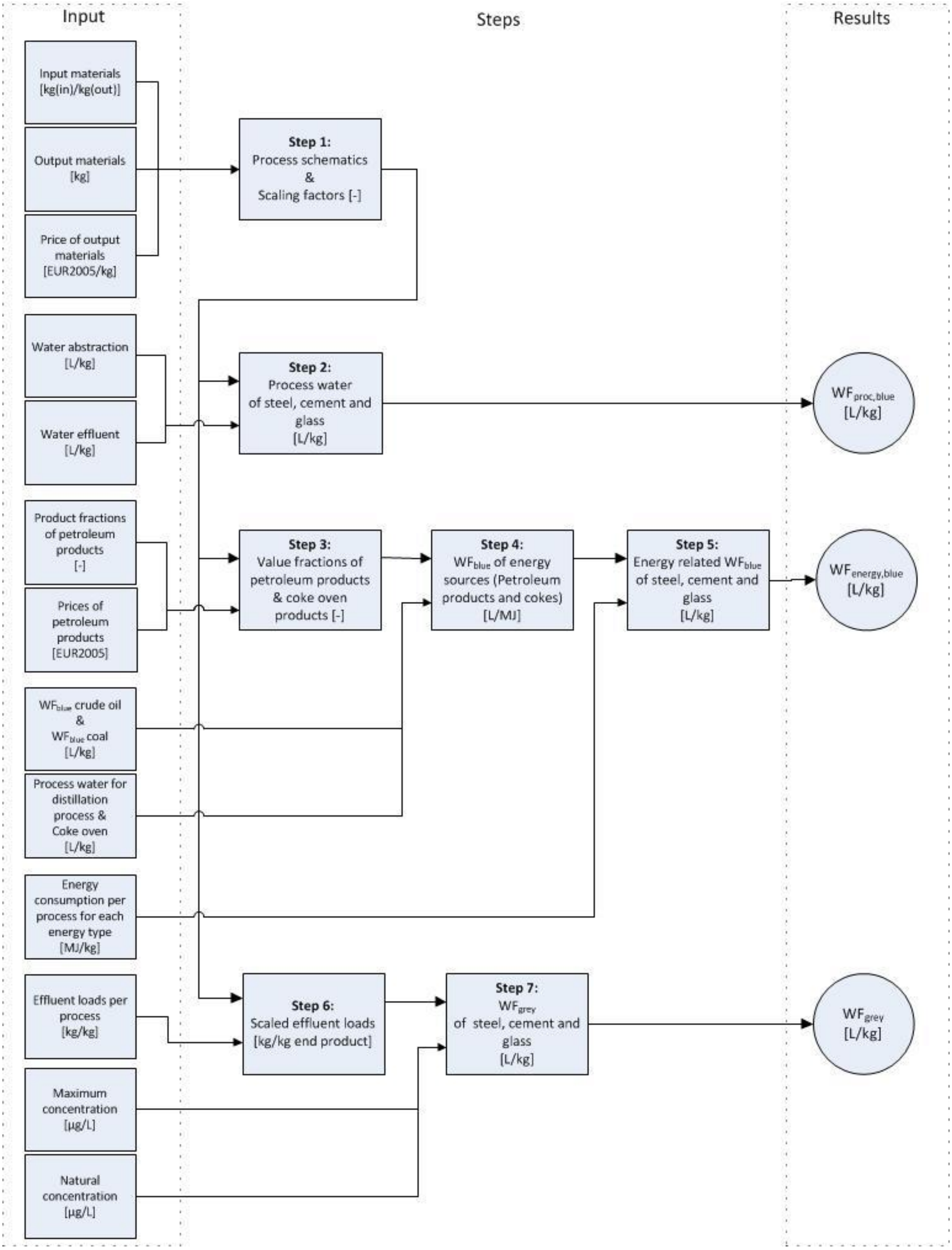

Figure 5: Steps of research methodology

3.2.1 (Step 1) Process schematics and scaling factors

The life cycle assessment (LCA) software program ‘GaBi’ is used to build process schematics based on the production chains discussed earlier in Chapter 2. GaBi is an LCA modelling, reporting and diagnostic software tool. The modelling capabilities of the program are used to keep track of the numerous product flows between all processes, but mainly to scale the processes to the right output amount for the end product. Based on the mass of the intermediate products and allocation to products, a scaling factor is applied to the processes by the software program. In this paragraph the process schematics as built in GaBi are presented and the scaling factor is explained in further detail.

Process schematics

Process schematics are made of the five products which are chosen to be included into the research: unalloyed steel, chromium-nickel alloyed steel, ordinary Portland cement, Portland composite cement and soda-lime float glass (Appendix II). Unlike the general production chains from Chapter 2, each arrow in the schematic represents one product. The thickness of the arrow indicates the mass used for the production of 1 kg end product. Boxes represent processes which are scaled to produce the right amount of output product as input for the subsequent process.

Scaling factors

Scaling factors are applied to all processes in the process schematics by GaBi. The scaling factors are used for two purposes:

1. Scaling
2. Allocation

Scaling: Processes are scaled including the output product, water and energy consumption as well as loads emitted in the effluents. The functional unit is one kilogram of the end product steel, cement or glass. This means that processes are scaled to get the amount of output product required for one kilogram of end product.

Allocation: In case a single process has multiple valuable output products, the water consumption, energy consumption and pollution are allocated over the multiple output products. The allocation is done according to the value fractions of the output products of that particular process.

The value fraction (f_v) of an output product (p) is defined as the ratio of the market value of this product to the aggregated market value of all the output product (p=1 to z) obtained from the input products (Hoekstra et al., 2011):

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_1^z (price[p] \times w[p])} \quad [-] \qquad (1)$$

Both purposes are combined by GaBi into one scaling factor. A way to define the scaling factor of process i then is:

$$f_s[proc_i] = f_v[p] \times f_w[p] \times f_s[proc_{i+1}] \qquad (2)$$

Herein:

$f_v[p]$ = value fraction of product p;

$f_w[p]$ = ratio between the weight of the input product [p] for process ($proc_{i+1}$) and the weight of the same product [p] as output from the process ($proc_i$);

$f_s[proc_{i+1}]$ = scaling factor of the process i+1.

3.2.2 (Step 2) Process water of steel, cement and glass

In this step the process water use per production process is calculated in L/kg end product. The process blue water footprint is the amount of fresh water that does not return to the same catchment within the same time period, either by evaporation, incorporation into the product or because it is returned to another catchment or in another time period. (Hoekstra, et al., 2011). Because not each of the above components are available for all process steps, the abstraction and discharge are used. The process water consumption is assumed to be the difference between abstraction and the discharge. By multiplying with the corresponding scaling factor of the process, the process blue water footprint of the end products steel, cement and glass are calculated.

$$WF_{proc,blue} = (Abstraction - Discharge) \times f_s \quad [\text{volume/mass}] \qquad (3)$$

Data tables on process water for the production processes can be found in Appendix III.

3.2.3 (Step 3) Value fractions of petroleum products and coke oven products

For many industrial processes heat is applied through burning natural gas, fuel oil, coal or hard coal cokes. The water footprint of these energy sources is needed to calculate the water footprint of steel, cement and glass. For the water footprint related to the use of electricity the global weighted average water footprint from Mekonnen et al., (2015) is used, as well as the water footprint of natural gas and coal.

Heavy fuel oil, light fuel oil and diesel are (petroleum) products derived from crude oil. For petroleum prodcuts and hard coal cokes the water footprint is calculated. In this step the value fractions of the petroleum products and the value fractions of the products from coking are calculated. In the following step (step 4) the water footprint of the fuels are calculated using these value fractions.

The value fraction (f_v) of an output product (p) is defined as the ratio of the market value of this product to the aggregated market value of all the output products (p=1 to z) obtained from the input products:

$$f_v[p] = \frac{price[p] \times w[p]}{\sum_1^z (price[p] \times w[p])} \quad [-] \qquad (4)$$

Table 1 shows the value fractions of the petroleum products. Table 2 shows the value fractions of hard coal cokes and the other output products from coking. The value fractions calculated in this step are used in Step 4 in order to calculate the blue water footprint of diesel, light fuel oil, heavy fuel oil and cokes.

Table 1: Product fractions and value fractions of petroleum products

Product	Product fraction[1] [-]	Price[1] [EUR2005/kg]	Value fraction [-]
Diesel	0.1	0.37	0.13
Heavy fuel oil	0.176	0.138	0.09
Kerosene	0.0668	0.297	0.07
Light fuel oil	0.268	0.268	0.26
LPG	0.0283	0.276	0.03
Naphtha	0.0679	0.265	0.07
Petrol	0.215	0.446	0.35
Pitch/bitumen	0.00106	0.23227	0.001
Own energy consumption	0.06	n/a	n/a

[1] (Jungbluth, n.d.)

Table 2: Product fractions and value fractions of the output product from coking

Product	Output weight[1] [kg]	Product fractions [-]	Price[1] [EUR2005/kg]	Value fractions [-]
Coke	0.80	0.58	0.172	0.64
Coke oven gas	0.175	0.13	0.375	0.31
Benzene	0.00798	0.0058	0.614	0.023
Coal tar	0.032	0.023	0.196	0.029

[1] (Bauer, n.d.), output for 1.38 kg of hard coal as input

3.2.4 (Step 4) Blue water footprint of energy sources

In this step the blue water footprint of diesel, light fuel oil, heavy fuel oil and cokes is calculated. The blue water footprints of petroleum products and hard coal cokes are calculated using the value fractions from Step 3 in the stepwise accumulative approach as described in the water footprint manual of Hoekstra et al., (2011):

$$WF_{prod}[p] = \left(\frac{WF_{proc}[i]}{f_p[p,i]} + \sum_{i=1}^{y} \frac{WF_{prod}[i]}{f_p[p,i]} \right) \times f_v[p] \quad [\text{volume/mass}] \tag{5}$$

Since, in the case of the distillation process of crude oil and coking of hard coal, the process water footprint is given per unit of a specific input product, the given volume needs to be divided by the product fraction for that input product ($f_p[p,i]$).

For the supply of conventional oil the water footprint reported by Mekonnen et al., (2015) ranges from 7.8 - 212 L/GJ heat. The median of 20 L/GJ is used for the calculations of the water footprint of the derived products. For the refining of petroleum products an average water consumption of 1.53 L/L crude oil is reported by Wu & Chiu (2011). The largest part is used for cooling.

For the supply of hard coal Mekonnen et al., (2015) mentions a blue water footprint of 6.6 - 228 L/GJ, with a median of 15 L/GJ which is used for the calculation of the water footprint of hard coal cokes. Ecoinvent reports 0.0489 MJ of electricity use and 0.62 L of water evaporation during the process of coking 1.38 kg of hard coal as input.

Table 3 shows the blue water footprint of the energy sources used in the production processes of the researched materials. The WF_{blue} from natural gas, coal and electricity are taken from Mekonnen et al., (2015). The WF_{blue} from diesel, light fuel oil, heavy fuel oil and hard coal cokes are calculated using the above described method. Appendix IV shows the blue water footprint of the other petroleum products and coking products.

Table 3: Blue water footprint of energy sources

Product	WF_{blue} [L/GJ][1]
Diesel	28 – 376 (80)
Light fuel oil	19 – 259 (55)
Heavy fuel oil	10 – 133 (28)
Natural gas	0.6 – 18 (2.2)
Coal[2]	6.6 – 228 (15-39)
Hard coal cokes[3]	42 – 321 (52-82)
Electricity	4,241

[1] The numbers between brackets of petroleum refined products are calculated with the median value for the fuel supply from Mekonnen et al., (2015) and the mean value from the water consumption in the petroleum refinery from Wu & Chiu, (2011). The range is calculated using the range for oil and coal supply from Mekonnen et al., (2015) and the range for process water use for distillation by Wu & Chiu (2011).

[2] 15 L/GJ is from Mekonnen et al, (2015). 39 L/GJ coal is calculated using ecoinvent data. With this data electricity use is included and may be responsible for the increase in WF_{blue} for coal.

[3] 52 L/GJ HCC when 15 L/GJ for coal is used; 82 L/GJ HCC when 39L/GJ for coal is used.

3.2.5 (Step 5) Energy related blue water footprint of steel, cement and glass

In this step the energy related blue water footprint ($WF_{energy,blue}$) is calculated. $WF_{energy,blue,}$ here is defined as the WF_{blue} of the energy consumed for the production of the product. The energy consumption for the processes involved for the production of steel, cement and glass is shown in Appendix V. The first column after the processes show the energy input per unit product as reported by ecoinvent. These values are multiplied by the corresponding scaling factor (acquired from step 1) of the process in order to arrive at the energy consumption in [MJ/kg end product]. By multiplying the energy use for the process with the corresponding water footprint of the energy source (acquired in step 4) the $WF_{energy,blue}$ is calculated per process.

3.2.6 (Step 6) Scaled effluent loads

Effluent data of the production processes is required in order to make a calculation of the grey water footprint (WF_{grey}). The effluent data consists of types of substances and loads present in the effluent. In the database of ecoinvent the loads are given in [kg/mass output material]. The effluent loads are scaled, using the corresponding scaling factors for each process, as previously mentioned in step 1. This results in loads of (chemical) substances and some water quality parameters, like the biological oxygen demand (BOD) and chemical oxygen demand (COD), in [kg/kg end product]. Appendix VI contains the scaled effluent loads per process. These loads are used in Step 7 to calculate the WF_{grey} of steel, cement and glass per production process.

3.2.7 (Step 7) Grey water footprint of steel, cement and glass

General calculation method

The grey water footprint is calculated by dividing the scaled load (Step 6) of a substance by the assimilation capacity of the water body (Equation 6). The assimilation capacity is the difference between the maximum allowable concentration and the natural concentration in the water body:

$$WF_{grey} = \frac{L}{c_{max} - c_{nat}} \text{ [volume/mass]} \tag{6}$$

The values referenced by Chapman (1996) are used for the natural concentration. The grey water footprint manual recommends to use these values when local natural background concentrations cannot be used. For the maximum allowable concentrations the lowest concentration of the guidelines from Canada (CCME), Europe (EU) and the United States (US-EPA) are used. Maximum concentrations for chemical (COD) and biochemical oxygen demand (BOD) are used from the EEC (1975) guideline.

Alteration of grey water footprint formula for pH values

ESAPA (2004) mentions that hydroxide is present in the effluent from the Solvay process, which is the process of chemically creating soda ash. No maximum concentration for hydroxide is set in the guidelines, but the CCME guideline mentions a pH range of 6.5 – 9. In order to calculate the grey water footprint for hydroxide ions, equation 6 is altered so that the concentration c_{max} and c_{nat} can be expressed in pH.

The pOH is defined as the negative log of the concentration OH^-[mol/l]:

$$pOH = -\log[OH^-] \tag{7}$$

$$10^{-pOH} = OH^- \tag{8}$$

pOH and pH are in equilibrium:

$$pOH + pH = 14 \tag{9}$$

Combining Equation 8 and 9:

$$OH^- = 10^{-14+pH} \tag{10}$$

Substituting in Equation 6:

$$WF_{grey} = \frac{L/M}{10^{-14+pH_{max}} - 10^{-14+pH_{nat}}} \text{ [volume/mass]} \tag{11}$$

Herein:

L: load of hydroxide ion [kg/kg];

M: molar mass of hydroxide, 0.01708 [kg/mol]; pH and pOH are calculated with the concentration in mol/litre, therefore the load is divided by the molar mass.

pH_{max}: maximum pH, from CCME: 9;

pH_{nat}: natural pH of the receiving water body.

This step results in the WF_{grey} of the end products per polluting substance for all individual processes. In Chapter 4 the results are shown of the steps that lead to the blue and grey water footprint of the researched materials.

4 Results

In this chapter the results of steps two, five and seven from the previous chapter are presented. Step two leads to the process blue water footprint ($WF_{proc,blue}$) for major production processes. The result from step five is the energy related blue water footprint ($WF_{energy,blue}$) per fuel source for production processes as shown in the process schematics. Adding these two water footprints results in the blue water footprint of steel, cement or glass in [L/kg end product]. The results from step seven are the grey water footprints (WF_{grey}) of the researched construction materials. The results from this step are presented in figures expressed in [L/kg end product] shown per polluting substance. Tables of the grey water footprint results are given in Appendix IX. First the results from unalloyed steel are presented, followed by the results from chromium-nickel alloyed steel (18/8). Then the results from ordinary Portland cement (CEM I) and Portland composite cement (CEM II/B) are shown. Finally the results from soda-lime float glass are shown.

4.1 Unalloyed steel

Figure 6 shows the process blue water footprint of unalloyed steel. The total calculated $WF_{proc,blue}$ of unalloyed steel is 7.6 L/kg steel. Most process water is used for actual steel production. Water uses in the integrated steelworks according to Remus et al., (2013) are: scrubbing water from BOF gas treatment, scrubbing water from the wet dedusting of desulphurisation, water from vacuum generation and water from direct cooling from continuous or ingot casting.

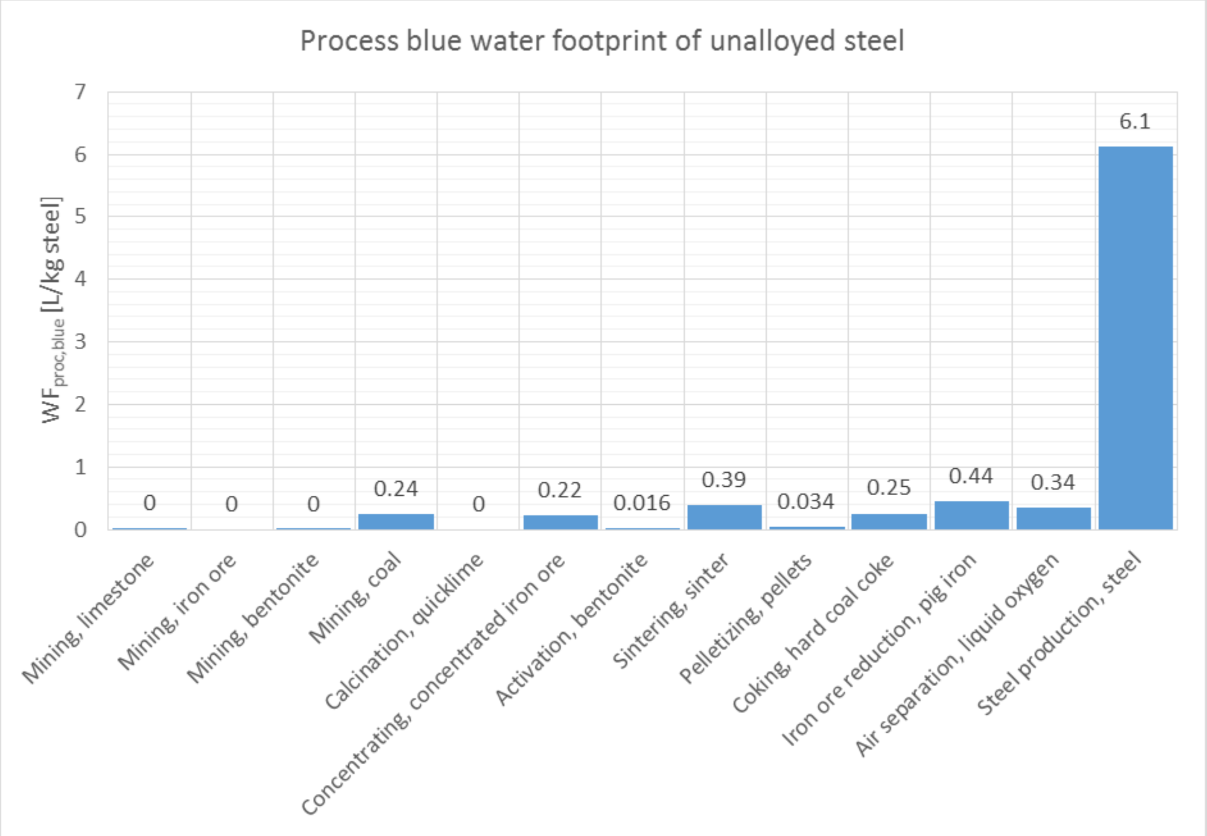

Figure 6: Process blue water footprint of unalloyed steel per production process

Figure 7 shows the energy related blue water footprint of unalloyed steel. The total $WF_{energy,blue}$ of unalloyed steel is 3.8 L/kg steel. The largest contributor for this is the production of liquid oxygen by cryogenic air separation. The largest amount of energy is consumed in the blast furnace for which mostly cokes are used as fuel. However, the water footprint of electrical power, assuming global weighted average for electrical power generation, is much larger than the water footprint of the other energy sources. Therefore, the energy related blue water footprint of cryogenic air separation is larger than that of the blast furnace process.

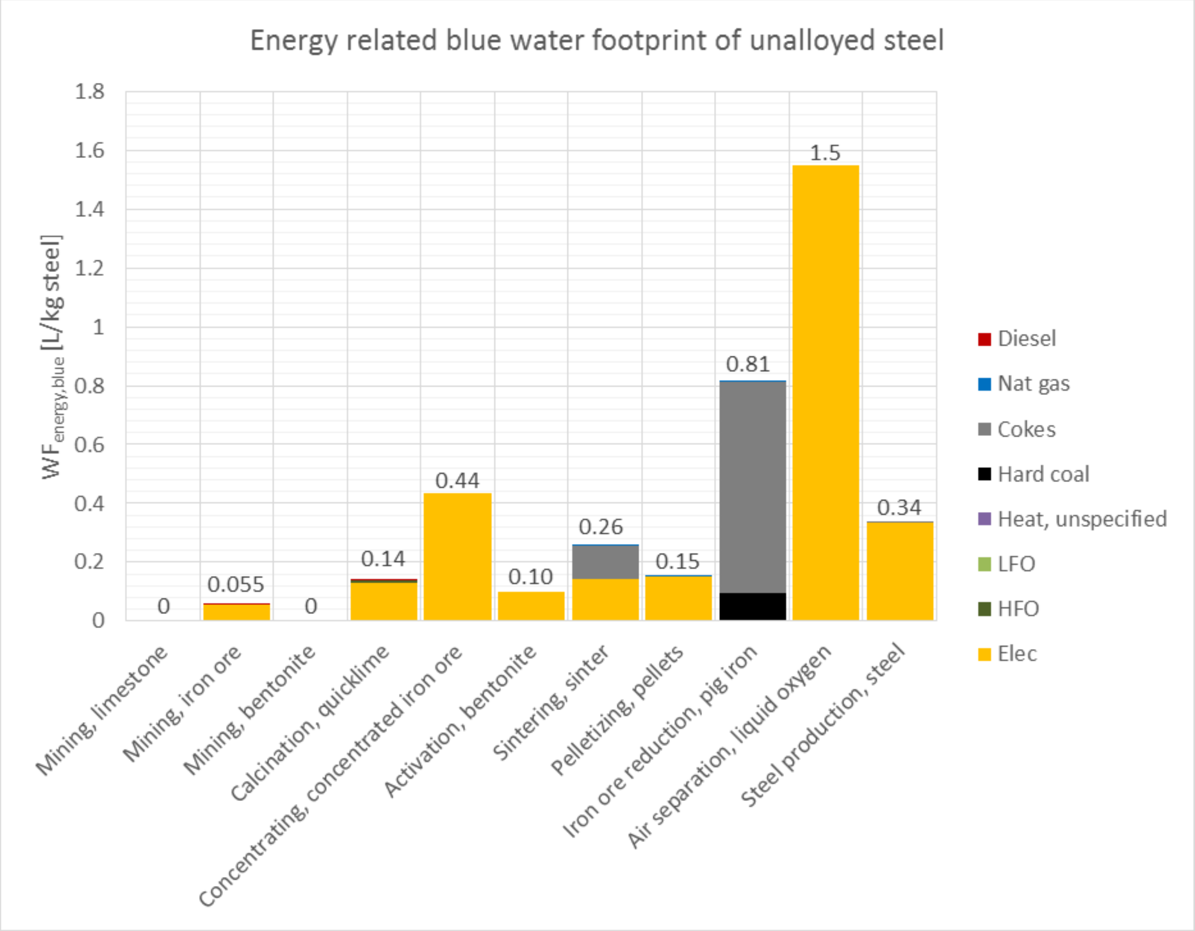

Figure 7: Energy related blue water footprint of unalloyed steel per production process

Figure 8 shows the grey water footprint of unalloyed steel. The WF_{grey} for unalloyed steel is 2,300 L/kg steel. This occurs for the substance cadmium ion. The largest contributing process is the concentrating of iron ore with 2,268 L/kg steel. Other processes contributing with small amounts are bentonite activation and pelletizing. After cadmium the next substance determining WF_{grey} would be copper and then mercury. Both water footprints of the substances occur most for the iron ore concentrating process.

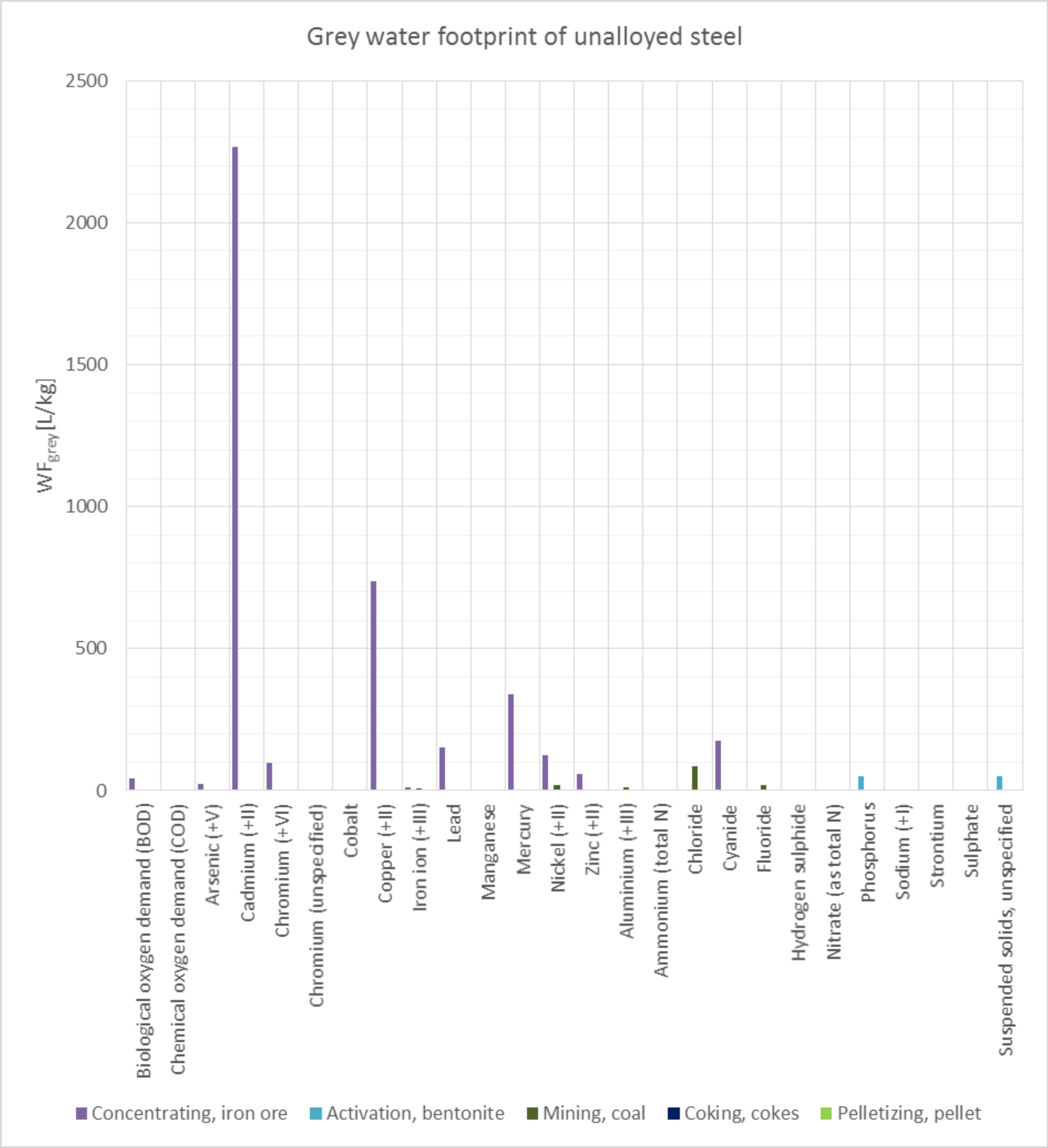

Figure 8: Grey water footprint of unalloyed steel per substance and production process

4.2 Chromium-nickel alloyed steel

Figure 9 shows the process blue water footprint of chromium-nickel alloyed steel. The total calculated $WF_{proc,blue}$ of chromium-nickel steel is 11 L/kg steel. For this type of steel the $WF_{proc,blue}$ of the processes required to produce pig iron (i.e. concentrating, sintering, pelletizing and iron ore reduction) are proportionally reduced compared to unalloyed steel. A significant amount of ferro-alloys in alloyed steel reduces the amount of pig iron used for steel. Part of the process water use for pig iron production is replaced by process water used for the production of ferro-alloys. In this case pre-treatment and direct reduction of ferrochromium. For mining and beneficiation of ferronickel, ecoinvent did not report water use.

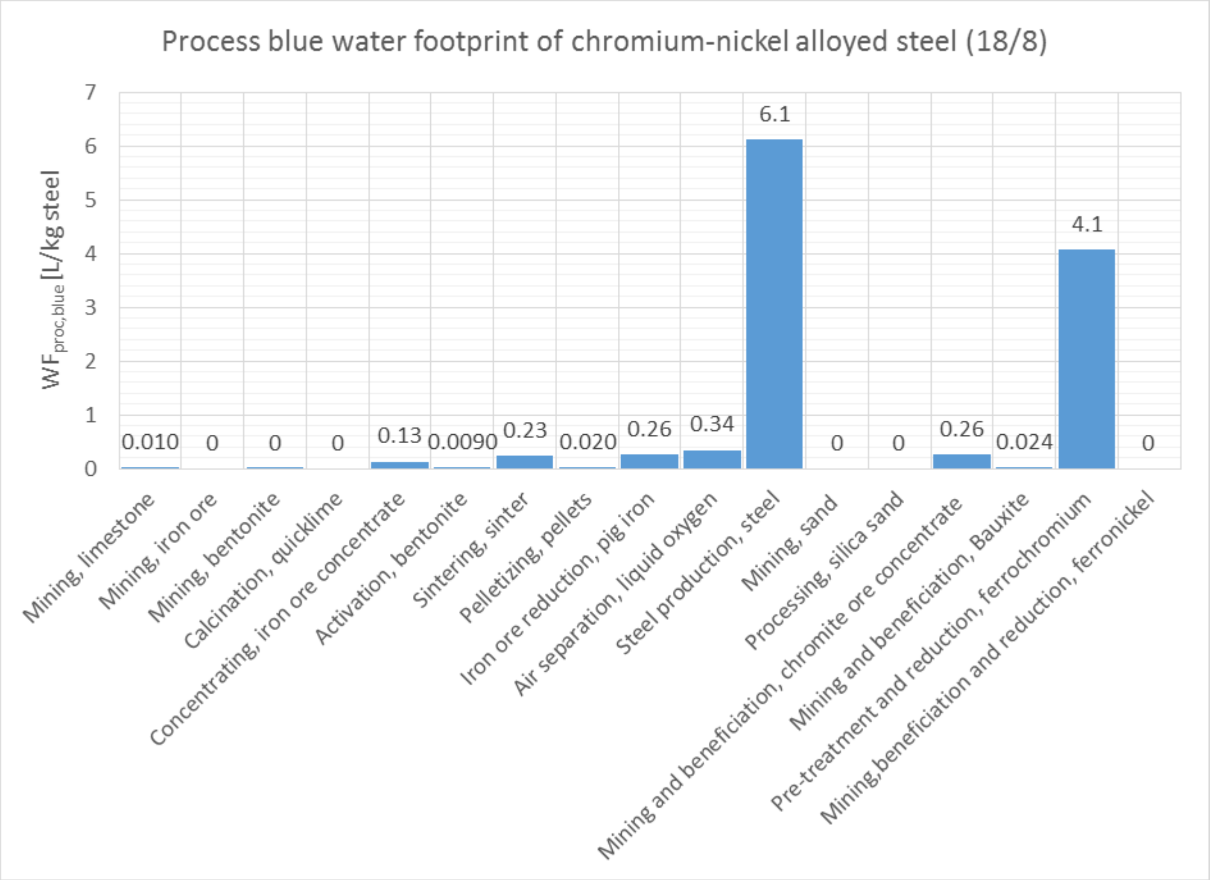

Figure 9: Process blue water footprint of chromium-nickel alloyed steel (18/8) per production process

Figure 10 shows the energy related blue water footprint of chromium-nickel alloyed steel. The total calculated $WF_{energy,blue}$ is 66 L/kg steel. The production of ferro-alloys is responsible for a large blue water footprint of alloyed steel. Ferro-alloys are generally produced in electric arc furnaces which use electricity as the main power source instead of cokes, as is the case for blast furnaces. The relative large value of the global weighted average WF_{blue} of electricity and a high use of electricity in electric arc furnaces result in a much larger $WF_{energy,blue}$ for alloyed steel than for unalloyed steel.

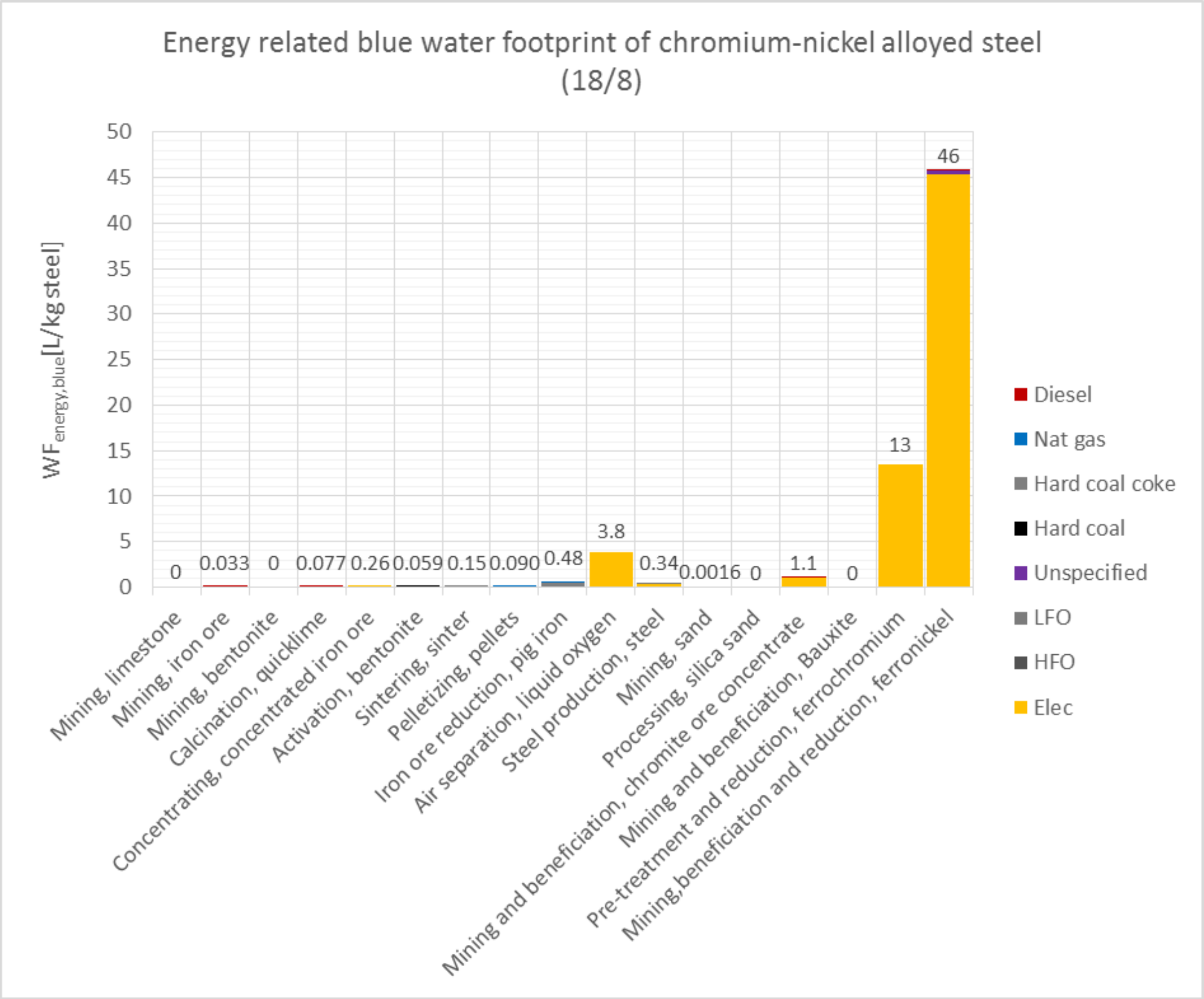

Figure 10: Energy related blue water footprint of chromium-nickel alloyed steel (18/8) per production process

Figure 11 shows the grey water footprint of chromium-nickel alloyed steel. Overall cadmium is the determining substance with a grey water footprint of 1,500 L/kg steel. Of which 1,300 L/kg is from concentrating iron ore, 180 L/kg from mining and beneficiation of ferrochromium and small amounts from pelletizing iron ore and activation of bentonite. The lower share of pig iron used in alloyed steel compared to unalloyed steel, results in a lower grey water footprint of some substances, because the process of iron ore concentrating is in proportion used less. However, concentrating of iron ore is still the largest contributing process to WF_{grey} of chromium steel. The additional processes of mining and beneficiation of ferronickel add to the grey water footprint of chromium-nickel alloyed steel.

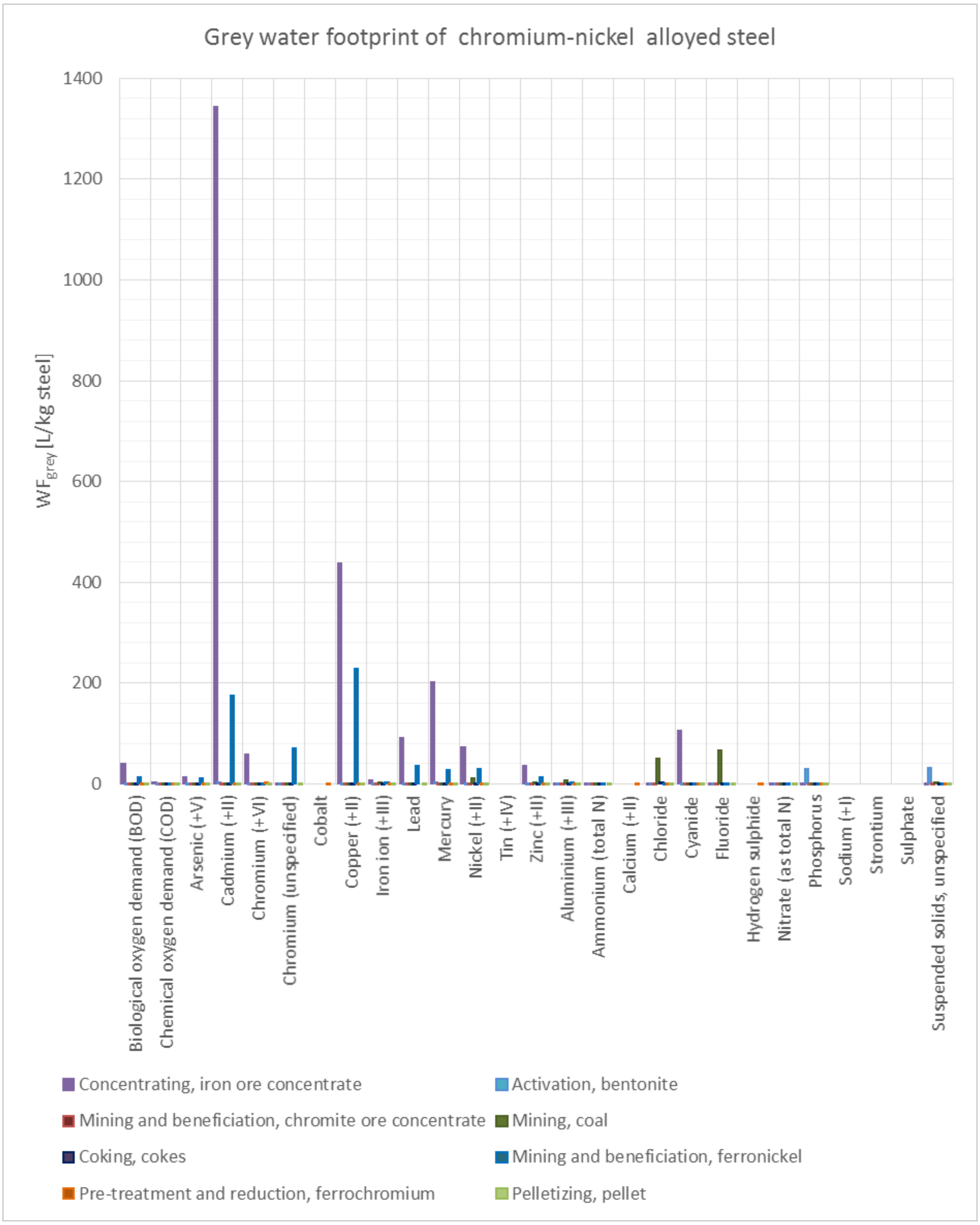

Figure 11: Grey water footprint of chromium-nickel alloyed steel (18/8) per substance and production process

4.3 Ordinary Portland cement

Figure 12 shows the process blue water footprint of ordinary Portland cement. The total calculated $WF_{proc,blue}$ of ordinary Portland cement is between 0.54 and 0.68 L/kg cement depending on the source of gypsum. Beside gypsum from a natural source, gypsum can also be obtained through flue gas desulphurisation. However, since gypsum is a by-product from desulphurisation from other processes, such as electricity generation, it can be argued that the water footprint should be allocated to the sulphur that is retained or to electrical power instead to cement.

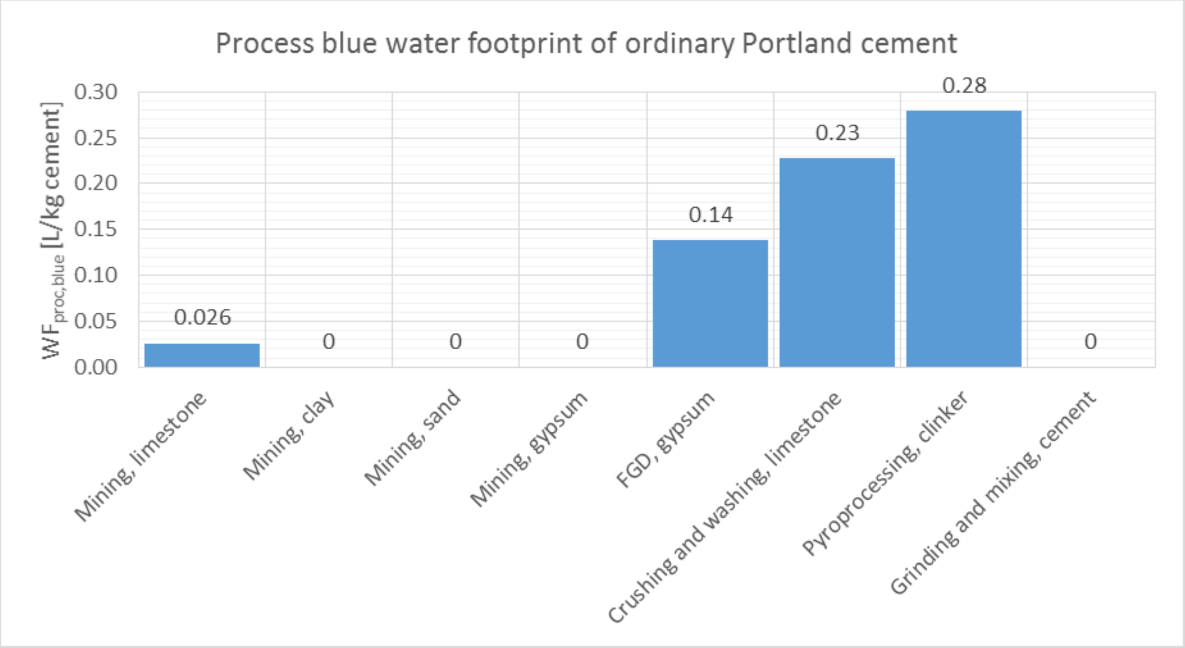

Figure 12: Process blue water footprint of ordinary Portland cement per production process

Figure 13 shows the energy related blue water footprint of ordinary Portland cement. The total calculated $WF_{energy,blue}$ is 1.5 L/kg cement. The largest $WF_{energy,blue}$ occurs during the production of clinker by pyroprocessing with 0.91 L/kg cement. However, comparing the energy consumption for clinker production reported by ecoinvent and by IEA (2007), the energy consumption reported by ecoinvent is lower than that of IEA; 2 MJ/kg (excluding waste products as fuel), versus 2.9 – 6.7 MJ/kg (depending on the production process and kiln technology). The energy related blue water footprint is thus possibly higher than calculated through this method. Using the same fraction of electrical power and using hard coal cokes as main fuel for the IEA reported energy consumption range, results in an energy related blue water footprint for clinker production between 1.1 and 1.3 L/kg instead of 0.91 L/kg cement. The energy related blue water footprint of ordinary Portland cement then is between 1.5 and 1.9 L/kg cement.

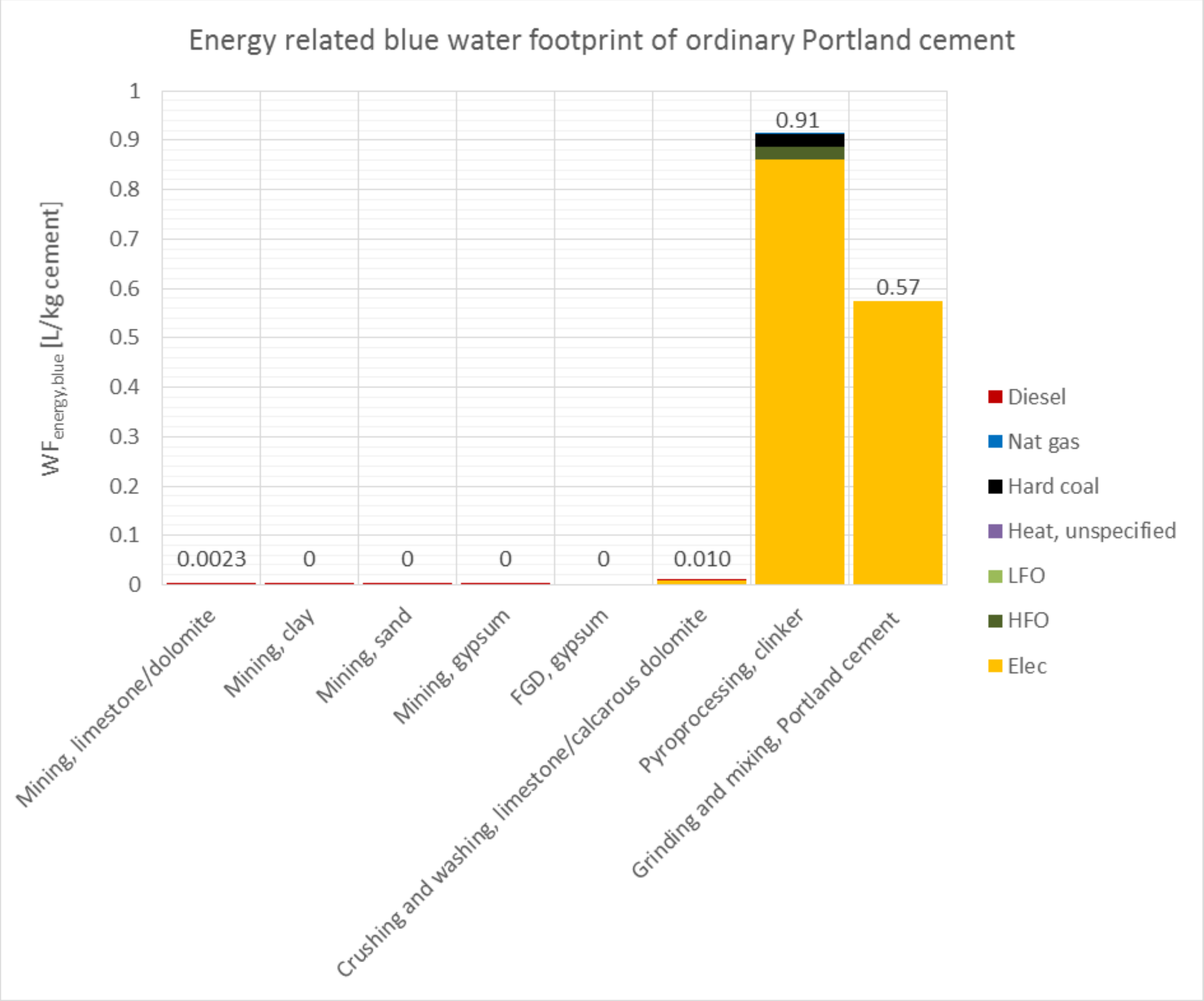

Figure 13: Energy related blue water footprint of ordinary Portland cement per production process

Figure 14 shows the grey water footprint of ordinary Portland cement. The WF_{grey} is determined by the load of mercury in the effluent from flue gas desulphurisation as mercury has the highest value of all substances. This results in a WF_{grey} of 210 L/kg cement. After mercury, cadmium has the largest value (140 L/kg) and then copper (90 L/kg). If the grey water footprint of FGD is not applicable then the clinker production results in a grey water footprint for the substance cadmium of 0.63 L/kg cement. The source of gypsum and whether it is allocated to cement is of large influence for the value of WF_{grey} for cement.

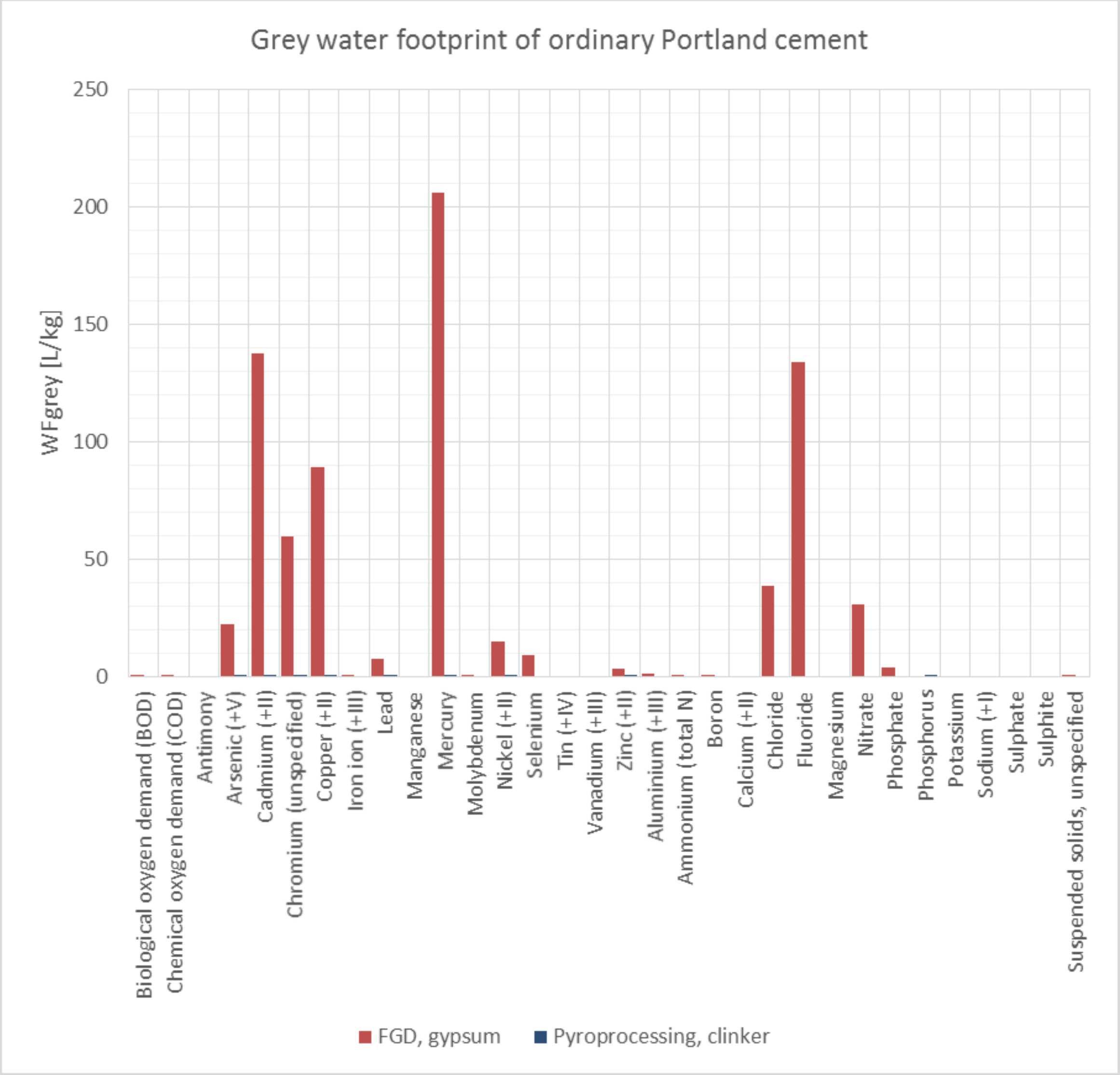

Figure 14: Grey water footprint of ordinary Portland cement per substance and production process

4.4 Portland composite cement

Figure 15 shows the process blue water footprint of Portland composite cement. The $WF_{proc,blue}$ as calculated in this research is 0.44 – 0.58 L/kg cement (depending on the source of gypsum), which is lower than that of ordinary Portland cement. Due to clinker substitutes, such as ground granulated blast furnace slag and fly ash, used in composite Portland cement, the clinker ratio is reduced. Thus effectively reducing $WF_{proc,blue}$ expressed in L/kg cement from clinker production. Water is however also used for the production of alternative constituents in the composite cement. Water is used for granulation of blast furnace slag and water can be used for particle rinsing of the ESP's. (EPA, n.d.). However, no quantitative data was found on the process water consumption for ESP. Flue gas desulphurisation (FGD) is not a necessary process for cement production. Gypsum is a by-product from FGD, however it can also be acquired through mining. The water footprint of gypsum production through FGD is not necessarily part of the water footprint of cement.

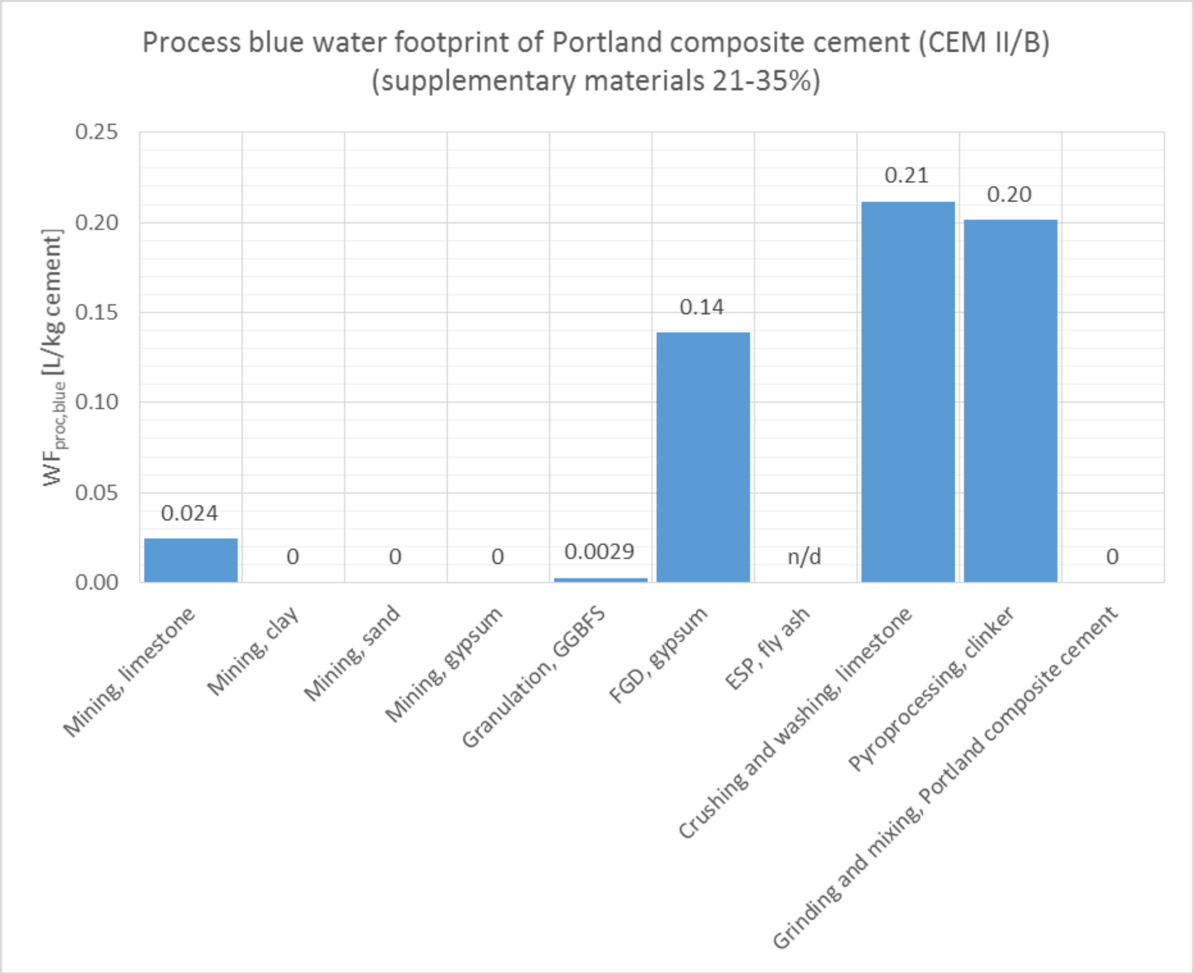

Figure 15: Process blue water footprint of Portland composite cement per production process

Figure 16 shows the energy related blue water footprint of composite Portland cement. The total calculated $WF_{energy,blue}$ is with 1.2 L/kg cement lower than that of ordinary Portland cement (1.5 L/kg cement). This can be attributed to the lower ratio of clinker present in the composite cement, as clinker production is by far the largest energy consuming process of cement production. $WF_{energy,blue}$ of 1.2 L/kg cement is calculated for the Portland composite cement with 21 – 35% alternative constituents, which are limestone, GGBFS and fly ash. Numerous other cement types can be made with different degrees of alternative constituents, resulting in different water footprints.

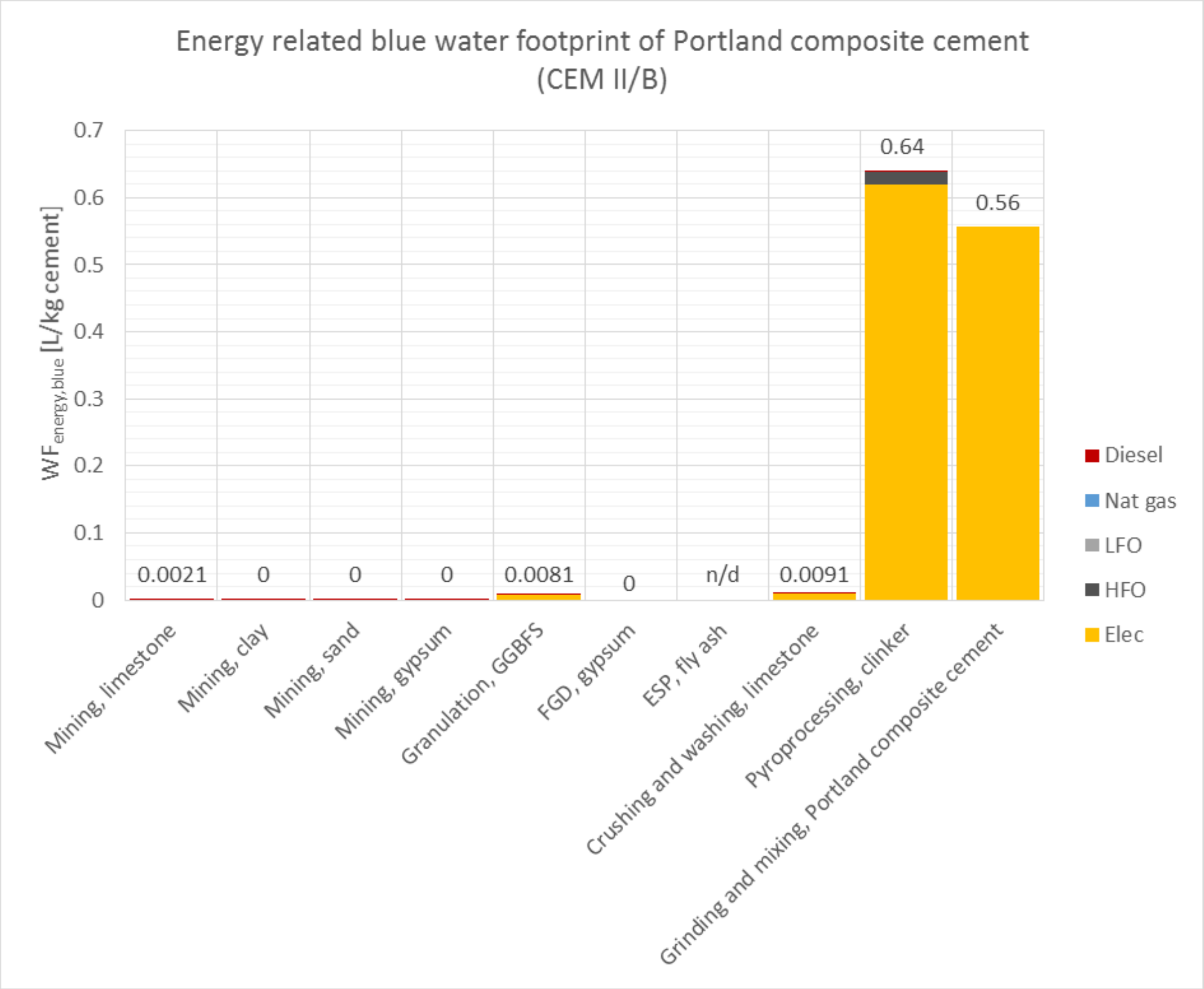

Figure 16: Energy related blue water footprint of Portland composite cement per production process

Figure 17 shows the grey water footprint of Portland composite cement. The figure shows that the grey water footprint of Portland composite cement is similar to that of ordinary Portland cement given that the share of gypsum in cement stays fairly the same (4-5%) (Verver & Fraaij, 2004), (Schrocht et al., 2013). If the grey water footprint of gypsum production through FGD is not attributed to cement or if FGD is not applied, then the substance cadmium, from clinker production, determines WF_{grey} with 0.45 L/kg cement instead of mercury with 210 L/kg cement.

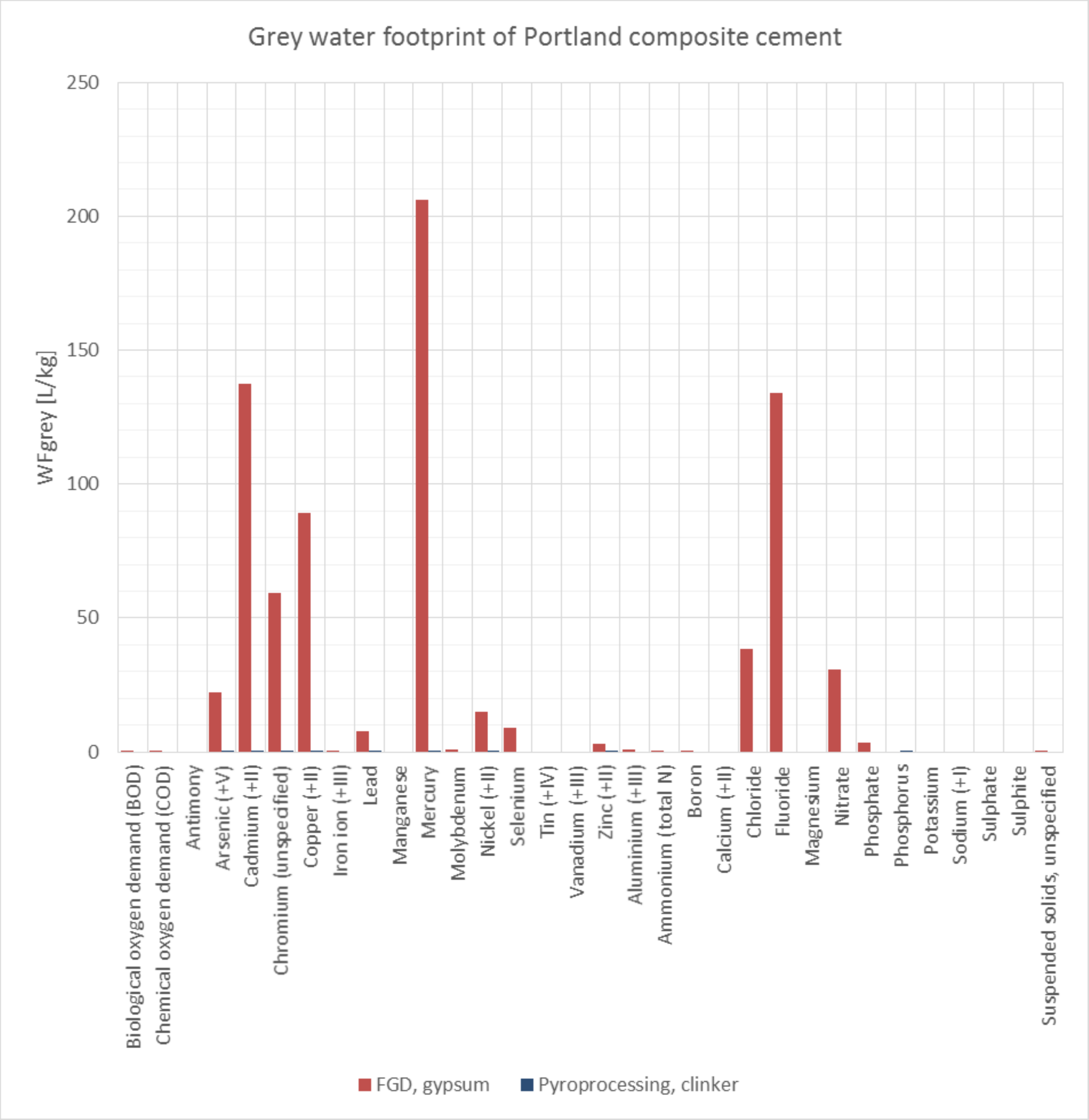

Figure 17: Grey water footprint of Portland composite cement per substance and production process

4.5 Soda-lime float glass

Figure 18 shows the process blue water footprint of float glass. The total calculated $WF_{proc,blue}$ using the Solvay process for soda ash is 3.2 L/kg glass. The process water footprint of float glass is strongly dependant on the water consumption from the Solvay process. No quantitative water consumption data on the alternative source of soda ash though mining of trona or nahcolite is found. The figures with the water footprint of soda-lime float glass has the category 'Glass production' instead of the individual processes (melting, annealing, crushing and cleaning cullet) because the exact distribution of water use over the processes is not clear and thus are clustered together. The most significant water use in the glass factory for glass production occurs during cooling and cullet cleaning. (IFC World Bank, 2007).

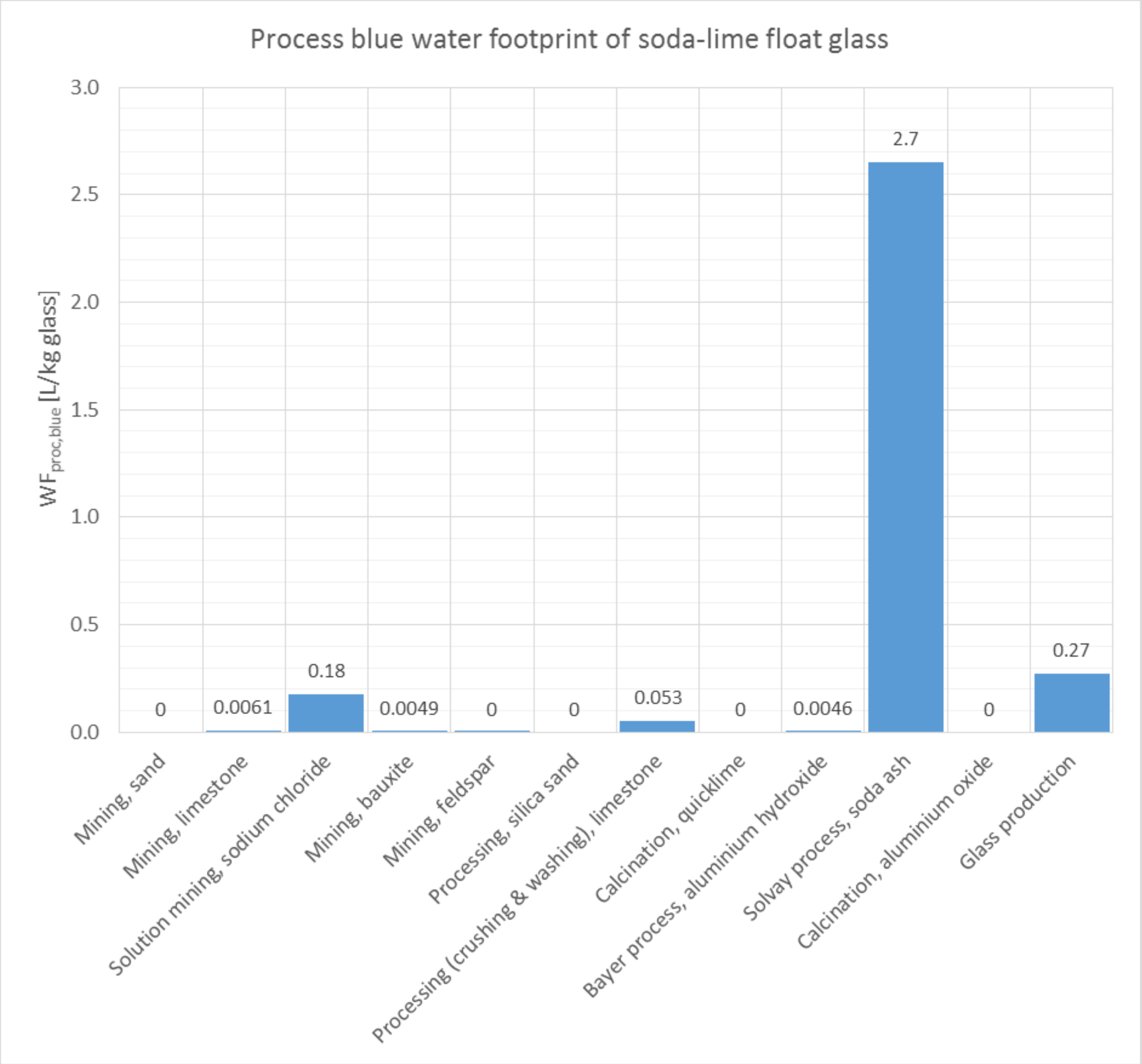

Figure 18: Process blue water footprint of soda-lime float glass per production process

Figure 19 shows the energy related blue water footprint of soda-lime float glass. The total calculated $WF_{energy,blue}$ is 2.6 L/kg. Most of the energy is used for glass melting. When additional electrical power is used for glass melting the blue water footprint of glass increases enormously. In this calculation the fuel distribution from ecoinvent is used, which is 58% natural gas, 38% heavy fuel oil and 5% electrical power. According to Scalet et al. (2013) an electrical boost of 10% is not uncommon. Appendix VII shows the energy related water footprint of float glass when a different fuel composition is used.

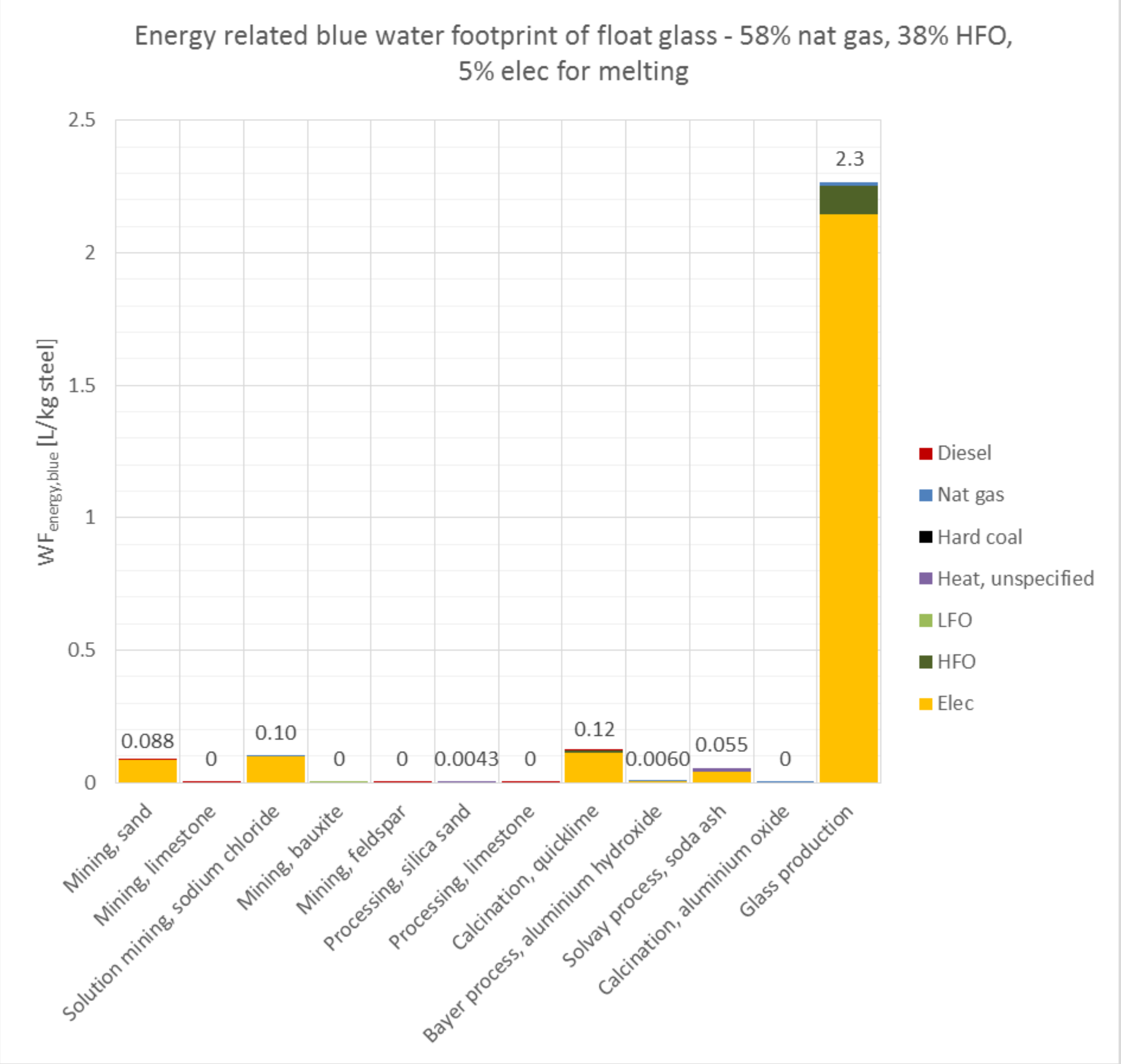

Figure 19: Energy related blue water footprint of soda-lime float glass per production process, with the ecoinvent energy distribution for melting

Figure 20 shows the grey water footprint of soda-lime float glass. The WF_{grey} is determined by the effluent of the Solvay process. Suspended solids reported by ecoinvent for the Solvay process result in a grey water footprint of 1,300 L/kg glass. Heavy metals in the effluent come from the raw materials used in the Solvay process and from the fuel source which are cokes. The raw brine is responsible for about 6% of the total heavy metals entering the soda ash plant, fuel for 21% and the limestone 73%.

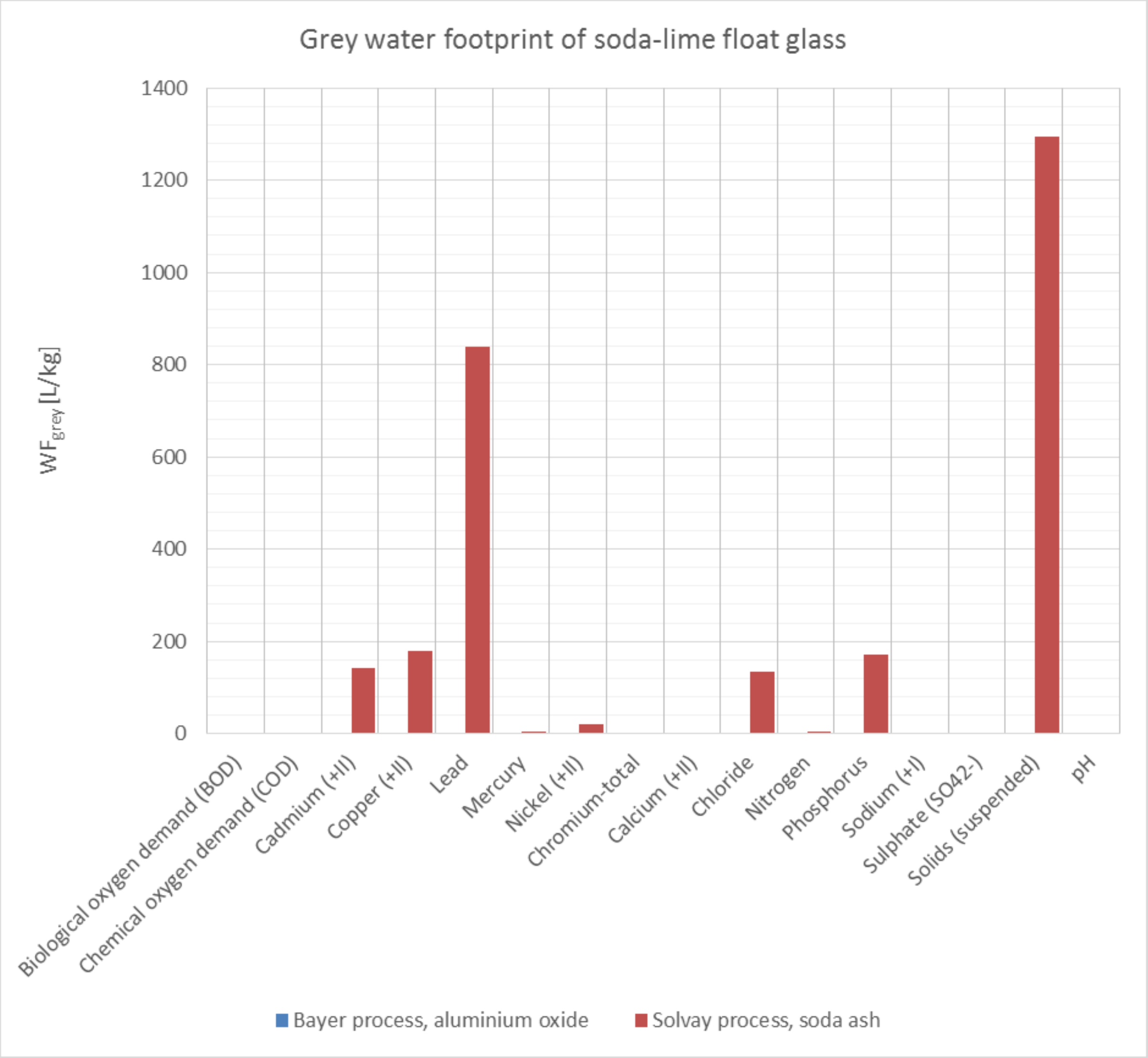

Figure 20: Grey water footprint of soda-lime float glass per substance and production process

ESAPA (2004) mentions an indicative range and two cases for substances in waste water from the Solvay process. The data includes an indicative range for hydroxide, which is not reported in the ecoinvent database. Figures of the calculated water footprints using ESAPA, (2004) data can be found in Appendix VIII. The high pH of the effluent comes from the milk of lime ($Ca(OH)_2$). The WF$_{grey}$ of hydroxide using the indicative range is 3,500 – 12,000 L/kg cement and for suspended solids: 1,200 – 9,100 L/kg cement. These reported ranges from ESAPA, (2004) are however before any waste water treatment is applied and are not necessarily emitted to surface water.

5 Discussion

In this chapter several remarks concerning the results of this research are mentioned. Effort has been done in order to validate input data by finding other data resources, however large amounts of data used still comes from a single source: the ecoinvent database. The data which is used for the study is assumed to contain no large errors that influence the results, however working with large datasets this cannot be excluded with all certainty.

At the time of consulting the ecoinvent database the cryogenic air separation for liquid oxygen contains an error, reporting an evaporation of 860 L/kg liquid oxygen. Ecoinvent is currently working on a new value for the water consumption. For this research 2.7 L/kg liquid is used from Althaus, et al., (2007). This value is based on the cooling water make up for an average produced waste heat. The products from cryogenic air separation are: 1 kg oxygen, 3.27 kg nitrogen and 0.06 kg argon. Resulting in a water consumption of 11.7 L/kg liquid oxygen. The accuracy of this value can be questioned because it is not specific for this process, but also shows the order of magnitude difference between the reported values.

The water footprint of electricity used for production processes is assumed to correspond to the global weighted average. However, some integrated steel plants are able to generate their own electric power from off gasses (Remus et al., 2013). Another possibility is that steel plants are located in parts of the world where the electric grid mix does not correspond to the global weighted average at all. In these cases the actual energy that is generated has different sources than is assumed. This can have an effect on the actual water footprint of the materials.

A poor accuracy of the water footprint of ferronickel and thus that from chromium-nickel alloyed steel should be assumed and the results should be used cautiously. The dataset is mainly based on a study of the energy and material streams from the production of class I nickel. Lacking data was taken from similar processes for copper winning. The lacking data concerns mainly process specific emissions (Classen, n.d.). The dataset is designed for the use of the metal as raw material in the manufacturing of stainless steels and alloys, as has been done in this study. However, Classen (n.d.) mentions that when the impact of ferronickel is considered to be high the data should not be used. The high electricity use of melting ferronickel does influence the blue water footprint of chromium-nickel alloyed steel. However, the grey water footprint of ferronickel is not very dominant for the grey water footprint of chromium-nickel steel calculation. Furthermore, ecoinvent did not report a process water consumption for the production of ferronickel, but EIPPCB (2001) reports 6.9 m^3/t water consumption for ferroalloys in general, although not specifically for ferronickel. The water uses are for wet off-gas cleaning, slag granulation and cooling.

Mostly the energy consumption mentioned in documents from IEA, documents from EIPCCB and the ecoinvent database are quite similar. However, for the energy consumption for clinker production the energy consumption reported by ecoinvent is lower than that of IEA; 2 MJ/kg (excluding waste products as fuel), versus 2.9 – 6.7 MJ/kg (depending on the production process and kiln technology). Part can be attributed to that ecoinvent lists waste products used as fuel but these are not included in the reported 2 MJ/kg. The water footprint tied to energy from waste is left out of the scope of this research.

Another difference between energy consumption data is the fuel distribution for glass melting. Ecoinvent mentions the following distribution: 58% natural gas, 38% heavy fuel oil and 5% electrical power. According to Scalet et al. (2013) an electrical boost of 10% is not uncommon. Since electrical power consumption has a large influence on the blue water footprint, the blue water footprint using 10% electrical boost would be 4.0 L/kg glass instead of 2.2 L/kg glass. Appendix VII shows the energy related water footprint of float glass with other energy distributions.

For float glass three alternative production possibilities are not taken into account for the calculation of the water footprint. For the Solvay process it is assumed that fresh water is used. ESAPA (2004) mentions that for brine production it is possible to use seawater. When seawater is used instead of fresh water the water footprint of the Solvay process could be much lower than calculated as the brine production is a large water requiring process (ESAPA, 2004). The alternative dry lime process instead of the usual use of liquid of lime has not been researched. This might also reduce the water consumption of the soda ash production. Furthermore, no quantitative data is found on mining of soda ash. Likely the water footprint of float glass using soda ash from mining is lower than that of float glass using soda ash from the Solvay process. These possibilities are not considered in this research.

The use of supplementary materials as clinker substitutes in cement production is reported to reduce greenhouse gas emissions (Flower & Sanjayan, 2007), (Lee & Park, 2005). The results from this research suggest that the water footprint can also be reduced by using clinker substitutes to produce Portland composite cement instead of ordinary Portland cement. By using clinker substitutes the water footprint tied to the energy consumption for pyroprocessing will be reduced. Crossin (2015) notes that the reduction of greenhouse gas emissions by using GGBFS depend on wether or not the byproduct is defined as a waste as this affects the allocation and which processes for the production of the supplementary materials are included in the analysis. The same argument applies for the water footprint of cement and other by products used as supplementary materials such as fly ash or gypsum from FGD.

The results of the grey water footprint should be interpreted cautiously, as the waste water is not always specified as emitted to the environment. For the solvay process, a production process of soda ash which is used for float glass production, ESAPA (2004) mentions some indicative ranges of substances in the effluent on top of the substances reported by ecoinvent. The data includes indicative ranges for chloride, suspended solids and hydroxide. These reported ranges from ESAPA, (2004) are however before any waste water treatment is applied and are not necessarily emitted to surface water. It is unclear whether all effluent loads reported by the ecoinvent database are emitted to the environment. This means that in reality waste water treatment could be applied which is not taken into account and that the calculated grey water footprint is only valid when the effluent is directly emitted to the environment.

Cadmium in the effluent of especially iron ore processing activities results in the largest grey water footprint of all the reported substances. Low levels of maximum allowable concentrations for cadmium are a cause of the high water footprint. Prevention from entering the environment by reducing the load in the effluent may reduce the grey water footprint of iron and steel. Water quality association (WQA, 2013) lists the following treatment methods for reducing cadmium: Strong Acid Cation Resin, Weak Acid Cation Resin, Reverse Osmosis, distillation, precipitation/filtration and lime softening. EIPPCB (2009) mentions several best available techniquest to reduce emissions to water specifically for mining activities. The by EIPPCB discussed method to remove dissolved metals uses the adsorption ability of finely ground tailings has a cleaning effect on water containing dissolved metals. Water treatment by precipitation for which sulphide or lime or a combination is used is also mentioned.

Future research

For expanding knowledge and accuracy about the water footprint of the researched materials the following options could be considered:

- Research on the actual electricity grid mixes of production facilities.
- Research on the grey water footprint of energy sources.
- Research on the water footprint of steel from steel scrap produced in electric arc furnaces.
- Research on the water footprint of trona and nahcohlite mining as a source for soda ash.
- Research on the water footprint of ferronickel for the production of alloyed steel.

6 Conclusions

The conclusions in this chapter answer the research questions of this research. First the blue water footprint and the grey water footprint of unalloyed and chromium-nickel alloyed steel are given. Then the largest contributing factors to these water footprints are discussed. Then followed by the same structure for ordinary Portland cement and Portland composite cement, and float glass is discussed. Finally, some general conclusions about the study are drawn.

Unalloyed steel has a blue water footprint of 11 L/kg steel and the grey water footprint is 2,300 L/kg steel for the substance cadmium.

Chromium-nickel alloyed steel (18/8) has a blue water footprint of 77 L/kg steel and a grey water footprint of 1,500 L/kg steel for the substance cadmium. The accuracy of the water footprint of chromium-nickel alloyed steel should be considered poor. The data from ecoinvent used for ferronickel is probably insufficiently accurate to use when the impact of ferronickel is very large.

Unalloyed steel has a much smaller blue water footprint than the calculated chromium-nickel alloyed steel. The ferroalloys are produced in electric arc furnaces which increase the blue water footprint as a result from electricity use. However, the grey water footprint of unalloyed steel is lower than that of chromium-nickel alloyed steel. The use of ferroalloys in alloyed steel reduces the factor of beneficiation (i.e. concentrating, sintering and pelletizing) of iron ore in steel making. Beneficiation of iron ore has the largest influence on the calculated grey water footprint. The production of ferroalloys adds to the grey water footprint of alloyed steel, however not as much as the grey water footprint is reduced by using less iron ore. Cadmium is the determining substance for the grey water footprint. After cadmium, copper and then mercury are the substances with the largest grey water footprint.

Ordinary Portland cement (CEM I) has a blue water footprint between 2.0 – 2.6 L/kg cement, depending on the source of gypsum. A grey water footprint of 210 L/kg cement is calculated for mercury when gypsum through flue gas desulphurisation is used for the production. Without the use of gypsum through FGD the grey water footprint will be 0.63 L/kg cement for cadmium.

Portland composite cement (CEM II/B) has a blue water footprint between 1.7 – 2.1 L/kg cement. A grey water footprint of 210 L/kg cement is calculated for mercury when gypsum through flue gas desulphurisation is used for the production. Without the use of gypsum through FGD the grey water footprint will be 0.45 L/kg cement for cadmium.

Ordinary Portland cement has a higher water footprint than Portland composite cement. The process of clinker production by pyroprocessing is the biggest contributor to the blue water footprint of Portland cement, due to high energy consumption. By using supplementary materials to substitute clinker the water footprint of cement can be reduced. Gypsum production from flue gas desulphurisation causes the largest grey water footprint with 210 L/kg cement for mercury. It can be argued that the water footprint from FGD should not be allocated to cement but to power generation, since this is a process to clean flue gas from power generation. When this process is not allocated to gypsum and cement production, the grey water footprint then will be much lower. The clinker production then results in a grey water footprint for the substance cadmium of 0.63 L/kg ordinary Portland cement and 0.45 L/kg Portland composite cement. From these results it can be concluded that from a water footprint point of view it would be better to choose for a Portland composite cement instead of ordinary Portland cement if both types of cement have the right properties for the circumstances under which it would be used.

Soda-lime float glass has a blue water footprint of 5.8 L/kg glass. This is for glass with soda ash acquired through the Solvay process. The water footprint of glass with natural sources of soda ash is not calculated due to lack of data. The grey water footprint of float glass is 1,300 L/kg glass for suspended solids.

Soda ash produced by the Solvay process has a big influence on both the blue and grey water footprint of float glass. A lot of process water is used for the Solvay process. Furthermore the effluent of Solvay processes can be high in heavy metals, suspended solids and can have a high pH value.

Overall it can be concluded that the blue water footprint tied to the energy consumption ($WF_{energy,blue}$) is a significant part of the total blue water footprint of the researched materials. This is because the production of these materials is very energy demanding but mainly because the water footprint of electricity is very large compare to other energy sources. The results show that the energy related blue water footprint is largely determined by the electricity use. Furthermore, for these researched materials the calculated grey water footprint is potentially much larger than the blue water footprint.

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APPENDICES

Appendix I: Input materials of a typical float glass composition

A typical soda-lime silica flat glass composition as mentioned by EIPPCB (2013) is used for the calculation of the water footprint. Table 4 shows the components of typical soda-lime flat glass. From these components the input materials were determined. Typically, around 20 % of the input mass consists of cullet. Significant use of *external* cullet is not present in the float glass production, because end of life cycle cullet often is polluted with unwanted materials. Cullet used in float glass production is from internal cuttings and breakage. From the internal cullet 95% will be reused. (Scalet et al., 2013).

Table 4: Typical soda-lime silica flat glass composition (source: EIPPCB, 2013)

Component	Mass percentage
Silicon dioxide (SiO_2)	72.6
Sodium oxide (Na_2O)	13.6
Calcium oxide (CaO)	8.6
Magnesium oxide (MgO)	4.1
Aluminium oxide (Al_2O_3)	0.7
Potassium oxide (K_2O)	0.3
Sulphur trioxide (SO_3)	0.17
Minor materials (colour modifiers and incidental impurities from raw materials)	Traces

There is a wide range of potential raw materials possible and used for glass making. The largest inputs are the materials containing silica (sand and glass cullet) and the carbonates (soda ash, dolomite and limestone). Silicon dioxide is derived mainly from sand and glass cullet. Cullet also provides a proportionately smaller level of the other oxides. Sodium oxide is derived mainly from soda ash, the calcium oxide mainly from dolomite and limestone, and the magnesium oxide from dolomite. (Scalet et al., 2013). Nepheline syenite, and feldspars are sources of aluminium oxide, but also of potassium oxide and sodium oxide. Other sources for aluminium are blast furnace slags, bauxite, gibbsite, diaspora. (Scalet et al.,), (Bray, 2001), (Potter, 2003). During the production of glass the mass of several materials in glass is reduced as the batch composition ($CaCO_3$ and $NaCO_3$) is changed to the different oxides (CaO and Na_2O) and gas (CO_2) is emitted. To calculate the batch materials a conversion factor (f_c) is used as mentioned in Bray (2001).

Table 5: Input materials of soda-lime-silica glass, based on a typical soda-lime-silica glass composition.

Material	Scaled input[a] [mass]	Input [%]	F_c [-][b]	Output [mass]	Component
Sand	0.546	47.4	1	0.546	silicon dioxide
Feldspar	0.018	1.6	8/6	0.014	silicon dioxide
			8/1	0.002	aluminium oxide
			8/1	0.002	potassium oxide
Soda ash	0.180	15.6	1.71	0.105	sodium oxide
Limestone	0.118	10.3	1.785	0.066	calcium oxide
Dolomite	0.056	4.9	1.785	0.032	magnesium oxide
Calcined alumina	0.003	0.27	1	0.003	aluminium oxide
Cullet	0.230	20.0	1	0.230	all proportionately
Total	1.151	100.0		1.000	

[a] For 1 mass output of glass

[b] Conversion factor: as mentioned in Bray (2001). E.g., for 0.105 kg of sodium oxide in the actual glass product, the amount of material of soda ash in the input batch should be: 0.105×1.71=0.18

Appendix II: Process schematics

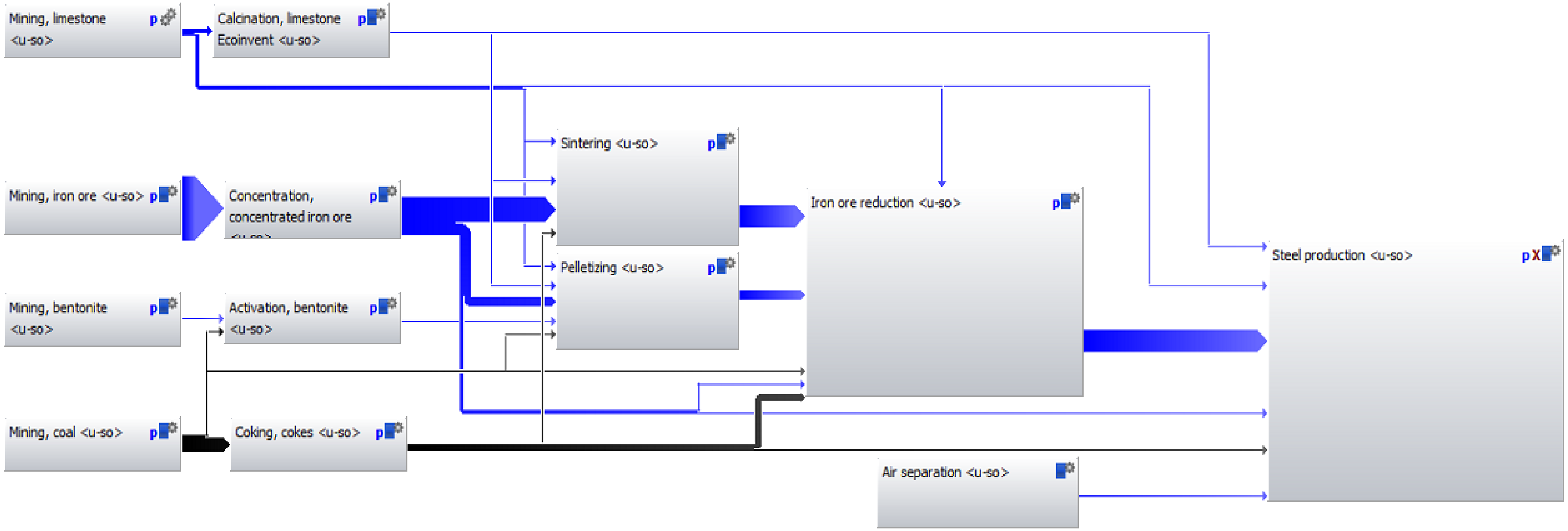

Figure 21: Process schematic of unalloyed steel. Boxes represent processes and arrows represent product flows. The thickness of the arrows indicate the mass of the flow.

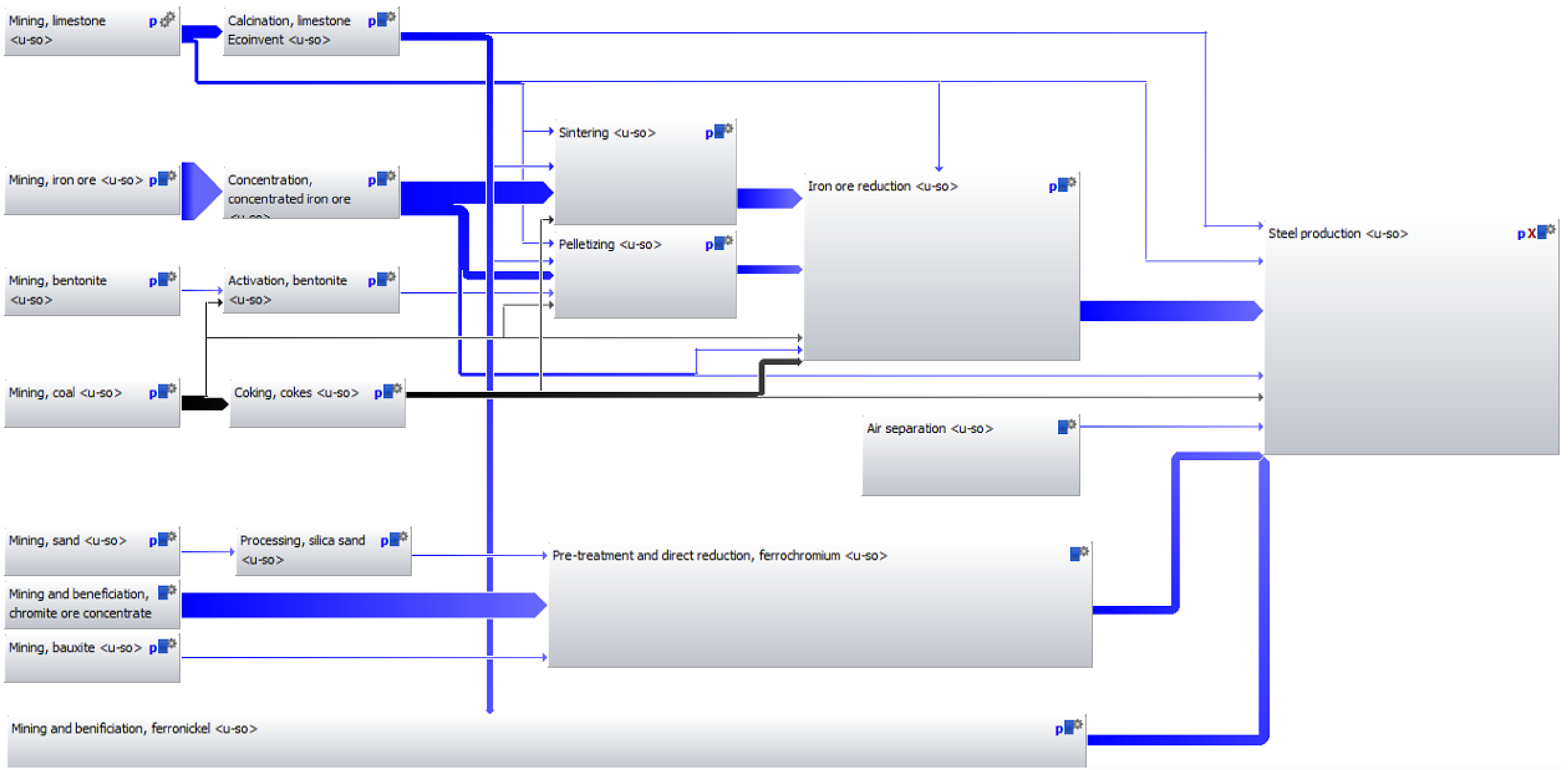

Figure 22: Process schematic of chromium-nickel alloyed steel. Boxes represent processes and arrows represent product flows. The thickness of the arrows indicate the mass of the flow.

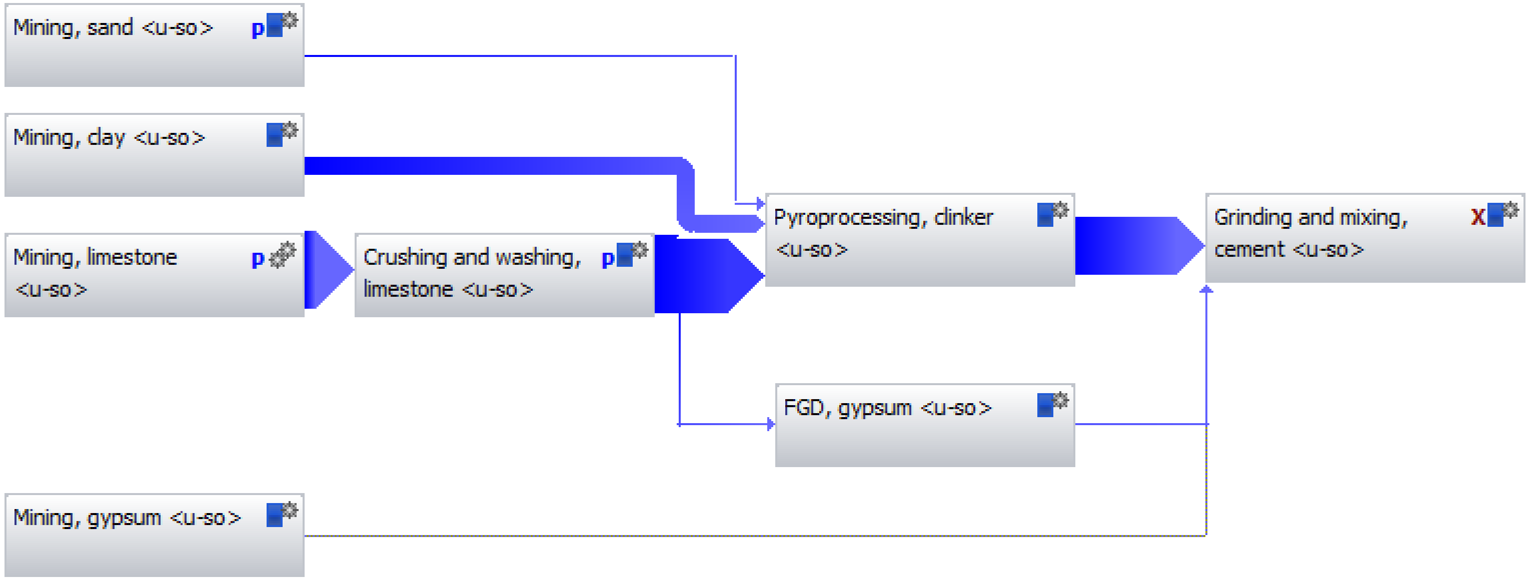

Figure 23: Process schematic of ordinary Portland cement. Boxes represent processes and arrows represent product flows. The thickness of the arrows indicate the mass of the flow. Two sources of gypsum are possible: gypsum from quarry and gypsum from flue gas desulphurisation.

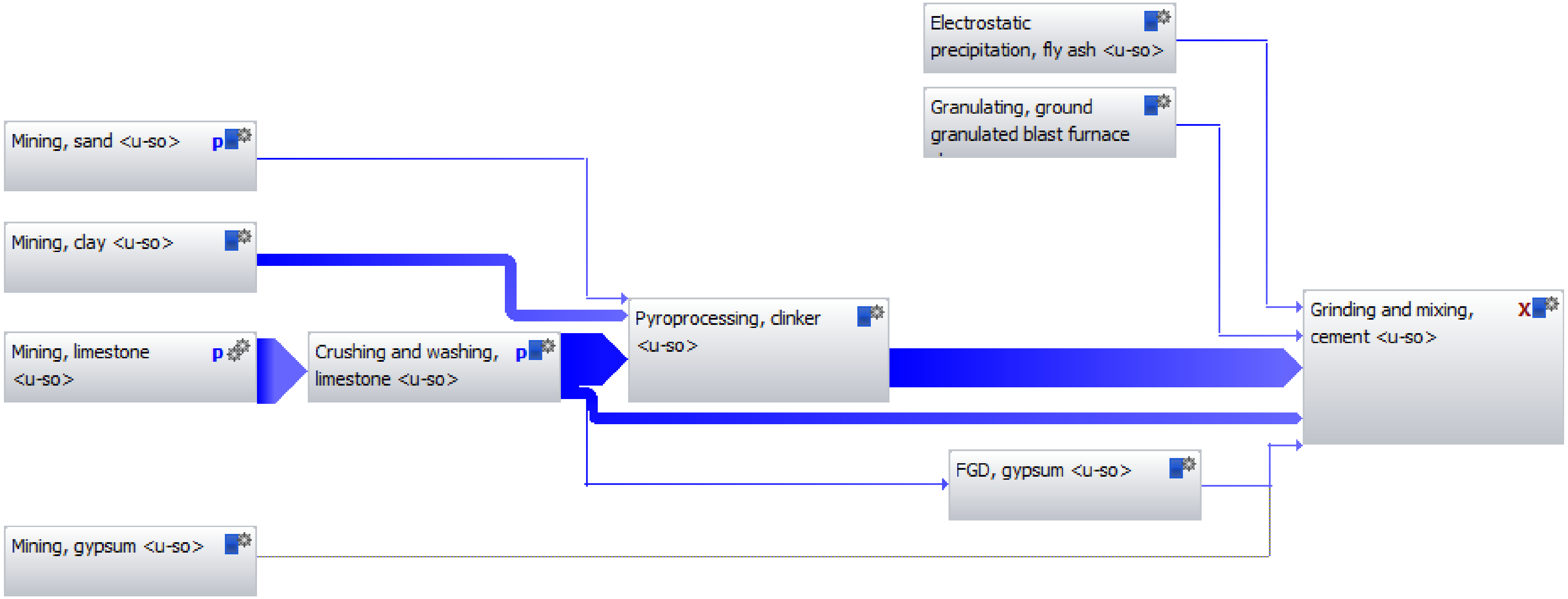

Figure 24: Process schematic of Portland composite cement. Boxes represent processes and arrows represent product flows. The thickness of the arrows indicate the mass of the flow. Two sources of gypsum are possible: gypsum from quarry and gypsum from flue gas desulphurisation.

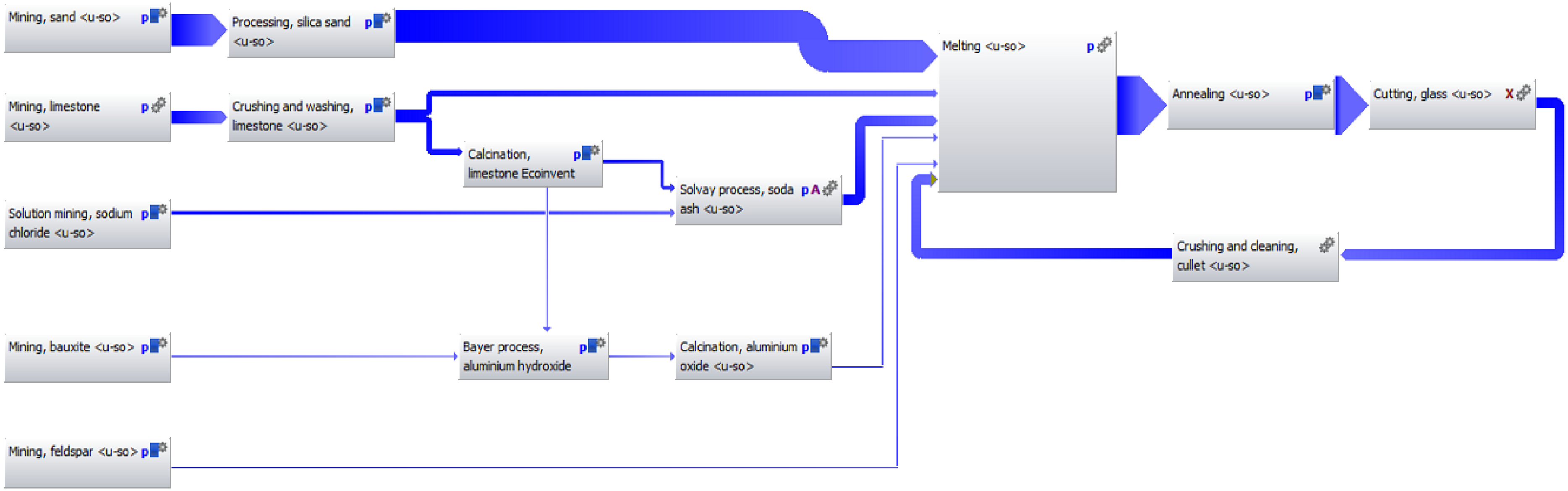

Figure: Process schematic of float glass. Boxes represent processes and arrows represent product flows. The thickness of the arrows indicate the mass of the flow

Appendix III: Process water use per production process

Table 6: Process water use for unalloyed steel production processes

Step No.	Process, product	Product output[1] [kg]	Water abstraction[1] [L]	Water effluent[1] [L]	Water evaporation[1] [L]	Water consumption [L]	Water application
1	Mining, limestone	1	0.021	0.000	0.021	0.021	Dust suppression[1]
1	Mining, iron ore	1	0	0	0	0	n/a
1	Mining, bentonite	1	0.046	0.031	0.009	0.015	n/d
1	Mining, coal	1	2.295	1.950	0.344	0.344	n/d
2a	Concentrating, iron ore concentrate	1	1.519	1.375	0.144	0.144	Dust suppression Classifying particles Magnetic separation Flotation[1]
2a	Activation, bentonite	1	7.521	6.393	1.128	1.128	n/d
2a	Sintering, sinter	1	1.002	0.584	0.417	0.417	Cleaning Cooling Gas treatment[2]
2a	Pelletizing, pellets	1	0.112	0.018	0.003	0.093	Rinsing[3]
2b	Calcination, quicklime	1	0	0.000	0.000	0	n/a
2c	Coking, hard coal coke	0.803	1.6	0.98	0.62	0.62	Wet quenching[3]
3	Iron ore reduction, pig iron	1	1.461	0.970	0.490	0.490	BF gas scrubbing Slag granulation Blowdown from cooling water circuits[3]
4	Air separation, liquid Oxygen By product: nitrogen By product: argon	1 3.27 0.06	n/a	n/a	n/a	11.7[4]	Cooling[4]
6	Steel production, steel	1	12.936	6.818	6.118	6.118	BOF gas scrubbing Vacuum generation Cooling[3]

[1] (Weidema et al., 2013)

[2] (U.S. EPA, 1994)

[3] (Remus et al., 2013)

[4] (Althaus, et al., 2007)

Table 7: Process water use for chromium-nickel alloyed steel production processes

Step No.	Process, product	Product output[1] [kg]	Water abstraction[1] [L]	Water effluent[1] [L]	Water evaporation[1] [L]	Water consumption [L]	Water application
1	Mining, limestone	1	0.021	0.000	0.021	0.021	Dust suppression[2]
1	Mining, iron ore	1	0	0	0	0	n/a
1	Mining, bentonite	1	0.046	0.031	0.009	0.015	n/d
1	Mining, coal	1	2.295	1.950	0.344	0.344	n/d
2a	Concentrating, iron ore concentrate	1	1.519	1.375	0.144	0.144	Dust suppression Classifying particles Magnetic separation Flotation[2]
2a	Activation, bentonite	1	7.521	6.393	1.128	1.128	n/d
2a	Sintering, sinter	1	1.002	0.584	0.417	0.417	Cleaning Cooling Gas treatment[3]
2a	Pelletizing, pellets	1	0.112	0.018	0.003	0.093	Rinsing[3]
2b	Calcination, quicklime	1	0,000	0.000	0.000	0.000	n/a
2c	Coking, hard coal coke	0.803	1.6	0.98	0.62	0.62	Wet quenching[3]
3	Iron ore reduction, pig iron	1	1.461	0.970	0.490	0.490	BF gas scrubbing Slag granulation Blowdown from cooling water circuits[3]
4	Air separation, liquid oxygen By product: nitrogen By product: argon	1 3.27 0.06	n/a	n/a	n/a	11.7[4]	Cooling[4]
6	Steel production, steel	1	12.936	6.818	6.118	6.118	BOF gas scrubbing Vacuum generation Cooling[3]
1	Mining, sand By product: gravel	0.35 0.65	1.39	1.39	0	0.00	n/a
	Processing, silica sand	1	0	0	0	0	n/a
1+2	Mining and beneficiation, chromite ore concentrate	1	2.69	2.287	0.404	0.404	Scrubbing Slag granulation Cooling[5]
1+2	Mining and beneficiation, Bauxite	1	0.5	0.05	0.314	0.45	n/d
5	Pre-treatment and direct reduction, ferrochromium	1	20	4.625	5.375	15.37	Cooling Granulation Wet cleaning[1]
1+2+5	Mining, beneficiation and reduction ferronickel	1	0	0	0	0	n/a

[1] (Weidema et al., 2013)

[2] (U.S. EPA, 1994)

[3] (Remus et al., 2013)

[4] (Althaus, et al., 2007)

[5] (EIPPCB, 2001)

Table 8: Process water use for ordinary Portland cement production processes

Step No.	Process, product	Product output[1] [kg]	Water abstraction[1] [L]	Water effluent[1] [L]	Water evaporation[1] [L]	Water consumption [L]	Water application
1	Mining, limestone/dolomite	1	0.021	0.000	0.021	0.021	n/d
1	Mining, clay	1	0	0	0	0	n/a
1	Mining, sand By product: gravel	0.35 0.65	1.39	1.39	0	0.00	n/a
1	Mining, gypsum By product: anhydrite rock	0.657 0.343	0	0	0	0	n/a
1	Desulphurisation of hard coal flue gas (wet lime scrubbing), gypsum	2.8	20	12.25	7.75	7.75	Scrubbing mixture[2]
1	Crushing and washing, limestone/calcarous dolomite	1	0.188	0.000	0.055	0.187	Washing[3]
2	Pyroprocessing, clinker	1	1.947	1.653	0.294	0.294	Cooling[2]
3	Grinding and mixing, ordinary Portland cement	1	0	0	0	0	n/a

[1] (Weidema et al., 2013)
[2] (IPPC, 2006)
[3] (EIPPCB, 2013)

Table 9: Process water use for Portland composite cement production processes

Step No.	Process, product	Product Output[1] [kg]	Water abstraction[1] [L]	Water effluent[1] [L]	Water evaporation[1] [L]	Water consumption [L]	Water application
1	Mining, limestone/dolomite	1	0.021	0.000	0.021	0.021	n/d
1	Mining, clay	1	0	0	0	0	n/a
1	Mining, sand	0.35	1.39	1.39	0	0.00	n/a
1	Mining, gypsum	0.657	0	0	0	0	n/a
1	Granulating, GGBFS	907.18	833.93	708.84	125.09	125.09	Granulating[2]
1	Desulphurisation of hard coal flue gas (wet lime scrubbing), gypsum	2.8	20	12.25	7.75	7.75	Scrubbing mixture[3]
1	Electrostatic precipitation, hard coal fly ash	n/d	n/d	n/d	n/d	n/d	Rinsing[2]
1	Crushing and washing, limestone/calcarous dolomite	1	0.188	0.000	0.055	0.187	Washing[4]
2	Pyroprocessing, clinker	1	1.947	1.653	0.294	0.294	Cooling[3]
3	Grinding and mixing, Portland composite cement	1	0	0	0	0	n/a

[1] (Weidema et al., 2013)
[2] (Remus et al.,2013), (Verver & Fraaij, 2004)
[3] (IPPC, 2006)
[4] (EIPPCB, 2013)

Table 10: Process water use for the production process of float glass

Step No.	Process, product	Product output[1] [kg]	Water abstraction[1] [L]	Water effluent[1] [L]	Water evaporation[1] [L]	Water consumption [L]	Water application
1	Mining, sand Gravel	0.35 0.65	1.39	1.39	0	0.00	n/a
1	Mining, limestone	1	0.021	0	0.021	0.021	n/d
1	Mining, sodium chloride	1	6.51	4.68	1.83	1.83	n/d
1	Mining, bauxite	1	0.5	0.05	0.314	0.45	n/d
1	Mining, feldspar	1	0.022	0.019	0.0033	0.003	n/d
1	Processing, silica sand	1	0	0	0	0	n/a
1	Processing (crushing & washing), limestone	1	0.188	0.000	0.055	0.1874	n/d
1	Calcination, quicklime	1	0	0.000	0.000	0	n/a
1	Bayer process, aluminium hydroxide	1	1.68	0.887	0	0.793	Incorporation in waste product redmud[1]
1	Solvay process, soda ash Calcium chloride	1 1.05	106.16	65.601	40.564	40.559	Apart from brine, the main use of process water is for the slaker to produce milk of lime. Process steam. Cooling water.[2]
1	Calcination, aluminium oxide	1	0	0	0	0	n/a
2+3	Glass production: Melting, molten glass Annealing, glass ribbon Cutting, glass Crushing and cleaning, cullet	1	0.7	0.429	0.271	0.271	Most significant water use during cooling and cullet cleaning.[3] No data available on the exact division of water use over these processes, therefore are combined in glass production.

[1] (Weidema et al., 2013)

[2] (ESAPA, 2004).

[3] (IFC World Bank, 2007).

Appendix IV: Blue water footprint of petroleum products and coking products

Table 11 shows the blue water footprint of petroleum products. The blue water footprint is derived from the water footprint of crude oil and the water use in the refinery.

Table 11: Blue water footprint of petroleum products, derived from WF_{blue} of crude oil using value fractions

Product	Product fraction [-] (Ecoinvent)	Product fraction [-] (GaBi)	Price[a] [EUR2005/kg]	Value $fraction_{Eco}$ [-]	Value $fraction_{Gabi}$ [-]	$WF_{blue,Eco}$ [L/kg]	$WF_{blue,GaBi}$ [L/kg]
Diesel	0.1	0.274	0.37	0.13	0.36	3.60	3.49
Heavy fuel oil	0.176	0.13[a]	0.138	0.09	0.06	1.34	1.30
Kerosene	0.0668	0.064	0.297	0.07	0.07	2.89	2.80
Light fuel oil	0.268	0.11	0.268	0.26	0.10	2.61	2.53
LPG	0.0283	0.04	0.276	0.03	0.04	2.69	2.60
Naphtha	0.0679	0.05	0.265	0.07	0.05	2.58	2.50
Petrol	0.215	0.19	0.446	0.35	0.30	4.34	4.20
Pitch/bitumen	0.00106	0.03	0.232	0.001	0.03	2.26	2.19
Own energy consumption	0.06	0.06					
		Water cons. [L/kg crude oil]					
Crude oil							
Fuel supply		0.926[c]					
Refinery – consumption		1.78[d]					

[a] Prices acquired from the Ecoinvent database are calculated as 90% of purchasers' price from International Energy Agency in 2009 for Germany and excl. taxes.

[b] Bunker fuel is included in heavy fuel oil

[c] Median value. Source: Mekonnen, Gerbens-Leenes, & Hoekstra, 2015 rewritten with a specific energy for crude oil of 46,3 MJ/kg

[d] Average value. Source: Wu et al, 2011. Using a crude oil density of 860 kg/m^3 to convert from consumption in L/L to L/kg.

Table 12 shows the blue water footprint of the products from coking. Two columns for the value fractions are shown, one ecoinvent allocation column and three columns are shown for the blue water footprint. In the first column the value fractions are calculated as usual. In the second column from the value fractions it is assumed that coke oven gas is reused in the process for heating of coking chambers, meaning that there will be no coke oven gas as by product and thus no allocation to coke oven gas. In the ecoinvent allocation column the allocation as mentioned by ecoinvent is shown. This allocation has been performed considering the energy content of the coke compared to all other by products. The first two columns from the blue water footprint show the water footprint calculated with the value fractions from the table. The third column shows the water footprint allocated over the products using ecoinvent allocation.

Table 12: Blue water footprint of the products from coking, derived from WF_{blue} of coal

Product	Output weight[1] [kg]	Product fractions [-]	Price [EUR2005/kg]	Value fractions [-]		Ecoinvent Allocation	WF_{blue} [L/kg]		
Coke	0.80	0.58	0.172	0.64	0.925	0.798	1.62	2.34	2.02
Coke oven gas	0.175	0.13	0.375	0.31	0.000	0.150	1.44	0.00	0.71
Benzene	0.00798	0.0058	0.614	0.023	0.033	0.011	2.36	3.41	1.14
Coal tar	0.032	0.023	0.196	0.029	0.042	0.041	0.75	1.09	1.06
	Water cons. [L/kg coal]								
Coal supply	0.87								
Electricity	0.15								
Evaporation	0.45								

[1] (Bauer, n.d.), output for 1.38 kg of hard coal as input

Appendix V: Energy use per production process

Table 13: Energy use for the production processes of unalloyed steel

Step No.	Process, product	Energy input[1] [MJ/kg process product]	Product output[1] [kg]	Scaling factor [-]	Energy consumption [MJ/kg steel]	Energy source[1]
1	Mining, limestone	0.018 0.0001	1	0.308	0.0055 0.0000	Diesel Elec
1	Mining, iron ore	0.0006 0.0051	1	2.530	0.0015 0.0127	Diesel Elec
1	Mining, bentonite	0.0921 0.0026 0.0082	1	0.014	0.0013 0.0000 0.0001	Diesel Elec Unspecified
1	Mining, coal	0.0314 0.1247	1	0.712	0.0221 0.0249	Diesel Elec
2a	Concentrating, iron ore concentrate	0.0674	1	1.527	0.1023	Elec
2a	Activation, bentonite	0.518 0.0002 1.633	1	0.014	0.007 0.0000 0.0235	Hard coal Diesel Elec
2a	Sintering, sinter	1.43 0.036 0.0009	1	0.945	1.35 0.034 0.001	Hard coal Elec Nat gas
2a	Pelletizing, pellets	0.239 0.098 0.008 0.066	1	0.360	0.086 0.035 0.003 0.024	Hard coal Elec HFO Nat gas
2b	Calcination, quicklime	0.015 0.053 4.387	1	0.090	0.001 0.005 0.395	Diesel Elec HFO
2c	Coking, hard coal coke	25.36 0.049	0.803	0.380	9.64 0.019	Hard coal Elec
3	Iron ore reduction, pig iron	9.724 2.756 0.1	1	0.900	8.75 2.48 0.09	Hard coal coke Hard coal Nat gas
4	Air separation, liquid oxygen	12.47	1	0.029	0.365	Elec
6	Steel production, steel	0.00025 0.079	1	1.000	0.00025 0.079	Hard coal coke Elec

[1] (Weidema et al., 2013)

Table 14: Energy use for the production processes of chromium-nickel alloyed steel

Step No.	Process, product	Energy input[1] [MJ/kg process product]	Product output[1] [kg]	Scaling factor [-]	Energy consumption [MJ/kg steel]	Energy source[1]
1	Mining, limestone	0.018 0.0001	1	0.472	0.0085 0.0000	Diesel Elec
1	Mining, iron ore	0.0006 0.005	1	1.500	0.0009 0.008	Diesel Elec
1	Mining, bentonite	0.092 0.003 0.008	1	0.008	0.0007 0.0000 0.0001	Diesel Elec Unspecified
1	Mining, coal	0.031 0.035	1	0.440	0.014 0.015	Diesel Elec
2a	Concentrating, iron ore concentrate	0.067	1	0.905	0.061	Elec
2a	Activation, bentonite	0.518 0.0002 1.633	1	0.008	0.004 0.000 0.014	Hard coal Diesel Elec
2a	Sintering, sinter	1.43 0.036 0.0009	1	0.554	0.792 0.020 0.001	Hard coal Elec Nat gas
2a	Pelletizing, pellets	0.239 0.098 0.008 0.066	1	0.211	0.050 0.021 0.002 0.014	Hard coal Elec HFO Nat gas
2b	Calcination, quicklime	0.015 0.053 4.387	1	0.220	0.003 0.012 0.967	Diesel Elec HFO
2c	Coking, hard coal coke	25.36 0.049	0.803	0.261	6.63 0.013	Hard coal Elec
3	Iron ore reduction, pig iron	9.724 2.756 0.1	1	0.528	5.13 1.45 0.05	Hard coal coke Hard coal Nat gas
4	Air separation, liquid oxygen	12.47	1	0.071	0.891	Elec
6	Steel production, steel	0.00025 0.079	1	1.000	0.00025 0.079	Hard coal coke Elec
1	Mining, sand By product: gravel	0.0147 0.0098	0.35	0.036	0.0005 0.0004	Diesel Elec
	Processing, silica sand	0.2	1	0.012	0.0	Unspecified
1+2	Mining and beneficiation, chromite ore concentrate	0.807 0.3715	1	0.643	0.519 0.238	Diesel Elec
1+2	Mining and beneficiation, Bauxite	0.003312 0.00646 0.014	1	0.061	0.0002 0.0004 0.0007	Elec HFO LFO
5	Pre-treatment and direct reduction, ferrochromium	3.325	1	0.265	0.880	Elec
1+2+5	Mining, beneficiation and reduction ferronickel	1.908 33.42 35.56 28.26	1	0.320	0.611 10.7 11.4 9.04	Diesel Elec Unspecified Nat gas

[1] (Weidema et al., 2013)

Table 15: Energy use for the production processes of ordinary Portland cement

Step No.	Process, product	Energy input[1] [MJ/mass process product]	Product output[1] [kg]	Scaling factor [-]	Energy consumption [MJ/kg cement]	Energy source[1]
1	Mining, limestone	0.018 0.0001	1	1.216	0.022 0.0001	Diesel Elec
1	Mining, clay	0.0297	1	0.309	0.009	Diesel
1	Mining, sand	0.0147 0.0098	0.35	0.028	0.0004 0.0003	Diesel Elec
1	Mining, gypsum	0.018 0.00092	0.66	0.07615	0.0014 0.00007	Diesel Elec
1	Flue gas desulphurisation, gypsum	0	2.8	0	0	n/a
1	Crushing and washing, limestone/calcarous dolomite	0.0034 0.0018	1	1.216	0.0041 0.0022	Diesel Elec
2	Pyroprocessing, clinker	0.2135 0.0132 0.6657 1.0070 0.0157 0.0071	1	0.950	0.203 0.013 0.632 0.957 0.015 0.007	Elec Diesel Coal HFO LFO Nat gas
3	Grinding and mixing, Portland cement	0.1354	1	1.00	0.135	Elec

[1] (Weidema et al., 2013)

Table 16: Energy use for the production processes of Portland composite cement

Step No.	Process, product	Energy input[1] [MJ/mass process product]	Product output[1] [kg]	Scaling factor [-]	Energy consumption [MJ/kg cement]	Energy source[1]
1	Mining, limestone/dolomite	0.018 0.000098	1	1.13	0.020 0.0001	Diesel Elec
1	Mining, clay	0.0297	1	0.223	0.0066	Diesel
1	Mining, sand	0.0147 0.0098	0.35	0.0202	0.0003 0.0002	Diesel Elec
1	Mining, gypsum	0.018 0.0009	0.65657	0.0761	0.0014 0.00007	Diesel Elec
1	Granulating, GGBFS	4.1011 82.7 0.9094 280	907	0.00002	0.00009 0.00191 0.00002 0.00647	Diesel Elec LFO Nat gas
1	Desulphurisation of hard coal flue gas (wet lime scrubbing), gypsum	0	2.8	0.0179	0	n/a
1	Electrostatic precipitation, hard coal fly ash	n/d	1	0.0252	n/d	n/d
1	Crushing and washing, limestone/calcarous dolomite	0.0034 0.0018	1	1.130	0.0038 0.0021	Diesel Elec
2	Pyroprocessing, clinker	0.2135 0.0132 0.6657 1.0070 0.0157 0.0071	1	0.684	0.146 0.009 0.455 0.689 0.011 0.005	Elec Diesel Hard coal HFO LFO nat gas
3	Grinding and mixing, Portland composite cement	0.1314 0.0067	1	1.000	0.1314 0.0067	Elec heat, unspecified

[1] (Weidema et al., 2013)

Table 17: Energy use for the production processes of float glass

Step No.	Process, product	Energy input [1] [MJ/kg product]	Scaling factor [-]	Energy use [MJ/kg glass]	Energy source
1	Mining, sand	0.001	2.050	0.020	Elec
	Gravel	0.015	2.050	0.030	Diesel
1	Mining, limestone	0.0001	0.285	0.000	Elec
		0.018	0.285	0.005	Diesel
1	Mining, sodium chloride	0.612	0.098	0.060	Elec
		0.005	0.098	0.000	Heat, unspecified
1	Mining, bauxite	0.003	0.017	0.000	Elec
		0.006	0.017	0.000	HFO
		0.011	0.017	0.000	LFO
1	Mining, feldspar	0.007	0.023	0.000	Diesel
		0.021	0.023	0.000	Elec
		0.262	0.023	0.006	Nat gas
1	Processing, silica sand	0.200	0.692	0.138	Heat, unspecified
1	Processing (crushing & washing), limestone	0.003	0.285	0.001	Diesel
1	Calcination, quicklime	0.053	0.078	0.004	Elec
		0.015	0.078	0.001	Diesel
		4.387	0.078	0.344	HFO
1	Bayer process, aluminium hydroxide	0.328	0.006	0.002	Elec
		1.130	0.006	0.007	HFO
		0.005	0.006	0.000	LFO
		3.280	0.006	0.019	Hard coal
		2.680	0.006	0.016	Nat gas
1	Solvay process, soda ash	0.144	0.065	0.009	Elec
	Calcium chloride	7.220	0.065	0.472	Heat, unspecified
1	Calcination, aluminium oxide	0.043	0.004	0.000	Elec
		0.969	0.004	0.004	HFO
		0.0004	0.004	0.000	LFO
		0.007	0.004	0.000	Hard coal
		2.100	0.004	0.008	Nat gas
	Glass production:	4.635	1.267	5.871	Nat gas
2	Melting, molten glass	3.037	1.267	3.847	HFO
3	Annealing, glass ribbon	0.340	1.267	0.506	Elec
3	Cutting, glass		1.267		
1	Crushing and cleaning, cullet		0.267		

[1] (Weidema et al., 2013)

Appendix VI: Effluent loads

This appendix shows the effluent loads of the individual processes for the production of unalloyed steel, chromium-nickel alloyed steel, ordinary Portland cement, Portland composite cement and soda-lime float glass. The initial load data is from the ecoinvent database version 3.2. In this appendix however, the loads are presented in mass per kilogram end product (e.g. unalloyed steel) by scaling them, using the scaling factor from step 1. The tables also show the maximum concentrations and when applicable the natural concentrations for surface water that are used for the calculation of the grey water footprint.

Table 18: Effluent loads of the production processes for unalloyed steel

	Loads [kg/kg steel]														Concentration		
	Steel unalloyed	Mining, limestone	Mining, iron ore	Mining, bentonite	Mining, coal	Concentrating iron ore	Activation, bentonite	Sintering, sinter	Pelletizing, pellet	Calcination, quicklime	Coking, cokes	Iron ore reduction, pig iron	Air separation	Steel production	C_{nat}[1] [µg/L]	C_{max} [µg/L]	Guideline C_{max}
Analytical measures to fresh water:	6.41E-04	0	0	0	1.12E-05	2.70E-04	0	0	0	0	3.57E-04	0	0	0			
Biological oxygen demand (BOD)	1.34E-04	0	0	0	0	1.33E-04	1.03E-06	0	0	0	0	0	0	0	n/d	3000	EEC
Chemical oxygen demand (COD)	1.33E-04	0	0	0	0	1.33E-04	5.13E-07	0	0	0	0	0	0	0	n/d	30000	EEC
Heavy metals to fresh water:	8.61E-06	0	0	0	2.40E-06	6.20E-06	6.92E-09	0	4.96E-09	0	0	0	0	0			
Arsenic (+V)	8.89E-08	0	0	0	0	8.84E-08	4.58E-10	0	2.23E-12	0	0	0	0	0	1	5	CCME
Cadmium (+II)	8.85E-08	0	0	0	0	8.84E-08	8.32E-11	0	1.12E-12	0	0	0	0	0	0.001	0.04	EU
Chromium (+VI)	8.84E-08	0	0	0	0	8.84E-08	0	0	0	0	0	0	0	0	0.1	1	CCME
Chromium (unspecified)	1.01E-10	0	0	0	0	0	8.32E-11	0	1.79E-11	0	0	0	0	0	0.1	1	CCME
Cobalt	2.23E-12	0	0	0	0	0	0	0	2.23E-12	0	0	0	0	0	0.1	n/d	n/d
Copper (+II)	4.42E-07	0	0	0	0	4.42E-07	1.25E-10	0	2.23E-12	0	0	0	0	0	1.4	2	CCME
Iron ion (+III)	4.60E-06	0	0	0	1.50E-06	3.10E-06	5.59E-09	0	4.25E-09	0	0	0	0	0	50	300	CCME
Lead	1.77E-07	0	0	0	0	1.77E-07	8.32E-11	0	2.23E-12	0	0	0	0	0	0.04	1.2	EPA
Manganese	7.50E-07	0	0	0	7.50E-07	0	0	0	6.70E-10	0	0	0	0	0	10	n/d	n/d
Mercury	8.97E-09	0	0	0	0	8.84E-09	1.25E-10	0	2.90E-13	0	0	0	0	0	n/d	0.026	CCME
Nickel (+II)	5.17E-07	0	0	0	7.50E-08	4.42E-07	2.09E-10	0	2.23E-12	0	0	0	0	0	0.4	4	EU
Zinc (+II)	1.84E-06	0	0	0	7.50E-08	1.77E-06	1.67E-10	0	8.93E-12	0	0	0	0	0	0.2	30	CCME
Inorganic emissions to fresh water:	1.12E-02	0	0	0	1.01E-02	8.84E-07	5.39E-05	0	4.38E-09	0	1.04E-03	0	0	0			
Aluminium (+III)	7.56E-07	0	0	0	7.50E-07	0	6.83E-09	0	0	0	0	0	0	0	40	100	CCME
Ammonium (total N)	7.54E-07	0	0	0	7.50E-07	0	4.16E-09	0	0	0	8.10E-06	0	0	0	15	6980	CCME
Chloride	1.04E-02	0	0	0	9.74E-03	0	2.39E-05	0	0	0	6.32E-04	0	0	0	3900	120000	CCME
Cyanide	8.84E-07	0	0	0	0	8.84E-07	0	0	0	0	0	0	0	0	n/d	5	CCME
Fluoride	2.25E-06	0	0	0	2.25E-06	0	0	0	0	0	0	0	0	0	n/d	120	CCME
Hydrogen sulphide	1.30E-06	0	0	0	0	0	0	0	0	0	1.30E-06	0	0	0	n/d	n/d	n/d
Nitrate (as total N)	3.12E-07	0	0	0	0	0	3.08E-07	0	4.11E-09	0	0	0	0	0	100	3000	CCME
Phosphorus	1.00E-06	0	0	0	0	0	9.99E-07	0	2.68E-10	0	0	0	0	0	0	20	CCME
Sodium (+I)	4.35E-04	0	0	0	0	0	2.87E-05	0	0	0	4.06E-04	0	0	0	n/d	n/d	n/d
Strontium	3.75E-06	0	0	0	3.75E-06	0	0	0	0	0	0	0	0	0	100	n/d	n/d
Sulphate	3.75E-04	0	0	0	3.75E-04	0	0	0	0	0	0	0	0	0	4800	n/d	n/d
Particles to fresh water:	2.97E-04	0	0	0	1.66E-05	0	2.62E-04	0	1.43E-08	0	0	0	0	0			
Suspended solids, unspecified	2.97E-04	0	0	0	1.66E-05	0	2.62E-04	0	1.43E-08	0	0	0	0	0	150000	+5000	CCME

[1] (Chapman, 1996)

Table 19: Effluent loads of the production processes for chromium-nickel alloyed steel

	Loads [kg/kg steel]																				Concentration		
	Total	Mining, limestone	Mining, iron ore	Mining, bentonite	Mining, coal	Concentrating, concentrated iron ore	Activation, bentonite	Sintering, sinter	Pelletizing, pellets	Calcination, quicklime	Coking, cokes	Iron ore reduction, pig iron	Air separation, oxygen	Steel production, steel	Mining, sand	Processing, silica sand	Mining and beneficiation, chromite ore concentrate	Mining and beneficiation, Bauxite	Pre-treatment and direct reduction, ferrochromium	Mining, beneficiation and reduction ferronickel	c_{nat}[1] [µg/L]	c_{max} [µg/L]	Guideline C_{max}
Analytical measures to fresh water	5.54E-04	0	0	0	6.60E-06	1.60E-04	1.01E-06	0	0	0	2.10E-04	0	0	0	0	0	2.77E-07	0	9.93E-05	7.70E-05			
Biological oxygen demand (BOD)	1.06E-04	0	0	0	0	7.86E-05	6.01E-07	0	0	0	0	0	0	0	0	0	7.71E-08	0	0	2.67E-05	n/d	3000	EEC
Chemical oxygen demand (COD)	1.06E-04	0	0	0	0	7.86E-05	3.01E-07	0	0	0	0	0	0	0	0	0	1.16E-07	0	0	2.67E-05	n/d	30000	EEC
Heavy metals to fresh water	6.76E-06	0	0	0	1.41E-06	3.67E-06	4.06E-09	0	2.91E-09	0	0	0	0	0	0	0	5.34E-09	0	2.04E-09	1.66E-06			
Arsenic (+V)	1.02E-07	0	0	0	0	5.24E-08	2.69E-10	0	1.31E-12	0	0	0	0	0	0	0	0	0	0	4.89E-08	1	5	CCME
Cadmium (+II)	5.93E-08	0	0	0	0	5.24E-08	4.88E-11	0	6.55E-13	0	0	0	0	0	0	0	0	0	0	6.83E-09	0.001	0.04	EU
Chromium (+VI)	5.24E-08	0	0	0	0	5.24E-08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.1	1	CCME
Chromium (unspecified)	6.66E-08	0	0	0	0	0	4.88E-11	0	1.05E-11	0	0	0	0	0	0	0	3.81E-11	0	2.04E-09	6.45E-08	0.1	1	CCME
Cobalt	2.00E-09	0	0	0	0	0	0	0	1.31E-12	0	0	0	0	0	0	0	0	0	0	2.00E-09	n/d	n/d	n/d
Copper (+II)	3.99E-07	0	0	0	0	2.62E-07	7.33E-11	0	1.31E-12	0	0	0	0	0	0	0	0	0	0	1.37E-07	1.4	2	CCME
Iron ion (+III)	3.47E-06	0	0	0	8.80E-07	1.83E-06	3.28E-09	0	2.49E-09	0	0	0	0	0	0	0	5.30E-09	0	0	7.44E-07	50	300	CCME
Lead	1.47E-07	0	0	0	0	1.05E-07	4.88E-11	0	1.31E-12	0	0	0	0	0	0	0	0	0	0	4.25E-08	0.04	1.2	EPA
Manganese	5.04E-07	0	0	0	4.40E-07	0	0	0	3.93E-10	0	0	0	0	0	0	0	0	0	0	6.32E-08	n/d	n/d	n/d
Mercury	6.04E-09	0	0	0	0	5.24E-09	7.33E-11	0	1.70E-13	0	0	0	0	0	0	0	0	0	0	7.27E-10	n/d	0.026	CCME
Nickel (+II)	4.15E-07	0	0	0	4.40E-08	2.62E-07	1.22E-10	0	1.31E-12	0	0	0	0	0	0	0	0	0	0	1.09E-07	0.4	4	n/d
Tin (+IV)	6.31E-08	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.31E-08	n/d	n/d	n/d
Zinc (+II)	1.47E-06	0	0	0	4.40E-08	1.05E-06	9.80E-11	0	5.24E-12	0	0	0	0	0	0	0	0	0	0	3.81E-07	0.2	30	CCME
Inorganic emissions to fresh water	1.44E-02	0	0	0	5.94E-03	5.24E-07	3.16E-05	0	2.57E-09	0	6.10E-04	0	0	0	0	0	9.19E-08	0	0	0.007849			
Aluminium (+III)	6.65E-07	0	0	0	4.40E-07	0	4.00E-09	0	0	0	0	0	0	0	0	0	0	0	0	2.21E-07	40	100	CCME
Ammonium (total N)	4.42E-07	0	0	0	4.40E-07	0	2.44E-09	0	0	0	0	0	0	0	0	0	0	0	0	0	15	6.980	CCME
Calcium (+II)	1.76E-03	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9.19E-08	0	0	1.76E-03	n/d	n/d	n/d
Chloride	6.10E-03	0	0	0	5.72E-03	0	1.40E-05	0	0	0	3.71E-04	0	0	0	0	0	0	0	0	0	3900	120000	CCME
Cyanide	5.24E-07	0	0	0	0	5.24E-07	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/d	5	CCME
Fluoride	1.32E-06	0	0	0	1.32E-06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	120	CCME
Hydrogen sulphide	7.63E-07	0	0	0	0	0	0	0	0	0	7.63E-07	0	0	0	0	0	0	0	0	0	n/d	n/d	n/d
Nitrate (as total N)	1.83E-07	0	0	0	0	0	1.81E-07	0	2.41E-09	0	0	0	0	0	0	0	0	0	0	0	100	3000	CCME
Nitrogen organic bounded	5.83E-05	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.83E-05	n/d	n/d	n/d
Phosphorus	5.86E-07	0	0	0	0	0	5.86E-07	0	1.57E-10	0	0	0	0	0	0	0	0	0	0	0	n/d	20	CCME
Sodium (+I)	2.55E-04	0	0	0	0	0	1.68E-05	0	0	0	2.39E-04	0	0	0	0	0	0	0	0	0	n/d	n/d	n/d
Strontium	2.20E-06	0	0	0	2.20E-06	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	n/d	n/d	n/d
Sulphate	6.25E-03	0	0	0	2.20E-04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.03E-03	4800	n/d	n/d
Particles to fresh water	1.63E-04	0	0	0	9.76E-06	0	1.54E-04	0	8.39E-09	0	0	0	0	0	0	0	0	0	0	0			
Suspended solids, unspecified	1.63E-04	0	0	0	9.76E-06	0	1.54E-04	0	8.39E-09	0	0	0	0	0	0	0	0	0	0	0	150000	+5000	CCME

[1] (Chapman, 1996)

Table 20: Effluent loads of the production processes for Portland cement

	Loads [kg/kg cement]									Concentration		
	Total	Mining, limestone	Mining, clay	Mining, sand	Mining, gypsum	FGD, gypsum	Crushing & washing, limestone	Pyroprocessing, clinker	Grinding and mixing, cement	c_{nat}[1] [µg/L]	c_{max} [µg/L]	Guideline C_{max}
Analytical measures to fresh water	1.88E-05	0	0	0	0	1.88E-05	0	0	0			
Biological oxygen demand (BOD)	4.46E-07	0	0	0	0	4.46E-07	0	0	0	n/d	3000	EEC
Chemical oxygen demand (COD)	1.34E-05	0	0	0	0	1.34E-05	0	0	0	n/d	30000	EEC
Heavy metals to fresh water	7.25E-07	0	0	0	0	7.25E-07	0	3.21E-10	0			
Antimony	5.36E-08	0	0	0	0	5.36E-08	0	0	0	n/d	n/d	n/d
Arsenic (+V)	8.94E-08	0	0	0	0	8.93E-08	0	1.23E-10	0	1	5	CCME
Cadmium (+II)	5.38E-09	0	0	0	0	5.36E-09	0	2.46E-11	0	0.001	0.04	EU
Chromium (unspecified)	5.36E-08	0	0	0	0	5.36E-08	0	4.92E-11	0	0.1	1	CCME
Copper (+II)	5.36E-08	0	0	0	0	5.36E-08	0	2.46E-11	0	1.4	2	CCME
Iron ion (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	50	300	CCME
Lead	8.95E-09	0	0	0	0	8.93E-09	0	2.58E-11	0	0.04	1.2	EPA
Manganese	8.93E-08	0	0	0	0	8.93E-08	0	0	0	10	n/d	n/d
Mercury	5.36E-09	0	0	0	0	5.36E-09	0	2.58E-13	0	n/d	0.026	CCME
Molybdenum	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0.8	73	CCME
Nickel (+II)	5.36E-08	0	0	0	0	5.36E-08	0	2.46E-11	0	0.4	4	n/d
Selenium	8.93E-09	0	0	0	0	8.93E-09	0	0	0	n/d	1	CCME
Tin (+IV)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	n/d	n/d	n/d
Vanadium (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	n/d	n/d	n/d
Zinc (+II)	8.93E-08	0	0	0	0	8.93E-08	0	4.92E-11	0	0.2	30	CCME
Inorganic emissions to fresh water	5.86E-03	0	0	0	0	5.86E-03	0	7.38E-11	0			
Aluminium (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	40	100	CCME
Ammonium (total N)	6.88E-08	0	0	0	0	6.88E-08	0	0	0	15	6980	CCME
Boron	5.89E-06	0	0	0	0	5.89E-06	0	0	0	8	29000	CCME
Calcium (+II)	8.93E-04	0	0	0	0	8.93E-04	0	0	0	n/d	n/d	n/d
Chloride	4.46E-03	0	0	0	0	4.46E-03	0	0	0	3900	120000	CCME
Fluoride	2.68E-06	0	0	0	0	2.68E-06	0	0	0	100	120	CCME
Magnesium	1.79E-04	0	0	0	0	1.79E-04	0	0	0	2.4	n/d	n/d
Nitrate	8.93E-05	0	0	0	0	8.93E-05	0	0	0	100	3000	CCME
Phosphate	3.57E-08	0	0	0	0	3.57E-08	0	0	0	10	20	CCME
Phosphorus	7.38E-11	0	0	0	0	0	0	7.38E-11	0	0	20	CCME
Potassium	8.93E-07	0	0	0	0	8.93E-07	0	0	0	1	n/d	n/d
Sodium (+I)	4.46E-05	0	0	0	0	4.46E-05	0	0	0	n/d	n/d	n/d
Sulphate	1.79E-04	0	0	0	0	1.79E-04	0	0	0	4.8	n/d	n/d
Sulphite	1.79E-06	0	0	0	0	1.79E-06	0	0	0	n/d	n/d	n/d
Particles to fresh water												
Suspended solids, unspecified	5.36E-08	0	0	0	0	5.36E-08	0	0	0	150000	+5000	CCME

[1] (Chapman, 1996)

Table 21: Effluent loads of the production processes for Portland composite cement

	Loads [kg/kg cement]											Concentration		
	Total	Mining, limestone/dolomite	Mining, clay	Mining, sand	Mining, gypsum	FGD, gypsum	Granulation, GGBFS	Electrostatic precipitation, fly ash	Crushing & washing, limestone	Pyroprocessing, clinker	Grinding and mixing, Cement	c_{nat}^1 [µg/L]	c_{max} [µg/L]	Guideline c_{max}
Analytical measures to fresh water	1.88E-05	0	0	0	0	1.88E-05	0	0	0	0	0			
Biological oxygen demand (BOD)	4.46E-07	0	0	0	0	4.46E-07	0	0	0	0	0	n/d	3000	EEC
Chemical oxygen demand (COD)	1.34E-05	0	0	0	0	1.34E-05	0	0	0	0	0	n/d	30000	EEC
Heavy metals to fresh water	7.25E-07	0	0	0	0	7.25E-07	0	0	0	2.31E-10	0			
Antimony	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	n/d	n/d	n/d
Arsenic (+V)	8.94E-08	0	0	0	0	8.93E-08	0	0	0	8.85E-11	0	1	5	CCME
Cadmium (+II)	5.38E-09	0	0	0	0	5.36E-09	0	0	0	1.77E-11	0	0.001	0.04	EU
Chromium (unspecified)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	3.54E-11	0	0.1	1	CCME
Copper (+II)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	1.77E-11	0	1.4	2	CCME
Iron ion (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	50	300	CCME
Lead	8.95E-09	0	0	0	0	8.93E-09	0	0	0	1.86E-11	0	0.04	1.2	EPA
Manganese	8.93E-08	0	0	0	0	8.93E-08	0	0	0	0	0	n/d	n/d	n/d
Mercury	5.36E-09	0	0	0	0	5.36E-09	0	0	0	1.86E-13	0	n/d	0.026	CCME
Molybdenum	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	0.8	73	CCME
Nickel (+II)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	1.77E-11	0	0.4	4	n/d
Selenium	8.93E-09	0	0	0	0	8.93E-09	0	0	0	0	0	n/d	1	CCME
Tin (+IV)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	n/d	n/d	n/d
Vanadium (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	n/d	n/d	n/d
Zinc (+II)	8.93E-08	0	0	0	0	8.93E-08	0	0	0	3.54E-11	0	0.2	30	CCME
Inorganic emissions to fresh water	5.86E-03	0	0	0	0	5.86E-03	0	0	0	5.31E-11	0			
Aluminium (+III)	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	40	100	CCME
Ammonium (total N)	6.88E-08	0	0	0	0	6.88E-08	0	0	0	0	0	15	6980	CCME
Boron	5.89E-06	0	0	0	0	5.89E-06	0	0	0	0	0	8	29000	CCME
Calcium (+II)	8.93E-04	0	0	0	0	8.93E-04	0	0	0	0	0	n/d	n/d	n/d
Chloride	4.46E-03	0	0	0	0	4.46E-03	0	0	0	0	0	3900	120000	CCME
Fluoride	2.68E-06	0	0	0	0	2.68E-06	0	0	0	0	0	100	120	CCME
Magnesium	1.79E-04	0	0	0	0	1.79E-04	0	0	0	0	0	2.4	n/d	n/d
Nitrate	8.93E-05	0	0	0	0	8.93E-05	0	0	0	0	0	100	3000	CCME
Phosphate	3.57E-08	0	0	0	0	3.57E-08	0	0	0	0	0	10	20	CCME
Phosphorus	7.38E-11	0	0	0	0	0	0	0	0	5.31E-11	0	10	20	CCME
Potassium	8.93E-07	0	0	0	0	8.93E-07	0	0	0	0	0	1	n/d	n/d
Sodium (+I)	4.46E-05	0	0	0	0	4.46E-05	0	0	0	0	0	n/d	n/d	n/d
Sulphate	1.79E-04	0	0	0	0	1.79E-04	0	0	0	0	0	4.8	n/d	n/d
Sulphite	1.79E-06	0	0	0	0	1.79E-06	0	0	0	0	0	n/d	n/d	n/d
Particles to fresh water														
Suspended solids, unspecified	5.36E-08	0	0	0	0	5.36E-08	0	0	0	0	0	150000	+5000	CCME

[1] (Chapman, 1996)

Table 22: Effluent loads of the production processes for soda-lime float glass

	Loads kg/kg glass		Concentration		
	Bayer process, aluminium hydroxide	Solvay process, soda ash[1]	c_{nat}[2][µg/L]	c_{max} [µg/L]	Guideline c_{max}
Water quality parameter	5.34E-07	0			
Biological oxygen demand (BOD)	2.67E-07	0	n/d	3000	EEC
Chemical oxygen demand (COD)	2.67E-07	0	n/d	30000	EEC
Heavy metals to fresh water	2.58E-13	1.17E-06			
Cadmium (+II)	0	1.13E-08	0.001	0.08	EU
Copper (+II)	0	1.08E-07	1.4	2	CCME
Lead	0	9.72E-07	0.04	1.2	EPA
Mercury	2.58E-13	1.14E-10	0	0.026	CCME
Nickel (+II)	0	7.50E-08	0.4	4	EU
Chromium-total	0	ESAPA	0	1	CCME
Inorganic emissions to fresh water	7.44E-06	2.22E-02			
Ammonium	0	ESAPA	15	6980	CCME
Calcium (+II)	0	6.52E-03	n/d	0	n/d
Chloride	0	1.57E-02	3900	120000	CCME
Nitrogen[3]	0	1.21E-05	100	3000	CCME
Phosphorus[4]	0	3.40E-06	0	20	CCME
Sodium (+I)	7.44E-06	0	n/d	n/d	n/d
Hydroxide (OH-)	0	ESAPA	see pH	see pH	see pH
Sulphate (SO_4^{2-})	0	ESAPA	4800	n/d	n/d
Particles to fresh water	5.73E-08	6.48E-00			
Solids (suspended)	5.73E-08	6.48E-00	150000	+5000	CCME
Inorganic acidity					
pH	n/d	See OH-	7	9	CCME

[1] ESAPA: loads reported by ESAPA result in a grey water footprint which are shown in appendix H.

[2] (Chapman, 1996)

[3] Nitrogen is unspecified. CCME Cmax for NO3 - N: 3000µg/L; NO2 - N: 60µg/L; ammonia: depends on temperature and pH.

[4] Depends on trophic status: ultra-oligotrophic <4; oligotrophic 4-10; mesotrophic 10-20; meso-eutrophic 20-35; eutrophic 35-100; hyper-eutrophic >100.

Appendix VII: Energy related blue water footprint of float glass using alternative energy consumption distribution for melting

Figure 25 to Figure 27 show the energy related blue water footprint of float glass for three scenarios other than the ecoinvent distribution (58% nat gas, 38% HFO, 5% elec for melting). The other processes are kept the same in all scenarios. For glass melting, the following distributions are explored:

1. heavy fuel oil + 10% electric boost,
2. 100% natural gas
3. 100% heavy fuel oil. .

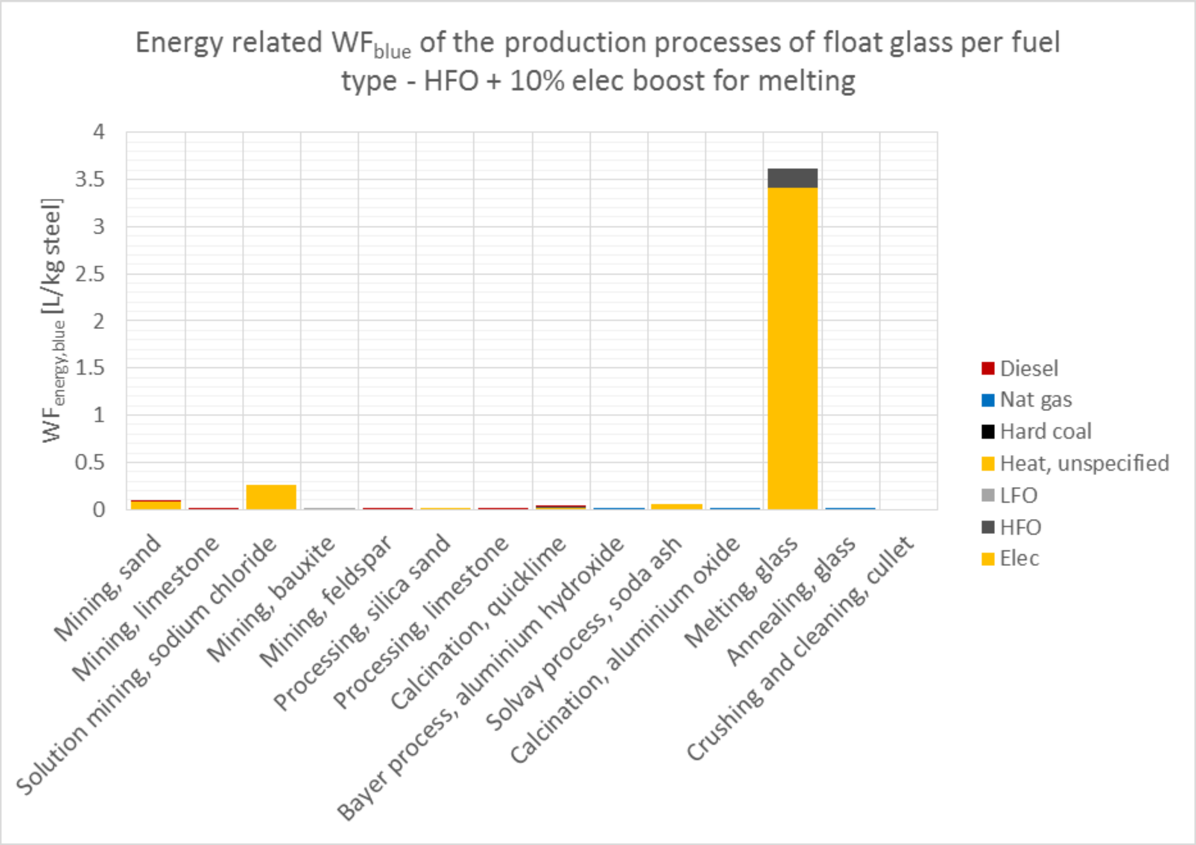

Figure 25: Energy related blue water footprint with heavy fuel oil as energy source and an additional 10% electricity boost for glass melting

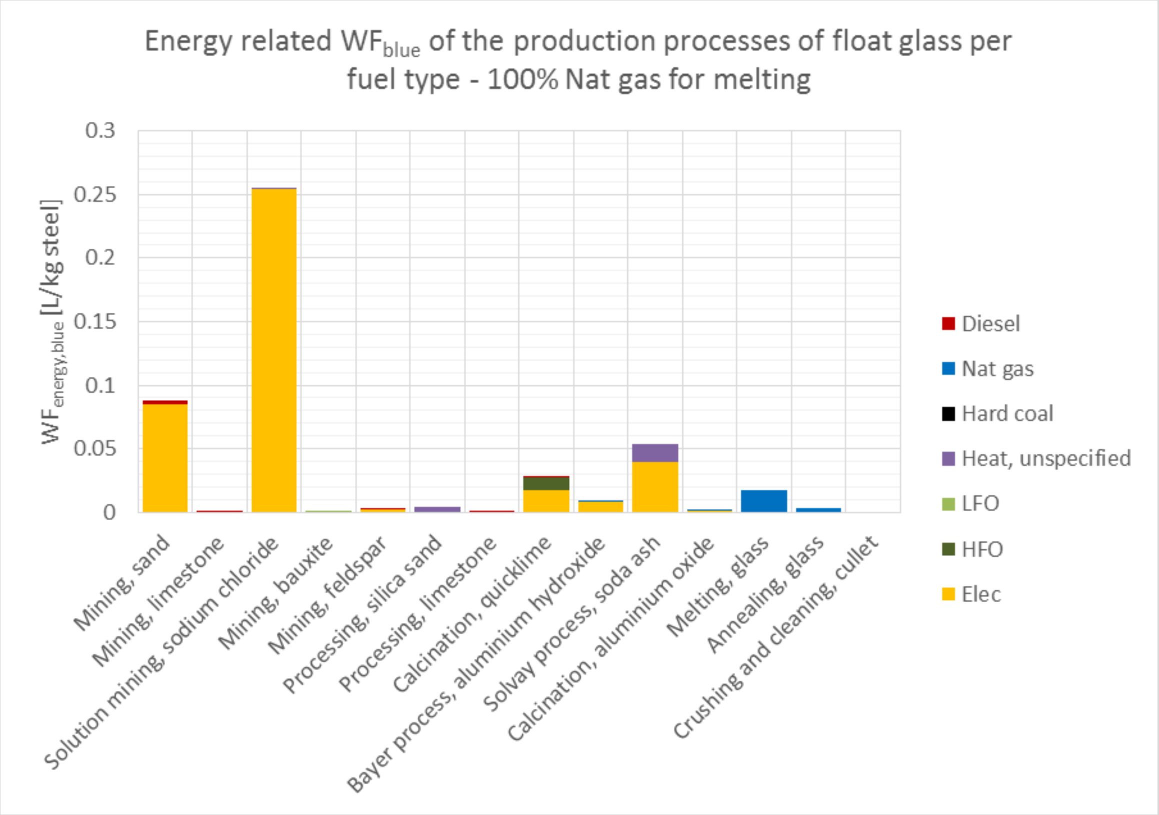

Figure 26: Energy related blue water footprint with natural gas as energy source for glass melting

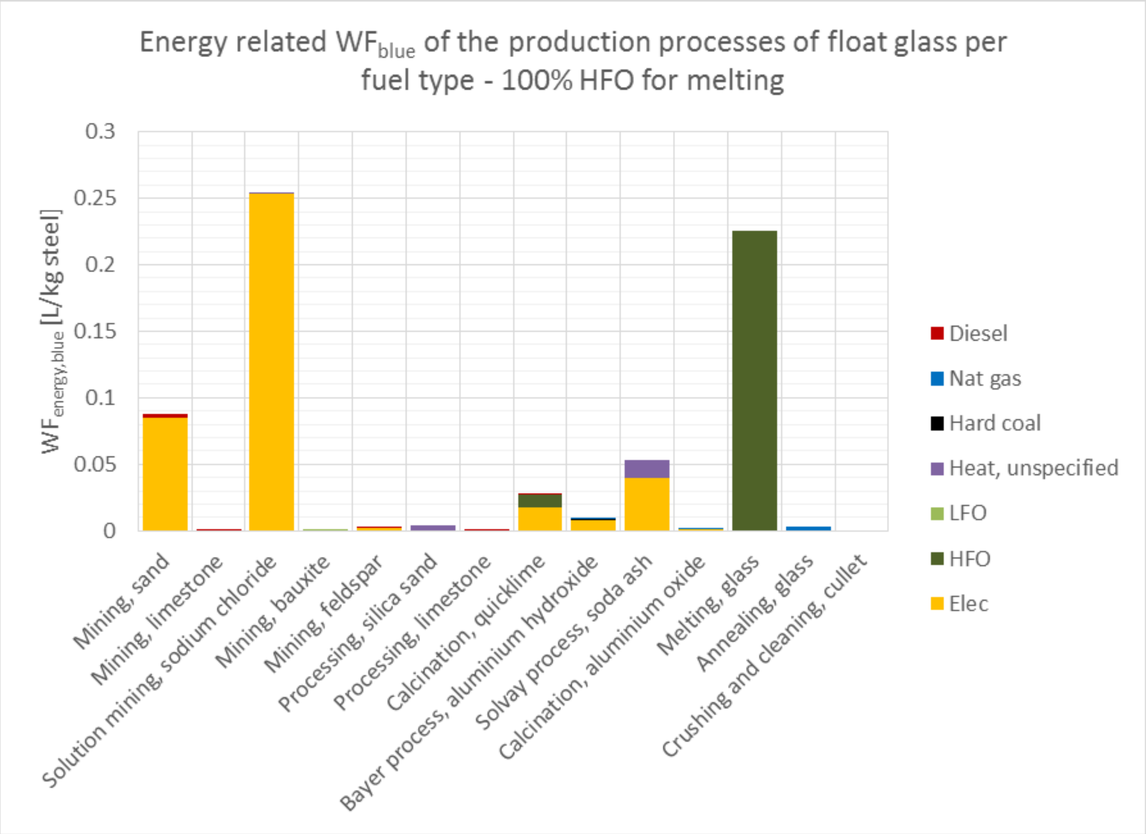

Figure 27: Energy related blue water footprint with heavy fuel oil as energy source for glass melting

Appendix VIII: Grey water footprint of Solvay process using effluent loads from ESAPA report

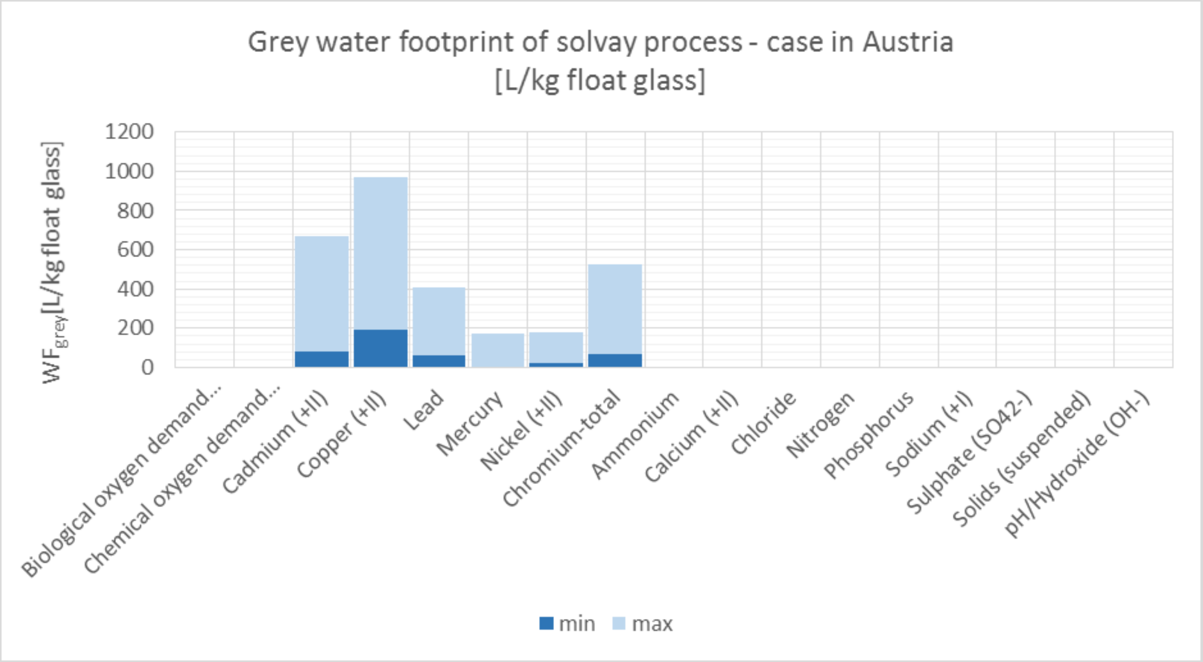

Figure 28: Grey water footprint as calculated with loads from ESAPA (2004), a minimum and a maximum range is given by the ESAPA report. Heavy metals are from only one case in Austria.

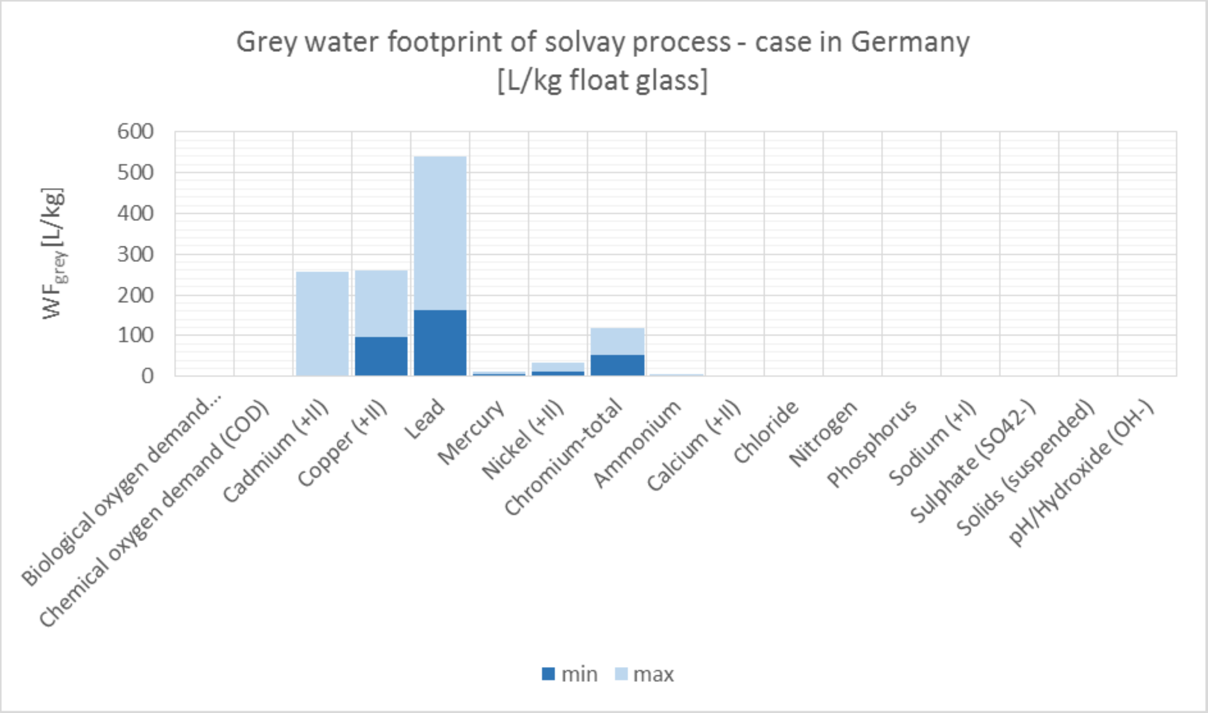

Figure 29: Grey water footprint as calculated with loads from ESAPA. A minimum and a maximum range is given by the ESAPA report. Heavy metals are from only one case in Germany.

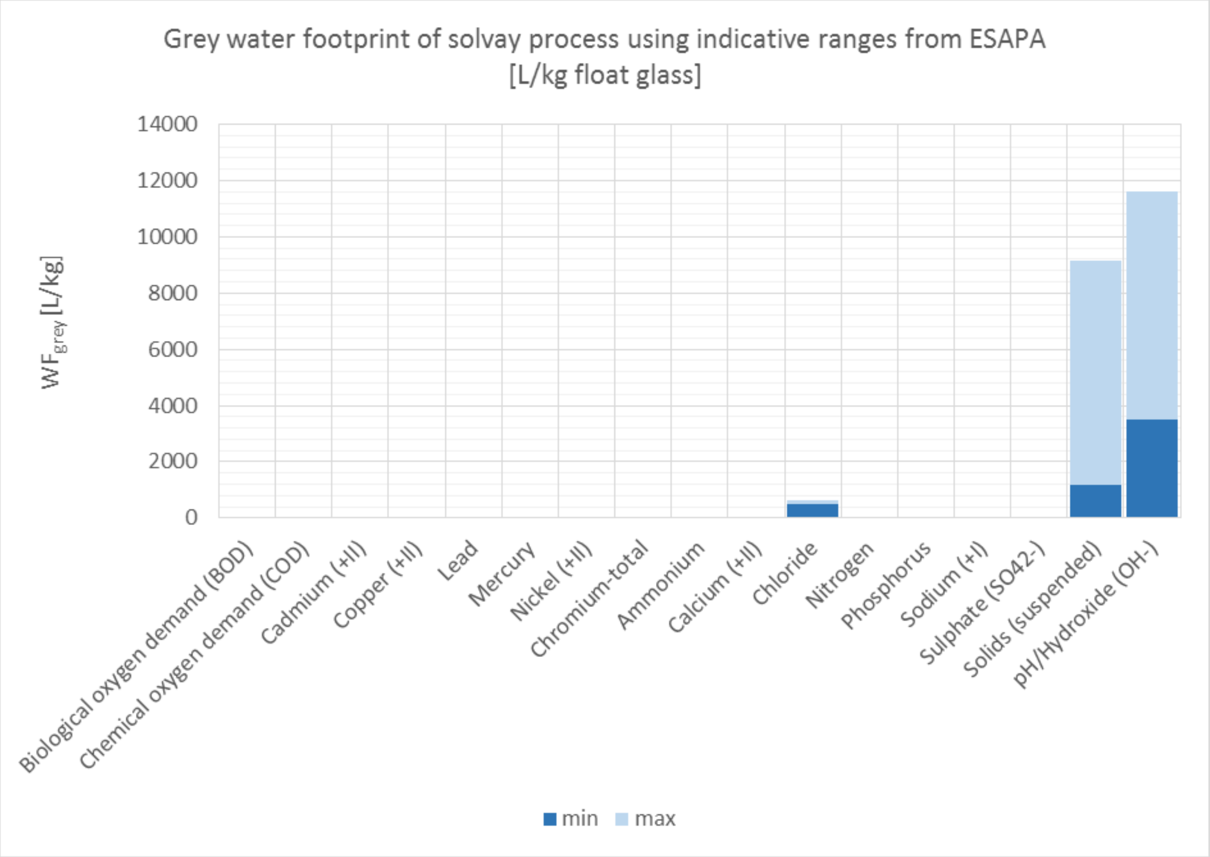

Figure 30: Grey water footprint of Solvay process calculated with indicative ranges for loads from ESAPA

These indicative ranges represent distiller effluent prior to any form of treatment and should not necessarily be considered as levels or concentrations emitted to the environment. For instance settling ponds can be used in order to efficiently remove solids from the effluent ESAPA (2004).

Appendix IX: Tabulated results of grey water footprint

This appendix shows the results of the grey water footprint for each substance and process in tabulated form using ecoinvent version 3.2 effluent load data.

Table 23: Grey water footprint of unalloyed steel

	Grey water footprint unalloyed steel [L/kg steel]													
	Mining, limestone	Mining, iron ore	Mining, bentonite	Mining, coal	Concentrating, iron ore	Activation, bentonite	Sintering , sinter	Pelletizing, pellet	Calcination, quicklime	Coking, cokes	Iron ore reduction, pig iron	Air separation	Steel production	Total
Analytical measures to fresh water														
Biological oxygen demand (BOD)	0.00	0.00	0.00	0.00	44.22	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	44.56
Chemical oxygen demand (COD)	0.00	0.00	0.00	0.00	4.42	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.44
Heavy metals to fresh water														
Arsenic (+V)	0.00	0.00	0.00	0.00	22.11	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	22.23
Cadmium (+II)	0.00	0.00	0.00	0.00	2267.81	2.13	0.00	0.03	0.00	0.00	0.00	0.00	0.00	**2269.97**
Chromium (+VI)	0.00	0.00	0.00	0.00	98.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	98.27
Chromium (unspecified)	0.00	0.00	0.00	0.00	0.00	0.09	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.11
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper (+II)	0.00	0.00	0.00	0.00	737.05	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	737.26
Iron ion (+III)	0.00	0.00	0.00	6.00	12.38	0.02	0.00	0.02	0.00	0.00	0.00	0.00	0.00	18.42
Lead	0.00	0.00	0.00	0.00	152.49	0.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	152.56
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mercury	0.00	0.00	0.00	0.00	340.17	4.81	0.00	0.01	0.00	0.00	0.00	0.00	0.00	344.99
Nickel (+II)	0.00	0.00	0.00	20.82	122.84	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	143.72
Zinc (+II)	0.00	0.00	0.00	2.52	59.36	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	61.88
Inorganic emissions to fresh water														
Aluminium (+III)	0.00	0.00	0.00	12.49	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.61
Ammonium (total N)	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00	0.00	1.27
Chloride	0.00	0.00	0.00	83.91	0.00	0.21	0.00	0.00	0.00	5.44	0.00	0.00	0.00	89.56
Cyanide	0.00	0.00	0.00	0.00	176.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	176.89
Fluoride	0.00	0.00	0.00	18.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	18.74
Hydrogen sulphide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (as total N)	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11
Phosphorus	0.00	0.00	0.00	0.00	0.00	49.97	0.00	0.01	0.00	0.00	0.00	0.00	0.00	49.98
Sodium (+I)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Strontium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particles to fresh water														
Suspended solids, unspecified	0.00	0.00	0.00	3.33	0.00	52.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	55.74

Table 24: Grey water footprint of chromium-nickel alloyed steel

	Grey water footprint chromium-nickel alloyed steel [L/kg steel]																			
	Mining, limestone	Mining, iron ore	Mining, bentonite	Mining, coal	Concentrating, iron ore concentrate	Activation, bentonite	Sintering, sinter	Pelletizing, iron ore	Calcination, quicklime	Coking, cokes	Iron ore reduction, pig iron	Air separation, oxygen	Steel production, pig iron	Mining, sand	Processing, silica sand	Mining and beneficiation, chromite ore concentrate	Mining and beneficiation, Bauxite	Pre-treatment and reduction, ferrochromium	Mining and beneficiation, ferronickel	total
Analytical measures to fresh water																				
Biological oxygen demand (BOD)	0.00	0.00	0.00	0.00	39.30	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	0.00	13.34	52.97
Chemical oxygen demand (COD)	0.00	0.00	0.00	0.00	2.62	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.89	3.52
Heavy metals to fresh water																				
Arsenic (+V)	0.00	0.00	0.00	0.00	13.10	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.21	25.38
Cadmium (+II)	0.00	0.00	0.00	0.00	1343.43	1.25	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	175.15	**1519.85**
Chromium (+VI)	0.00	0.00	0.00	0.00	58.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.22
Chromium (unspecified)	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.00	2.27	71.65	74.03
Cobalt	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Copper (+II)	0.00	0.00	0.00	0.00	436.62	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	227.54	664.28
Iron ion (+III)	0.00	0.00	0.00	3.52	7.34	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	2.98	13.88
Lead	0.00	0.00	0.00	0.00	90.33	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	36.60	126.97
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mercury	0.00	0.00	0.00	0.00	201.51	2.82	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	27.97	232.31
Nickel (+II)	0.00	0.00	0.00	12.22	72.77	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.34	115.37
Tin (+IV)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc (+II)	0.00	0.00	0.00	1.48	35.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	12.80	49.44
Inorganic emissions to fresh water																				
Aluminium (+III)	0.00	0.00	0.00	7.33	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.68	11.08
Ammonium (total N)	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
Calcium (+II)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chloride	0.00	0.00	0.00	49.25	0.00	0.12	0.00	0.00	0.00	3.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	52.57
Cyanide	0.00	0.00	0.00	0.00	104.79	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	104.79
Fluoride	0.00	0.00	0.00	66.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	66.01
Hydrogen sulphide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate (as total N)	0.00	0.00	0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.06
Nitrogen organic bounded	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Phosphorus	0.00	0.00	0.00	0.00	0.00	29.30	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	29.31
Sodium (+I)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Strontium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particles to fresh water																				
Suspended solids, unspecified	0.00	0.00	0.00	1.95	0.00	30.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	32.69

Table 25: Grey water footprint of ordinary Portland cement

	Grey water footprint ordinary Portland cement [L/kg cement]								
	Mining, limestone	Mining, clay	Mining, sand	Mining, gypsum	FGD, gypsum	Crushing & washing, limestone	Pyroprocessing, clinker	Mixing, cement	total
Analytical measures to fresh water									
Biological oxygen demand (BOD)	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.22
Chemical oxygen demand (COD)	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.45
Heavy metals to fresh water									
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic (+V)	0.00	0.00	0.00	0.00	22.32	0.00	0.03	0.00	22.35
Cadmium (+II)	0.00	0.00	0.00	0.00	137.36	0.00	0.63	0.00	137.99
Chromium (unspecified)	0.00	0.00	0.00	0.00	59.52	0.00	0.05	0.00	59.58
Copper (+II)	0.00	0.00	0.00	0.00	89.29	0.00	0.04	0.00	89.33
Iron ion (+III)	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.21
Lead	0.00	0.00	0.00	0.00	7.70	0.00	0.02	0.00	7.72
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mercury	0.00	0.00	0.00	0.00	206.04	0.00	0.01	0.00	**206.05**
Molybdenum	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.74
Nickel (+II)	0.00	0.00	0.00	0.00	14.88	0.00	0.01	0.00	14.89
Selenium	0.00	0.00	0.00	0.00	8.93	0.00	0.00	0.00	8.93
Tin (+IV)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium (+III)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc (+II)	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	3.00
Inorganic emissions to fresh water									
Aluminium (+III)	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.89
Ammonium (total N)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Boron	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.20
Calcium (+II)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chloride	0.00	0.00	0.00	0.00	38.45	0.00	0.00	0.00	38.45
Fluoride	0.00	0.00	0.00	0.00	133.93	0.00	0.00	0.00	133.93
Magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate	0.00	0.00	0.00	0.00	30.79	0.00	0.00	0.00	30.79
Phosphate	0.00	0.00	0.00	0.00	3.57	0.00	0.00	0.00	3.57
Phosphorus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium (+I)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particles to fresh water									
Suspended solids, unspecified	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01

Table 26: Grey water footprint of Portland composite cement

	Grey water footprint Portland composite cement [L/kg cement]										
	Mining, limestone/dolomite	Mining, clay	Mining, sand	Mining, gypsum	FGD, gypsum	Granulation, GGBFS	Electrostatic precipitation, fly ash	Crushing & washing, limestone	Pyroprocessing, clinker	Mixing, Cement	total
Analytical measures to fresh water											
Biological oxygen demand (BOD)	0.00	0.00	0.00	0.00	0.22	0.00	0.00	0.00	0.00	0.00	0.22
Chemical oxygen demand (COD)	0.00	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.45
Heavy metals to fresh water											
Antimony	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arsenic (+V)	0.00	0.00	0.00	0.00	22.32	0.00	0.00	0.00	0.02	0.00	22.34
Cadmium (+II)	0.00	0.00	0.00	0.00	137.36	0.00	0.00	0.00	0.45	0.00	137.82
Chromium (unspecified)	0.00	0.00	0.00	0.00	59.52	0.00	0.00	0.00	0.04	0.00	59.56
Copper (+II)	0.00	0.00	0.00	0.00	89.29	0.00	0.00	0.00	0.03	0.00	89.32
Iron ion (+III)	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.21
Lead	0.00	0.00	0.00	0.00	7.70	0.00	0.00	0.00	0.02	0.00	7.71
Manganese	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mercury	0.00	0.00	0.00	0.00	206.04	0.00	0.00	0.00	0.01	0.00	**206.05**
Molybdenum	0.00	0.00	0.00	0.00	0.74	0.00	0.00	0.00	0.00	0.00	0.74
Nickel (+II)	0.00	0.00	0.00	0.00	14.88	0.00	0.00	0.00	0.00	0.00	14.89
Selenium	0.00	0.00	0.00	0.00	8.93	0.00	0.00	0.00	0.00	0.00	8.93
Tin (+IV)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Vanadium (+III)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zinc (+II)	0.00	0.00	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00	3.00
Inorganic emissions to fresh water											
Aluminium (+III)	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00	0.00	0.89
Ammonium (total N)	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01
Boron	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.20
Calcium (+II)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chloride	0.00	0.00	0.00	0.00	38.45	0.00	0.00	0.00	0.00	0.00	38.45
Fluoride	0.00	0.00	0.00	0.00	133.93	0.00	0.00	0.00	0.00	0.00	133.93
Magnesium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrate	0.00	0.00	0.00	0.00	30.79	0.00	0.00	0.00	0.00	0.00	30.79
Phosphate	0.00	0.00	0.00	0.00	3.57	0.00	0.00	0.00	0.00	0.00	3.57
Phosphorus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Potassium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sodium (+I)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphate	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulphite	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Particles to fresh water											
Suspended solids, unspecified	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.01

Table 27: Grey water footprint of soda-lime float glass

	Grey water footprint soda lime float glass[1] [L/kg glass]												
	Mining, sand	Mining, limestone	Solution mining, sodium chloride	Mining, bauxite	Mining, feldspar	Processing, silica sand	Processing (crushing & washing), limestone	Calcination, quicklime	Bayer process, aluminium hydroxide	Solvay process, soda ash	Calcination, aluminium oxide	Glass production	Total
Water quality parameter													
Biological oxygen demand (BOD)									0.13	0.00			0.13
Chemical oxygen demand (COD)									0.01	0.00			0.01
Heavy metals to fresh water													
Cadmium (+II)									0.00	142.80			142.80
Copper (+II)									0.00	179.33			179.33
Lead									0.00	837.62			837.62
Mercury									0.01	4.39			4.40
Nickel (+II)									0.00	20.83			20.83
Chromium-total									App H	App H			App H
Inorganic emissions to fresh water													
Ammonium									0.00	1.73			1.73
Calcium (+II)									0.00	0.00			0.00
Chloride									0.00	134.80			134.80
Nitrogen									0.00	4.16			4.16
Phosphorus									0.00	169.87			169.87
Sodium (+I)									0.00	0.00			0.00
Hydroxide (OH-)									0.00	App H			App H
Sulphate (SO_4^{2-})									0.00	0.00			0.00
Particles to fresh water													
Solids (suspended)									0.01	1295.09			**1295.10**
Inorganic acidity													
pH									0.00	App H			App H

[1] App H: Appendix H shows the grey water footprint of these substances calculated with ESAPA (2004) data. Ecoinvent did not report loads on these substances and thus are considered separately.

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