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Life Cycle Assessment of Concrete from Bauxite Residue in China

A case study based on “applying the zero-waste concepts” to the Chinese Aluminium industry

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Industrial Ecology
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Abstract

Currently, environmental problem is widely concerned by the society; and the industry has been revealed as a major contributor by researchers. Although it is helpful to alleviate it with "***reducing***" the industrial wastes, but "reducing" won't be infinitely. Since most of the "industrial activity" creates residue and needs raw material simultaneously, theoretically, "***reusing*** the wastes" seems having infinite possibilities. Whatever the residue is reused in the same or another field, it will benefit the environment by "utilizing industrial waste" and "reducing usage of primary material".

Metallurgic production is not trivial in the industrial sectors, and it is not removable from current human life. Since both construction and "aluminium production" are still significant in China. In this research, we have addressed applying the "reusing" concept in mainland of China, via a case study on "using the bauxite residue to produce inorganic binder for concrete".

We have investigated the case with one specific alumina plant and applied the Life Cycle Assessment to quantify the environmental impact. Then the dominant "impact categories and contributors" have been figured out to support "decision-making or improvement-seeking".

Further, we have compared the results between an EU case and a Chinese case regarding the production of "Bauxite Residue Concrete". Meanwhile, 3 transporting scenarios have been analysed regarding the "significance of transportation" in total impact. Furthermore, we have anticipated the possible changes in the future, based on the governmental policy, and the previous status.

Alongside presenting the result and conclusion, the LCA method has been introduced. Meanwhile, the uncertainty was discussed, further, the "possible topic for deeper research" was indicated as well.

For tiden er miljøproblemet mye bekymret av samfunnet; og industrien har blitt avslørt som en stor bidragsyter av forskere. Selv om det er nyttig å lindre det med å "redusere" industriavfallet, vil det ikke være uendelig å "redusere". Siden mesteparten av "industriaktiviteten" skaper rester og trenger råmateriale samtidig, ser det teoretisk sett ut til at "gjenbruk av avfallet" har uendelige muligheter. Uansett hvilken rest som gjenbrukes på samme eller et annet felt, vil det være til fordel for miljøet ved å "utnytte industriavfall" og "redusere bruken av primærmateriale".

Metallurgisk produksjon er ikke triviell i industrisektorene, og den kan ikke fjernes fra dagens menneskeliv. Siden både konstruksjon og "aluminiumsproduksjon" fortsatt er betydelige i Kina. I denne forskningen har vi tatt for oss å bruke "gjenbruk"-konseptet på fastlandet i Kina, via en casestudie om "bruk av bauksittresten til å produsere uorganisk bindemiddel for betong".

Vi har undersøkt saken med ett spesifikt aluminaanlegg og brukt livssyklusvurderingen for å kvantifisere miljøpåvirkningen. Deretter har de dominerende "påvirkningskategoriene og bidragsyterne" blitt funnet ut for å støtte "beslutningstaking eller forbedringssøking".

Videre har vi sammenlignet resultatene mellom en EU-sak og en kinesisk sak angående produksjon av "Bauxite Residue Concrete". I mellomtiden har 3 transportscenarier blitt analysert angående "betydningen av transport" i total innvirkning. Videre har vi forutsett mulige endringer i fremtiden, basert på regjeringens politikk og tidligere status.

Ved siden av presentasjon av resultat og konklusjon er LCA-metoden introdusert. I mellomtiden ble usikkerheten diskutert, videre ble også "mulig tema for dypere forskning" angitt.

Preface

My study was started after accomplishing bachelor study for 25 years, during the unemployment plus middle age crisis. The initial motivation was to learn some new knowledge which was not populated yet, therefore it might be easier to find a new job. Fortunately, I was accepted by NTNU and Norway.

I am so grateful about being offered an opportunity to learn my master's degree of industrial ecology in NTNU. Sustainability is essential for all over the world, and I am so happy with learning so much new knowledge, furthermore I am so proud that our master program has promoted me from an almost absolute outsider into a qualified expert. Surely, I am not an excellent student, but the achievement was outstanding regards my own expectation.

It most likely after this paper is submitted, getting back to where I was from, the connection to the world will be dramatically different. But the experience and memory will always remind me about NTNU and Norway, and all the staff and classmate regarding their tolerance, patience, and kindness. When and Wherever I am or will be, till the end…

Especially, thanks to my supervisor and co-supervisor, for helping me towards all the difficulty in my academic progress. And thanks for their patience when I brain did not work properly...

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List of Abbreviations (or Symbols)

NTNU	The Norwegian University of Science and Technology
AOP	Area of Protection
BR	Bauxite Residue
BRC	BR- geopolymer Concrete
CE	Circular Economy
ELCE	Extraordinary Leuven Cement
FU	Functional Unit
GIS	Geographical Information System
GHG	Green House Gases
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
Mha	Million Hectares
MS	Metallurgical Slag
MSR	Metallurgical Slag Ratio
Mton	Million Tons
NBSC	National Bureau of Statistics of China

Impact Categories at LCIA Endpoint

GW, HH.	Global warming, Human health
P M F.	Fine particulate matter formation
GW, TrEC.	Global warming, Terrestrial ecosystems
Tr, ACD.	Terrestrial acidification
FRS	Fossil resource scarcity

Elements in Life Cycle Inventory

P. Coke	Petroleum Coke
Sodium S	Sodium Silica

1 Introduction

This report addressed a case study of Life Cycle Assessment (LCA) about “reusing bauxite residue”. We have presented the “reason and motivation” in the ***background***, and relevant research in the ***literature review***. “Research questions and system definition” were introduced in ***goal and scope*** section.

1.1 Background

Metal production was essential for the human’s civilization from thousands of years ago, and it became vital for the industrialization, since a few centuries years ago. Because of metal has been engaged more and more into human’s daily life, e.g., buttons on dressing, machines in workshop, cars on the road, and reinforced concrete in buildings.

Metal production is important, due to not only “providing metals to human’s life”, but also “offering numerous jobs for people”. On the other hand, it also generates Metallurgical Slag (MS) and emission. So, its environmental impact has attracted the caution of scientific research for a few decades. From the sustainable perspective, the environmental impact cannot be reduced through simply cutting off the metal production.

As a discrete branch of Industrial Ecology[1], Circular Economy(CE) [2]seeks the possible solutions that “eliminate or reduce” harm to the environment while maintaining economic prosperity. One of the measures under the circular economy’s “zero waste principle” is material reuse[2, 3], which is to utilize “the by-products or wastes as raw material” in the same or another field. Therefore, the purpose of this thesis is to evaluate the environmental impact of “***reusing bauxite residue***” into construction, with the specific focus on a case in China.

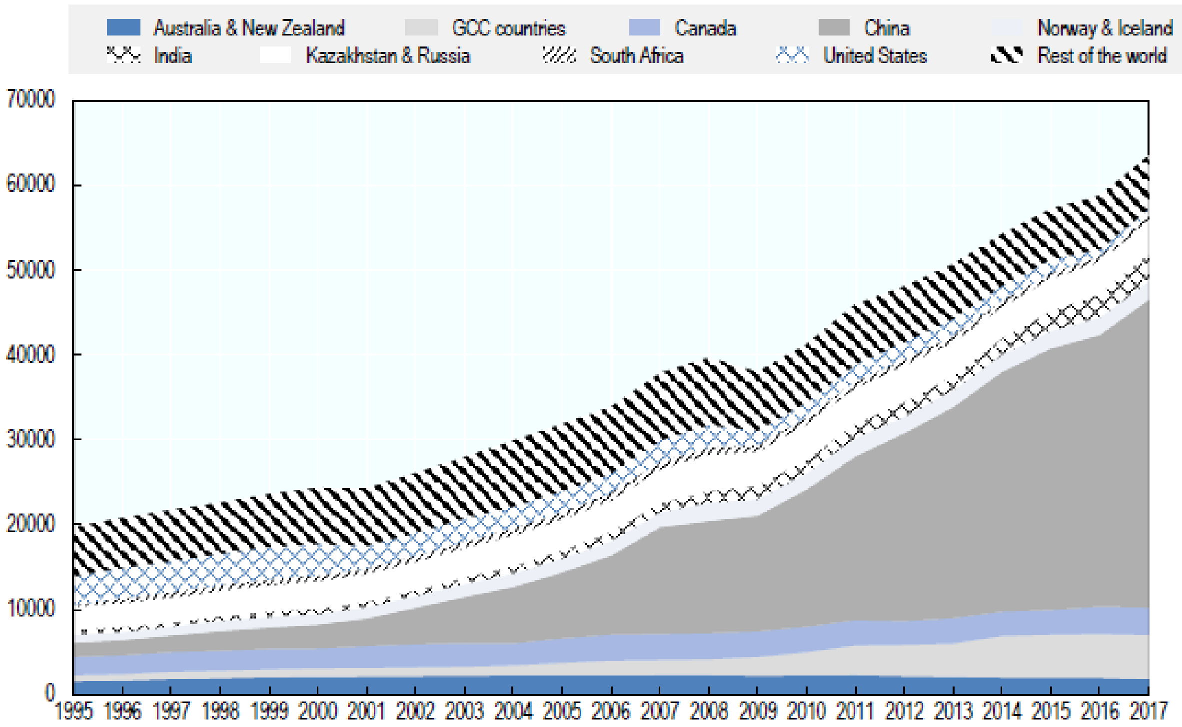
Metallurgical slags are mineral wastes from metal production. Large volumes are generated globally, and lead to large management costs, as well as environmental concerns. SMITHERS has considered that MS could become a substitution for the customer who relies on “aggregates, cement, mortars” etc. Those are opportunities to “consume the MS” and “benefit the environment” simultaneously. But for ***non-ferrous slags***, “regional availability” is a factor could suppress the implementation[4].

SMITHERS’ has argued that the “largest end-use application in volume” was about “35%”. Which refers to the “*non-ferrous slag*” has been utilized by civil engineering in 2019. On the other hand, they have anticipated that “Global non-ferrous slag volumes to reach 133.7 Mt by 2029” [4].

As a typical “non-Ferrous metals”, ***Aluminium*** is used world-widely. Meanwhile, ***Alumina*** is the semi-product during aluminium production. Historically, most of Alumina was produced with the “Bayer process”[5], where the “Bauxite Residue (BR)” is generated from [6].

According to the OECD report— ***“Measuring distortions in international markets: the aluminium value chain”*** — “primary aluminium production” has been significantly increased in China (Figure 1.1), and it was accounted for almost half of global yield in 2017[7]. Since the “Bayer process” has been invented more than 100 years[8], the generated BR is predictably huge in amount. And if there was no applicable method to use it, it has been cumulated largely. Then “reusing the existed BR” could be a new option.

Global production of primary aluminium, 1995-2017 (in thousand metric tonnes)



Source: US Geological Survey and OECD research.

Figure 1.1:Global Primary Aluminium Production Statistics

1.1.1 Generation of Bauxite Residue

Bauxite Residue (BR) was generated during the production of Alumina, and Alumina yield has been used to estimate the "annual yield of Bauxite Residue". It will be inaccurate to calculate BR yield based on the "bauxite production volume" in China. Because of large amount of bauxite has been imported into China(Figure 1.2) according to the report from OECD [7].

World trade in bauxite, 2005-16 (in million metric tonnes)

Source: OECD on the basis of data from the BACI database.

Figure 1.2: Bauxite Imports Growth in China

1.1.2 Allocation of Alumina Production

“Producing aluminum” is not the only metallurgical production in China[9]. And, the alumina production is equipped unevenly in mainland of China, which is approximately 960Mha in size[10]. The regional heterogeneity may differentiate the alumina yield in each region. Some other factor could affect it as well, e.g., the ore storage.

Therefore, Alumina yield was unevenly distributed in provinces (Figure1.3). According to NBSC statistics, 16 regions have been equipped with Alumina production, but continuous production has been recorded only in 9 regions. Correspondingly, continuity of “raw material (BR) for the inorganic binder” can be expected in these 9 regions. In another word, it is not reasonable to establish the “BR geopolymer production” in all regions, where “Alumina plant” is installed.

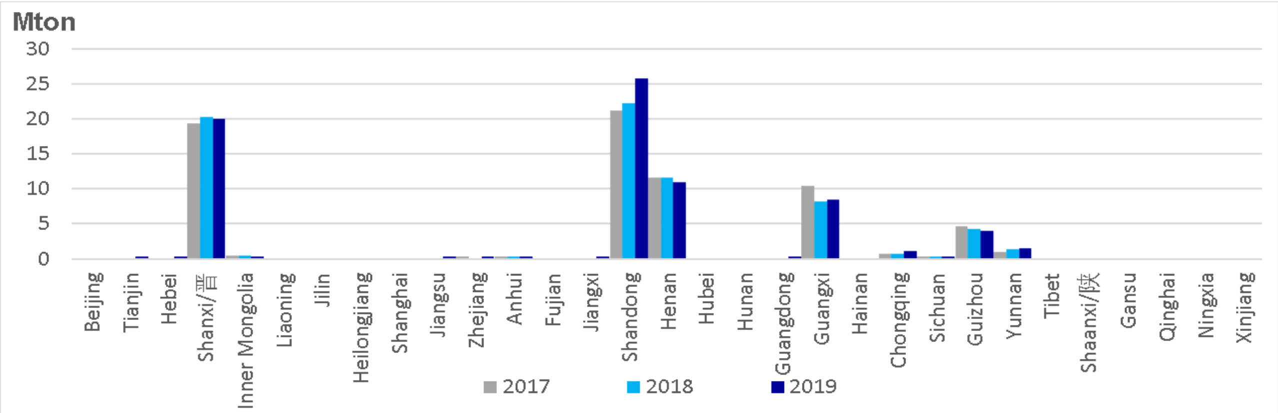


Figure 1.3: Previous Alumina production in China

1.1.3 Distribution of Alumina Production Capacity

According to the ranking in Chinese web media [40], the top 9 “Alumina productive” regions were intermittently distributed (Figure 1.4). And the regional capacity was largely variant in 2019 [11].

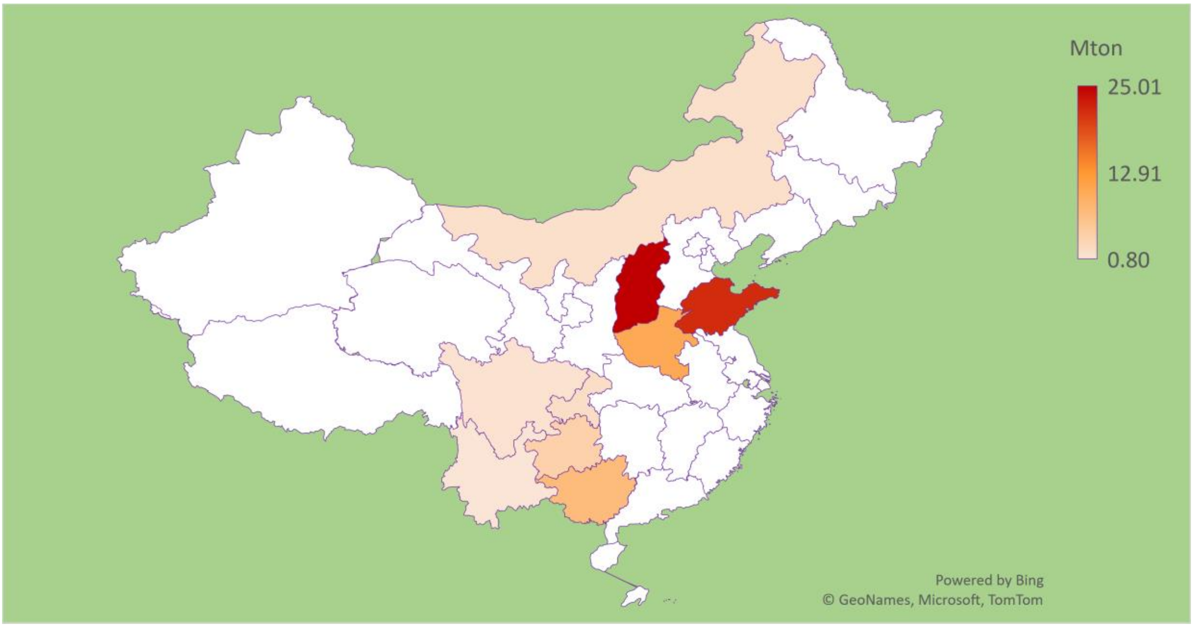


Figure 1.4: Alumina Production Capacity Distribution 2019

1.1.4 Transportation Conctributes to Climate Changes

Global warming has become an environmental concern for decades, and it is being continuously investigated by several "international working groups" on the "Intergovernmental Panel on Climate Change (IPCC)". In the Synthesis Report (SYR) of the "Fifth Assessment Report(AR5)", they have argued that "Human influence has been detected in warming of the atmosphere and the ocean, in changes in the global water cycle, in reductions in snow and ice, and in global mean sea level rise; and it is extremely likely to have been the dominant cause of the observed warming since the mid-20th century."[12]

Additionally, "It is extremely likely that more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in GHG concentrations and other anthropogenic forcings together. Historical emissions have driven atmospheric concentrations of carbon dioxide, methane and nitrous oxide to levels that are unprecedented in at least the last 800,000 years. Total annual anthropogenic GHG emissions have continued to increase over 1970 to 2010 with larger absolute increases between 2000 and 2010 (high confidence)."[12]

As an indicator of climate change, "The Global Warming Potential (GWP) was introduced in the IPCC First Assessment Report."[12] To express different "climate forcing agent" in one common unit(called 'CO2-equivalent emissions'), other climate forcing agent has been transferred into GWP with same unit. It has practically copped with the problem for comparing multi-component with differently original unit.

The "100-year GWP (GWP_{100})" has been adopted by the "United Nations Framework Convention on Climate Change (UNFCCC)", and it has been used widely as the default metric. Correspondingly, GWP_{20} refers to the "20-year GWP", which is normally used to indicate the climate impact in shorter period. They are same type of metrics with different time horizons. Another one is the "Global Temperature change Potential (GTP)", which is "based on the temperature response at a specific point in time with no weight on temperature response before or after the chosen point in time."[12] The "GTP_{100}" refers to the 100-year "Global Temperature change Potential".

According to the analysis on data in 2010, ***transporting emission*** has contributed 14% to the total GHG emission (GWP_{100} in Figure 1.5), which was ranked the 3rd position, after "Electricity and heat production (24%)" and "Industry (21%)". It has presented lower proportion in GWP_{20} (9.8%), but higher occupation in GTP_{100} (16%). Which means transporting emission could affect "the climate changing" more in ***long term*** than in short term.

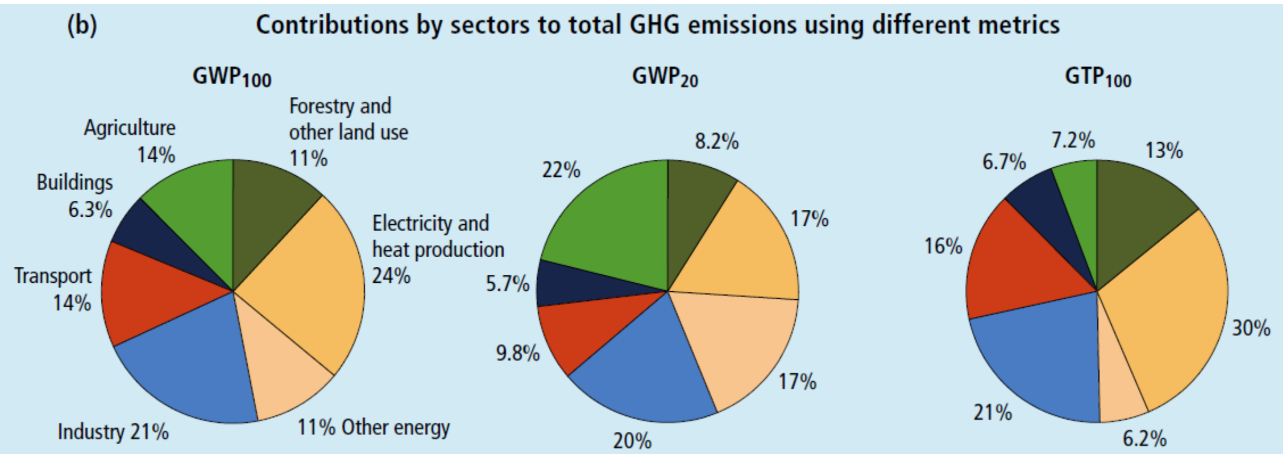


Figure 1.5: Proportion of Sectors in GHG emission by Sectors in 2010[14]

In China, scholars have also paid more attention about the “transporting emission” contributes to GHG emissions. According to one research article which was published in 2020, the authors have presented that “In China, the transportation sector contributes about 18% of the total carbon emissions”[13].

And “X. Tan et al.” have argued that “carbon emissions from China's transportation sector increased from 436 Mt to 810 Mt at an average annual growth rate of 6.39%” in 2018[14].Whilst, “X. Mao et al.” have argued that transportation sector had contributed 5.4% to total national CO_2 emission in 1994, and the proportion have increased to 7.0% in 2007 and 10.6% in 2008 respectively[15].

The “freight trucks” which was distinguished from “passenger vehicles”, has been identified with contributing 8.9% of the total CO_2 emission to the annual emission in 2012 by “Y. Li et al.” [16]. Meanwhile, “X. Yang et al.” have argued that heavy-duty trucks had emitted over 70% of “NO_x and $PM_{2.5}$” in the total emission from transportation[17].

1.2 Literature Review

"Reusing BR" is the main topic in this research. Whilst ***transportation*** is the unavoidable activity for "launching BR concrete" into reality. Meanwhile, ***electricity*** is a key "energy agent" in "BR concrete production". Therefore, we have investigated relevant research in this section.

1.2.1 Life Cycle Assessment as a Tool

In "***Life cycle assessment***"[18], Klöpffer. Walter has explained that "The basic idea of LCA is that all environmental burdens connected with a product or service have to be assessed, back to the raw materials and down to waste removal." And "In the years from 1990 to 1993, SETAC and SETAC-Europe shaped the development of LCA in a series of important workshops culminating in the 'Code of Practice' of 1993."

On the other hand, the structure in ISO standard is slightly different from the SETAC structure, which the last phase is called "Interpretation" in the "international standard 14040". The LCA has been applied in this report, which has flowed the guidance by ISO 14040:2006 [18, 19].

1.2.2 Evolution of Bauxite Residue Management

Flowing the increase of aluminium production, the "BR generation" has kept rising in past decades. It is noticeable that the annual yield was over 120 million tonnes in2009 (cited by Y. Pontikes & Angelopoulos)[20], whilst it was 150 million tonnes in 2016[6, 21].

BR has been handled with more than 1000 registered patents, but the "productive" utilization was only about "2 - 3 %" annually till 2016[6]. Historically, the "end of life treatment" of BR can be categorized into three general phases: **discharging**, **storing**, and **reusing**.

The first phase spans "1940s to 1960s"**,** when ***discharging*** was a widely accepted practice. During that period, BR was discharged into the sea through pipelines, rivers, or ships, ***with*** or ***without*** neutralization. it became obsoleted "by the end of 2015"[6].

After discharging, BR were generally handled by ***storing,*** a method to stack red mud on either open ground or landfills. Some safety measures, such as damming or sealing, were taken to avoid contamination, but the effectiveness of those measures was variable due to the temporal and spatial differences. After 1980, an improved method called "dry stacking storage" was introduced, which has 3 advantages: "lower risk of leakage", "less land area occupation", and "maximum recovery of soda and alumina". Currently it is still the preferred approach for BR storage, with recent adoption of better water removal technology, such as filtration [6].

Reusing of BR is still an active area of research, and these efforts can be divided into 2 main categories: "elemental material recovery" including metal recovery, or "production of construction material" such as tiles and bricks. Some researchers are even exploring ways to make construction material by combining BR with other wastes [6].

Alternatively, in some regions, new technology was introduced "in recent 20 years" for alumina production. Which was switching the feed from bauxite to "aluminium hydroxide"[6]. The question was whether it is more sustainable, although the BR yield has been suppressed.

Some risks were noticed alongside the "evolution of the BR treatment methods". **Alkalinity** was one of the concerns for storage, "If the residue material is not neutralized before discharge", it will risk "health and safety". The second concern is the "leaching of **heavy metals**" when BR was used as raw material in construction. The last one is **radioactivity**, since "Most bauxites will contain low levels of radioactive elements"[6].

1.2.3 Research on Reusing Bauxite Residue in Europe

BR has been researched to recovery material[21], and "making inorganic binder" to replace organic binder[20] in Europe. One of the main concerns was the remained heavy metal when making construction material, Some research has argued that "53%–77%" heavy metal ions could be removed combining with "Granulated Blast Furnace Slag" [22], which is another MS has been widely generated from metal industry[11].

There was different research for "using BR to make the inorganic binder", Leuven University has one research on "producing geopolymers as the cementitious binder" with several metallurgic slag. They named it "Extraordinary Leuven Cement(ELCE)"[23].

Additionally, in another research from KU Leuven (KUL) which was published in 2016, authors have suggested to convert the Bayer process into "zero-waste", via producing inorganic binder with Bauxite Residue (BR). The key argument was "firing BR at 1100 °C", the recipe was "88.6 wt% BR, 1.4 wt% C, and 10.0 wt% SiO2" for the best performance [24].

But, in this research, we have applied the LCA in a case with "BR concrete" as the deliverable. Which means "BR polymer" is one of the components in it. Because concrete is the ***final product*** will be directly used in the construction.

LCA system was modelled according to the BRC flowsheet (Appendix A) from the research by KUL in the "RemovAL project"[25]. The concrete is made with "***Geopolymer, Sodium Silicate, Sand, and Gravel***" as raw materials. Moreover, the "BR concrete" density has complied with the "concrete specifications in Chinese standard"[26].

1.2.4 Studys of Transporting Emission in China

Scholars have suggested different measures to address issues of transporting emission in the previous decade. Some suggestions are supportive to policy makers, such as:

In "***Achieving CO2 emission reduction and the co-benefits of local air pollution abatement in the transportation sector of China***", authors have investigated taxation as instrument to reduce the CO2 emission. After comparing different type of tax, they argued that "energy and fuel taxes, with the tax rates set, are the two most promising instruments for CO2 emission intensity reduction to reach the 2020 carbon intensity reduction targets, whereas subsidies are the least promising options"[15].

In "***Inventory and policy reduction potential of greenhouse gas and pollutant emissions of road transportation industry in China***", the authors have emphasized to optimize the information system about "logistics and emission". They have recommended "By carrying out logistics informatization to reduce the unloaded ratio and improve energy efficiency;" and "A unified statistical system of road transportation energy consumption and emissions should be built"[16].

In "***Controlling GHG emissions from the transportation sector through an ETS: institutional arrangements in Shenzhen, China***", the authors have argued that "Carbon emissions trading schemes (ETSs) are widely used in industry and are effective in reducing the overall social cost of emissions abatement." And they have proof their argument about the "carbon Emissions Trading Schemes (ETSs)" in the Shenzhen case study[27].

In "***Scenario analysis of urban road transportation energy demand and GHG emissions in China—a case study for Chongqing***" , authors have suggested policy-makers to focus on "improving the fuel economy of conventional vehicles" and "promoting alternative fuel vehicles"[14].

On the other hand, some other suggestions are focused on improving the "measuring method":

In "***Characterization of road freight transportation and its impact on the national emission inventory in China***", authors have introduced a "road emission intensity-based (REIB)" approach to estimate the inventory of nitrogen oxides (NOx) and primary particulate matter smaller than 2.5 µm (PM2.5) from the transportation sector. They argued that "The REIB approach matches better with traffic statistical data on a provincial level"[17].

In "***Measuring the energy and carbon emission efficiency of regional transportation systems in China: chance-constrained DEA models***", authors have suggested a "Data Envelopment Analysis (DEA)" *model to* "address the uncertain carbon emissions" *for* "measuring the energy and carbon emission efficiency (ECEE) of regional transportation systems (RTS)".Additionally, they have argued that it can provide more valuable information to decision-makers, regarding the concern of reducing "fuel consumption and CO2 emission"[13].

1.2.5 Lower Emission Technology about Electricity

In ***"Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options"***, authors have suggested that "Many electricity generation technologies can achieve lower GHG emissions per kWh than conventional coal, gas or oil fired power plants: solar, wind, hydro, nuclear, biomass, and geothermal power"[28].

In the ***"Climate change 2014 synthesis report"*** from the "Intergovernmental Panel on Climate Change (IPCC)", the pro and con of "renewable electricity generation" have been presented. Accordingly, Renewable Electricity (RE) technologies have presented similar GHG emission to nuclear power (Figure 1.6), which is much lower than "electricity that is generated from coal, oil or Natural Gas" [31]. It has shown that the "median value of GHG emission" is less than 50 [gCO_2 eq./Kwh] from "nuclear power or renewable electricity", but the "emission from 3 conventional electricity technologies" has shown minimum 250[gCO_2 eq./Kwh].

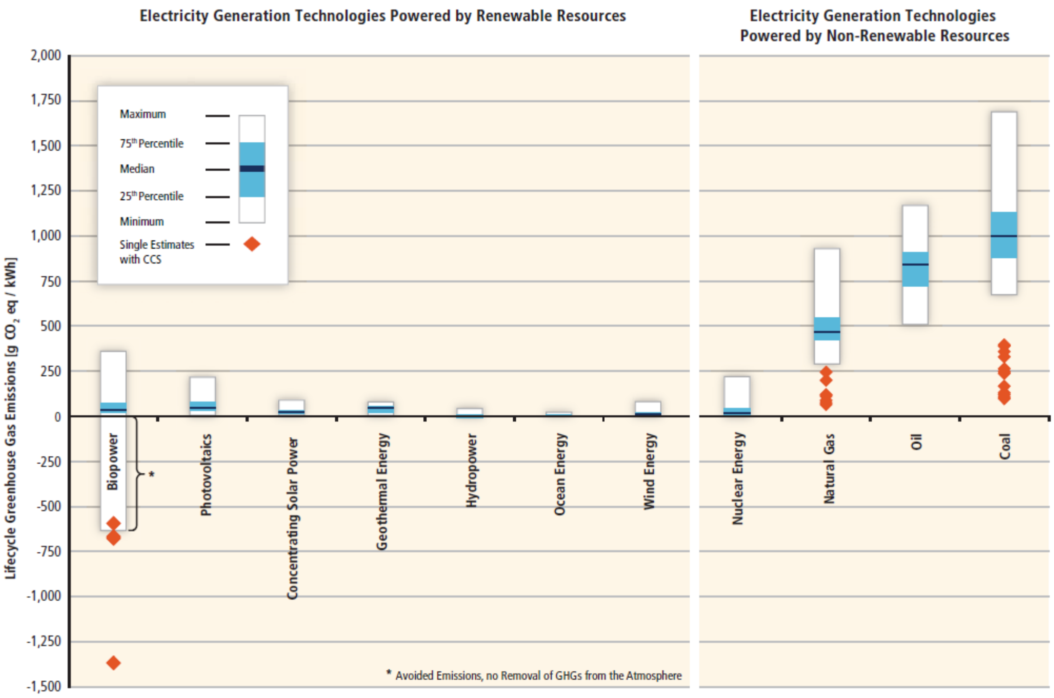


Figure 1.6: Lifecycle GHG Emission of Different Electricity Technologies

1.3 Goal and Scope

We have presented the ***objective*** and ***research questions*** in this chapter. "***System definition, case province, and case plant***" have been introduced as well. Additionally, the "***Functional Unit***" was presented as well.

1.3.1 Rationale for adopting BR Concrete in China

Both Aluminium production and construction are still active in China. From the data in "CHINA STATISTICAL YEARBOOK 2019", construction GDP kept rising continuously during 2014 - 2017[9]. If the BR concrete can be introduced into the construction, then it could become a win-win solution for both environment and economy.

According to earlier and recent researches, the main measure to handle BR in China was still "Storing" [29, 30]. If there was not applicable technology had been launched to reuse it, huge volume of BR might be accumulated during these 10 years (2009 – 2019). And it can become a new option to utilize the BR in China, which is "using BR as raw material" to produce the "BR concrete".

1.3.2 Goal

In this research, we have presented a pattern that "applying Life Cycle Assessment (LCA) as a quantitative tool" to analyse the environmental impact in a specific CE action. Which is to consume the BR via "producing inorganic binder" for concrete. The results can be provided to decision-maker if the environmental impact is concerned. Moreover, the methods can be employed by who intends to study similarly individual cases, for supporting the relative decision. E.g., business investment or governmental permission.

LCA can be used to "make comparison, identify significance, and anticipate future trends". This research aims to address a case study about "the environmental impact of BR concrete" with: comparison of production in different area; the significance of transportation; and the possible changes in future. Therefore, 3 research questions have been formed:

- ***First***, what is the "difference of the BRC production" between in EU and in mainland of China, regarding the environmental impact?
- ***Second***, what is the significance of transport in different scenarios, regarding the Chinese BRC Scheme?
- ***Third***, could these results change in the future?

To answer these 3 questions, LCA has been applied (Ch. 2.2 and 2.3). Then results of "BR concrete production" (Ch. 3.4) were compared with peer group research[31] for answering the 1st question. To answer the 2nd question, significance was presented in percentage of major impact categories (Ch. 3.5).

To answer the 3rd question, we have investigated 2 factors: 1) the extension of transporting distance (Ch.3.6.1); 2) the "allocation of electricity production" and "future energy policy" in China (Ch.3.6.2).

1.3.3 Scope

The comprehensive system is started with "BR Piling up" and end up with "Commercial concrete arriving construction site". While BR is being used as a raw material of concrete, the "BR disposal" is avoided. Additionally, if the conventional concrete is substituted, the production of organic binder is avoided as well (Figure 1.7). But we have only addressed environmental impacts of ***BR concrete production*** and ***transportation*** in this research.

In mainland of China, commercial concrete is normally mixed in the "batching plant"[32], and delivered to the construction site by vehicle. Since transporting vehicle will consume energy and create emission[11]. So, transporting ***methods*** and ***distance*** become factors that could alter its significance in total impact. Meanwhile, we have figured out the "impact from the production" as well.

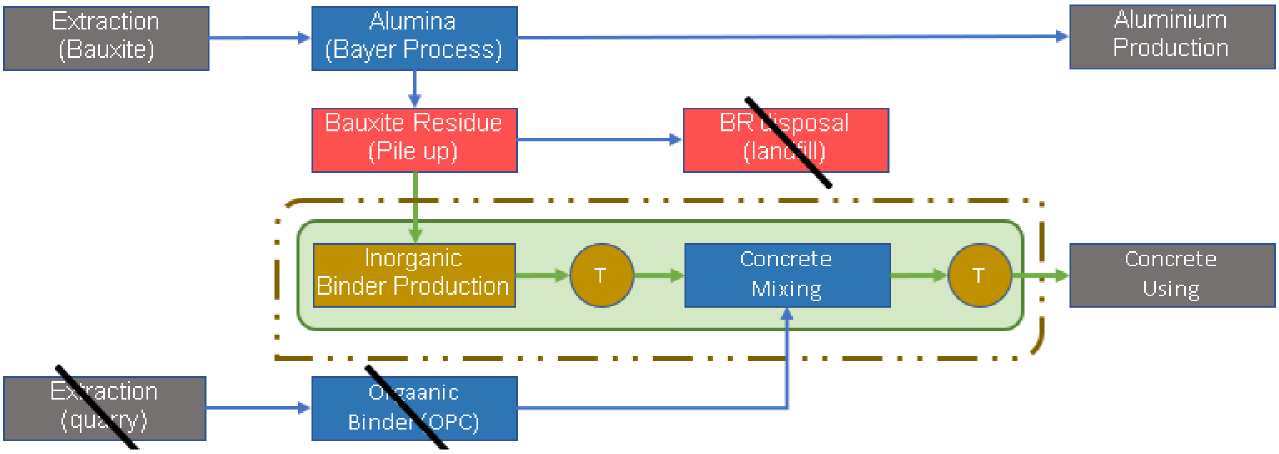


Figure 1.7: Comprehensive System
T = transport

1.3.3.1 Substitute Potential in 2020

In previous research, we have calculated the Substitute Potential (SP) based on "BR polymer replacing organic binder"[11]. In some extents, "cement demand" can reflect the "concrete demand". So, the substitution potential can indicate the potential market of "BR concrete application" as well.

Shanxi (SX) has kept the highest scale (47.3%) in substitute potential (Figure 1.8). Therefore, Shanxi (SX) has been chosen as case province.

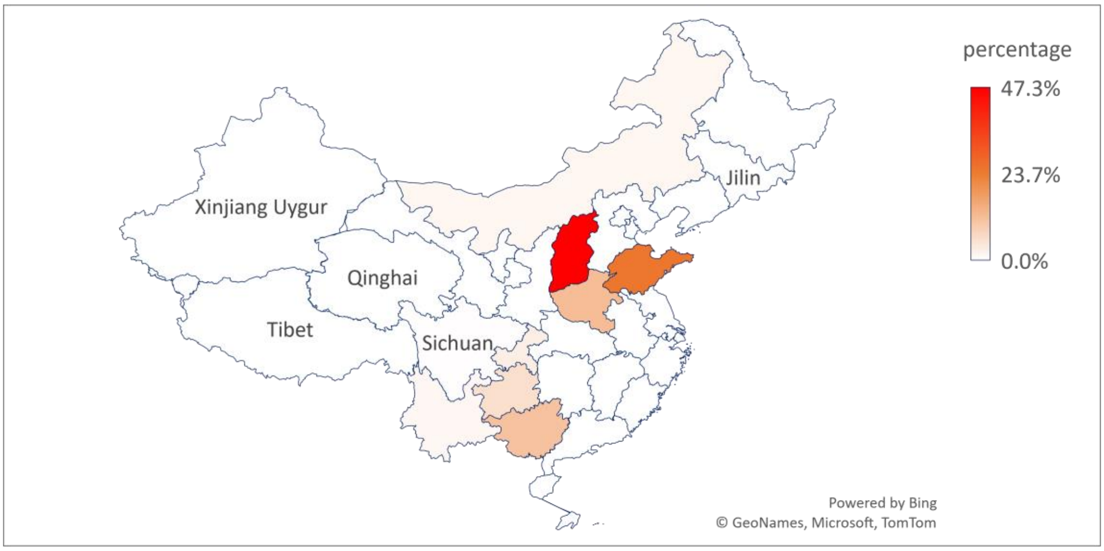


Figure 1.8: Substitute Potential 2020

1.3.3.2 Case Province (SX)

Not all alumina plants in mainland China were addressed in this research. There are 15 alumina plants has been found in Shanxi (SX). Since the major Aluminum production was going through Alumina(95%), and the majority(90%) of Alumina was produced by the Bayer process[33]. We have considered BR is the waste in the "sampled Alumina plant", which is generated from the Bayer process[6].

The chosen alumina plant is "Zhongdiantou Shanxi Aluminum Co., Ltd.", because it is located in the middle of the province, and their capacity(Table 1.1) was not trivial. Moreover, it has been established for almost 20 years, the production activities have been stabilized already.

1.3.3.3 Alumina Plant Distribution in Case Province

The location of "15 Alumina plants" is scattered (Figure 1.9). Assuming the BR will be transformed in the same plant, transportation is necessary to deliver the "inorganic binder or concrete".

Table 1.1: Capacity of Alumina Plant in SX

Name	Initiated Year	Productivity(Mton)
Zhongdiantou Shanxi Aluminum Co., Ltd.	2002	2.6
Shanxi Huaze Aluminum&Power Co., Ltd.	2003	2.5
Shanxi Tongde Aluminum Industry Co., Ltd.	2004	1
Xiaoyi Pastoral Chemical Co., Ltd.	2005	0.4
Liulinsenze Coal Aluminum Co.,Ltd.	2006	1.3
Shanxi Jiaokou Feimei Aluminum Co., Ltd.	2007	2.4
Xiaoyi Taixing Aluminum and Magnesium Co., Ltd.	2008	0.26
Xiaoyi Xingan Chemical Co., Ltd.	2008	2.8
Shanxi Zhaofeng Aluminum Industry Co., Ltd.	2008	1.1
Shanxi Huaxing Aluminum Co., Ltd.	2010	2
Shanxi Aokaida Chemical Co., Ltd.	2010	0.3
Jinzhong Oriental Hope Aluminum Co., Ltd.	2010	2
Shanxi Xinfa Chemical Co., Ltd.	2011	3.6
Zhonglv Xinghua Tech. Co., Ltd.	2011	0.35
Shanxi Fusheng Aluminum Co., Ltd.	2013	2.4
Total		**25.01**

Those 15 alumina plants have been verified on web map (Table 1.1), meanwhile, location and capacity have been identified (Figure 1.9). Regarding the capacity and location, they were irregularly distributed in Shanxi (SX) province. One transport scenario may not be sufficient to demonstrate the delivery from all plants.

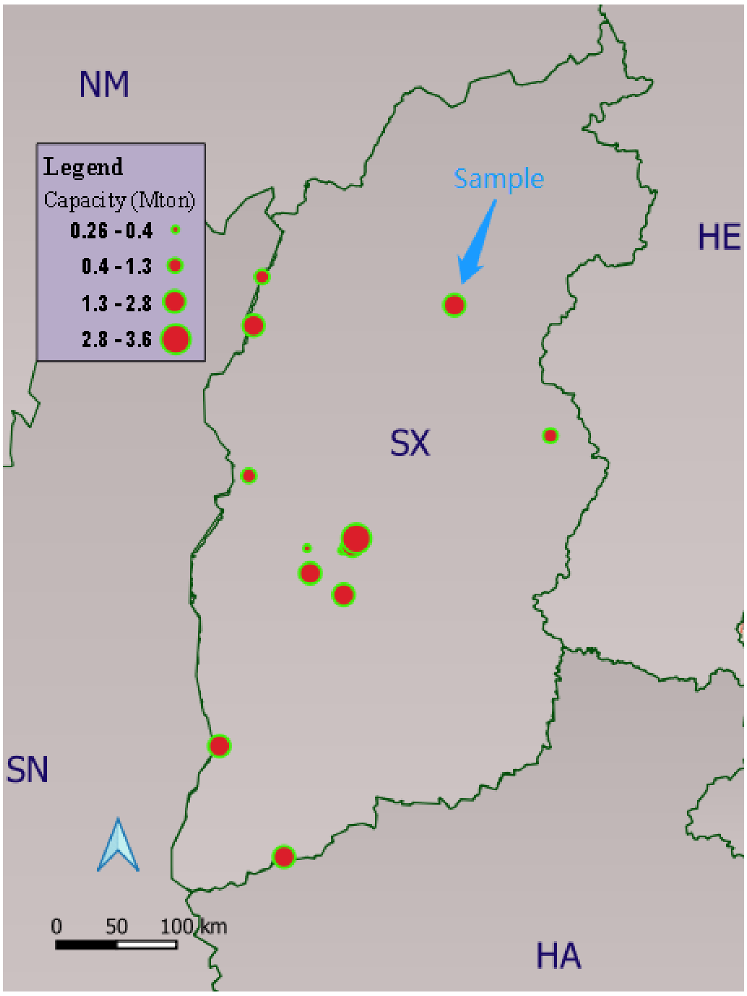


Figure 1.9: Alumina plants Deployment in SX (2019)

NM= Iner Mongolia, HE=Hebei, SN=Shaanxi, HA= Henan

"Summing of the capacity" is 2501 Mton for 15 alumina plants. Those numbers were collected from two sources, the web- media[34], or their official introduction.

1.3.3.4 Transporting boundary

Transportation is normally flexible according to the carrier or business model. There was no regulation, but concrete property could limit the delivering distance. We have considered that the BR concrete is delivered similarly as commercial concrete in China. On the other hand, the BR polymer might be delivered crossing provinces, depending on "where is the customer".

1.3.4 Functional Unit

The Functional Unit (FU) was defined as "1-ton of dry bauxite residue is consumed" in this research. It is because the "moisture proportion" may be affected by other factors, e.g., how long or where they were stored. I.e., water evaporation could be varied due to the "difference of regional climate" and temporal difference[35]. Or some might be dewatered by the artificial processing[6, 35] for the dry stack storage.

2 Methodology

In this chapter, we have presented the ***tools** and **software*** which have been involved, as well as the ***basic concept of LCA***. ***Data** collecting* and "*data gap deriving*" have been introduced together with "*constructing **the life cycle inventory***". The concept and method of "***Life Cycle Impact Assessment***" have been explained either.

2.1 Geographical Information System in Brief

Geographical Information System (GIS) is a multi-functional tool, which can present information based on ***atlas***[36]. According to "Esri", one of the GIS software providers, GIS can be used to gather and analyse data, and it can be used for sharing information, monitoring change as well[37]. Since the information is presented on maps, it is more intuitive to illustrate the regional difference or to indicate location. We have applied "QGIS[38] " to present alumina plants in the case province (Figure 1.9).

GIS mapping needs at least 2 inputs, the boundaries[39] and the data. Due to the complexity of administrative division in China[40], we have employed the GIS boundary at the province-level (Appendix C). It is because of the similarity of their administrative responsibility, on the other hand, it is also because of the "homogeneity of data", which is provided by NBSC [41].

In ***mainland of China***, there are total "31 provincial regions", they are: 4 metropolitans (province-level Municipality), 5 autonomous districts, and 22 provinces [9, 10]. Details of "names, size (Mha), and the abbreviation code[42]" has been listed in attachment(Appendix C).

2.2 Life Cycle Assessment in General

LCA refers to Life Cycle Assessment, which is a tool to quantify the "environmental impacts" of one product along its lifetime. This means it includes not only the impact from the "manufacturing" but also the "using phase" and "after-use treatment". It has been standardized by ISO. But it "typically does not address the economic or social aspects of a product"[19].

2.2.1 Definition and Term

Those major terms regarding LCA in ISO14040:2006 were applied in this research, which was presented in this section[19].

Environmental aspect

Factors which are "can interact with the environment", regarding "activities, products or services".

Product

"Any goods or service", I.e., those deliverables which are provided to the consumer.

Product system

"collection of unit processes with elementary and product flows, **performing** one or more defined **functions**, and which models the life cycle of a product."

Life cycle

continuously connected phases of a “product system”, going through stages about “raw material acquisition or generation” from nature to “final disposal”. I.e., from natural material extraction to end-of-life treatment.

Life Cycle Assessment

“compilation” of the inputs and outputs, to evaluate the “potential environmental impacts of a product system” along its “life cycle”.

Process

Those activities are applied to “transform inputs into outputs”.

Raw Material

“primary or secondary material that is used to produce a product”, recycled material is accounted as “secondary material”.

Input

“product, material or energy flow that **enters** a unit process”, e.g., “raw materials, intermediate products, and co-products”.

Output

“product, material or energy flow that **leaves** a unit process”.

2.2.2 Framework

According to the ISO14040:2006, an LCA is structured into 4 general stages(Figure 2.1)[19]. They are: “Goal and scope”, “Inventory analysis”, “Impact assessment” and “Interpretation”, more details has been explained in the two ISO standards [19, 43].

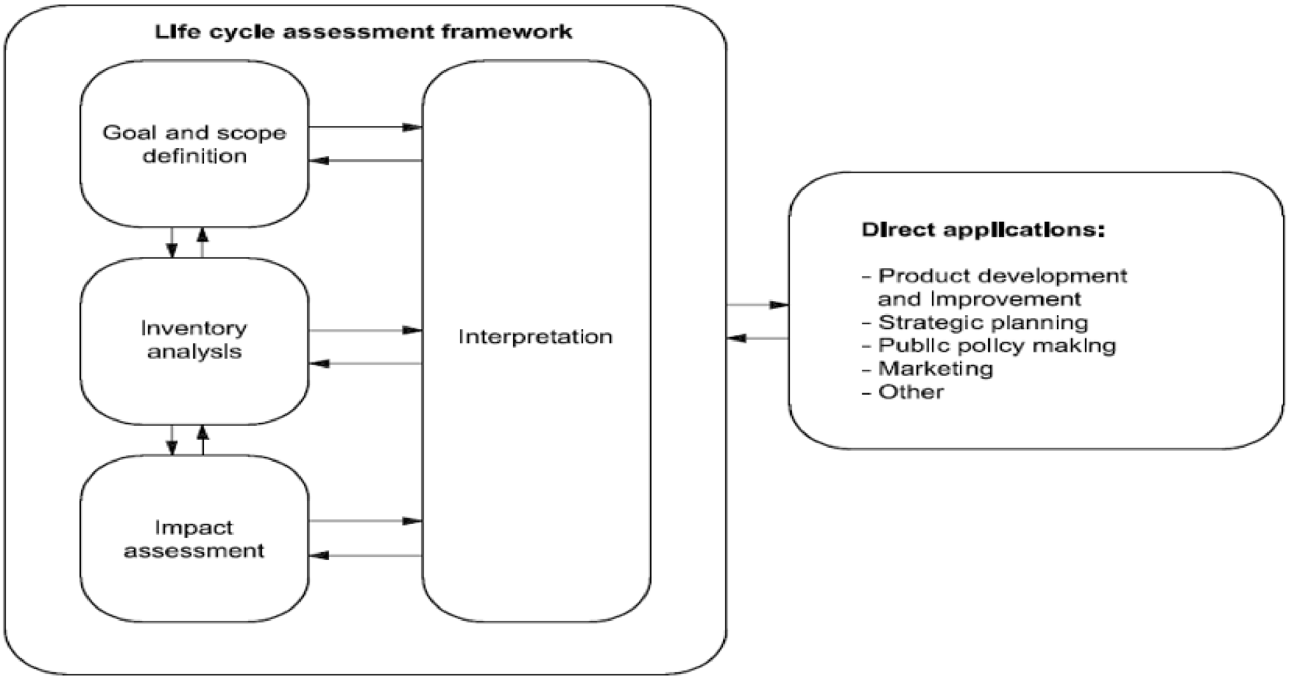


Figure 2.1: Structure Overview of LCA [19]

In brief, an LCA project is normally started with “Goal and scope definition” and ended up with “Interpretation” (Figure 2.1). The quantitative result can be interpreted from 2 stages, the “Inventory analysis” or “Impact assessment”. Therefore, “Interpretation” is still the final stage. In the case that “Impact assessment” has NOT been applied, it is named as “ LCI study”, but not “LCA” [19].

In our case study, LCA was applied, which means the “Impact assessment” (Figure 2.1) has been included as well [19]. The “Impact assessment” refers to Life Cycle Impact Assessment(LCIA)[19], whose purpose is to “translate emissions and resource extractions into a limited number of environmental impact scores utilizing so-called ***characterization factors***”. It has been explained in one article about “ReCiPe2016” [44], which is “characterizing method” in this research.

According to “ReCiPe2016” method (Figure 2.2), the environmental impact has been allocated into 17 categories at ***midpoint***, and 3 “Area of Protection (AOP)” at the ***endpoint***. They are named as “Damage of human health”, “Damage to ecosystem” and “Damage of resource availability” with units : “DALY” , “species.year” and “USD($)” respectively[44]. Correspondingly, “DALY” refers to “the years that are lost or that a person is disabled due to a disease or accident”; “species.year” represents “local relative species loss in terrestrial, freshwater and marine ecosystems” ; and “USD($)” stands for “the extra costs involved for future mineral and fossil resource extraction”[44].

Those concepts have been applied in later chapter. But “ReCiPe2016” is not the only characterization approach for LCIA, at least 2 other methods are simultaneously active, which are “LC- IMPACT”[45] and “IMPACT World+”[46].

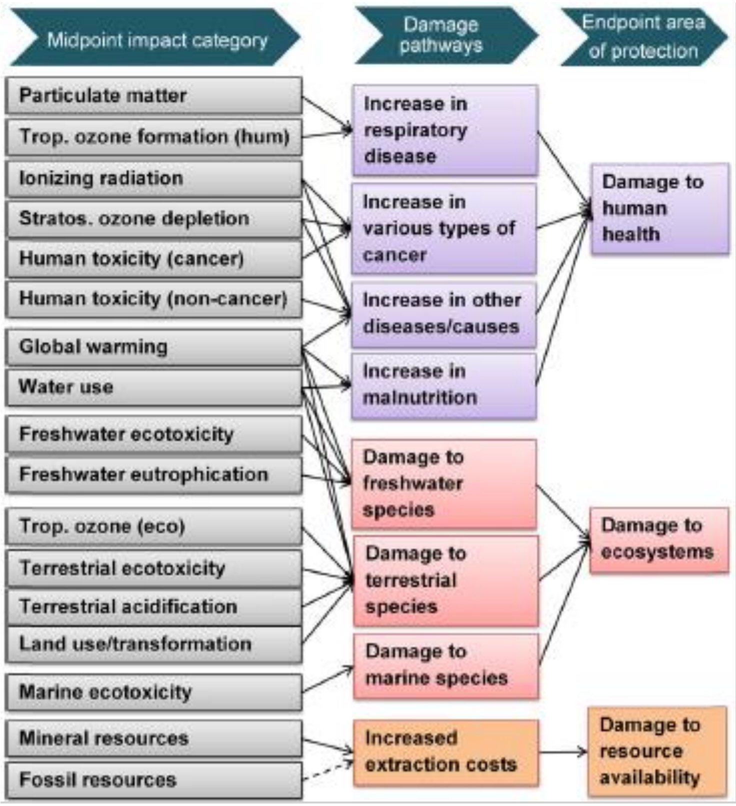


Figure 2.2: Characteristic Factor Framework of Recipe2016[44]

Among those 3 methods, "LC-IMPACT" is the only method that the result has been directly aggregated into 3 areas of protection(AOP), i.e., "human health, ecosystem quality, natural resources"[45]. Besides, "Life cycle impact assessment" used to be standardized separately in 2000[47], but it was "Revised by" the ISO 14040:2006 and ISO 14044:2006[19, 43] later. Interestedly, none of those 3 characterization methods has explained the relationship with ISO standard (LCA) in the reference[44-46].

2.2.3 Interpretation

Interpretation is to translate the numeric results into understandable meaning. Since not every contributor has stressed equally on all impact categories or has presented equal severity. In this phase, significance ought to be identified, presented, and explained[43].

Accordingly, the major issue can be emphasized with a predictable consequence or unpredictable risk. But the numerous minor issues could be mentioned or neglected based on their importance in the total impact. To demonstrate the uncertainty for an "LCA" case, "timeliness of data and technology" could be discussed as well, which may affect the accuracy of the LCA result.

"Conclusions", "limitations" and "recommendations" have been suggested in the interpretation by ISO14044:2006 as well[43]. Since "recommendations" could be varied due to the background knowledge, with my understanding, it is more informative than decisive.

2.3 Case Study

LCA calculation is a complicated task, it is quite time consuming for “seeking the data”, and “implementing the calculation”. Furthermore, bias might exist, due to the gaps between samples and the whole industry.

2.3.1 Software and Database

We have got the educational access to one LCA software —SimaPro, which has been developed for 30 years[48]. Through the SimaPro(Ver. 9.1) platform, we were able to access the Ecoinvent(Ver. 3.5) database, which was initiated from 2007[49].

In the SimaPro user interface, database is named as “libraries”, there are several options for the ecoinvent database. And “Ecoinvent 3 – allocation at point of substitution – unit” was the one that we have chosen for picking the items. Further, “majority of elements in Eco-inventory” were picked from “processes” in that “library”.

The chosen database is suitable for “attributional LCA”, which means to calculate the environmental impact for a product was already exist, i.e., the environment burdens has been created before applying the LCA. Another different type of LCA that is called “Consequential LCA”, which means to evaluate the foreseeable environmental burdens from some future activities[50].

For our research case, it is somewhere in between. Because of the BR was already exist which should apply with “attributional LCA”. But the BR geopolymer has not been produced yet, which is supposed to be a “Consequential LCA” case.

2.3.2 Pathway of Life Cycle Impact Assessment

“Recipe 2016[44]” is the chosen “characterization method”, the units have been presented as same as they are displayed in SimaPro. Which are “***DALY***” for the “damage of human health”, “***species.yr***” for the “damage of ecosystem” and “***USD2013***”for the “damage of resource”.

There are 22 impact categories at endpoint in Simapro (Table 2.1), they are deduced from the “Midpoint indicators” through the “Damage pathways”. Therefore, several endpoint results may be connected to 1 midpoint category, e.g., “Global warming, Human health”, “Global warming, Terrestrial ecosystems “and “Global warming, Freshwater ecosystems” are from the “Global warming” at midpoint.

And the only ambiguous one was “Marine eutrophication”. Although, it has been presented in SimPro at midpoint as well, but it was not mentioned in the reference ---- “***ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level***”. It may be a new impact category has been employed in Version 1.1. Because “Recipe 2016 ver.1.1” was the version in SimaPro, but the version was not clarified in the reference[44].

Table 2.1: Connection between SimaPro Endpoint and Recipe 2016 Midpoint

Demage Category	EndPoint Impact categories in SimaPro	Unit	Recipe 2016 MidPoint Impact Category
Damage to Human Health(DHH)	Global warming, Human health	DALY	Global warming
	Stratospheric ozone depletion		Stratos. Ozone Depletion
	Ionizing radiation		Ionizing radiation
	Ozone formation, Human health		Trop.Ozone Formation (hum)
	Fine particulate matter formation		Particulate matter
	Human carcinogenic toxicity		Human toxicity(Cancer)
	Human non-carcinogenic toxicity		Human toxicity(non-Cancer)
	Water consumption, Human health		Water use
Damage to Ecosystem(DECO)	Global warming, Terrestrial ecosystems	species.yr	Global warming
	Global warming, Freshwater ecosystems		Global warming
	Ozone formation, Terrestrial ecosystems		Trop.Ozone Formation (eco)
	Terrestrial acidification		Terrestrial Acidification
	Freshwater eutrophication		Freshwater eutrophication
	Marine eutrophication		
	Terrestrial ecotoxicity		Terrestrial Ecotoxicity
	Freshwater ecotoxicity		Freshwater Ecotoxicity
	Marine ecotoxicity		Marine Ecotoxicity
	Land use		Land use/transformation
	Water consumption, Terrestrial ecosystem		Water use
	Water consumption, Aquatic ecosystems		Water use
Damage to Material Availability(DRES)	Mineral resource scarcity	USD2013	Mineral Resources
	Fossil resource scarcity		Fossil Resources

2.3.3 Comparison and Transporting Scenarios

LCIA result has been employed to analyse the "significance of transportation" and to compare "producing Bauxite Residue Concrete" in different place (in Europe VS in China). In general, we have considered the BR polymer is produced in the ***same*** plant where BR is generated.

Regarding ***BR concrete production***, the "endpoint result" has been compared with the EU case from peer group research [31]. The recipe (Appendix A) of "inorganic binder and concrete" is the same, but the "material (BR and others) and energy" were supplied from different geographic locations, i.e., from Europe VS from China.

Regarding the ***significance of transportation***, 3 simulative scenarios were analyzed. And the "endpoint result" has been used to figure out the key contributors in "dominant impact categories". In the 1st scenario, we have simulated that the "BR concrete" is produced in the same alumina plant, and only *delivered once* by truck to the construction site (local distribution). Whilst, in the 2nd scenario, it was configured as that "BR geopolymer" has been transported(250km) by train (Appendix B) to the concrete plant, then concrete is delivered by truck to the construction site.

To anticipate the ***possible further changes***, the 3rd scenario was analyzed as hypothetical transportation. Which is assuming the "BR polymer" has been transported (1000km) by train to the concrete plant, later, concrete is delivered by truck to the construction site. Regards the energy supply, we have investigated the previous "allocation of electricity production" and the newest policy in China.

2.3.4 Life Cycle Assessment Modelling

Modelling is a method of simplification, and it is not as complicated as reality [51]. But it provides a way to investigate the major "character and property" of a *system* with reasonable time consuming. In this case, the LCA modelling was focused on processes of "BRC production and transportation". And individual difference about "machine and vehicle" was neglected. Further, two transporting methods were addressed, they are lorry (truck-mixer) and freight train.

A LCA system modelling is normally based on processes[52]. To start a LCA case, the first step is to clarify the "processes and system boundary", and the second step is to "fix the functional unit", then the next step is to "figure out the input and output", i.e., the Life Cycle Inventory (LCI). Which should include ***volume*** of the "raw material, energy consumption and emission", per functional unit (FU). In SimaPro, "inventory items" is organized with 7 categories, which are: *material, energy, transport, processing, use, waste scenario and waste treatment*. Data elements are provided by eco-invent database. We need to synchronize the quantities of fundamental element with the FU in the "life cycle inventory".

2.3.4.1 System Boundary and Functional Unit

Based on the comprehensive system description (Figure 1.7). Four main processes have been setup in the system boundary, they are "Inorganic Binder production, BR geopolymer transport (to batching plant), Concrete mixing and Concrete Transport (to construction site)". In this case, Commercial concrete was mixed somewhere and delivered to construction site, which is the popular business approach in mainland of China. And the functional unit was defined as "1-ton of dry bauxite residue is consumed" (Ch. 1.3.4).

2.3.4.2 Structure of Life Cycle Inventory in Simapro

According to the internal information from RemoVAL project [25], the concrete can be produced with "*Geopolymer, Sodium Silicate, Sand, and Gravel*", meanwhile the Geopolymer is produced with "*Bauxite residue, limestone, Carbon*". Energy is provided from electricity and heat for "Geopolymer production", and the emission is mainly the off-gas with 2 major chemical material, i.e., H_2O and CO_2. All input and output have been linked to the FU (Figure 2.3). Since the moisture in BR could be variant in different Alumina plant, the water in BR was normalized in LCI.

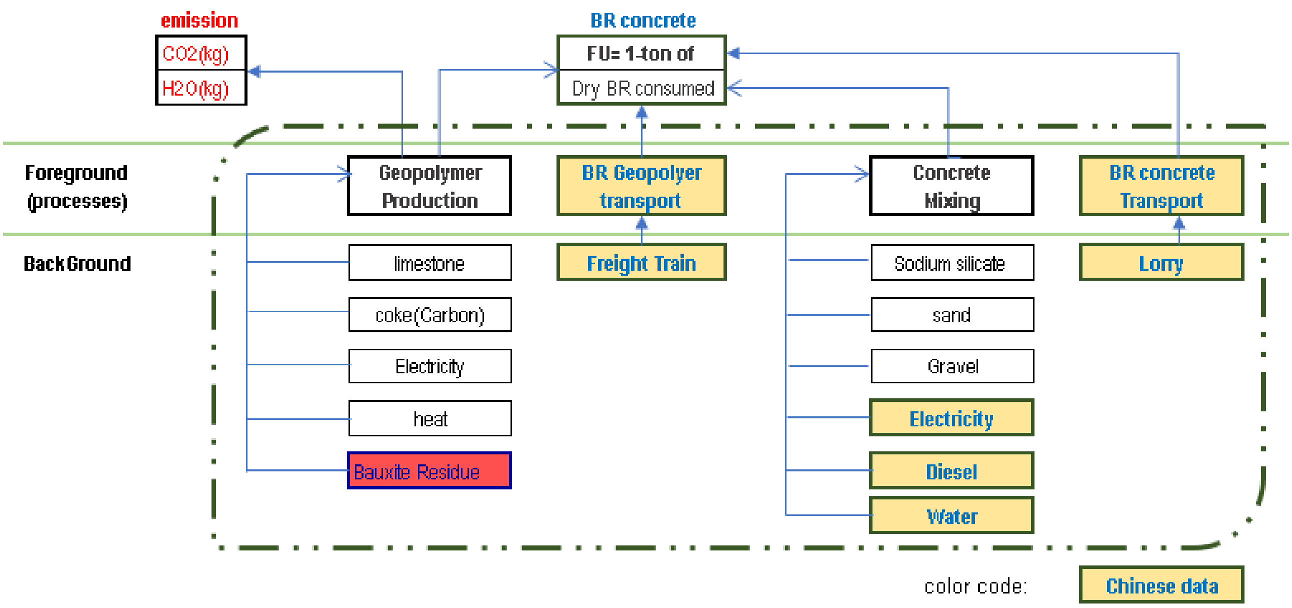


Figure 2.3: Flowsheet in SimaPro

2.3.5 Dataset in Life Cycle Inventory

Since data in ecoinvent was initiated by institute in Switzerland[53]. Therefore, not all data is available for specific Chinese case. In Simapro, we have chosen the metadata from library of "Ecoinvent 3 – allocation at point of substitution (APOS) – unit". But same material may have different choices regarding the location. As a general rule, the selection is prioritized (high →low) as: regional specific element (e.g., electricity |SX), national specific element (e.g., CN), and the Rest of World(i.e.,RoW).

The research of Geopolymer concrete was in still progress. In case it was still ***not authorized*** to publish, when this thesis has been submitted, details was presented separately (Appendix A).

In our case, the material list for "BR geopolymer and concrete" was fixed by the provided flowsheet, as well as the "energy consumption" for "producing the BR geopolymer". But for the "energy consuming in mixing the BR concrete", it has been described "***as same as normal concrete***" in the original source.

Since the BR concrete will be produced in China, the energy consuming pattern and amount has been extracted from the Chinese research. Additionally transporting inventory (Chinese scenario) has been derived from the Chinese data as well, calculating method was introduced in later chapter (Ch***2.5***). As data source, we have found 2 Chinese research articles regarding the energy consumption in "concrete mixing" [54, 55].

2.4 Data Processing

Three types of data sources have been employed: *web-media*, *official business website*, *research article*. The *web media* was chosen for its timeliness, providing more "fresh" information. E.g., top 10 Alumina productivity in China[34]. Meanwhile the *official business information* was chosen for obtaining the specific information. E.g., fuel consumption for truck mixers.

The *research article* has been mainly involved to extract or derive the quantitative input of LCI, which is essential for "calculating the environmental impact". Because of accuracy is overwhelmingly important than the timeliness for "calculating the environmental impact". And the research article is more rigorous.

2.4.1 Data collection and Quality Control

New data for alumina production was collected, with the same method as previous research[11]. They have been published on the "Nation DATA" website through the English interface[56], and the period has covered from 2017 to 2020.

Most of the data for "constructing the LCI" has been obtained from the internal flowsheet (Appendix A), except the data of Chinese "concrete mixing" and transportation. In this case, the data has been obtained from one Chinese research about the "energy consumption for commercial concrete production" (Ch. 2.5.2). Meanwhile, "parameter for concrete transportation" has been inferred with the method that was explained later (Ch. 2.5.3).

Data Quality was controlled with the same method in the previous research[11]. Which means "random checking on the alumina monthly data" was applied, and no error was found. Each location of alumina plants has been verified to be sure that 15 alumina plant are real plant, but not a registered office, to check the reliability of data from web media.

2.4.2 Verifying the Location of Alumina plant

There was 15 active alumina plant found in Shanxi province (SX)during this research (Table 1.1). Enterprise was sought from “Qi ChaCha”, a third-party platform that providing basic business information of companies. It provides company name, address, and capacity in some cases (not all). Therefore, the capacity of each plant was found from either their official website or the company introduction in “QiChaCha”. The “mobile APP” was employed, because of the website (Qcc.com) was not accessible outside of China's mainland during data collecting.

To verify whether it was an office building or an alumina plant, we have applied the visual check through the “satellite view” on the web map. Two large map providers were involved, the “Google Map” and “Baidu Map”, which were the popular used outside and inside Chinese mainland.

We input each company name into the “searching window” on the web-map, then select the item with the same address from “QiChaCha”. Afterwards, checking the satellite view, to see whether it looks like an alumina plant (Figure 2.4). As we explained in an earlier chapter, in most cases, BR was a “pile-up”, they maybe not appeared with a large open area, but it should not look like an office building. Perfectly, those 15 plants were all workshops. The priority was “Google map[57]” first, because it works quicker than “Baidu map[58]” with internet in Norway.

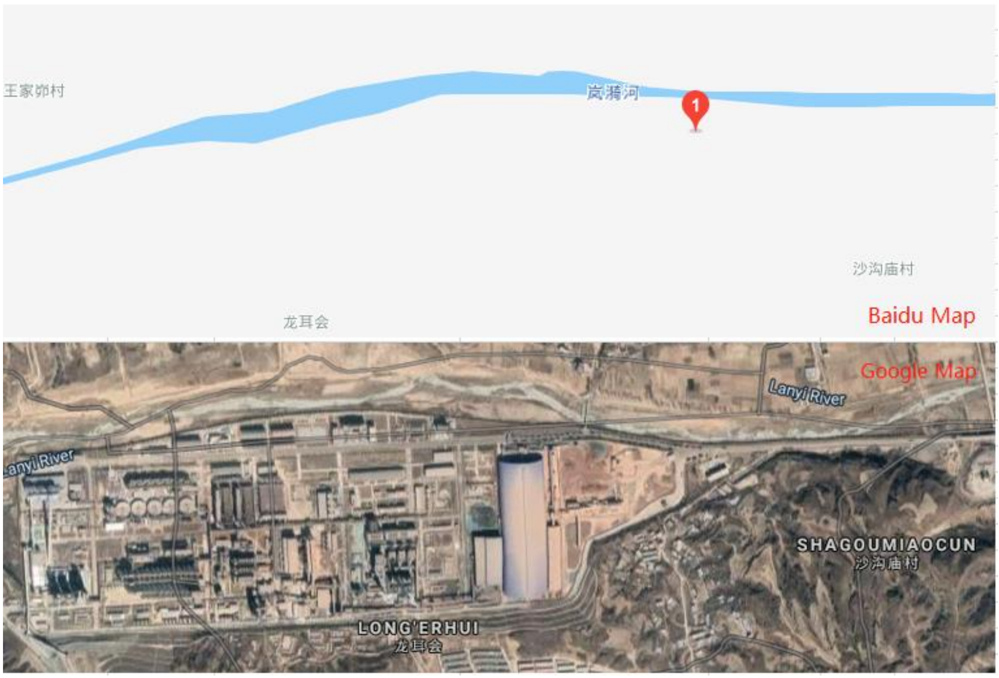


Figure 2.4: Checking Alumina Plant on Web Map

2.5 Derivation of Data Gaps

2.5.1 Provision of Bauxite Residue

Continuity of material supply is important for launching the new technology into industry. Since there was no statistics regarding the "bauxite residue yield", so the "yearly BR volume" was deduced from "statistics of alumina production". According to recent research, there will be "1- 1.5 tons" of Bauxite residue generated ,while 1-ton of alumina is produced (Bayer process) [6]. The **mean** value (1.25) was applied as "***Metallurgical Slag Rate*** (MSR)" which refers to "*how much BR is generated accompanying per ton of Alumina is produced*". Because of the Slag volume could be varied from one production to another. Which is depending on not only the technology, but also being fluctuated by other factors, e.g., the quality of ore. Therefore, we have chosen the mean value to calculate the BR yield by equation:

$$yearly\ BR\ yeild(Mton) = yearlyAlumina\ yeild(Mton) \times MSR(1.25)$$

2.5.2 Metadata in Life Cycle Inventory for Chinese Concrete Mixing

According to the Chinese research, "water, diesel and electricity" were consumed in "concrete mixing", The water was used for making concrete and cleaning, meanwhile, diesel and electricity are for driving machines[55]. And the amounts were presented with "per m^3". Yet, the Functional Unit is "1-ton dry bauxite residue is consumed", which can produce "2.91m^3" BR concrete accordingly. Therefore, the amount (in LCI) has been calculated by multiplying the numbers (in reference) with "2.91", to obtain the quantities of "electricity, diesel and tap water" in the LCI.

2.5.3 Metadata in Life Cycle Inventory for Transportation by Truck

Since the Functional Unit is not equal to "1 m^3 concrete", to translate concrete transportation (per FU) into the same unit***(tkm)*** in the Eco-inventory, it was calculated by the equation:

$$Lorry\ \ Transportation(tkm/FU) = Route\ Length(km) \times Concrete\ Density(t/m^3) \times concrete\ volume(m^3/FU)$$

2.5.3.1 Calculation of Route-length

The popular way of "providing commercial concrete to the construction site" was, the concrete is produced at mixing station, then it is delivered by a "truck mixer"[55]. But the distance is a fluffy parameter. Because of the precise route-length of each time cannot be exactly the same, even repeating the same point-to-point delivery. Besides, there was no statistics from NSBC for the distance of transporting commercial concrete, and it was not found anywhere else.

Therefore, we deduced the route-length from the diesel usage (per delivery) and specified "fuel consumption" of a truck. The calculation was applied with the equation (results in Ch. 3.2.2):

$$Route\ Length(km) = \frac{Container\ Capacity(m^3)\ \times Statistic\ Fuel\ usage(L/m^3)}{Fuel\ consumption(L/hkm)} \times 100$$

According to the "energy-consuming analysis of commercial concrete" in 2012, the diesel usage were presented with "1.9L/m^3 " and "1.6 L/m^3" for trucks with "12 m^3" and "15m^3" containers respectively, as the "Industrial statistics" [55].

The calculation could be skewed by two factors. Firstly, the timely variance of "fuel consumption of a truck", for minimizing the possibility of this bias, we should find the "fuel consumption" for a truck, which has been used around 2012. Because the fuel energy efficiency was continuously improved for reducing truck-emission, due to the improvement of technology and restriction, after the transportation has been revealed as a large emitter of GHG. So, "calculating with a newer truck having less fuel consumption" will lead to a "over estimation" of the route length, then the environmental impact would be overestimated finally.

Secondly, regarding the "Industrial statistics" of diesel usage, there was no clear clue about "whether the 'curb weight (empty truck)' was included or not?". But, after unloading the concrete, the truck is normally emptied in returning. In this case, to minimize the uncertainty, we have made a simple analysis through the "fuel consumption" of several trucks.

2.5.3.2 Fuel Consumption of the Truck

It is the emission, that a truck contributes the most to climate change. Different truck mixers may be deployed for delivering the commercial concrete. But in a general case analysis, we have used the "fuel consumption of one typical truck" to calculate the route-length. And for matching the diesel usage data in 2012(Industrial statistics), the truck should be launched around 2012.

We managed to find market analysis for "truck mixer", it has presented that the "best-sold truck mixer" was produced by "Sanyi" [59]. Then, we have selected 4 "Sanyi" trucks(Table 2.2) for further analysis, which were equipped with similar engine (Model), according to the datasheet on their official website [60].

The Euro III emission standard, which was voluntary until the beginning of 2013[61], so, it is most likely the "former 3 trucks" were provided to the European market in 2013. Meanwhile, "China V" was earliest restricted in Beijing(BJ) by February 2013[62]. As a peer product, "**SY312C-8**" is most likely a truck which has been launched in China between 2012 - 2013. And its fuel consumption(45L/hkm) is workable for calculating the route-length.

Table 2.2: Technical Parameters of Four Mixer Trucks

Truck Model	Container size(m3)	Fuel Consumption (L/100km)	Fuel Use per m^3 (L/hkm. m^3)	Emissions	Engine Model
SY307C-8	7	≤ 35	**5.00**	Euro III	Hino P11C
SY308C-8	8	≤ 38	**4.75**	Euro III	Hino P11C
SY310C-8	10	≤ 42	**4.20**	Euro III	Hino P11C
SY312C-8	12	≤ 45	**3.75**	China V	Hino P11C

2.5.3.3 Analysis of the Diesel usage in the "Industrial Statistics"

In the "Industrial statistics" of diesel consumption, "1.9L/m^3" was presented for the "12m^3 truck", but there is no clear demonstration about "whether diesel usage of the empty truck has been included?". We have analysed the "fuel consumption" of 4 trucks. And it is most likely that "1.9L/m^3" was the aggregating fuel usage of the truck for one delivery operation (empty return is included in bi-direction), therefore we have used it in the calculation of route-length accordingly.

Suppose the full loading (7 m^3,8 m^3,10 m^3,12m^3) mix trucks will consume maximum diesel on the road(Table 2.2), which diesel is combusted with “35, 38,42, and 45 (L/hkm)” respectively. Then we have calculated the fuel usage which is allocated to “each m^3 of concrete”. The change is relatively small regarding the loadings (container size). So, the fuel is mainly consumed for driving the truck itself. Additionally, it is declining while load is increased, “the declining trends” has matched the argument in the reference, which is the truck with bigger container consumes less fuel in per delivery[55].

On the other hand, regarding the distance between “concrete batching plant” and construction site, it has been suggested that “It’s better to keep the product mixing station at a distance of 10 kilometres, but ***not more than 50 kilometres***” in the technical guidance from a “concrete machinery manufactories”. They have argued that it is because of the “long-during transportation” may lead concrete to the “early solidification” , and lose their performance [63].

Suppose the “industrial statistic (1.9L/m^3)” is indicating diesel usage for a whole transporting operation, we have calculated the route-length for the truck-sample (***SY312C-8***, with ‘45L/hkm’ as fuel consumption) with “12m^3” container. And the “1.9L/m^3” diesel usage has represented around 50km in route-length (Ch. 3.2.2), which is close to the suggested ***maximum distance***. So, the statistics most likely reflects the aggregated diesel usage for a “round-trip” delivering operation.

2.5.4 Metadata in Life Cycle Inventory for Transportation by Train

Freight train has been selected for “carrying ‘BR polymer’ to the concrete plant” with travelling 250km (Appendix B). In the recipe (Appendix A), “1-ton of dry bauxite residue” can generate ***almost*** “1-ton of BR polymer”. So, the metadata of train transport has been applied with “250tkm”.

3 Result and Analysis

In this chapter, we have presented the ***result*** of "Life Cycle Impact Assessment" and have explored the meaning of the result. Further, dominant "impact ***categories*** and ***contributors***" have been clarified accordingly. Meanwhile, "*life cycle inventory*" and "*material availability*" has been presented as well.

3.1 Provision of Bauxite Residue

There was no data found for either the BR generation or the BR utilization. Therefore, the BR yields were derived with calculation (Ch. 2.5.1). Further, "Where the BR was located" is a factor affecting transport significance in total impact, via the transporting distance and methods, which are influenced by the supply chain setup.

Alumina production was distributed unevenly in 31 provinces (Appendix C), but annually yield has not fluctuated much from the large producer. In fact, only 16 regions have been recorded with Alumina production, 9 of these 16 regions has presented continuous production. Further, 4 regions have generated more than 10Mton of BR per year, and the highest yield has increased around 10% in 2020(Figure3.2) than in 2019(Figure 3.1).

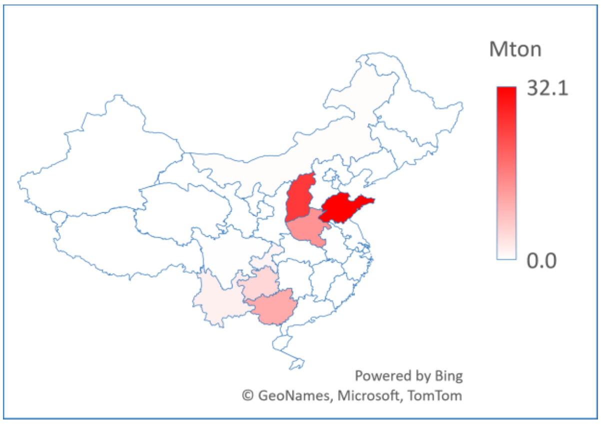


Figure 3.1: BR Estimation 2019

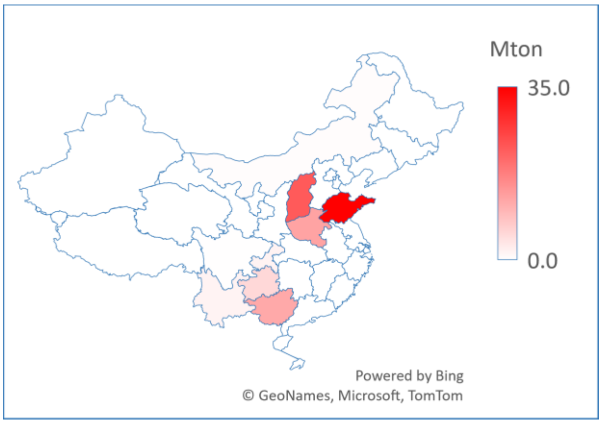


Figure 3.2: BR Estimation 2020

Focusing on the production of 4 top regions (Table 3.1), the BR generation is continuously increasing in Shandong (SD) province, whilst it is decreasing in Henan (HA) province. In the other 2 provinces, it has shown irregularly changes.

Table 3.1: Variance of Bauxite Residue Generation in Top 4 Regions

BR yield Variance	Shanxi/SX	Shandong/SD	Henan/HA	Guangxi/GX
2017 - 2020 BR yield Estimation				

3.2 Life Cycle Inventory

3.2.1 Water and Energy Consuming for Concrete Mixing

Regarding the energy consumption of "concrete mixing", it was described "as same as normal concrete" in the flowsheet (Appendix A). According to the Chinese reference, water and energy have been consumed in the Chinese case [55]. And they have been translated for matching the "functional unit" into the LCI (Table 3.2).

Table 3.2: Water and Energy Consuming in Life Cycle Inventory

materials	Reference usage /m3	**Usage in LCI /FU**
Diesel (kg)	0.13	**0.38**
Electricity(kWh)	1.36	**3.96**
Water(kg)	187.95	**546.93**

3.2.2 Freight Lorry in Life Cycle Inventory

Based on the equation which was described earlier (Ch. 2.5.3), the "route-length" was calculated as "$50.67(km)$". And according to the flowsheet (Appendix A), BR concrete density is "2.4ton/m^3". And based on the dosage of inorganic binder in concrete, "1-ton of dry bauxite residue" can produce "2.91m^3" BR concrete. therefore, the inventory of Lorry was calculated as:

$$Lorry\ Transportation(tkm/FU) = 50.67(km) \times 2.4(t/m^3) \times 2.91(m^3/FU) = 353.88(tkm)$$

3.2.3 Freight Train in Life Cycle Inventory

In the 2nd transporting scenario, freight train was introduced for carrying "BR polymer" to the "concrete batching plant", and the "travelling distance" is 250km. Since "1-ton of dry bauxite residue" can generate ***almost*** "1-ton of BR polymer" (Appendix A). So, "***250tkm***" has been set as the metadata of train transport.

3.2.4 Dataset in Life Cycle Inventory

Combining "information from the flowsheet (Appendix A)" with the calculated parameters in Chinese case, the life cycle inventory has been finalized (Table 3.3). So far, there was no element for BR as material in Ecoinvent database, therefore the "***minus*** BR treatment" was chosen, which refers to BR is consumed as raw material, and its environmental impact is avoided. And the symbol is "*BR Management*".

Table 3.3: Life Cycle Inventory per Function Unit in Simapro

LCI Items	Qty.	Unit	Representative inventory in ecoinvent	Symbol
Dry BR	-1000.00	kg	Redmud from bauxite digestion {RoW}| treatment of, residual material landfill | APOS, U	BR Management
Water	-500.00			
Limestone	196.00	kg	Limestone, crushed, washed {RoW}| market for limestone, crushed, washed | APOS, U	Limestone
Coke	24.63	kg	Petroleum coke {GLO}| market for | APOS, U	P. Coke
Heat	2188.47	MJ	Heat, central or small-scale, natural gas {RoW}| market for heat, central or small-scale, natural gas | APOS, U	Heat
Water	328.16	kg	Water (evapotranspiration)	Direct Emission
CO_2	202.87	kg	Carbon dioxide	
Sodium silicate	497.91	kg	Sodium silicate, solid {RoW}| market for sodium silicate, solid | APOS, U	Sodium S
Sand(0-4mm)	2370.01	kg	Silica sand {GLO}| market for | APOS, U	Sand
Gravel	3126.77	kg	Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	Gravel
Diesel	0.38	kg	Diesel {RoW}| market for | APOS, U	Diesel
Electricity	57.45	kWh	Electricity, high voltage {CN-SX}| electricity production, hard coal | APOS, U	Electricity
Tap water	546.93	kg	Tap water {RoW}| market for | APOS, U	Water
Freight Lorry	353.88	tkm	Transport, freight, lorry, unspecified {RoW}| market for transport, freight, lorry, unspecified | APOS, U	Truck
Freight Train	250	tkm	Transport, freight train {CN}| market for | APOS, U	Train
Concrete	6989.44	kg	Bauxite Residue Concrete Production |Function unit	BR Concrete

3.3 Damage Assessment and Overview of Impact Categories

Overall, "BR Management" has contributed to the negative impact in all 3 damage categories (Figure 3.3). Especially, in "damage of human health", it has presented around *threefold* negative scale (≈75%) comparing to the "positive impacts scale" (≈25%), which lead the total impact into negative value (-1.65E-03 DALY). But it has presented less negative influence in ecosystem (≈10%) and resource scarcity (≈5%). Therefore, total value in "damage of ecosystem (1.50E-06 species.yr)" and "damage of resource (2.24 USD2013)" have remained positive.

Which means "transferring bauxite residue into inorganic binder" can compensate the impact of "damage to human health, ecosystem, and resource". But it can only turn the total impact into negative on "damage of human health".

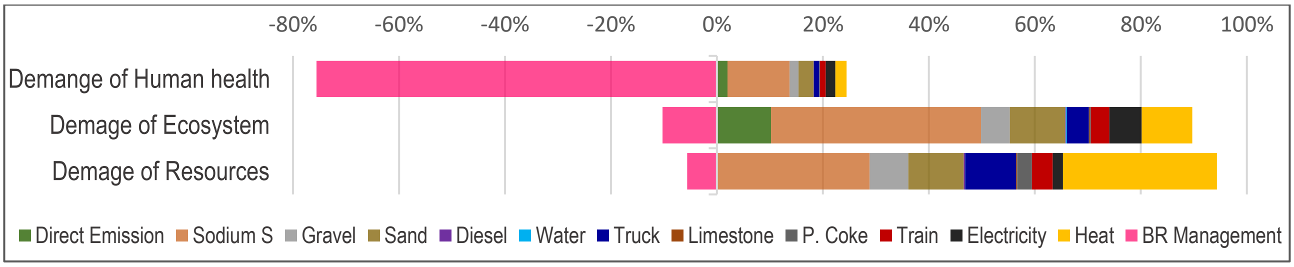


Figure 3.3: Overview of Damage Assessment

There are 22 impact categories in LCIA result at endpoint (Table 2.1), 5 of them are toxic indicators, and the rest 17 are non-toxic impact categories. We have presented them separately.

3.3.1 Toxic Impacts

There are 2 toxic impact categories in "damage of human health", the largest value has displayed in "Human carcinogenic toxicity (-0.007 DALY)", whilst the impact of "Human non-carcinogenic toxicity" is relatively trivial (Figure 3.4). The largest negative contributor is "BR Management", which has introduced far more negative impact than the positive scale in "Global warming, Human Health".

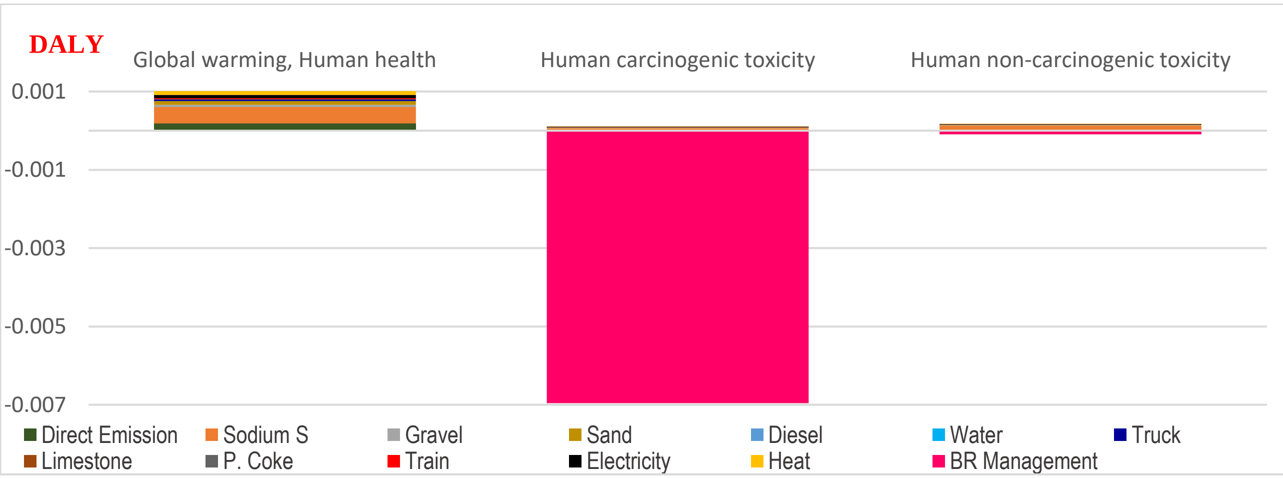


Figure 3.4: Toxic impact on Damage of Human Health

Nevertheless, for the "damage of ecosystem", the "BR Management" has ***not*** presented the largest negative impact in 3 Eco-toxic categories, but in "Freshwater eutrophication (-3.37E-07 species.yr)". Anyway, its negative scale in "Freshwater ecotoxicity" is still larger than in "Terrestrial ecotoxicity" and "Marine ecotoxicity". Additionally, comparing with the positive impact on "Global warming, Terrestrial ecosystems", those negative impact are relatively small (Figure 3.5).

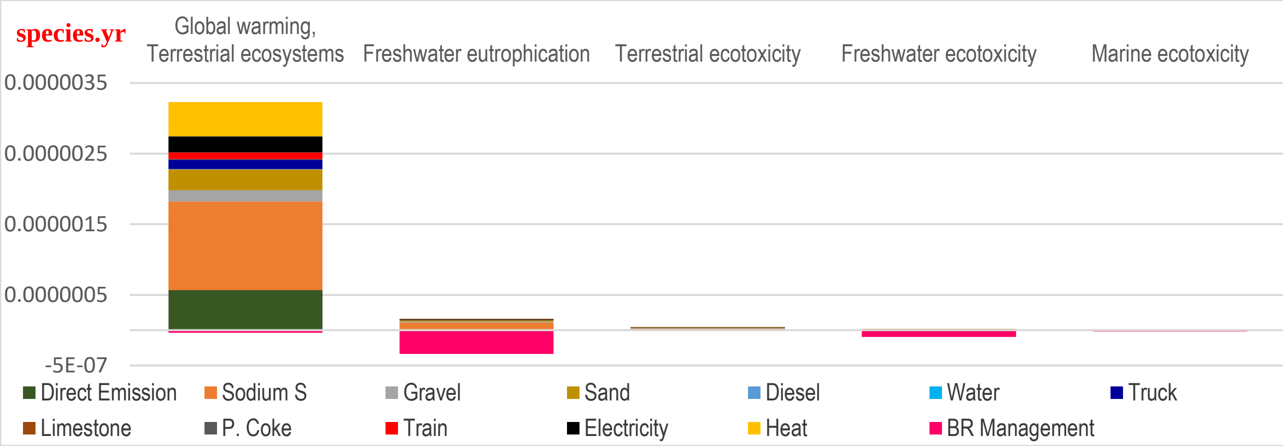


Figure 3.5: Toxic impact on Damage of Ecosystem

In general, "transferring bauxite residue into inorganic binder" has tremendously contributed to reduce the human toxicity. But, the negative contribution to the ecosystem is more obvious in the "Freshwater eutrophication" than the "eco-toxic categories".

3.3.2 Non-toxic Impact

Further analysis has been focused on 17 **non-toxic** impact categories. For the "damage of human health", the 2 dominant impact categories are "Global warming(0.001DALY)" and "Fine particulate matter formation(0.0009DALY)" (Figure 3.6).

The top 3 contributors in "Global warming, Human health" are "Sodium silicate (Sodium S)", "direct emission" from production and "Heat". Whilst the top 3 contributors in "Fine particulate matter formation" are "Sodium silicate (Sodium S)", "Sand" and "Electricity" respectively. Additionally, "Sodium silicate (Sodium S)" has contributed about 50% in both impact categories, which is even higher than the sum of 2nd and 3rd contributors.

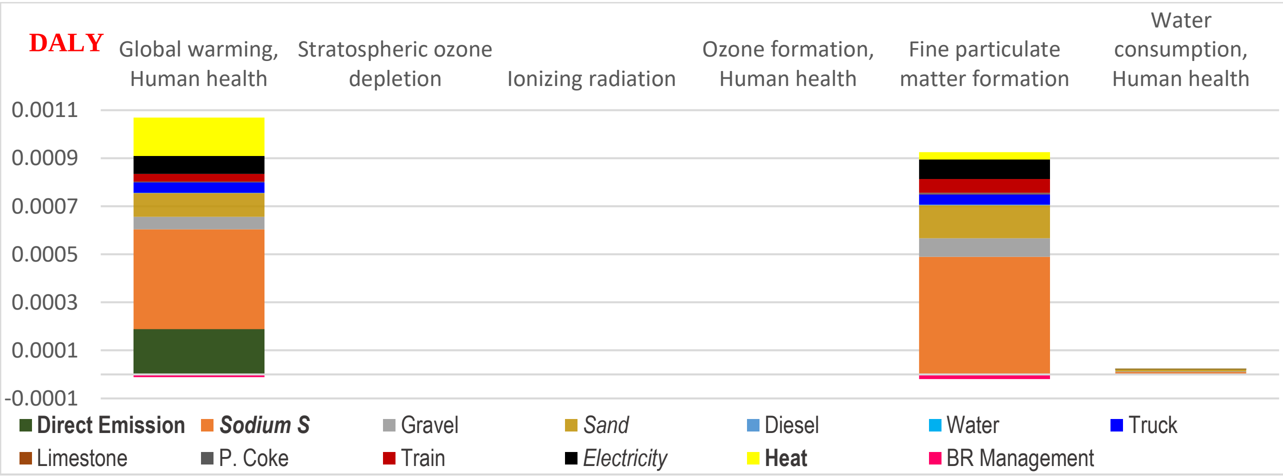


Figure 3.6: Non-Toxic contributors in Damage of Human Health

For the “damage of ecosystem”, “Global warming, Terrestrial ecosystems (3.19E-06 species.yr)” has presented overwhelmingly higher positive score than the other impact categories. It is about fourfold of the “Terrestrial acidification (7.87E-07 species.yr)”, which is the second largest positive category (Figure 3.7).

The top 3 contributors in “Global warming, Terrestrial ecosystems” are “Sodium silicate (Sodium S)”, “direct emission” from production and “Heat”. Meanwhile, the top 3 contributors in “Terrestrial acidification” are “Sodium silicate (Sodium S)”, “Sand” and “Electricity”. In both impact categories, “Sodium silicate (Sodium S)” has contributed about 50%, which is much higher than the 2^{nd} and 3^{rd} contributors.

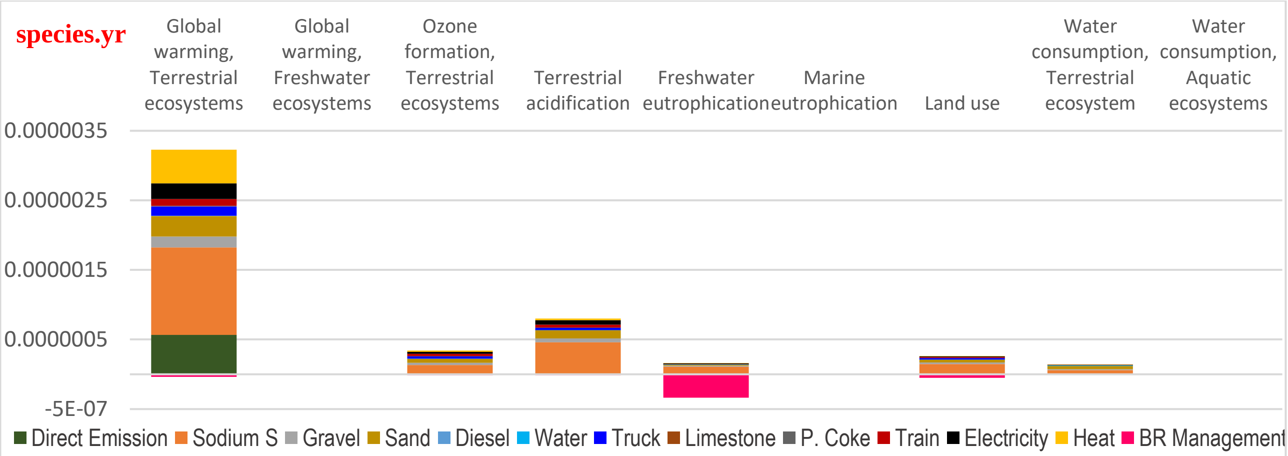


Figure 3.7: Non-Toxic contributors in Damage of Ecosystem

For the “damage of resource”, the dominant category is “Fossil resource scarcity (65 USD2013)”. On the contrast, “Mineral resource scarcity” is relatively trivial (Figure 3.8). And the top 3 contributors in “Fossil resource scarcity” are “Heat”, “Sodium silicate (Sodium S)”, and “Sand” respectively. But the “Sodium silicate (Sodium S)” has presented almost the same proportion as “heat” in this impact category. And the sum of these 2 contributors has occupied more than 50% in the total positive value.

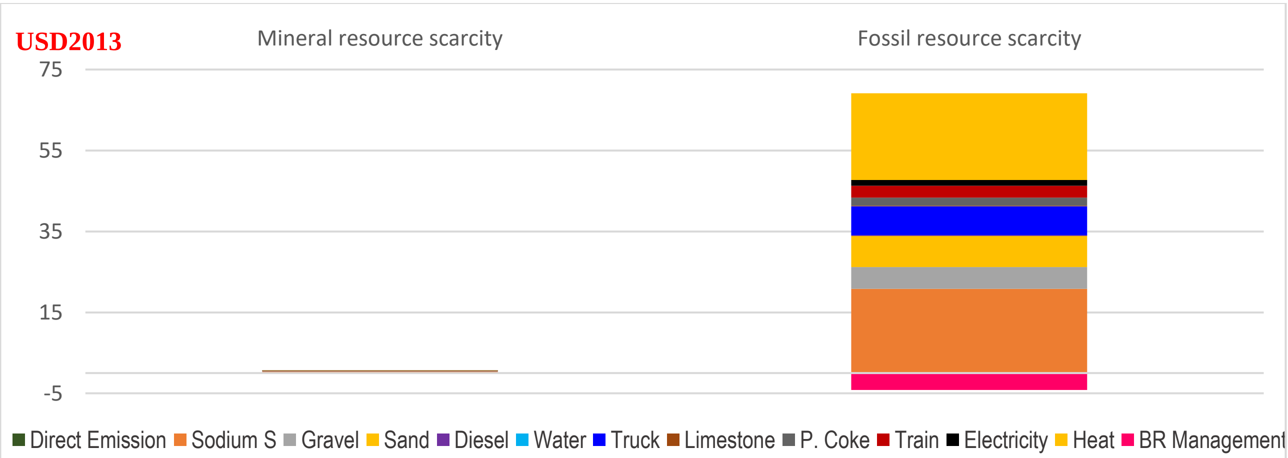


Figure 3.8: Non-Toxic contributors in Damage of Resource

In general, among 17 **non-toxic** impact categories, 5 major categories have presented dominance on positive impact. The "Global warming, Human health" and "Fine particulate matter formation" are for the "Damage of human health". The "Global warming, Terrestrial ecosystems" and "Terrestrial acidification" are for the "damage of ecosystems". And "Fossil resource scarcity" has dominated the impact on "damage of resource".

"Sodium silicate" is the top contributor to the major impact categories in the "damage of human health" and "damage of ecosystems", and it is the second largest contributor to "Fossil resource scarcity", which is the "dominant impact category" in the "damage of resource" (Table 3.4).

On the other hand, although the transporting contribution is not the smallest in these 5 major impact categories, but it has not altered the ranking of contributors. Which means the top 3 contributors are the same in "BRC production" and in "BRC Production plus transportation".

Table 3.4: Key Contributors in Major Impact Categories

Damage category	Impact category	BRC Production	BRC is delivered (Truck+ Train250km)
Human Health (DALY)		**Figure 3.10**	**Figure 3.6**
	Global warming, Human health	Sodium silicate	Sodium silicate
		Direct Emission	Direct Emission
		Heat	Heat
	Fine particulate matter formation	Sodium silicate	Sodium silicate
		Sand(0-4mm)	Sand(0-4mm)
		electricity	electricity
Ecosystem (species.yr)		**Figure 3.12**	**Figure 3.7**
	Global warming, Terrestrial ecosystems	Sodium silicate	Sodium silicate
		Direct Emission	Direct Emission
		Heat	Heat
	Terrestrial acidification	Sodium silicate	Sodium silicate
		Sand(0-4mm)	Sand(0-4mm)
		electricity	electricity
Resources (USD2013)		**Figure 3.14**	**Figure 3.8**
	Fossil resource scarcity	Heat	Heat
		Sodium silicate	Sodium silicate
		Sand(0-4mm)	Sand(0-4mm)

color code:	Top	Contributor
	Second	
	Third	

3.4 Comparison of Producing Bauxite Residue Concrete in EU and China

In our peer group, "Philip Gjedde" has investigated the life cycle impact of inorganic binder (BR geopolymer) in the case that it was **produced** in EU. The " 'ReCiPe2016' endpoint result" was calculated in Simpro, with the same recipe[31].The difference in the life cycle inventory is that material and energy supply has been chosen from EU sources.

Additionally, the impact of "substituting normal concrete" is included in his figure, which is presented as "***Lean concrete***" (Figure 3.9, 3.11, 3.13). It has contributed the largest *negative* impact on all 3 "damage area" by suppressing certain amount of "Lean concrete" usage. But we have only compared the impact of "BR concrete production", which is mainly the ***positive*** scales in those figures.

3.4.1 Impact on Human Health

Regarding the "damage of human health", total scale of "Global warming, Human health" is around "0.0007 DALY" in the EU case (Figure 3.9), which is about 30% lower than in the Chinese case (≈0.001DALY in Figure 3.10). And the dominant contributors are "Sodium silicate" and "direct emission" in EU case. But in the Chinese case, alongside the dominance of "Sodium silicate (Sodium S)", the "Heat" has presented similar impact as "direct emission from production".

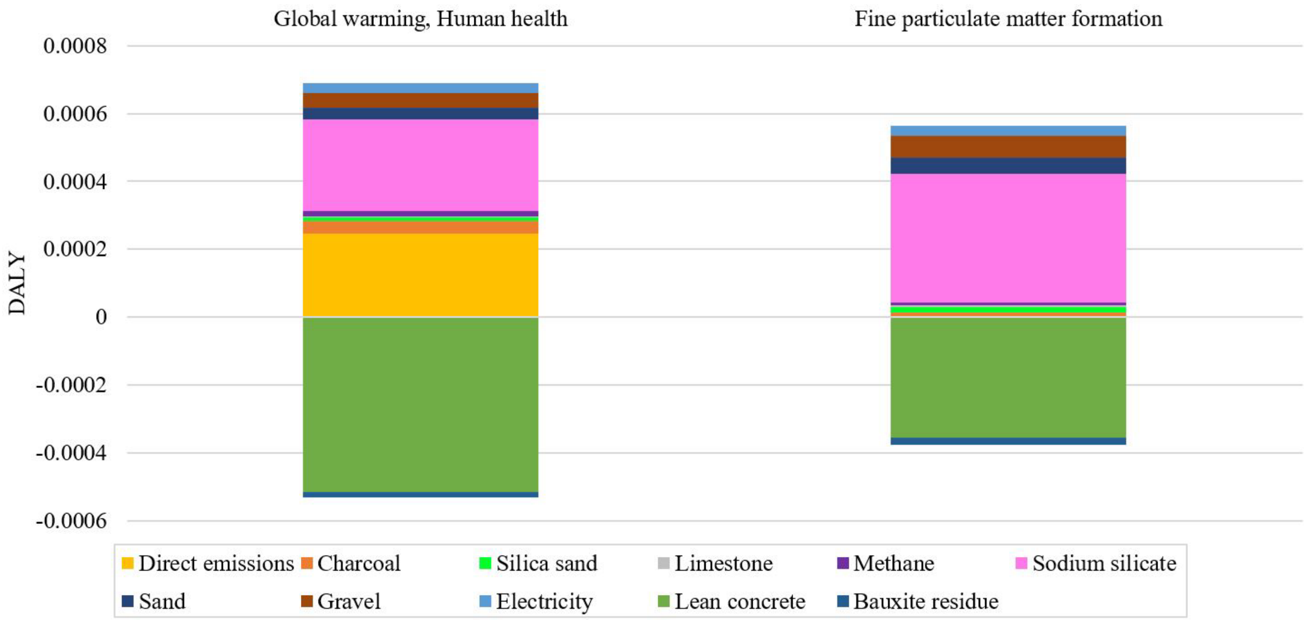


Figure 3.9: Contributors in Impacts on Damage of Human Health (EU)[31]

The impact on "Fine particulate matter formation" has shown similar relevance, which the value is about 70% (0.00058DALY) in EU case (Figure3.9) comparing with Chinese case (≈0.0008DALY in Figure 3.10). Among those contributors, "Sodium silicate (Sodium S)" is the dominator in both EU case (≈ 70%) and Chinese case (≈ 60%). But "Sand" has shown different importance between EU case and Chinese case. It is the 2nd largest contributor in Chinese case, but it seems likely the 3rd in EU case which is after the "Gravel".

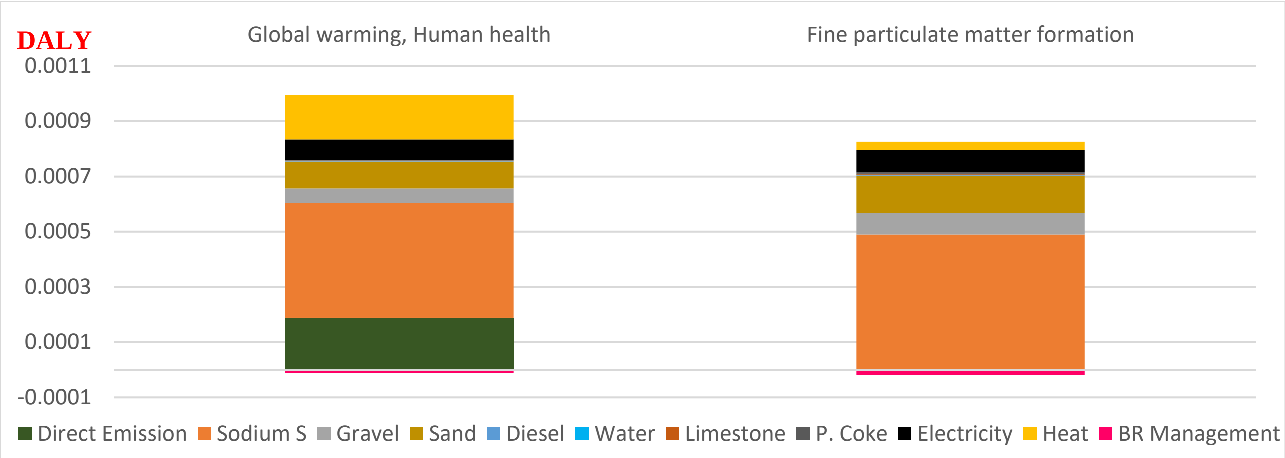


Figure 3.10: Contributors in Impacts on Damage of Human Health (CN)

In both major impact on "damage of human health", the EU case has presented lower positive impact in total value. Which is accounted for approximately 70% of the Chinese case.

3.4.2 Impact on Ecosystem

Among those impact categories for "damage of ecosystem" (Figure 3.11and Figure 3.12), the EU "Global warming, Terrestrial ecosystems (≈0.0000021species.yr)" is about 30% less than the Chinese value (≈0.000003species.yr); whilst, the EU "Terrestrial acidification (≈0.0000004 species.yr)" is approximately 40% lower than Chinese scale(≈0.0000007 species.yr). But the "Land use" in EU (≈0.0000006 species.yr) is almost doubled up comparing with the Chinese number (≈0.0000003 species.yr).

The positive values in "Ozone formation, Terrestrial ecosystems" and "Freshwater eutrophication" are almost the same in both cases. Interestedly, "consuming 'Bauxite residue' (BR Management)" has contributed "largest negative impact" to the "Freshwater eutrophication" in both cases.

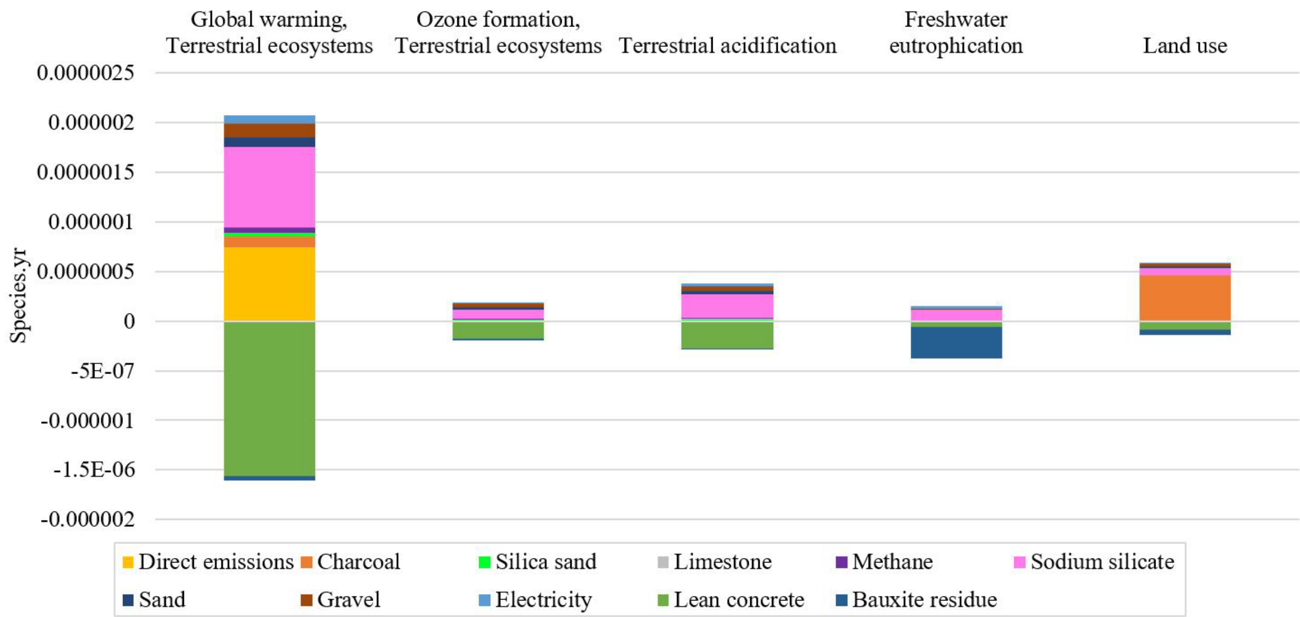


Figure 3.11: Contributors in Impacts on Damage of Ecosystem (EU)[31]

Among those contributors to the "Global warming, Terrestrial ecosystems" and "Terrestrial acidification", the "Sodium silicate (Sodium S)" is still the dominator in both EU and Chinese case. But the "key contributor to the 'Land use' in EU case" is "Charcoal" (≈ 80%).

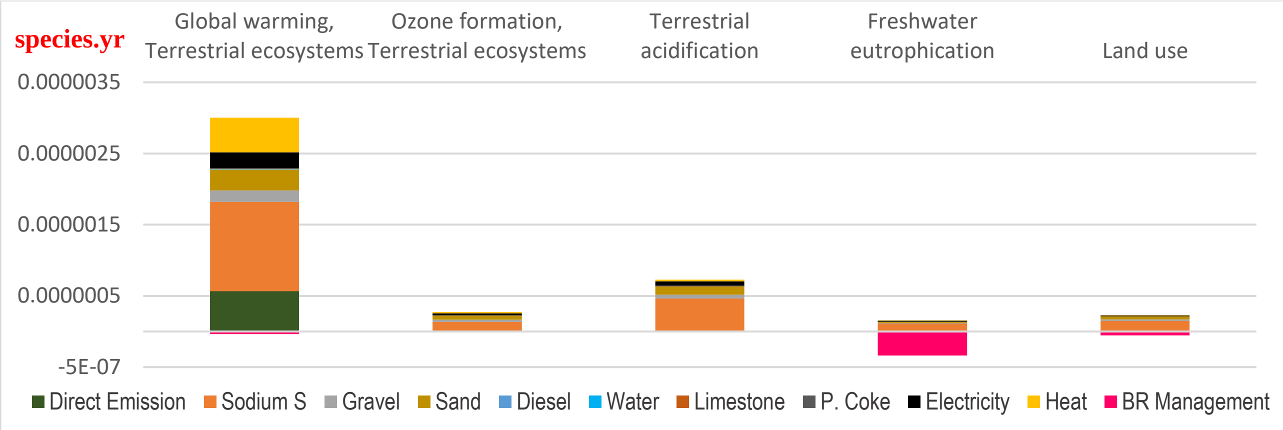


Figure 3.12: Contributors in Impacts on Damage of Ecosystem (CN)

In brief, for the positive impact on "Global warming, Terrestrial ecosystems" and "Terrestrial acidification", EU case has presented "30 - 40%" lower total amount than the Chinese case. But the "Land use" in EU case is much higher. Meanwhile, avoiding "Lean concrete" hasn't contributed negative impact in all categories.

3.4.3 Impact on Resource Scarcicity

"Fossil resource scarcity" is the dominant category of impact on the "damage of resource" in both EU(Figure 3.13) and Chinese case (Figure 3.14). The number is approximately "48 USD2013" in EU case, which is about 80% of the amount in Chinese case (≈59 USD2013).

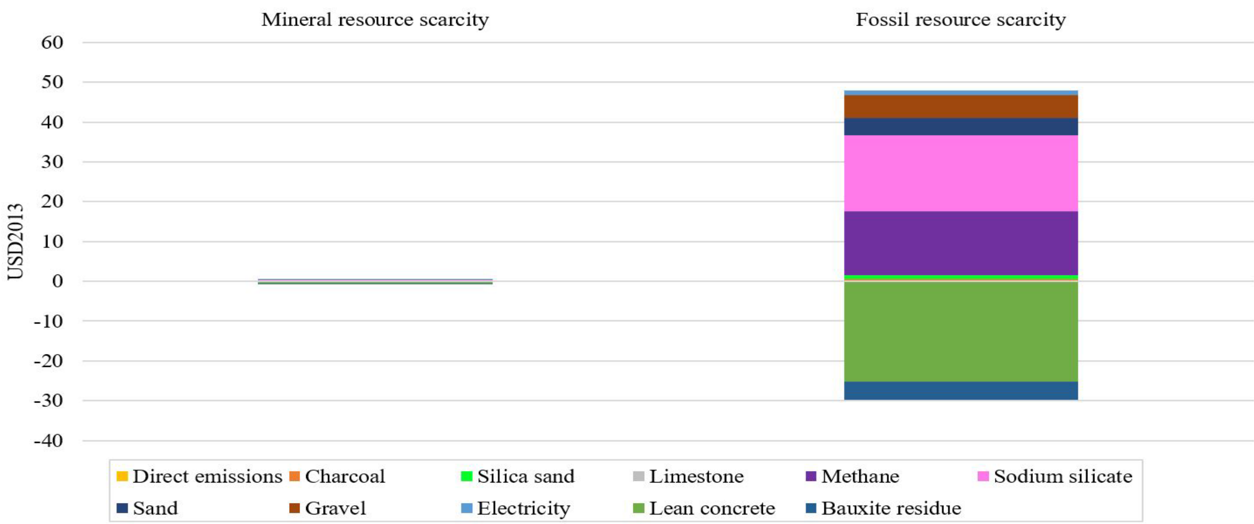


Figure 3.13: Contributors in Impacts on Damage of Resource (EU)[31]

The “Sodium silicate (Sodium S)” is top contributor in EU case, but it is the second in Chinese case. The largest contributor is the “Heat” to the Chinese “Fossil resource scarcity”.

For the EU case, “Methane” is the second largest contributor to the “Fossil resource scarcity”. But if it was ***only*** used for *generating heat*; then, “sodium silicate” and “heating” are the top 2 factors in both cases. However, and “Sand” has contributed more in the Chinese case than in the EU case.

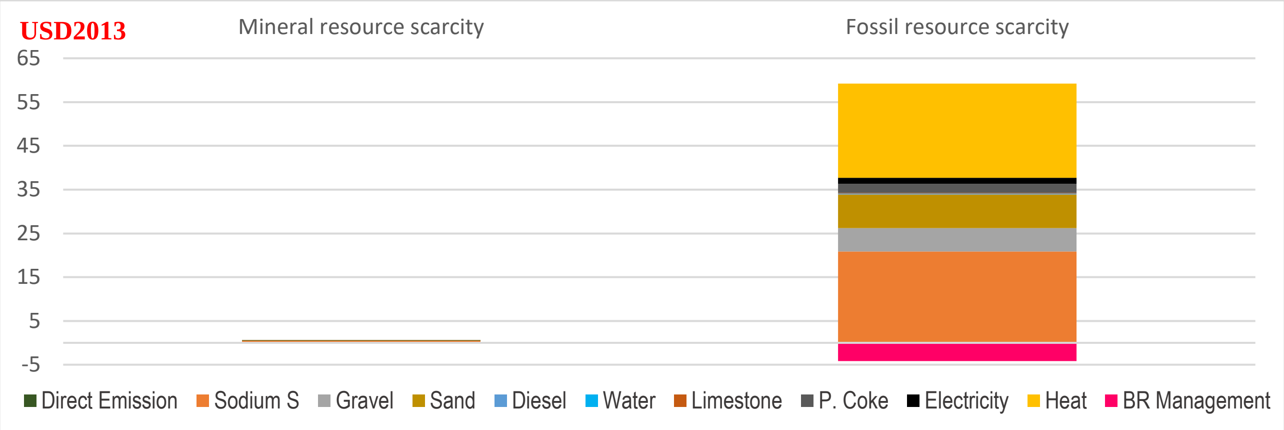


Figure 3.14: Contributors in Impacts on Damage of Resource (CN)

3.5 The Significance of transportation in Commercial Scheme

Normally, the commercial concrete is not applied at where they were produced. Therefore, to reflect the total environmental impact, transportation is ought to be accounted. In the overview of damage assessment which was presented in *percentage* (Figure 3.3), transportation has not presented as key contributor to any of the 3 damage areas.

Two scenarios of transportation were investigated in this section, they are “local supply” and “regional supply”. In the “local supply”, only transporting lorry was accounted, to simulate that the BR concrete is produced in the same alumina plant and delivered(50.67km) to the surrounding construction site. Whilst the “regional supply” has simulated that the “BR polymer” has been carried to the “concrete batching plant” by train(250km), and after mixing there, it is delivered by lorry(50.67km) to the construction site.

Although “Sodium silicate (Sodium S)” has shown the dominance. But, to understand how important the transportation is, especially in climate change, we have also analysed the percentage of transporting impact in 5 major impact categories.

They are: the “Global warming, Human Health (GW, HH.)” and “Fine particulate matter formation (P M F.)” in “damage of human health”, the “Global warming, Terrestrial ecosystems (GW, TrEC.)” and “Terrestrial acidification (Tr, ACD.)” in “damage of ecosystems”. And the “Fossil resource scarcity (FRS)” is the impact category to the “damage of resource”.

3.5.1 Local Supply Scenario

In the case of BR concrete is delivered only by truck to the surrounding construction site (Figure 3.15), the highest significance (by truck) was in the impact on “Fossil resource scarcity (FRS)”, which is almost 12%. The proportion is around 4 – 5 % in the other 4 major categories.

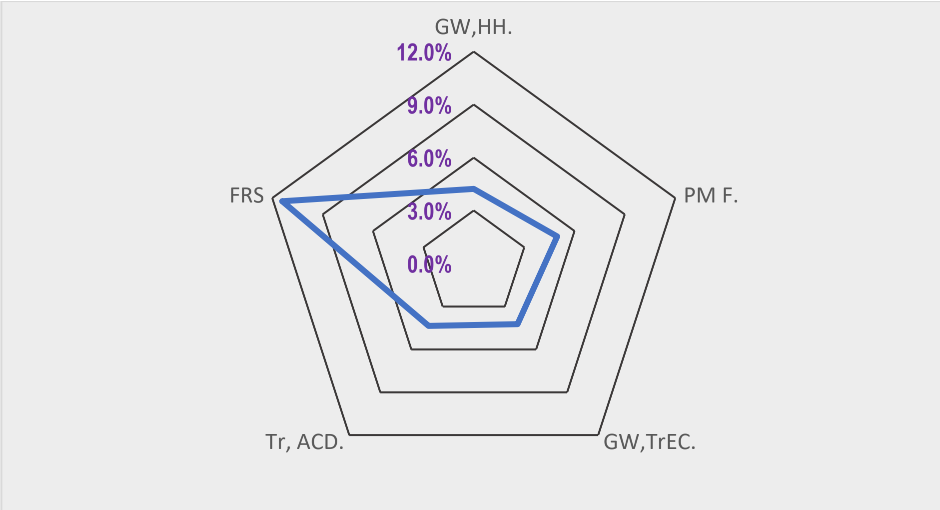


Figure 3.15: Transporting Significance in Local Supply Scenario

GW, HH. = Global Warming, Human Health, P M F. = fine Particulate Matter Formation, GW, TrEC. = Global Warming, Terrestrial Ecosystems, Tr, ACD. = Terrestrial acidification, FRS = Fossil Resource Scarcity

3.5.2 Regional Supply Scenario

In the case that the “BR polymer” was transported by train(250km) and the BR concrete is delivered by truck(50.67km) to construction sites (Figure 3.16), the highest significance of “truck” was still in the impact on “Fossil resource scarcity (FRS)”, which is almost 12%.

The train has presented higher proportion than the truck in “Fine particulate matter formation (P M F.)” and “Terrestrial acidification (Tr, ACD.)”. Which are approximately 7% and 5% respectively.

Regarding the summing of 2 transporting percentage, the highest proportion is still in the impact on “Fossil resource scarcity (FRS)”, which is almost 15% in total (Truck + Train). Whilst they are approximately “9% – 11%” in “Fine particulate matter formation (P M F.)” and “Terrestrial acidification (Tr, ACD.)”.

Interestedly, it is only about 7% in the “Global warming, Human Health (GW, HH.)” and the “Global warming, Terrestrial ecosystems (GW, TrEC.)”. which means the significance of transport is relatively low in the impact on “Global warming”, but it is higher on the “Fossil resource scarcity”.

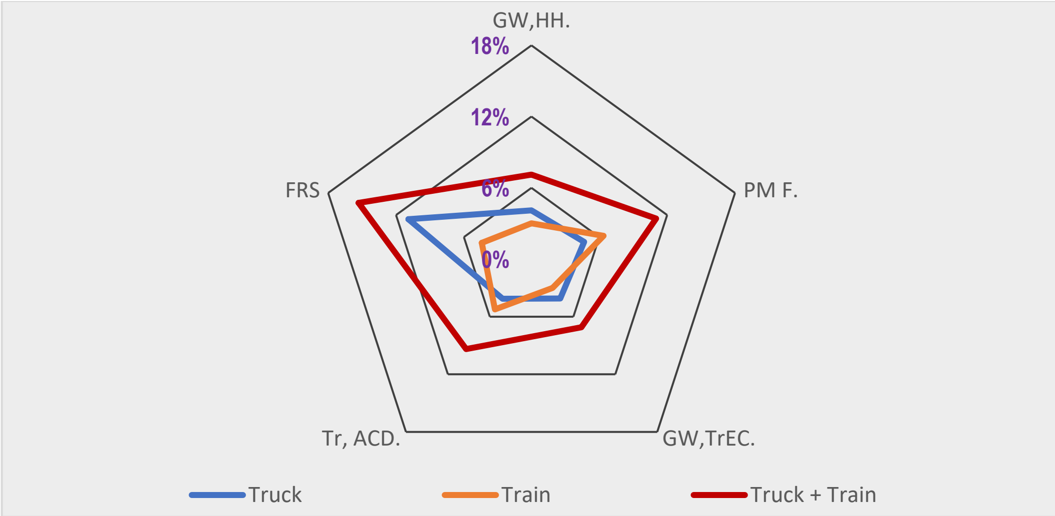


Figure 3.16: Transporting Significance in Regional Supply Scenario

GW, HH. = Global Warming, Human Health, P M F. = fine Particulate Matter Formation, GW, TrEC. = Global Warming, Terrestrial Ecosystems, Tr, ACD. = Terrestrial acidification, FRS = Fossil Resource Scarcity

The detailed percentage of transporting impact in 5 major categories have been calculated (Table 3.5). In general, lorry transport has shown the dominance in "Fossil resource scarcity" for 2 former transporting scenarios. When the train is employed, percentage of "lorry transport" is still higher than "freight train" in "Global warming, Human Health (GW, HH.)" and "Global warming, Terrestrial ecosystems (GW, TrEC.)".

But, if the train has travelled long enough, its proportion could exceed the lorry transport. E.g., suppose the BR polymer is transported with 1000km(by train), the result would change accordingly.

Table 3.5: Transporting Significance in Three Scenarios

Transporting Scenario / Impact Categories	Local Supply	Regional Supply			Interprovincial supply		
	Truck	Truck	Train(250km)	Truck + Train	Truck	Train(1000km)	Truck + Train
Global warming, Human health	4.2%	4.1%	3.0%	7.1%	3.8%	11.0%	14.8%
Fine particulate matter formation	5.0%	4.7%	6.4%	11.0%	3.9%	21.4%	25.3%
Global warming, Terrestrial ecosystems	4.2%	4.1%	3.0%	7.1%	3.8%	11.0%	14.8%
Terrestrial acidification	4.4%	4.1%	5.2%	9.4%	3.6%	18.1%	21.7%
Fossil resource scarcity	11.4%	10.9%	4.4%	15.3%	9.6%	15.6%	25.2%

3.6 Possibly Change of those results

The recipe of "BR polymer and concrete" was predefined in this research, but the result may be altered by some factors. We have investigated 2 variables which could influence the result, one is for the *transport significance*, the other is for the impact of *BR concrete production*.

3.6.1 Interprovincial Supply Scenario

There are 31 provinces in mainland of China (Appendix C), in some cases, the inorganic binder (BR polymer) could be sold to the construction site in another province. And to convey the BR polymer, freight train could travel far more than 250km.

Since “250km train traveling” has reached the north boundary of Shanxi (SX) province, and it has reached over half of distance to the south boundary (Appendix B). Then, “1000km by train” should be practical to “convey the BR polymer to the neighboring provinces”. So, we have analyzed the “Interprovincial supply” with “1000km train traveling”.

In the case that “BR polymer” is transported by “freight train” with 1000km, and the “BR concrete” is delivered by truck(50.67km) to construction sites (Figure 3.17), the “highest percentage of ***truck”*** was still the impact on “Fossil resource scarcity (FRS)”. But it has dropped to around 10%, and it is approximately 4 % in other 4 major categories. But the ***train*** has presented much higher proportion than *truck* in all 5 major impact categories, especially in the “Fine particulate matter formation (P M F.)” and “Terrestrial acidification (Tr, ACD.)”, which are around 20%.

Regarding the summing of 2 transporting impact, the highest proportions have been presented in the “Fossil resource scarcity (FRS)” and “Fine particulate matter formation (P M F.)”, which are around 25% in total (Truck + Train). And it is about 20% in “Terrestrial acidification (Tr, ACD.)”. Meanwhile, it has raised up to 15% in the “Global warming, Human Health (GW, HH.)” and the “Global warming, Terrestrial ecosystems (GW, TrEC.)”. which means the significance of transport is ***not trivial*** to the impact on “Global warming” anymore.

In other words, “extending the BR polymer transport (by ***train***)” could increase the significance of transportation in total impact. But the route-length for delivering concrete(by truck) is relatively anchored(≤ 50km), due to the concern of “early solidification” regarding its performance [63]. So, the truck transport is not a major concern in this case.

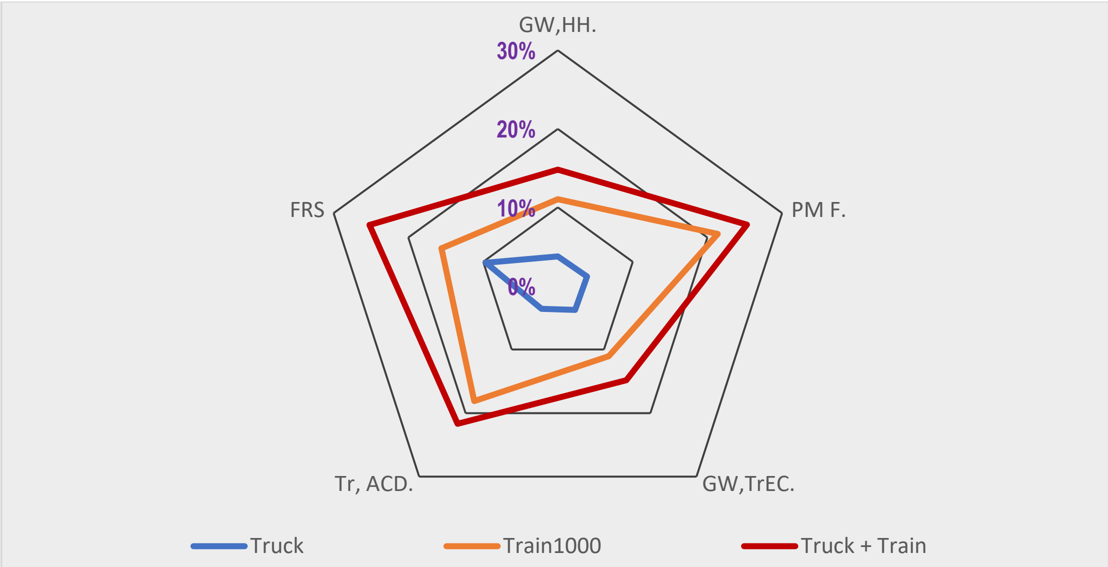


Figure 3.17: Transporting Significance in Interprovincial Supply Scenario

GW, HH. = Global Warming, Human Health, P M F. = fine Particulate Matter Formation, GW, TrEC. = Global Warming, Terrestrial Ecosystems, Tr, ACD. = Terrestrial acidification, FRS = Fossil Resource Scarcity

3.6.2 Deployment of Lower-carbon-emission Electricity

According to the statistics from NBSC[56], The proportion of Thermal power has kept declining during last decade in China(Table 3.6), whilst the total electricity production was rising. Meanwhile, as “low carbon emission power resources”, occupation of “nuclear power and wind power” was continuously increased, but the “percentage of hydro power” was fluctuated.

Table 3.6: Allocation of Electricity Production in China

year	2011	2012	2013	2014	2015	2016	2017	2018	2019	Varying Trends
Total Electricity (billion kw.h)	4713.02	4987.55	5431.64	5794.46	5814.57	6133.16	6604.45	7166.13	7503.43	
Thermal Power(%)	81.3%	78.1%	78.2%	75.9%	73.7%	72.3%	72.0%	71.1%	69.6%	
Hydro Power(%)	14.8%	17.5%	16.9%	18.5%	19.4%	19.3%	18.1%	17.2%	17.4%	
Nuclear Power(%)	1.8%	2.0%	2.1%	2.3%	2.9%	3.5%	3.8%	4.1%	4.6%	
Wind Power(%)	1.5%	1.9%	2.6%	2.8%	3.2%	3.9%	4.5%	5.1%	5.4%	

On the other hand, ***Solar Power***, as another renewable energy resource, was lack of data from NBSC. But the photovoltaic capacity has continuously increased, “China's domestic PV market has seen a steady growth, with its cumulative installed capacity rising from140 MW in 2008 to 300 MW in 2009, and to 800 MW in 2010, then surging to 3300 MW in 2011”[64]. Afterwards, solar has been tremendously deployed in China, until the end of 2020, the “photovoltaic capacity” was 253GW already[65].

Recently, BBC has reported that, the Chinese top leader has given a speech to the “UN General Assembly” in September 2021. According to the official translation, “We aim to have CO2 emissions peak before 2030 and achieve carbon neutrality before 2060.” is the ambition of Chinese government for contributing to “climate change mitigation” [66].

According to news from “Xinhua agency”, the government has released a new working guidance for achieving the goal of “carbon peak and carbon neutrality”. The major objective was presented as:

“二、主要目标

到 2025 年，绿色低碳循环发展的经济体系初步形成，重点行业能源利用效率大幅提升。单位国内生产总值能耗比 2020 年下降 13.5%；单位国内生产总值二氧化碳排放比 2020 年下降 18%；非化石能源消费比重达到 20%左右；森林覆盖率达到 24.1%，森林蓄积量达到 180 亿立方米，为实现碳达峰、碳中和奠定坚实基础。

到 2030 年，经济社会发展全面绿色转型取得显著成效，重点耗能行业能源利用效率达到国际先进水平。单位国内生产总值能耗大幅下降；单位国内生产总值二氧化碳排放比 2005 年下降 65%以上；非化石能源消费比重达到 25%左右，风电、太阳能发电总装机容量达到 12 亿千瓦以上；森林覆盖率达到 25%左右，森林蓄积量达到 190 亿立方米，二氧化碳排放量达到峰值并实现稳中有降。

到 2060 年，绿色低碳循环发展的经济体系和清洁低碳安全高效的能源体系全面建立，能源利用效率达到国际先进水平，非化石能源消费比重达到 80%以上，碳中和目标顺利实现，生态文明建设取得丰硕成果，开创人与自然和谐共生新境界。”[67]

From google translation in English, it means:

“By 2025, an economic system of green and low-carbon circular development will take shape, and the energy efficiency of key industries will be greatly improved. Energy consumption per unit of GDP will be reduced by 13.5% compared to 2020; carbon dioxide emissions per unit of GDP will be reduced by 18% compared to 2020; the proportion of non-fossil energy consumption will reach about 20%; the forest coverage rate will reach 24.1%, and the forest stock will reach 18 billion cubic meters, laying a solid foundation for achieving carbon peak and carbon neutrality.

By 2030, significant results will be achieved in the overall green transformation of economic and social development, and the energy efficiency of key energy-consuming industries will reach the international advanced level. Energy consumption per unit of GDP has dropped significantly; carbon dioxide emissions per unit of GDP have dropped by more than 65% from 2005; the proportion of non-fossil energy consumption has reached about 25%, and the total installed capacity of wind power and solar power has reached more than 1.2 billion kilowatts; forest coverage The rate reached about 25%, the forest stock volume reached 19 billion cubic meters, and the carbon dioxide emissions reached the peak and achieved a steady decline.

By 2060, a green and low-carbon circular economic system and a clean, low-carbon, safe and efficient energy system will be fully established. The energy use efficiency will reach the international advanced level, and the proportion of non-fossil energy consumption will reach more than 80%. The goal of carbon neutrality will be successfully achieved. The construction of civilization has achieved fruitful results, creating a new realm of harmonious coexistence between man and nature”[67].

In the case of “***Producing BR concrete in China***”, the energy was provided by diesel and electricity to drive the machine in “concrete mixing”. Since emission from the “lower carbon emitting electricity” (Figure 1.6) is trivial comparing with fossil technologies (oil, gas, coal). Therefore, with 25% of “non-fossil electricity” is deployed, the emission would reduce approximate 25% as well. Meanwhile the reduction will be “1-2%” in the 5 major impact categories.

If the **heat** is also generated by electricity, “25% reduced emission” will lead to “3-9%” of declining in 5 major impact categories. And it would decrease “9 – 28%” when 80% non-fossil electricity is in use.

4 Discussion and Conclusion

In this chapter, we have introduced the *assumption* and *uncertainty*. “***Findings, value, and limitation”*** have been discussed. We have also dropped the ***conclusion*** and left some ***recommendation*** for further research.

4.1 Discussion

4.1.1 Assumption

Above all, we assumed there is no technical barrier would prevent to launch the BRC production. Which means the processes are feasible for most of the alumina plants in mainland of China.

4.1.1.1 Materials

Regarding the material availability, we have assumed that “bauxite and Bayer process” are still the majority for alumina production. And it would be continuously employed for years. Furthermore, we assumed that the “BR in Chinese alumina plant” has similar performance with the “BR in the KUL research”.

4.1.1.2 Concrete Performance

We did not compare the performance of BR concrete with the conventional concrete. So, the precondition is that their performance is similar in the realistic application. At least the BR concrete can replace some type of conventional concrete which is widely used in mainland of China.

4.1.1.3 Life Cycle Inventory

In the LCI list, there are quite a few elements chosen from “RoW” (Table 3.3), Which means we assumed that property of “RoW item” is close enough to the Chinese case. Gap may also exist if technology is developed between the periodical updating in Eco-invent database.

4.1.1.4 Transporting Method

“BR concrete” is still under research, which was not launched into business yet, therefore the “data and method of transportation” has been borrowed from the “operation of conventional concrete”. We assumed that the truck mixer is applicable for carrying BR concrete. Furthermore, there is no extra demand for freight train to carry BR polymer.

4.1.1.5 Construction Technology

“BR concrete” may **not** be launched in China recently, therefore we assumed that the current construction technology will be continued in China, and commercial concrete would ***not*** be eliminated from the construction activity. On the other hand, we assumed that the energy consuming will not increase in “concrete mixing” with time on.

4.1.2 Key Findings

In general, the LCIA result has indicated that the negative impact is highly depending on the "BR Management". Because of "BR Management" was the major contributor to the negative impact on all 3 damage areas. However, it can only turn the total impact into ***negative*** on "damage to human health", but not on the "damage of ecosystem" and the "damage of resource".

There are 22 impact categories in LCIA result at endpoint (Table 2.1), expect the 5 toxic categories, the rest 17 are non-toxic impact categories. And "avoiding toxicity in BR" is the key factor which contributes the negative impact on "damage to human health". Therefore, the ***total impact*** has not presented negative values in "non-toxic categories". Obviously, the "BR Management" has negatively impacted on 2 "**non-toxic categories"**, they are: "Freshwater eutrophication" in "damage of ecosystem", and "Fossil resource scarcity" in "damage of resource".

Among 17 **non-toxic** impact categories, 5 major categories have presented dominance on positive impact. "Global warming" and "Fine particulate matter formation" are 2 major impact categories in the "damage of human health" (Figure 3.6). For the "damage of ecosystem", the positive impact has mainly presented on the "Global warming, Terrestrial ecosystems" and the "Terrestrial acidification" (Figure 3.7). Whilst the dominant impact has been presented on "Fossil resource scarcity" in the "damage of resource" (Figure 3.8).

"Sodium silicate" is the top contributor to the major impact categories in the "damage of human health" and "damage of ecosystems", and it is the second largest contributor to "Fossil resource scarcity", which is the dominant impact category in the "damage of resource" (Table 3.4). On the other hand, although the transporting contribution is not the smallest in these 5 major impact categories, but it does not alter the ranking of contributors. Which means the top 3 contributors are the same in "BRC production" and in "BRC Production plus transportation".

4.1.2.1 Raw material availability

BR was not generated in all 31 provinces, among those BR producers, 4 provinces has present continuously large amount of alumina production (table3.1). So, "sufficiently supplied bauxite residue" was expectable in these 4 regions.

4.1.2.2 Comparing Production in EU Case and Chinese Case

Regarding the ***positive impact*** from the "BR concrete production", the EU case has presented lower total amount in 2 major categories of "damage of human health". Which is accounted for approximately 70% of the Chinese case in "Global warming" and "Fine particulate matter formation".

For the ***positive impact*** on "damage of ecosystems", the EU case has presented "30 - 40%" less than the Chinese case on "Global warming, Terrestrial ecosystems" and "Terrestrial acidification". But the "Land use" in EU case is higher.

"Fossil resource scarcity" is the dominant category of impact on the "damage of resource" in both EU case (Figure 3.13) and Chinese case (Figure 3.14). The number in EU case (≈48 USD2013), which is approximate 80% of the number in Chinese case (≈59 USD2013).

4.1.2.3 Significance of transport

Transporting by lorry has shown the highest percentage in "Fossil resource scarcity" for 2 simulated transporting scenarios ("Local supply" and "Regional supply"). In the condition that "freight train" is accounted in the "Regional supply" (Figure 3.16), the percentage of "lorry transport" is still higher than train in "Global warming, Human Health (GW, HH.)" and "Global warming, Terrestrial ecosystems (GW, TrEC.)". But, if the train has travelled 1000km, its proportion would exceed the lorry transport (Table 3.5).

4.1.2.4 Possible Change in Future

The transport is not a trivial contributor to the impact of "Global warming", especially when the BR polymer is interprovincially transported by freight train(1000km). Which means the "extension of transporting BR polymer" is possible to change the significance of transport in total impact. Since the route-length of delivering concrete(by truck) is relatively anchored(≤ 50km), due to the concern of "early solidification" regarding its performance [63]. Truck cannot alter the significance of transportation in environmental impact.

Regarding the "production of BR concrete" in Chinese case, the energy was provided by diesel and electricity to drive the machine in "concrete batching plant". In the past, the statistics has shown that the "deployment of non-fossil electricity technology" was kept increasing, while the electricity production was rising (Table 3.6). Furthermore, the authority has setup the goal of reducing fossil energy by 2030(25%) and 2060(80%).

Since the emission from the "non-fossil electricity" (Figure 1.6) is trivial comparing with fossil technologies (oil, gas, coal). If 25% of "non-fossil technology" is applied in electricity, the electricity emission would reduce approximate 25% as well. Meanwhile the total impact would reduce "1-2%" in the 5 major impact categories.

If the **heat** is generated by electricity as well, "reducing 25% of fossil electricity" will lead to "3-9%" of declining in 5 major impact categories. And it would decrease "9 – 28%" when 80% non-fossil electricity is deployed.

4.1.3 Uncertainty

There is A few other factors might influence the result or future trends. Which were not addressed as primary part in this research, but they could be extended in future research.

4.1.3.1 Toxicity

The toxicity of "bauxite residue" was the normal concerning, because of the mobilized Al and "Chromium hexavalent form (Cr VI)", but "water- soluble Al" was recognised as a "neurotoxic agent"[68]. And the Chromium has been argued that it could not be mobilized in Bauxite residue[69], which is normally presented as a "highly alkaline slurry (pH 10–12.5)"[68]. Additionally, "Ecoinvent data" has taken the "Cr(VI) was emitted to freshwater" into the largest account, some researchers have argued that it was "overestimated" in result of LCIA[70]. Therefore, the extent of ecotoxicity is uncertain.

4.1.3.2 Continuity of Material avaiability

Regarding the alumina production, a new technology was introduced "in recent 20 years". Which was switching the feed from bauxite to "aluminum hydroxide"[6]. Whatever whether the total environmental impact could be reduced or not. But it may alter the BR availability as raw material.

4.1.3.3 Data Qualilty

We took the updated data via the English user interface [56].Since there was some errors found in previous research, it might be different in the future. Another uncertainty is about the regional "alumina production capacity", it is possible that some mini alumina plant was not found through our data collecting process.

4.1.3.4 Ecoinventory and LCI uncertainty

Eco-invent is a large database, the database is being updated periodically, even the LCI input is the same, the results can be different. I.e., the presented result was calculated on 25th June 2021, but it could be different in 2022.

There was no dedicated element for " Truck Mixer". Therefore, freight lorry was applied in our calculation, but it was uncertain how big the gap could be on the fossil consumption and emission.

4.1.3.5 Environmental benefit

In our case, environmental benefit has ***not*** been investigated for “replacing conventional concrete with the BR concrete”. However, even the total impact “from BR concrete production” is ***less*** than “from conventional concrete production”, the advantage might be washed away by the other activity. E.g., longer transporting for BR polymer. Or more general, the supply chain setup could turn the weakly environmental *benefit* into *burdens*.

4.2 Conclusion

In general, the damage assessment has indicated that the negative impact is highly depending on the “BR Management”. “Avoiding toxicity in BR” is the key factors contributing the negative impact on “damage to human health”. But, the total impacts were not negative in “non-toxic categories”.

Among 17 **non-toxic** impact categories, 5 dominant impact categories are “Global warming, human health”, “Fine particulate matter formation”, “Global warming, Terrestrial ecosystems”, “Terrestrial acidification” and “Fossil resource scarcity”. Which have contributed the majority of positive impact on 3 damage area. And “Sodium silicate” is the **key** contributor to **5** major impact categories**, although** it is the second largest contributor to “Fossil resource scarcity”, but the value is very close the largest contributor — “Heat”.

On the other hand, “transporting contribution” does not alter the ranking of contributors. Which means the top 3 contributors are the same in “BRC production” and in “BRC Production plus transportation”.

Regarding ***BR concrete production***, the difference with the Chinese case is that, the EU case has presented lower positive impact in total amount. In the 5 major impact categories, it is accounted for approximately “60% - 80%” of the positive contributions of Chinese case. But EU case has presented higher positive impact in “Land use” than the Chinese case.

Regarding the ***significance of transportation***, lorry(50.67km) has shown stronger impact on “Fossil resource scarcity” than other categories. When the “train transporting for BR polymer (250km)” is accounted in the “Regional supply”, the “percentage of lorry transporting in total impact” is still higher than the train in 2 “Global warming” categories and the “Fossil resource scarcity”.

Concerning about the ***possible changes***, travelling distance of the freight train is the factor which may alter the “significance of transportation in the positive environmental impact”. Whilst the “deployment of electricity technology” may affect the positive impact on BR concrete production.

The transporting contribution was not trivial (≈ 4% or 11%) to the impact of “Global warming”. But if the “BR polymer” is transported 1000km by train, the “transporting positive-impact” could raise up to “15% - 25%” in those 5 major impact categories.

For the “BR concrete production” in the Chinese case, the energy was provided by diesel and electricity to drive the machine in “concrete batching plant”. Since the deployment of non-fossil electricity technology was kept rising (Table 3.6) in the previous decade. According to the authority, “reducing fossil energy by 2030(25%) and 2060(80%)” has been setup as the goal in future.

Considering electricity consumption, with 25% of deployment of “non-fossil electricity”, it could lead to approximate 25% reduction in GHG emission. And the total impact would reduce “1-2%” in the 5 major impact categories.

If the **heat** is generated by electricity as well, “reducing 25% of fossil electricity” could lead to “3-9%” of declining in 5 major impact categories. And the reduction would be “9 – 28%” when 80% “non-fossil electricity” is deployed.

4.3 Values and Limitation

In this research, we have introduced the basis of LCA, and some extended LCA knowledge besides the ISO standard. Further, we have introduced a “thinking- pathway” to analyse LCIA result.

4.3.1 Values

Firstly, we have introduced the key point of picking element from database of Eco-inventory. We also presented a way to construct the “life cycle inventory”, and to apply it in a LCA software (SimaPro). Which can save much time than manually LCA. It will increase efficiency when LCA become a “frequently daily work”.

Secondly, we have presented a method to analyse the LCIA result. Which is “to identify the major impact categories and key contributors”. Moreover, we have introduced: how to compare environment impact, how to figure out the significance of one contributor in total impact, and how to anticipate future trends with relative information.

Finally, we have concluded that, even with same recipe, the “BR concrete production” has present lower contribution to environmental impact in EU than in China. But it could be reduced by deploying more “non-fossil electricity” in the Chinese case. The significance of transporting impact is relevant with the supply chain setup, and the “train travelling distance” is essential.

4.3.2 Limitation

We have focused on figuring out the dominators but not absolute number. But numbers are also supportive for decision-makers or policymakers, if their target is to reach some specific number in some impact categories.

Major limitation of our research is regarding the “resolution”. Which means it may be accurate enough to address the issue regarding one ***technology***, but maybe not enough for address an individual case. e.g., environmental impact of “applying the BRC production in one specific alumina plant”. Because the “individual case study” needs more specific data.

4.4 Recommendation of Further Research

In this research, we have not investigated the total impact on “replacing normal concrete with BR concrete”. Moreover, we did not investigate performance of BR concrete comparing with normal concrete.

The extending research could address these two issues together. It is because of “Avoiding normal concrete” will contribute negative impact. But to figure out whether the result will be positive or negative, it needs more precise information about substitution ratio. It needs to be clarified that “how much normal concrete can be replaced by $1m^3$ BR concrete”, while the same functional performance is provided.

There are two possible directions for improving the “production of BR concrete” as well. Although “BR concrete with current recipe” might introduce *higher environmental impact* than conventional concrete, it is possible to improve with “reducing the Sodium Silicate”. Furthermore, the “Heat” as big contributor, which is most likely can be improved with more advanced technology in the future.

Regarding the transporting impact, according to the Chinese Railway report in 2019[71], 71.9% of railway has been electricalized. I.e., the impact from “freight train” may decrease when the “electricity emission” is reduced. And further research about transporting impact can be focus on addressing this issue.

In General, “turning bauxite residue into inorganic binder” can contribute tremendous negative impact on “damage of human health”. It is an option in the case that human toxicity is mainly concerned. “BR concrete production” has presented higher positive impact in Chinese case than in EU case, but it is possible to reduce. Transporting impact is not the key contributor to “Global warming”, but “long-haul delivery” may raise up its significance in positive impact.

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5 Appendix A

Flowsheet of Bauxite Residue Polymer and Concrete

The flowsheet from the original source (KUL) has been uploaded separately, In case it was still ***not authorized*** to publish, when this thesis has been submitted.

6 Appendix B

Travelling Distance of the Freight Train for Regional Supply

We have measured the railway length from the sampled alumina plant to the north along the railway. And “250 km” is long enough to reach the farthest city at the north boundary (Figure 5.1). Meanwhile, we have checked the location along railway to the south(250km), it is located at approximately 2/3 of total distance from the north boundary to the south boundary.

So, it has been verified that bidirectional 250km on railway has covers approximately 2/3 of SX province from north to south. therefore, “250km travelling” by freight train in Life Cycle Inventory is a realistic setup.

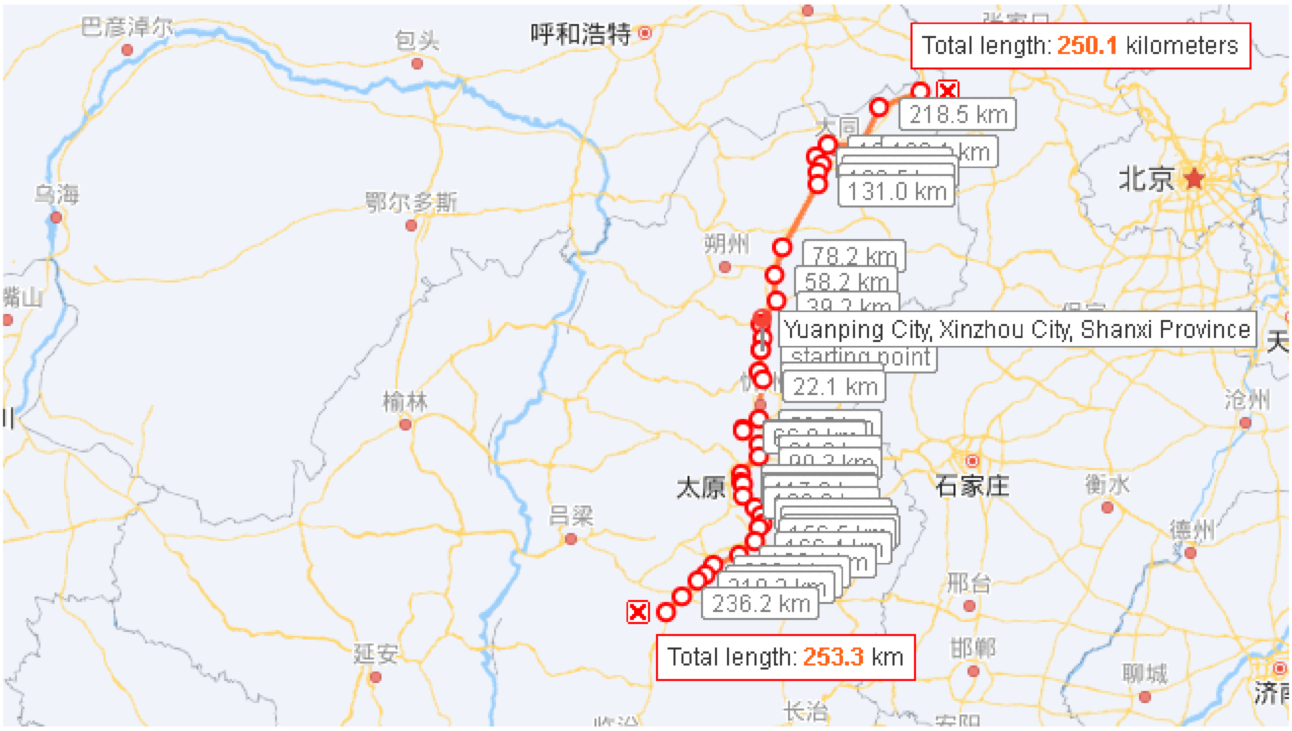

Figure 6.1: Railway Tracks on Train kilometrage [58]

7 Appendix C

Geographic Division in Mainland of China

There are 31 administrative districts in mainland of China, they are equally weighted in the governmental hierarchy. But, their sizes and population density vary vastly. E.g., more than 24 million people live in Shanghai (around 0.634 Mha), but the number in Tibet(123 Mha) is only 3.51 million [10]. The English names, area(Mha), and the *abbreviation code*[42] are listed(Table 6.1), the *abbreviation code* could be used as a regional indicator instead of a full name.

All the regions are irregularly shaped (Figure 6.1), in addition, the administrative division might be changed to comply with the national developing strategy in the future. The status quo in this research was presented on the governmental webpage in 2018 [10]. Those tiny regions, which even the *abbreviation code* is not readable, are marked with the same colour as background in the table. (Table 6.1).

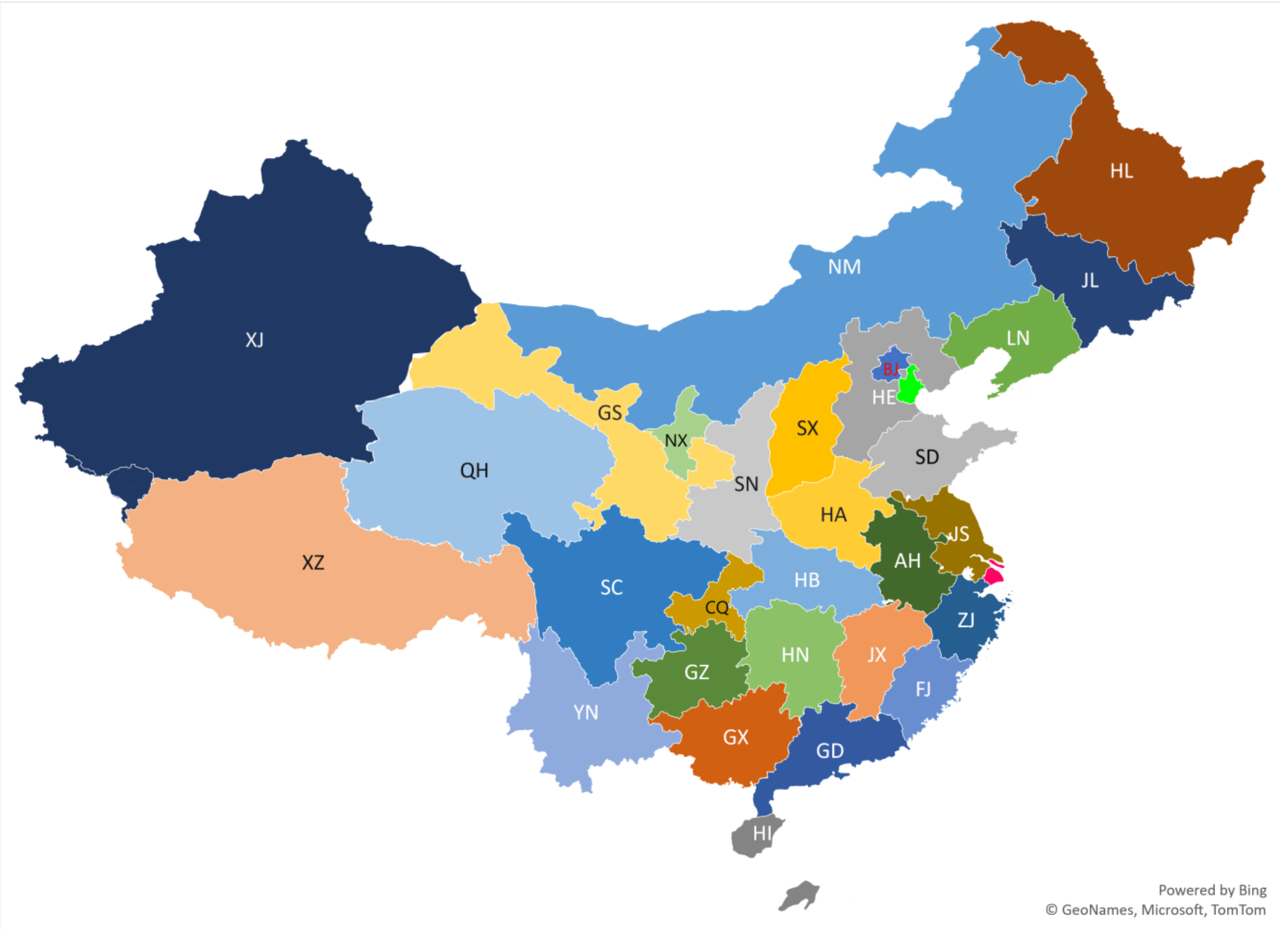

Figure 7.1: Province Level Districts in 2018

Table 7.1: 2018 Chinese Administrative District in Mainland

Full name	Code	(Mha)	Full name	Code	(Mha)
Beijing Municipality	BJ	1.7	Hubei Province	HB	19
Tianjin Municipality	TJ	1.2	Hunan Province	HN	21
Hebei Province	HE	19	Guangdong Province	GD	18
Shanxi Province（晋）	SX	16	Guangxi Zhuang Autonomous Region	GX	24
Inner Mongolia Autonomous Region	NM	118	Hainan Province	HI	3.4
Liaoning Province	LN	15	Chongqing Municipality	CQ	8.2
Jilin Province	JL	19	Sichuan Province	SC	49
Heilongjiang Province	HL	46	Guizhou Province	GZ	18
Shanghai Municipality	SH	0.63	Yunnan Province	YN	39
Jiangsu Province	JS	10	Tibet Autonomous Region	XZ	123
Zhejiang Province	ZJ	10	Shaanxi Province (陕）	SN	21
Anhui Province	AH	14	Gansu Province	GS	43
Fujian Province	FJ	12	Qinghai Province	QH	72
Jiangxi Province	JX	17	Ningxia Hui Autonomous Region	NX	6.6
Shandong Province	SD	16	Xinjiang Uyghur Autonomous Region	XJ	166
Henan Province	HA	17			